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PARAMETRIC MODELLING OF A SOLAR HEATER / DRYER

BY

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THE UNIVERSITY OF ZAMBIA
SCHOOL OF ENGINEERING
DEPARTMENT OF MECHANICAL ENGINEERING

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2001

DECLARATION

I, SATNAM SINGH VIRDY, do hereby declare that this dissertation represents my own work and that, to the best of my knowledge, it has not been previously submitted for the award of a degree at this or any other university.

Signed : ....

Date : 27/02/2001

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APPROVAL

This Dissertation of VIRDY SATNAM SINGH is approved as partial fulfillment of the requirements for the award of the Degree of Master of Engineering in Thermofluids by the University of Zambia..

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ABSTRACT

A numerical model for determining the size of a forced - convection solar fish dryer comprising of a drying bin (in which the fish is kept), a flat plate solar collector and a fan, has been developed. The model comprises of two sections with the first section calculating the technical parameters of the dryer and the second carrying out a cost analysis of the designed dryer. The model is in Delphi code and a number of simulations were carried out for Lusaka weather conditions.

The results of the simulations are presented in two sections. In the first section, dryer simulations are carried out for a design value of 100%-saturated air at the bin outlet whereas in the second, a design value of 80% saturation is used. The parameters studied in the first section include the monthly solar radiation received on both horizontal and inclined surfaces, the variation of collector area required for different seasons, radiation levels, and quantities of fish; the bin size for different quantities of fish; the variation of air flow rate and heater power for different quantities of fish; the total system fan power and the drying times for different quantities of fish for the months of July and October. In the second section, for the solar collector, the variation of collector area, dimensions, hydraulic diameter, efficiency, fan power, and drying time with the heat transfer coefficient were investigated. The drying times required for reducing the moisture content to various levels were studied for various batch sizes. A cost analysis of dryers has also been carried out in this section. For this section, all the simulations were carried out for the month of October.

For the first section, it was found that for a collector mounted in Lusaka, the orientation was only critical for the months of March to October during which it should face north. For the other months, this parameter is not critical. As expected, it was seen that the collector area reduces with increasing radiation. It was also found that the solar collector area, the airflow rate and the heater power vary linearly with increasing fish quantity while the total system fan power varies almost linearly with increasing fish quantity. As would be expected, the drying time in October is shorter than that in July for the same fish quantity. The drying curve also provides a means of deducing the optimum drying periods in a particular day. For the second section, it was found that the collector area, collector width and the drying time show an exponential decrease with increasing heat transfer coefficient. The collector hydraulic diameter however shows a slight exponential decrease with the heat transfer coefficient. On the other hand, the collector efficiency increases exponentially, while the collector fan power increases parabollically with increasing heat transfer coefficient, and the drying time increases linearly with increasing batch size. A cost analysis to obtain the cost per unit of moisture evaporated and the optimum drying time in the day revealed that the cost per unit of moisture evaporated decreases to a minimum at around 15:00 hrs Zambian time which is also the optimum drying time of the day.

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May god bless you all,

Satnam

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DEDICATION

He, whom the True Guru blesses with the collyrium of knowledge, his darkness of ignorance is dispelled.

Guru Arjun dev jee – Fifth Guru

****

To "WAHEGURU", *the creator and almighty, who enables me to strive through the various challenging encounters in life, and to my late brother* Captain Simerpal Singh Virdy.

****

NOMENCLATURE

A = Area (m^2)
A_{ap} = Absorber plate area (m^2)
A_B = Basic bin cross - sectional area (m^2)
A_{BI} = Bin insulation area (m^2)
A_{BSp} = Area of back and side plates (m^2)
A_c = Solar collector area, (m^2)
$A_{c,c}$ = Corrected collector area (m^2)
A_{cc} = Collector cover area (m^2)
A_{cI} = Collector insulation area (m^2)
A_f = Area fraction (Dimensionless)
A_m = Material Area (m^2)
A_{msh} = Mesh area (m^2)
A_S = Surface area of the drying material (m^2)
A_{SBI} = Standard bin insulation area (m^2)
A_{SBSp} = Standard back and side plate area (m^2)
A_{Scc} = Standard collector cover area (m^2)
A_{ScI} = Standard collector insulation area (m^2)
A_{sh} = Bin covering sheet area (m^2)
A_{Smsh} = Standard mesh area (m^2)
A_{Sp} = Standard plate area (m^2)
A_{Ss} = Standard sheet area (m^2)
A_T = Total cross-sectional area, (m^2)
a_v = Particle specific surface area (m^2)
A_v = Void area for air flow (m^2)
A_{vL} = Void area along tray length (m^2)
A_{vW} = Void area along tray width (m^2)
C_{ap} = Cost of absorber plate (Kwacha)
C_{Bf} = Cost of bin frame (Kwacha)
C_{BI} = Cost of bin insulation (Kwacha)
C_{Bin} = Cost of the drying bin (Kwacha)
C_{BSp} = Cost of back and side plates (Kwacha)
C_{cc} = Cost of collector cover (Kwacha)
C_{cf} = Cost of collector frame (Kwacha)
C_{cI} = Cost of collector insulation (Kwacha)
$C_{Collector}$ = Cost of the solar collector (Kwacha)
C_{Cover} = Cost per standard collector cover (Kwacha)
C_{Dryer} = Cost of dryer (Kwacha)
CE = Cost of Electricity (Kwacha)
$C_{Evaporated\ Moisture}$ = Cost per unit of evaporated moisture (Kwacha)
CI = Capital investment
$C_{Insulation}$ = Cost per standard piece of insulation (Kwacha)
C_{Length} = Cost per standard length (Kwacha)
C_{Mesh} = Cost per standard unit of mesh (Kwacha)
C_{msh} = Cost of mesh (Kwacha)
C_p = Specific heat capacity of air (kJ/kg K)
$C_{p,Fish}$ = Specific heat capacity of fish (kJ/kg K)
C_{Plate} = Cost per standard plate (Kwacha)

C_{sh} = Cost of bin covering sheet (Kwacha)
C_{Sheet} = Cost per standard bin covering sheet (Kwacha)
C_{Tray} = Cost of single tray (Kwacha)
C_{Trays} = Cost of number of trays (Kwacha)
C_{Wire} = Cost per standard tray wire (Kwacha)
C_{wr} = Cost of tray frame wire (Kwacha)
d = Material layer thickness (m)
$d_{a.c}$ = Actual collector depth (m)
d_{bin} = Height of drying bin (m)
d_c = Collector depth (m)
D_{hyd} = Hydraulic diameter (m)
dM/dt = Rate of moisture content reduction (% /hr)
$d_{material}$ = Height of stack material (m)
D_p = Particle diameter (m)
DPC = Daily pumping cost
DRC = Daily running cost
DSV = Daily salvage value
dT/dx = Temperature gradient in the x direction (K/m)
f = Friction factor
f_{ca} = Effective absorptivity -transmissivity product of cover and absorber plate.
F_h = Fish height (m)
F_L = Fish length (m)
F_{th} = Fish thickness (m)
g = Acceleration due to gravity (m/s^2)
G = Air mass flow rate (kg/hm^2)
G_a = Mass flow rate per unit collector area (kg/sm^2)
G_d = Mass flow rate per unit collector duct cross sectional area (kg/sm^2)
G_L = Gap along bin length (m)
G_o = Extra-terrestrial radiation (W/m^2)
G_{sc} = Solar constant (W/m^2)
G_W = Gap along bin width (m)
h = Air enthalpy (kJ/kg)
h = Heat transfer coefficient between air and absorber plate (W/m^{2}K)
H = Total bin height (m)
H_B = Bin height (m)
h_c = Convective heat transfer coefficient (W/m^{2}K)
h_f = Air enthalpy at bin outlet (kJ/kg)
h_i = Air enthalpy at collector inlet (ambient condition) (kJ/kg)
H_o = Integrated daily extra-terrestrial radiation (W/m^2)
H_R = Integrated daily radiation (W/m^2)
I = Hourly radiation (W/m^2)
i = Interest rate (%)
$I_{c,ave}$ = Average solar intensity on tilted solar collector surface, (W/m^2)
$I_{c,t}$ = Insolation at any time on titlted solar collector, (W/m^2)
I_d = Diffuse insolation, (W/m^2)
$I_{h,t}$ = Insolation at any time on horizontal surface, (W/m^2)
I_o = Hourly extra-terrestrial radiation (W/m^2)
K = Drying constant (hr^{-1})
K = Pressure loss coefficient (Dimensionless)

k = Thermal conductivity (W/m^2K)
k_1 = Whillier's correction factor for air flow (Dimensionless)
k_2 = Whillier's correction factor for the heat transfer coefficient (Dimensionless)
k_a = Thermal conductivity of air (W/m^2K)
k_i = Thermal conductivity of insulation (W/m^2K)
k_m = Thermal conductivity of plate material (W/m^2K)
K_T = Daily clearness index (Dimensionless)
k_T = Hourly clearness index (Dimensionless)
$L_{a.c}$ = Actual collector length (m)
L_B = Bin length (m)
L_{Bf} = Bin frame length (m)
L_c = Collector length (m)
$L_{c.f}$ = Collector frame length (m)
L_m = Length occupied by material (m)
L_{SBf} = Standard bin frame length (m)
L_{Scf} = Standard collector frame length (m)
L_{Swr} = Standard tray wire length (m)
L_T = Total bin length (m)
L_{Twr} = Tray frame wire length (m)
L_v = Void length (m)
m = Drying rate (kg/hr) = Batch size (kg) / Desired drying time (hrs)
M = Moisture content of fish (%)
m_1 = Amount of air needed (Air flow rate) (kg/s)
M_B = Total Batch size (kg)
$mc_{i,f}$ = Wet base Initial and Final moisture content of product (%)
M_i = Initial moisture content (%)
m_s = Drying rate with reference to the solid (kg/hr)
M_t = Moisture content at any time after start of drying process (%)
m_w = Amount of evaporated water (kg/hr)
n = Day number from January 1; Life of the device (Years)
N = Number of air passes (Dimensionless)
$\mathcal{N}$ = Number of bays (Dimensionless)
N_{BSp} = Number of standard back and side plates (Dimensionless)
N_c = Number of fish per bin cross - section (Dimensionless)
N_L = Number of fish across bin length (Dimensionless)
N_{SBI} = Number of standard pieces of bin insulation (Dimensionless)
N_{Scc} = Number of standard collector covers (Dimensionless)
N_{Scf} = Number of standard collector frame lengths (Dimensionless)
N_{ScI} = Number of standard pieces of collector insulation (Dimensionless)
N_{SLB} = Number of standard bin frame lengths (Dimensionless)
N_{Smsh} = Number of standard units of mesh (Dimensionless)
N_{Spt} = Number of standard plates (Dimensionless)
N_{Ss} = Number of standard bin covering sheets (Dimensionless)
N_{Swr} = Number of standard tray wire lengths (Dimensionless)
N_T = Number of fish per tray (Dimensionless)
N_t = Number of trays (Dimensionless)
N_W = Number of fish across bin width (Dimensionless)
P_B = Bin fan power (W)
P_c = Collector fan power (W)

P_T = Total fan required power (W)
ΔP_B = Pressure drop through the drying bin (N/m^2)
ΔP_c = Pressure drop through the solar collector (N/m^2)
Q = Heater power (kW)
q = Quantity of heat transferred (W)
R_b = Geometric factor (Dimensionless)
R_{hyd} = Hydraulic radius of collector duct (m)
SFF = Salvage fund factor
S_p = Particle surface area (m^2)
SV = Salvage value
T = Temperature (^{o}C)
T_1 = Collector inlet temperature (^{o}C)
T_2 = Collector outlet temperature (^{o}C)
T_3 = Bin outlet temperature (^{o}C)
T_a = Ambient temperature (^{o}C)
T_c = Drying air temperature (K)
t_{dr} = Desired drying time (Hours)
T_{evap} = Evaporation temperature (^{o}C)
t_i = Thickness of insulation (m)
T_L = Tray length (m)
t_m = Thickness of plate material (m)
T_N = Number of trays (Dimensionless)
T_{th} = Tray thickness (m)
T_v = Number of trays placed vertically (Dimensionless)
T_w = Temperature of wet surface (Wet bulb temperature) (K)
T_W = Tray width (m)
ΔT = Desired temperature rise; Temperature difference over which heat is transferred (K)
Δt = Time interval (Hours)
U_L = Collector heat loss coefficient (W/m^{2}K)
U_o = Collector front loss coefficient (W/m^{2}K)
U_s = Collector side loss coefficient (W/m^{2}K)
V = Air velocity through the drying bin (m/s)
v_1 = Volumetric air flow rate (m^3/s)
V_B = Batch volume (m^3)
V_c = Air velocity through the collector (m/s)
V_m = Material volume (m^3)
V_p = Particle volume (m^3)
V_T = Total bed volume (m^3)
V_V = Void volume (m^3)
W = Mass of wet solid (kg)
$W_{a,c}$ = Actual collector width (m)
W_B = Bin width (m)
W_c = Collector width (m)
W_F = Average mass of a single fish (kg)
$W_{F,c}$ = Mass of fish per bin cross-section (kg)
W_{fc} = Mass of fish per bin cross - section (kg/m^2)
W_m = Width occupied by material (m^3)
W_S = Mass of dry solid (kg)
W_T = Total bin width (m)

W_v = Void width (m)
x = Moisture content of air (kg/kg)
x_1 = Moisture content of the air at collector inlet (ambient condition) (kg/kg)
x_2 = Moisture content of the air at collector outlet (kg/kg)
x_3 = Moisture content of the air at bin exit (kg/kg)
X_{eq} = Equilibrium moisture content (dry basis) (%)
X_f = Final moisture content of the fish (dry basis) (%)
X_i = Initial moisture content of the fish (dry basis) (%)

Greek

β = Slope angle - (Latitude angle – Declination angle) (Degrees)
γ = Surface azimuth angle (Degrees)
δ = Declination angle (Degrees)
ε = Void fraction (Dimensionless)
φ = Latitude Angle (Degrees)
θ = Angle of incidence (Degrees)
$\theta_{h,t}$ = Angle of incidence of beam at any time on a horizontal collector (Degrees)
θ_{op} = Operating time (Hours)
ϖ = Hour angle (Degrees)
λ = Latent heat of vaporization (MJ/kg) (Taken as 2.3 MJ/kg in the model)
ρ_a = Air density (kg/m^3)
$\rho_{b,Fish}$ = Bulk density of fish (kg/m^3)
ρ_f = Air density at bin outlet (kg/m^3)
ρ_g = Ground reflectance
$\eta_{B,M}$ = Combined blower and motor efficiency.
η_{wc} = Whillier's Collector efficiency
η_c = Collector efficiency
ω = Specific air resistance of fish (m^{-1})
μ = Dynamic viscosity (N.s/m^2)

Dimensionless numbers

Re = Reynolds number
Nu = Nusselt number
Pr = Prandtl number
Gr = Grashof number

Chapter 1
INTRODUCTION

1.1 BACKGROUND

The preservation of foodstuffs can be regarded as one of the first and most important techniques of food processing. Traditionally, since the early days of civilisation, man has had to set aside or store a sufficient amount of his food supply obtained during the growing season to feed himself until the next harvest [1]. Of the various methods used for this purpose, drying using the sun's energy was the most common. It is worthy recalling that sun drying is nature's way of preserving seeds produced by plants during the growing season so that they are in a viable state for germination the following spring. Consequently, for the early civilisations, which developed in the sunnier areas of the world, sun drying was an obvious choice as a method of preserving foodstuff [1].

Many ways of preserving commodities are now at hand. These include salting and brining of fish, meat and vegetables, sugaring of fruit, drying of grain and many other food stuffs, complemented over the last century or so, by canning, freezing, chilling and freeze drying techniques. In each region, the techniques selected depend upon many factors such as the nature of the foodstuff, climatic conditions, availability of materials and degree of available technology. Sun drying however is still by far the most widely practised agricultural processing operation in the world.

The direct use of sunlight to supply the basic human needs for energy is also of primary importance to man's continued survival on earth because the stored fossilised or organic fuels are being consumed at an incredible rate. The onus is therefore on scientists and engineers, through research, to develop suitable processes to convert the sun's energy into fuel and food for living beings as well as for commercial development on a large scale but at the same time on a practical and low cost basis.

Solar energy is one alternative source of energy that is rapidly becoming attractive due to the high rate of depletion and high cost of conventional energy sources. It is preferred to other energy sources as it is abundant, inexhaustible, non - polluting, has no dangers of fire and other hazards and can be tapped at low cost. The applications of solar energy are vast ranging from providing process heat for various applications to electric power generation. The heat can be stored in a suitable medium for future use such as providing comfort heating of buildings, water heating for both domestic and industrial processes, cooking and drying of various food and non food stuffs. The use of solar energy is therefore one form of appropriate drying technology that is proving to be quite promising. In fact, the *Food and Agricultural Organisation (FAO)* states that in 1968 two hundred and fifty five million tonnes of agricultural produce were dehydrated using solar energy [1].

In rural areas of Africa, the need to dry food commodities requires no justification for well known reasons such as prolonged shelf life, nutritional quality, reduction in weight, and risk of contamination by toxic moulds, since the other modes of preservation are either not fully, or simply not developed. The improvement of suitable drying technologies for the urban and rural communities is therefore a priority throughout Africa. This priority has been recognised by the *Institute de Technologie Alimentaire*, together with the *Food and Agricultural Organisation* of the *United Nations (FAO)* and the *U.S. Agency for International Aid (USAID)*[2].

The process of drying also finds itself an important place in the post-harvest food system. The *Post-Production Systems Group in the Agriculture, Food and Nutrition Sciences Division* of the *International Development Research Centre (IDRC)* has supported several projects in the subject [3]. It has been reported by *Bruce Scott* [3], that the loss of food after harvest represents a significant wastage of existing food production. The development of an appropriate technology to overcome this problem is therefore very much related to the vast range of development problems on the African continent. Attempts to develop better preservation methods have shown that factors such as drying criteria, consumer acceptance, commodities to be dried, heat sources, etc, are location specific [3].

1.2 EVOLUTION OF SOLAR DRYING

1.2.1 Traditional Drying

The traditional technique for sun drying involves spreading of the commodity in the sun on a suitable surface, hanging it from trees, the eaves of buildings or drying in stalk by standing in stooks or bundles as in the case of cereal crops. This method requires little in terms of capital or expertise and is one that can give a product of acceptable quality in a reliable climate. It however has many limitations such as intermittent and irregular loss of moisture and the drying rate of the product is generally low. This increases the risk of spoilage during the drying process. The final moisture content of the dried product can be high due to low air temperatures and high humidities, which can result in spoilage during subsequent storage. The product quality is also likely to vary with part of the batch being over - dried and the other part being under - dried with probable contamination with dust and insects. Also, during the time of drying, the product is liable to theft or damage because of the shallow bed depths, relatively large areas of land or other surface required, over which the commodity is spread. There is also need for labour to scare away predators. Further, the direct exposure to sunlight, or more precisely ultra - violet radiation, can greatly reduce the level of nutrients such as vitamins in the dried product [1].

Due to ever-increasing labour costs, improvement of quality standards and climate uncertainties at certain times, there has been a trend towards artificial dryers in highly industrialised countries. These dryers are capable of providing a high quality product regardless of the weather. Because of their size and complexity, they are incompatible with the requirements of a farmer with relatively small quantities of crops to be dried for short seasons throughout the year. They are capital intensive and mainly tend to be designed for large throughputs of a single product and in some cases designed for continuous (24 hours per day) operation. In addition, they invariably require a source of power and a supply of skilled labour for operation and more importantly, for maintenance of the equipment [1].

1.2.2 Solar Drying

Solar drying on the other hand differs from sun drying in that a structure, often of simple construction, is used to enhance the effect of insolation. This could, for example, be a simple box covered with clear plastic sheet to trap the sun's heat.

Compared with sun drying, solar dryers can generate higher temperatures and consequential lower relative humidities which are both conducive for improved drying rates and lower final moisture contents of the dried material. As a result, the risk of spoilage is reduced, both during the actual process and during storage. The higher temperatures are also a deterrent to insect and microbial infestation. Additionally, drying in an enclosure enhances protection against dust, insects and other animals. All of these factors contribute to the improved and more consistent product quality. Furthermore, as the throughput per unit area is increased due to higher drying rates and higher bed loadings possible, the demand for suitable land is reduced. Solar dryers can also be water proofed thereby minimising the need of labour to move the drying material under cover in the case of rain or at the end of the day [1].

In many cases, solar drying is a good alternative, in whole or in part, to artificial drying although not capable of a comparable throughput or providing comparable consistence in product quality. Although a source of power is required for some dryers, considerable savings in energy costs are still possible. This is so since solar dryers can be made from materials that are relatively cheap and readily available in rural areas, and existing drying or storage buildings can be modified to incorporate a solar collector to supplement conventional fuel supplies.

Solar dryers can also be a feasible alternative to natural convection dryers that use wood or agricultural waste products as fuel. In this context, the saving of wood would be the main attraction.

1.3 STATUS OF PRESENT DAY SOLAR DRYERS

Amongst the various types of dryer systems, the forced-convection system in which a solar collector, a blower and a drying bin are inter connected in series, has been found to have relatively high potential for use in developing countries [4]. This is because of its high holding capacity, simplicity in construction and promising thermal and economic performance. In general, the performance of such a system depends upon the type of dryer and collector area. Over-sizing the system would make it too expensive while under sizing would give a very low drying rate [4].

Although numerous studies to develop solar dryers have been carried out by several researchers throughout Africa for commodities such as timber, rice, vegetables, maize, and fish, the use of solar dryers in rural areas of Africa has been severely restricted due to the following reasons: improper sizing of the dryers to match the farmer's needs, which gives rise to poor performance and makes their use uneconomical or inappropriate; low air flow rates through the dryers as the air is circulated by natural convection since energy sources such as electricity, required to run a fan in order to increase the air flow rate are not available in most rural areas of Africa; high capital cost of the dryers due to the low income of most rural farmers; and uncontrolled, improper or insufficient testing of the developed dryers by the intended users. Also, the previous studies have been purely experimental and no extensive theoretical investigations of the designs were carried out before the dryers were constructed. Therefore, no clear means of improving the performance of the dryers nor reasons for ill performance could be deduced from the experimental results [3].

1.4 OBJECTIVES

The present research was aimed at developing a computer model in order to simulate the size and performance of a solar dryer required to dry a certain quantity of commodity in a specified time and under specified weather conditions. The study is confined to the determination of certain key solar dryer parameters and thereafter optimising these parameters.

The primary objectives of the study were to:

1) Identify the material to be dried and the type of dryer to be used for drying it.
2) Determine the information required for establishing the solar dryer parameters.
3) Use the information so gathered to determine the optimum collector area given a particular heating / drying load.
4) Develop a mathematical model for:
    (a) Heat transfer study of the chosen dryer.
    (b) Optimisation of the design for obtaining the most efficient structure.
    (c) Cost analysis for determining the minimum cost for a given design or drying capacity.

1.5 SCOPE

Although the procedure for sizing dryers for various commodities is almost the same, it was decided to focus on a particular commodity due to the vast variation of the properties for different commodities to be dried. These properties play a very important role in the sizing of dryers. Therefore, in the present study, the subject of fish drying was chosen. The topic was chosen because of the drying problems faced by non - industrialised countries and also due to its great potential to "take off" in the region as fishing has been and still is a traditional occupation for most people living on the banks of rivers and lakes throughout Africa. Also, fish is a major source of protein in Africa and indeed in Zambia. Since the cold chain has not yet been fully developed in Zambia, it is very important to process the fish before storage and consumption. Of the various methods of fish preservation, drying is the most common.

In Zambia, most of the drying is carried out using the traditional method of sun drying. As stated earlier, this method has a lot of limitations and drawbacks, which lead to a low quality product as well as large losses due to spoilage. This is because the fish is normally spread on a sandy beach where it is sun-dried for a few days. The dried fish is then gathered into heaps and packed (along with a considerable amount of sand and stone) into jute bags. Even in cases where the fish is placed on racks raised from the ground, sand blown by wind contaminates the fish. The products are therefore too sandy for consumption, unless well washed before cooking. They are also often mouldy or infested with beetles and are strongly off-flavoured. It is therefore necessary to find an improved drying method that gives a better quality of fish.

The present research focuses on the development of a theoretical model to determine the dimensions and other technical solar dryer parameters for drying fish under various weather conditions and at different locations. A cost analysis of the designed dryer has been incorporated in the study.

The choice of using computer simulation for the research was made since the use of the simulation method in the study of solar processes is relatively cheap and flexible. It is uniquely suited to parametric studies and offers the process designer the capability to explore effects of the design variables on long term system performance. It also offers the opportunity to evaluate effects of the system configuration and alternative system concepts. In addition, it has the advantage that the weather used to drive systems is reproducible, allowing parametric and configuration studies like collector tilt, collector dimensions, material and their physical characteristics to be made without uncertainties of variable weather, i.e. a system can be "operated" by simulations in a wide range of climates to determine the effects of weather on design. Hence the computer model is intended to circumvent physical experimentation for the characteristics of solar heater dryers which would otherwise be a very costly venture.

1.6 LAYOUT OF THE DISSERTATION

The dissertation hereafter is presented in nine chapters.

Chapter 2 takes a look at literature on previous research carried out in the subject of solar drying. The chapter discusses various techniques used, achievements made, and problems encountered by researchers in using the technology. This gives an overview of the history as well as the current state of the art in the area, and thus establishes the gap for the present work in the area.

Chapter 3 discusses the fundamental theory of the drying process. Only the main aspects of the theory that are relevant to the present work are presented.

Chapter 4 gives an overview of the application of solar energy to the drying process. Various types of solar dryers along with their advantages and disadvantages are described in this chapter. This gives an indication of the types of dryers that are in existence and helps in selecting the most suitable dryer for drying the commodity in question – fish.

Chapter 5 deals with the selection of the type of solar dryer to be modelled and the conceptual design of the chosen dryer. A choice of modelling the forced convection solar dryer is made, and possible layouts of this type of dryer are given towards the end of the chapter.

Chapter 6 presents in detail, the method and model equations for modelling the forced convection solar dryer.

Chapter 7 describes the model equations for obtaining the drying time of a dryer designed using the method and equations described in Chapter 6.

Chapter 8 carries out a detailed cost analysis of the designed dryer.

Chapter 9 presents results of simulations for solar dryers designed for drying various quantities of fish under different weather conditions. In addition, investigations of the interaction of various technical dryer parameters with each other are carried out in this chapter. Results of a cost analysis for the designed dryers are also presented. A detailed discussion is given for each case.

Finally in Chapter 10, the general conclusions that can be drawn from the study are outlined. Suggestions for future work in the study are also highlighted.

Chapter 2
LITERATURE REVIEW

2.1 BACKGROUND

According to *Tressler* [5], the basic principle in the drying of food, wheather by natural or artificial means, is the reduction of moisture content to such an extent that decomposition by both bacterial putrefaction and enzymatic autolysis is stopped, or at least sufficiently inhibited to ensure reasonable keeping quality. *Jason* [6] pointed out that sun drying is one of the conventional methods of fish preservation. It is a process in which removal of moisture is effected by exposure of the product to natural currents of air and humidity that are dependent on climatic conditions. The advantage of this method is that no specialised equipment is necessary, but drying by exposure to the wind is a relatively slow process. It results in a great loss through spoilage, lack of uniformity in the final product and development of undesirable flavours due to exposure to various sources of contamination such as air - borne dust, wind - blown debris, insect infestation and moulds. The sun-dried products usually appear discoloured, brittle and mouldy. Thus a typical wastage of about 30% of the total foodstuff is incurred [7].

Solar dryers were designed to solve problems affecting the traditional sun-drying method where the wind provides the flow rate to carry away the moisture. Sun drying was fine for drying of clothes, but for foods, a safer method had to be found to meet present day needs.

Anon [8], suggested that these dryers could be classified according to the manner in which heat is transferred from solar radiation to the material being dried as follows:

(i) The Direct or absorption type, where heat is transferred by direct absorption from solar energy to the material being dried. This is achieved through the use of an enclosure covered with transparent material like plastic or polyethylene sheet.

(ii) The convection type or indirect type wherein air heated in a solar collector is conveyed through a heat exchanger to a drying chamber.

(iii) The combined method wherein heat transfer is activated by a combination of direct and indirect methods of heat transfer.

Economic conditions on the African continent dictate the use of low-cost drying systems in attempting to improve traditional methods. Thus African researchers have actively pursued solar drying research because solar energy is free and abundant on the continent. However, despite the volume of research results obtained, solar dryers have not yet been effectively introduced for various technical and socio-economic reasons as pointed out by *Werecko-Brobby et al.,* [9]. These include factors such as low air flow rates in natural convection solar dryers used in rural areas, due to the absence of electricity to run a fan, and low income of farmers which leads to purchasing cheap and inappropriate materials, and hence construction of a less durable and reliable dryer.

2.2 OVERVIEW OF PREVIOUS RESEARCH

With few exceptions, papers on previous research on the preservation of foods using solar energy fall into two main categories. One group of authors is primarily user-oriented, and presents research that is conducted principally in the domain of the user, identifying the dryer hardware as a potential means of improving the quality of the preserved food product. The emphasis for this category is on drying problems. The second group of authors tends to deal with specific hardware configurations, and presents performance data that have usually been acquired under laboratory or research station conditions. The emphasis of this category is on dryers. The present work basically falls in the second category.

In general, one finds that user-led researchers often tend to treat specific technical issues lightly, resulting in insufficient reporting of data relating to say, engineering or food science. Conversely, researchers who emphasise on the hardware appear to be presenting solutions that would be resolving their problems. It is interesting to note that the respective strengths of these research approaches and the logic of combining forces to solve a total problem have not yet received sufficient attention.

Along with these two main categories, research on solar drying can further be classified in two main sections comprising experimental and theoretical-based studies. Brief descriptions of some of these studies along with their main conclusions related to the present work are given in the following sections.

2.2.1 Experimental-Based Research

A publication by *Bassey et al.*, [10] discusses the prerequisites for the development of natural-convection solar crop dryers in Sierra Leone, particularly focusing on experimental studies on hybrid and solar dryers, pointing out the useful contributions made and constraints in their design. The paper is particularly instructive and represents a welcome addition to the literature. It describes a complete research process beginning with the identification of a user-problem, includes the generation of a technical design, and ends with proving the design in the user-domain. It is also particularly explicit in identifying the authors' perceptions of the shortcomings in the total research process. These were described as follows:

- A general lack of preliminary studies before a dryer is built to identify the commodities that must be dried, i.e. it is necessary to correctly identify the drying problem, taking into account the scarcity of funds, and its viability on a national and economical base. In other words, superficial identification of a drying problem is an unsatisfactory approach and could very easily lead to a solution that is useless to the intended beneficiary.
- Improper sizing of the dryers to match the needs of the user makes their use uneconomical and inappropriate.
- High capital cost of the dryers due to the low income for most rural users.
- Poor performance of the dryers as a result of drying flaws.
- Low air flow rates through the dryers as air is circulated by natural convection.
- Improper or insufficient testing of the developed dryers by the intended users.

In a portion of this paper, the authors also underline the importance of augmenting the sun's ability to dry under overcast conditions by introducing a hybrid dryer and give a practical example of how agricultural waste material may be used in such dryers.

The main conclusions derived in this paper that are related to the present work indicate that the initial needs-assessment studies are a prerequisite for the wide-scale adaptation of improved drying systems. The identification of the product to be dried along with its internal and external parameters is very important in any design. It also indicates that solar dryers can be used effectively, provided substantial research and development work is done before appropriate systems can be obtained. The main areas for future work are design with the help of modelling and experimentation followed by field-testing. The present study is a response to these main conclusions.

Although the paper discusses results obtained from experiments on natural-convection solar dryers, the design philosophy is very much applicable to forced convection dryers. Also, the problem of low airflow rates can be overcome and controlled more effectively using a forced convection system as in the present work.

Werecko-Brobby [11] presents the engineer with the central question: "Are you sure that you are working on the correct problem?" His paper emphasises the need for multidisciplinary research teams if the user is to derive any real benefits and points out the need to adopt and improve socio-economic methodologies. This publication underlines the often repeated, but also often neglected statement that for an improved hardware or technology to be adopted, it must demonstrate technical soundness, social acceptability, and economic viability.

The present work is confined to fish drying using solar dryers (as opposed to sun drying), which received considerable appreciation at two local conferences held during the course of the study. The study therefore seems to be working on the right problem as the technology is still new in this part of the continent.

Amouzou et al., of Togo [12] indicate that a major drying problem lies at the large scale level. Their paper indicates that correctly locating the drying problem in the post harvest sequence guides the scope and emphasis of any technical research. In this research, three types of dryers were constructed and tested with load capacities ranging from 15 to 2000kg of maize. The study focussed on both the efficiency and the economic profitability of the dryers. The first dryer takes in about 10 to 15kg of maize at a time and takes three days to dry it. It uses a collector area of $1m^2$ and is based on natural convection. The second dryer is based on forced-convection with variable flow rates and can dry 80 to 100kg of product in three days. This dryer has a collector area of $6m^2$. The third dryer can dry between 2000 to 2500 kg of cereals using forced convection and a collector area of $81m^2$. The results however showed that none of the systems were economically viable for Togo.

From the paper, it can be concluded that obtaining large values for the collector area for large throughputs is not unusual. Results of this nature should therefore be expected in the present work. It also goes to show that developing a theoretical model to predict the size of such dryers and thereafter carrying out a cost analysis would considerably cut down experimental time and cost.

Minka [13] shows the importance of defining the drying problem in the user context and suggests that issues such as dirt exclusion and the ability to leave the dryer unattended while the user is active on other chores may be far more important than the reduction of drying times. His interpretation of experimental results challenges the engineer to acknowledge that hard measures such as drying efficiency may need to take second place to other considerations in certain contexts. The paper further states that the tests carried out for simple direct type solar dryers compared to the traditional tent type dryers, showed that the efficiencies of the different traditional dryers are essentially the same and that natural convection dryers in general do not necessarily reduce the drying times compared with sun dryers. However, the results show that solar dryers are useful during periods of rainfall.

An effort has been made in the present work to address the challenge set by *Minka* by developing a procedure for modelling the drying bin in which the fish is kept, and protected against rain and other impurities. It can also be left unattended for some of the time. The procedure developed also takes into account the various drying parameters, which ensure a high quality product.

The solar tent dryer designed by *Doe et al.*, [14] operates by absorbing solar radiation through a clear polyethylene sheet thus increasing the temperature of the air in the dryer. With no wind blowing, a draught is induced within the dryer due to the tent that acts as the chimney. Moisture removed from the fish during drying is either carried out with the air exhausted through vents at the top of the dryer or condenses on the inside surface of the polyethylene. An advantage in allowing condensation is that it enhances the green house effect. By increasing the air flow through the vents, although the heat loss from the dryer through the polyethylene increases, thereby relatively reducing the air temperature inside the dryer, more mass transfer takes place. Therefore, by using a forced convection system as in the present case, drying can be done more effectively.

In addition to the tent type of dryer, different types of solar and augmented dryers were constructed and tested [15,16]. Comparisons between the dryers in terms of cost and efficiency (moisture content of the fish versus drying time) were made. However, no conclusions of the study were reported in the publication.

Pablo [17] has also used agro-waste dryers that operate by the combination of direct and indirect methods of heat transfer for the drying of fruits. The publication does not report any findings of the study.

Sison et al., [18] has done work on the development and evaluation of artificial dryers with varying capacity. Some dryers are equipped with a furnace and a blower assembly driven by a petrol engine to force the hot air to the drying chamber. Some were fuelled by rice hulls, LPG or kerosene. Although no findings of the work were reported in this publication, it was thought that this method of drying could be capital intensive. The present work therefore adopts solar energy as the fuel, since fuels such as LPG, and kerosene can be quite costly, especially for large-scale applications.

2.2.2 Theoretical-Based Research

A critical examination of the research literature in solar drying leads to the hypothesis that some of the research work reported lacks a linkage to theoretical analysis. Thus, one finds researchers abandoning a particular design on the basis of limited and often disappointing performance results, in favour of a new design, but in the absence of a clearly documented analysis of the reasons for the abandonment. Further, one sees some evidence of apparently random alteration of certain design parameters, without reference to a theoretical analysis.

A significant contribution, therefore, to the research landscape is the convergence of theory, design, and testing of prototypes. There appears to be a general conclusion that low air flow rates constitute the limiting condition for natural convection solar dryers. The technical addition of an electrically or engine driven fan is either not feasible in many rural areas due to absence of electricity or is financially prohibitive in the case of petrol or diesel-driven fans.

A paper by *Oosthuizen* [19] identifies the role of theoretical analysis and modelling techniques as a promising research contribution to the field. The paper describes a computer model for obtaining various parameters such as the air velocity, heat transfer coefficient and drying time, for a natural convection solar grain (rice) dryer. The model was further validated against available experimental data and good agreement between the predicted and experimental results was achieved.

The present work endeavours to develop a model on similar grounds as *Oosthuizen*, but applicable to forced-convection solar fish drying.

Janjai et al., [4] describe a procedure / simulation model for determining the optimum collector area for a solar paddy drying system. The procedure is applicable to forced convection drying systems operating without an auxiliary heat source. The paper also describes a drying cost analysis that provides solar designers with a tool to determine the optimum collector area for a paddy drying system. The analysis may however be extended to other drying applications such as the one described in this dissertation.

Garg et al., [20] describe a theoretical analysis for the optimisation of rock bed storage coupled to a double pass, single cover solar collector. The study investigates effects of various system parameters on the total energy stored and the cost per unit of energy stored in the rock bed for winter conditions of Delhi. Although the study is based on energy storage, the procedures outlined contribute to the design of solar systems keeping the aspect of cost effectiveness in view. Some of the procedures for carrying out the cost analysis are therefore adopted in the present work.

Bassey and Schmidt [3] report that researchers have identified certain problems and constraints that have characterised past research on solar drying. Possible remedies to these problems have also been outlined.

The problems have been classified into four main groups as follows:

1. Technical problems, gaps and research needs:

- The absence of a sequential technical design procedure;
- The inadequacy of existing testing and monitoring procedures;
- The need to evolve a common method for evolution and comparison of final dryer designs.

In order to overcome some technical problems, it is generally recommended that a comprehensive design procedure for solar dryers must be developed. This should attempt to provide a step by step guide to practitioners to the specific tasks and requirements for the development of the technology. Along with the design procedure, a rigorous program for performance testing, monitoring and evaluation must also be established. This includes:

- Developing better modelling techniques;
- Matching modelling to field experimentation;
- Improving air flow through dryers by better design of chimneys and / or incorporation of other devices such as fans and blowers.

The present work therefore is an effort to contribute to the above set targets.

2. Socio-economic aspects:

- Failure to set solar dryer technology development in the context of an overall drying problem;
- Failure to identify specific elements of the socio-economic context, including identifying user problems, establishing a basis for evolution, and developing methodologies for appraisal.
- Failure to establish a relative priority of drying in the national food postproduction system (i.e. are storage problems more important than drying problems?)

Methodologies for identifying user problems and assessing the economic profitability of various dryer designs in specific social-cultural environments must therefore be developed. The economical appraisal methodology should concentrate on establishing techniques for qualifying the specific impacts of intangibles, such as improved health and quality of life on the techno-economic feasibility of solar dryers.

3. Linkage between R&D and implementation:

Despite the experience of several years of experimentation, there are still few operational dryers in the field. Most of the efforts still seem to be concentrated in the area of fundamental organisation and optimisation of various dryer components and systems. There is little interaction between researchers, end-users and extension workers during the development and testing of dryers. This often leads to the design of inappropriate technologies of limited relevance to the ultimate consumers.

4. Collaboration among scientists:

It generally appears that there is a need for researchers to collaborate, both in research activities and in the exchange of experiences. Lack of this often leads to duplication of efforts since access to information on past and present work is limited. Collaboration is therefore encouraged.

For reasons cited in points (3) and (4), a target was set to publish part of this work during the course of the study.

2.3 FISH DRYING

Although fish is a nutritious and relatively safe protein food, the extensive utilisation of fish as food raises public health problems common with any other food industry and with the same risk of products being contaminated with pathogenic organisms and toxins. The need to take care of these fish processing problems therefore strongly influences the future prospects of developing countries in maintaining their positions as suppliers of fish to important foreign markets [21].

Of the various methods of preserving fish, drying is quite common in developing countries. Under fine weather conditions, fish can be sun-dried within five days and within three days using solar dryers due to relatively higher air temperatures possible in them. Also any insects or larvae carrying pathogenic bacteria, present on the fish get killed at high temperatures, thereby giving a higher quality product and reduced health hazards. A period of 20 hours at 45°C is recommended for complete disinfestation of drying fish in solar dryers [22].

Considering the foregoing, the present study dwells on the process of drying using solar dryers, as a way of contributing to the improvement of the quality of dried fish.

2.3.1 Fish Drying in Zambia

Research carried out by *Harumine* [23] suggests that the most common way of processing fish in Zambia is sun-drying and smoking. The research was aimed at introducing a chorker kiln for drying and smoking fish all around the country, and in particular Kafue flats, since it was pointed out that great losses take place if the drying of fish both before and after the smoking process is not properly undertaken. The chorker kiln basically consisted of an enclosure made of clay bricks to accommodate the charcoal, on top of which a tray for placing the fish would be kept. The fish would then be heated by fire from the bottom. The whole arrangement is sheltered from rain since it is made of mud.

Large losses in the traditional method occur because after the fish is caught, scaled, gutted and cleaned the fishermen place it on roofs for sun drying. The fish is then smoked by roasting and thereafter dried again. The smoking is done to add flavour, colour and to dry the fish faster in order to avoid rotting. This method uses a lot of firewood and is quite inefficient. Unfortunately, there are not many trees in the Kafue flats, which could be used as firewood or charcoal to smoke the fish, and thus it is difficult to sufficiently dry it. This situation gave highly unhygienic conditions leading to poor quality fish contaminated with maggots in most cases.

The results of the report indicate that although the chorker kiln was seen to be an appropriate technology, it was not wholly accepted by the local people, possibly due to the lack of firewood in certain areas.

2.4 KEY POINTS IN THE LITERATURE REVIEW

The key points observed in the literature review relating to the present study are:

1. Sun drying of products is a relatively slow and unhygienic process that results in high losses and low product quality when compared with solar drying. The quality of the dried product can be improved using solar dryers.
2. Most of the research work carried out on solar dryers is experimental based. Very little literature is available on the theoretical aspect of the research. Generally speaking, researchers have gone directly into building the prototype and conducting experiments on these models. The results

obtained cannot assist one to ascertain the performance of the dryer under different weather conditions or at a different location.

3. There seems to be a lack of sequential technical design procedures of solar dryers. There also seems to be a break in the linkage between research and development (R&D) and implementation.
4. There is need for the development of better modelling techniques and further matching of these to field experimentation.
5. It has generally been concluded that the air flow in solar dryers needs to be improved in order to improve parameters such as efficiency, drying times and also to have more control over the drying process.
6. Methodologies taking user-problems into account and assessing the economic aspects of the dryer need to be developed.
7. The problem of fish drying is quite serious in terms of quality and public health for both domestic and commercial dealers. Better processing techniques require to be implemented in the field. Also, since the traditional method of smoking and drying fish uses a considerable amount of firewood, which contributes to heavy deforestation and hence environmental degradation, an alternative to the problem has to be found.

From the foregoing review, it can clearly be seen that an improvement in the designs of solar dryers is still necessary. The main short falls for natural convection solar dryers are the low and non-uniform air flow rates, which do not allow one to predict the performance accurately. It can also be noted that most of the work carried out was purely experimental and no clear reasons for the poor results obtained could be deduced. Hence not much improvement was done once a study gave negative results. Consequently, the development of a numerical model to simulate solar dryers, taking the key parameters into account is not out of place.

The discussion on "Fish drying in Zambia" clearly indicates that large losses take place with the method used for drying fish in rural areas, which is quite unhygienic and inefficient. An improvement in the method is therefore necessary in order to raise the quality of dried fish and more importantly, the health standards of the general public.

The present study therefore contributes to the improvement of existing designs of solar fish dryers. The study sought to develop a numerical method that could be used to predict the required size of an indirect forced-convection dryer for a specified batch size of fish to be dried at a specified place and time of the year.

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Chapter 3
FUNDAMENTALS OF THE DRYING PROCESS

3.1 GENERAL

Despite considerable research, a complete understanding of the drying process has yet to be fully achieved. However, it is generally agreed that drying can be described as a process of decreasing water in a product by a concentration difference between the product and the surrounding medium. There are two basic phenomena involved in the drying operation. These are:

(i) Evaporation of moisture from the surface

(ii) Migration of the moisture from the interior of a particle to the surface.

The process of drying is necessary in many cases since the initial moisture content of any commodity is much higher than the optimum moisture content for storage when the product is harvested as in the case of vegetables, and when it is fresh as in the case of meat and fish. A high moisture content during storage in warm and humid conditions is a conducive environment for fungi, moulds and insects to multiply. Therefore, a lower moisture content is required to prevent spoilage of the product.

Controlling certain properties of the drying air controls the process of drying. Amongst the most important air properties are the air flow rate, relative humidity, and air temperature. Properties of the drying air are known as "external parameters" whereas properties of the drying material are known as "internal parameters".

The present chapter describes the internal and external parameters and their effects on the drying process. The use of the psychrometric chart for the drying process has been described in section 3.2.1. Section 3.6 gives an overview of some drying strategies along with some commonly used ventilation systems.

3.2 PROPERTIES OF THE DRYING AIR - EXTERNAL PARAMETERS

There are eight thermodynamic properties of moist air generally used in the drying process. These are vapour pressure, relative humidity, humidity ratio, dry bulb temperature, due point temperature, wet bulb temperature, enthalpy and specific volume. The effect of the parameters on one another can be seen on a psychrometric chart. Definitions of some of these parameters are given in Appendix 1.

3.2.1 The Psychrometric Chart (Humidity Chart of Air-Water Vapour Mixtures)

The air humidity can be determined by using a psychrometer, which consists of both a wet bulb thermometer and a dry bulb thermometer. It can also be determined from psychrometric tables or a psychrometric chart. In the chart, (see Figure 3.1) the relations of dry bulb temperature, wet bulb temperature, humidity ratio, relative humidity, specific volume, enthalpy and saturation point are shown for a barometric pressure of 101.325 kPa. The curve marked 100% running upward to the right gives the saturation humidity as a function of the temperature. Any point below the saturation line represents unsaturated air-water vapor mixtures. The curved lines below the 100% saturation line and running upward to the right represent unsaturated mixtures of definite percentage humidity. Going downward vertically from the saturated line at a given temperature, the line between 100% saturation and zero humidity (the bottom horizontal line) is divided evenly into 10 increments of 10% each.

Evaporation of moisture into an air stream involves both heat and mass transfer. As the moisture evaporates, both the air stream and water surface lose sensible heat to provide the latent heat of vaporisation of the water. If the temperature of this water is the adiabatic saturation temperature, then the heat for evaporation will come from the air and therefore a relationship between gain in humidity and temperature drop can be found. This relationship is shown by the adiabatic cooling lines on the chart.

Other parameters can also be found from the psychrometric chart but the terms discussed so far (and defined in Appendix 1), are enough for the purpose of evaluating and predicting dryer performance.

3.2.2 Use of the Psychrometric Chart for the Drying Process

During the drying process, latent heat of vaporisation of water in the drying material is exchanged for sensible heat of the drying material and the drying air. This causes the temperature of the drying material to become equal to the wet bulb temperature of the air. The resulting change is shown on the psychrometric chart as a parallel line to the wet bulb line. In order to improve the moisture carrying capacity of air (decreasing the humidity), the air is preheated (e.g. by a solar collector) before the actual drying process. This process is shown on the psychrometric chart as a horizontal line from left to right.

In order to clearly show the effectiveness of the drying air to the drying process after being preheated, a process with preheated air and one without preheated air are drawn on the psychrometric chart and compared in form of an example, considering typical weather conditions of the month of July in Lusaka.

Given an ambient dry bulb air temperature of 10°C and relative humidity of 60%, point 1 can be plotted on the psychrometric chart as shown in Figure 3.1.

If this air is allowed to pass over some wet material and if no external heat is supplied, the sensible heat of air and the material is exchanged for latent heat of vaporisation of water. The path travelled on the psychrometric chart will be the 6.5 °C wet bulb line shown by line 1-1'. During this process, the humidity ratio changes from 0.0046 to 0.006 i.e. about 0.0014 kg of vapour per kg of dry air is absorbed.

Now, considering that external heat is supplied to the air prior to passing over the drying material, (e.g. by using solar energy), and the air is heated to say, 55 °C, the relative humidity is reduced to about 5%. During the drying process, this air is cooled adiabatically along the 23.4 °C wet bulb line, and the final humidity ratio will be 0.0182 assuming 100% saturation. Thus the moisture evaporated with the heated air will be 0.0136 kg of vapour per kg of dry air which is almost ten times the water evaporated compared to when the air was unheated.

3.3 PROPERTIES OF THE PRODUCT - INTERNAL PARAMETERS

The following sections describe the internal parameters that play an important role in the drying process.

3.3.1 Moisture Content

The wet material holds a certain amount of water at the beginning of the drying process. This is often given as a percentage called the initial moisture content, mc_i. After drying, the material still holds a certain amount of water called the final moisture content, mc_f. The moisture content of a material is an index of the quality of the dried product. It can be expressed as a decimal fraction or percentage of moisture based on either dry matter weight (dry basis) or wet weight (wet basis). If W is the mass of the wet solid in kg (total water plus dry solid), and W_S is the mass of the dry solid in kg, then the definition for values in wet basis is:

$$mc_{i,f} = [(W - W_S) \text{ kg total water } / \, W \text{ kg wet material}]*100\% \quad (3.1)$$

For values in dry basis (which are most commonly used in scientific work),

$$X_{i,f} = [(W - W_S) \text{ kg total water } / \, W_S \text{ kg dry material}]*100\% \quad (3.2)$$

For converting a value in wet basis into a value in dry basis, the following relation is used:

$$X_{i,f} = mc_{i,f} \, / \, (100 - mc_{i,f}) \quad (3.3)$$

3.3.2 Equilibrium Moisture Content

Most materials derived from living matter exhibit hygroscopic behaviour. This means that when dried below a certain equilibrium moisture content level, they absorb moisture from the ambient humid air (hygroscopic moisture), and give off water to the dry ambient air. When the rate at which a product loses moisture to the surrounding is identical to the rate at which it absorbs moisture from the surrounding air, the product is said to be in equilibrium and its moisture content is known as the equilibrium moisture content or hygroscopic equilibrium.

Because the drying process is theoretically still not solved, a general equation to calculate the equilibrium moisture content does not exist. The connection between the equilibrium moisture content and the humidity of ambient air is graphically shown in experimentally obtained curves known as the sorption isotherm curves. These curves are available for many materials and show the equilibrium water content of a certain material against the relative humidity of air. Some curves that are available for certain types of fish are included in Appendix 2.

3.4 EFFECT OF THE BASIC PARAMETERS ON THE DRYING PROCESS

The basic parameters of the drying process that influence drying rate are discussed in the following sections.

3.4.1 Drying Air Temperature

Although very hot air is best for drying, the air temperature cannot be increased arbitrarily because many drying materials can only withstand a certain maximum temperature, T_{max} without deteriorating or getting spoilt. This is particularly true for foodstuffs in which nutrients can get destroyed. The only time that the drying temperature may exceed T_{max} is when the matter is covered by a water film or only for a short period of time.

3.4.2 Air Relative Humidity

Although the evaporation of water requires heat, the driving force for drying is provided by the gradient of water vapour pressure between the ambient air and the evaporation surface. The best indication of the drying potential of ambient air is the relative humidity. In drying theory, it is an important quantity because it is one of the main parameters determining the equilibrium moisture content of a product. In fact, the idea of heating air prior to drying found its basis in reducing the relative humidity.

3.4.3 Air Flow Rate

Since large amounts of water are evaporated during the drying process and since the drying air can only take up little moisture, a rather large amount of air has to be passed through or over the drying material. As the moisture leaves the surface it passes into the air immediately adjacent to it. This increases the humidity of the surrounding air, which in turn will slow down the rate of evaporation. Thus unless the air surrounding the particle is replaced by fresh, relatively dry air, an equilibrium between the air and the product will be reached and evaporation will not continue. Therefore, it is very necessary to have a certain air flow rate during the drying process. In large dryers, this air flow is achieved by fans or blowers.

3.4.4 Moisture Content

The moisture content is the most important factor affecting the quality of the product, which in turn determines the market price. The moisture content of the product also determines whether it is dry enough for safe storage.

3.5 THE DRYING PROCESS

The process of drying is quite complicated to be modelled mathematically. One of the reasons is the complicated flow of water in the product. Mostly, empirical representation of the process is used in analytical work. A drying process is usually represented by one of the following three curves:

1) Moisture content versus time
2) Drying rate versus time
3) Drying rate versus instantaneous moisture content

The rate of drying depends on the rate of moisture migration from the interior to the moisture surface of the product and on the air properties. The migration depends on the type and thickness of material to be dried.

For materials that do not contain residual bound moisture, the drying can be carried out to a moisture content level of zero percent. Such materials are called non - hygroscopic materials. Materials that contain residual bound moisture i.e. water trapped in the material and unbound water held within the material by the surface tension of the water itself, are known as hygroscopic materials. For such materials, the migration resistance of the water is determined by the moisture content of the material itself.

3.5.1 Phases of the Drying Process

With the gradual removal of water from the product, the drying behaviour of the product changes. For both hygroscopic and non-hygroscopic materials, the drying process is initiated by an unsteady state adjustment period during which the material temperature is brought to an equilibrium value. If the initial material temperature is low, the drying rate will increase and vice-versa as shown by processes *A-B* and *A'-B* in Figure 3.2. However, this period is quite short and is often ignored in the analysis of drying times. After this period, there is a constant drying rate (constant rate period), shown by line *B-C* in Figure 3.2, terminating at the critical moisture content, *Xc*, followed by a falling drying rate (falling rate period) starting from point *C* and terminating at point *E* in Figure 3.2. [24] These two phases of the drying process are discussed in the following sections.

3.5.1.1 Phase 1 - The constant rate period

The constant-rate of drying is the initial stage of the drying process when the surface of the drying material is very wet and a continuous film of water exists on the drying surface. This water is essentially unbound water and acts as if the solid were not present. Increased roughness of the solid surface may lead to higher rates as compared to those from a flat surface. If the material is porous, most of the water evaporated during this period is supplied from the interior of the solid. The period lasts only as long as water is supplied to the surface as fast as it is evaporated. This depends on the difference between the partial water pressure at the surface and the surroundings. Under dynamic equilibrium conditions, the rate of water evaporated, dM/dt, is equal to the rate of heat transfer to the surface and can be found from the following relation described by *Garg and Prakash* [25]:

$$dM/dt = A_S h_c (T_c - T_w) / \lambda \tag{3.4}$$

Where the convective heat transfer coefficient h_c, is found from:

$$h_c = 4.2G^{0.37}\ (W/m^2K) \tag{3.4a}$$

From equation (3.4), it is seen that the drying rate in the constant rate period can be increased by increasing: the initial air temperature, the surface area of the material, the heat transfer coefficient i.e. increasing the air flow rate and the drying air temperature with respect to the wet bulb temperature (using air with low humidity).

A constant rate of evaporation on the surface of the material maintains the surface at a constant temperature which in the absence of other thermal effects, is very near the wet bulb temperature. If the product is heated by direct radiation and conduction, the temperature of the product will be between the wet and the dry bulb temperature.

After a certain time of the drying process has elapsed, a stage is reached where there is insufficient water on the surface to maintain the continuous film of water. At this point, the drying rate begins to decrease. This point is a critical point and the moisture content at this point is called the "critical free moisture content".

3.5.1.2 Phase 2 - The falling rate period

After the critical moisture content point, the falling rate period begins. This period is further divided in two parts, which are, the "first" and "second" falling rate periods. These two periods are represented by *C-D* and *D-E* respectively in Figure 3.2. During the first falling rate period, the entire surface is no longer wetted, and the wetted area continuously decreases until the surface is completely dry. At this point, the second falling rate period begins. The plane of evaporation slowly recedes from the surface and heat of evaporation is transferred through the solid to the zone of vaporisation. Vaporised water moves through the solid into the air stream. The amount of moisture removed in the falling rate period may be relatively small but the time required may be long.

The constant drying rate for both hygroscopic and non-hygroscopic materials is the same while the period of falling rate is a little different [25]. For non-hygroscopic materials, in the falling rate period, the drying rate goes on decreasing until the moisture content becomes zero. In hygroscopic materials, the falling rate period is similar only for a period until the unbound moisture is completely removed, which continues until the vapour pressure of the material becomes equal to the vapour pressure of the drying air. The drying rate becomes zero when equilibrium is reached. The constant drying rate period is referred to as adiabatic drying since the heat content of the air remains the same and depends on external factors such as air flow rate, the thermodynamic state and transport properties of the air and state of aggregation of the material.

3.5.2 Heat Transfer

During the drying process, water vapour is transported from the interior of the product to the ambient air. The energy needed for transforming the water into vapour can be obtained either by one, two or all three modes of heat transfer namely conduction, convection and radiation. Part of this heat propagates to the interior of the product by conduction, which raises the temperature, and evaporates the water. The moisture from the interior diffuses to the surface to replenish the evaporated surface moisture while the water vapour in the air surrounding the product is continuously removed by diffusion and the flow of air. Therefore, the initial process of drying essentially takes place on the surface of the material by convection. For cases where the temperatures are not too high, heat transfer by radiation is relatively small and can be neglected [24].

3.6 DRYING STRATEGIES

There are several drying strategies that can be employed for the drying process depending upon the type of commodity to be dried. The strategies can also be combined to suit the condition under which drying is to take place. Some strategies are described in this section.

3.6.1 Thin Layer Drying

Thin layer drying refers to the drying of a product with the entire surface exposed to the dying air moving over the product. The drying rate is determined from the airflow rate, air temperature, relative humidity, moisture content and the type of the product. The drying rate as reported by *Exell* [26], can be evaluated from the following relation:

$$dM / dt = -K (X - X_{eq}) \tag{3.5}$$

This equation can be used for the whole drying process by substituting different values of K for each phase of the drying process. Values of K for various materials can be obtained from standard tables. The time necessary to reach a moisture content level between the initial moisture content and the equilibrium moisture content can be found by integrating equation (3.7).

$$t = (-1/K)\ln[(X(t) - X_{eq}) / (X_i - X_{eq})] \tag{3.6}$$

3.6.2 Deep Layer Drying

Drying mostly takes place in a "drying zone" which moves through the product in the direction of the air movement. In deep layer drying, the layers close to the bed inlet are generally over-dried. The greater the depth of the bed, the greater is the over drying of the layers for a particular flow. The drying of food products in a deep layer can be thought of as the drying of several thin layers in which the humidity and temperature of the air entering and leaving each layer vary depending upon the stage of drying. The volume of the drying zone in deep bed drying also depends on the temperature and humidity of the air entering the dryer. Usually, as the air moves through the bed, it removes moisture from one layer and adds it to the next layer. The subsequent layers remain wet until the drying front reaches them. The difference in the humidity of air entering and leaving the bed decreases with an increase in air flow rate. Drying ceases as soon as the product is in equilibrium with the surrounding air. In contrast with thin layer drying, the air velocity is very critical in deep layer drying. The rate at which the drying front moves is proportional to the air velocity. During deep layer drying, two distinct drying rate periods can be identified, one for the constant rate period and the other for the falling rate period, for various types of dryers.

3.6.3 Wind Ventilation

Drying of a product using wind ventilation is considered in regions where the average wind velocity is in the order of 5m/s or above. In order to make use of the wind pressure, narrow vertical bins have to be installed perpendicular to the direction of the wind. The bottom should be at least half a meter above the ground. If the wind is to blow through the drying matter, air resistance must be below 15N/m^2 at a wind speed of 5m/s or about 60N/m^2 at a wind speed of 10m/s [27]. That means that this type of ventilation is applicable only for large size materials like maize cobs, and large yam cubes.

3.6.4 Natural Convection

Ventilation by natural convection makes use of the fact that hot air has a lower density than cold air and thus tends to rise as shown in Figure 3.3. The figure shows that a draught of air is established in the drying bin, as air enters from the bottom, gets heated, and rises by natural convection. This draught depends on the height difference between the air inlet and outlet, and the corresponding air densities. The draught is expressed as a pressure difference as follows [27]:

$$\Delta P = gH(\rho_f - \rho_a) \tag{3.7}$$

The air densities depend on the temperature of air and to a lesser extent on its moisture content. This is shown from the following expression [27]:

$$\rho = \rho_o (1+x) / [1 + (T / 273)] \quad (3.8)$$

Where, ρ_o, is taken as 1.29 kg/m^3

3.6.5 Forced Convection

When large amounts of material have to be dried, fan forced ventilation is necessary. Fans are chosen according to the air flow rate offered and the pressure created by the fan. The electrical power of the fan is given as [27]:

$$P_B = m_l \ \Delta P / \eta_{B,M} \quad (3.9)$$

The choice between a natural and a forced convection system depends on the requirements of the user. In a natural convection system, only thermal energy is required and in tropical regions, solar radiation can generate this energy. The system is therefore independent of commercial energy sources and is thus preferable for places where commercial energy is not available. Another advantage is the low cost because of the possibility to work with local materials. The disadvantage is that such systems depend upon the weather and therefore have an irregular drying process. In contrast, the forced convection system provides a more constant drying rate and can be sized and optimised for a given commodity along with its properties. However, such systems are more costly as they require a commercial energy source and also may require materials other than local ones.

3.6.6 Ventilation Systems

There are two basic types of ventilation systems that are applicable and are described in the following sections.

3.6.6.1 Cross-draught ventilation

Figure 3.4 shows two examples of cross ventilation in which the drying air is passed over the material. Dry air enters the drying chamber, absorbs moisture from the product, and leaves the chamber as wet air.

In these types of systems, very little energy is exchanged between the air and the matter. The necessary heating is therefore established by other means such as solar radiation. The blower has to produce little pressure of about $10N/m^2$ or less depending upon the geometry of the bin [27]. This type of ventilation is used for drying large pieces of material, e.g. wood, leather, pottery, and bricks. When used for grain, fruit, etc. it is applicable only in connection with thin layers of the product up to a few centimetres or thicker layers when the material is turned frequently.

3.6.6.2 Through - draught ventilation

Figure 3.5 shows an example of a through draught ventilation system. Drying air enters the drying chamber and is made to flow through the drying material. Wet air then leaves through the outlet of the chamber. This method offers a good heat exchange between the air and the drying material. Thicker layers of matter offer air resistance against the blower. The air resistance depends upon the air velocity and the layer thickness and is expressed as a pressure difference, which the blower must be able to subdue. The relation between the pressure difference, layer thickness and the air velocity is given as [27]:

$$\Delta P = \omega d \rho V^2 / 2 \tag{3.10}$$

The value for the specific air resistance increases considerably as the size of the drying particle decreases. Wet materials also offer a higher resistance. Actual values may be obtained from available standard tables [27].

3.6.7 Indirect and Direct Drying

Drying can be classified as direct or indirect depending on the type of exposure of the product to the heat source.

3.6.7.1 Direct drying

In "direct" drying, the evaporation of moisture from the product takes place due to heat absorbed by the product itself. In solar drying, the product is exposed to direct sunshine for this case.

3.6.7.2 Indirect drying

In "indirect" drying, the drying product is not exposed to the heat directly, and the heat for evaporation is transmitted to the drying product via a medium by convection and/or conduction. In the case of solar drying, the radiation is absorbed by an absorber and passed on to the product via a medium, which is often air.

Indirect drying becomes important when the product is to be dried under certain specifications like controlled temperature, humidity and drying rate.

3.7 CONCLUDING REMARKS

The various parameters that are involved in the drying process (the internal and external parameters), along with their effects on the drying process have been described in this chapter. An important aspect in dryer design, which involves the use of the psychrometric chart, has also been described. Drying strategies, types of ventilation systems and the types of drying techniques have been described briefly.

Various combinations of the described strategies and methods can be used for the purpose of fish drying. Selection of the dryer to be modelled considers these and other factors elaborated in Chapters 4 and 5.

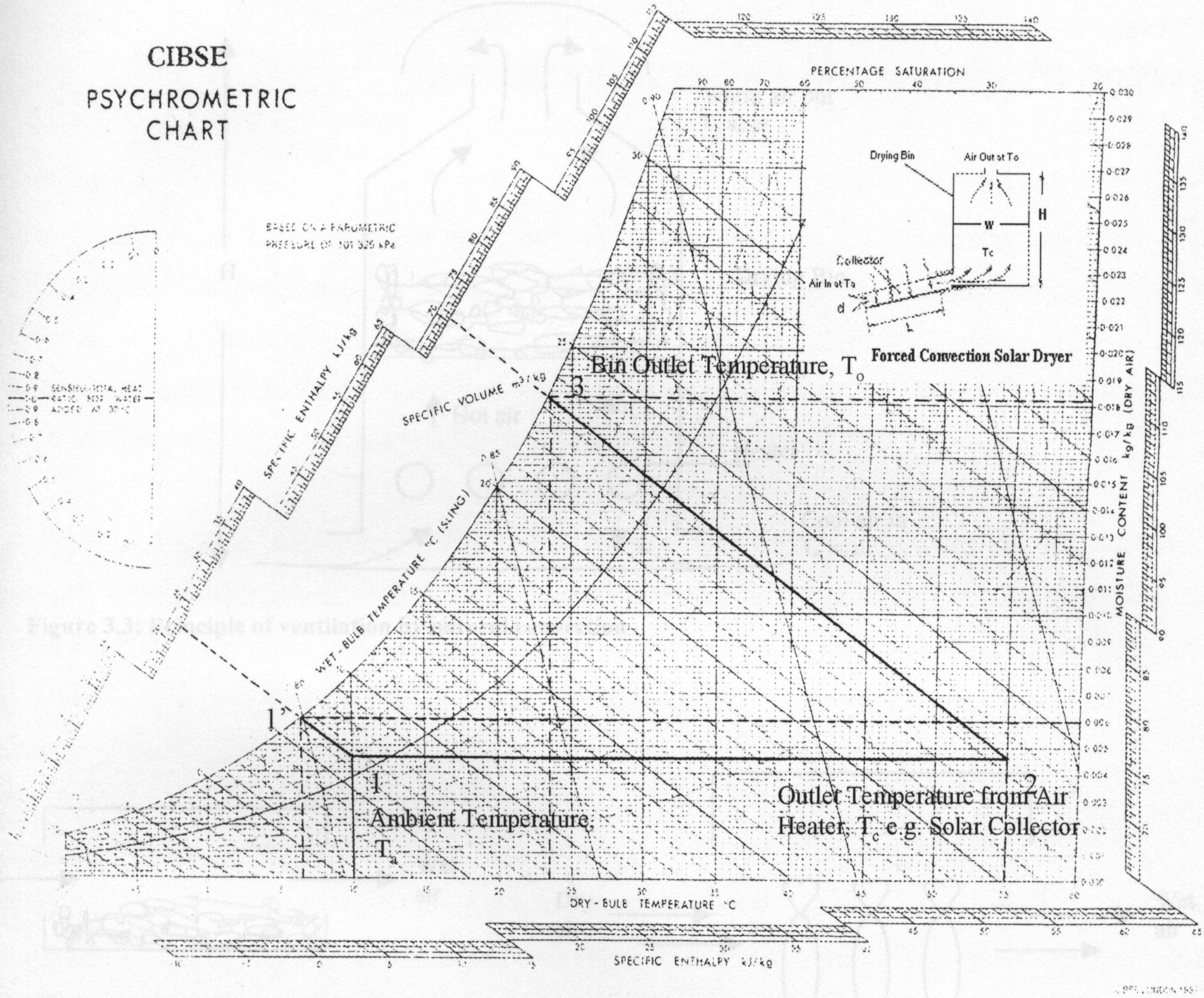


Figure 3.1: Representation of the drying process on a psychrometric chart

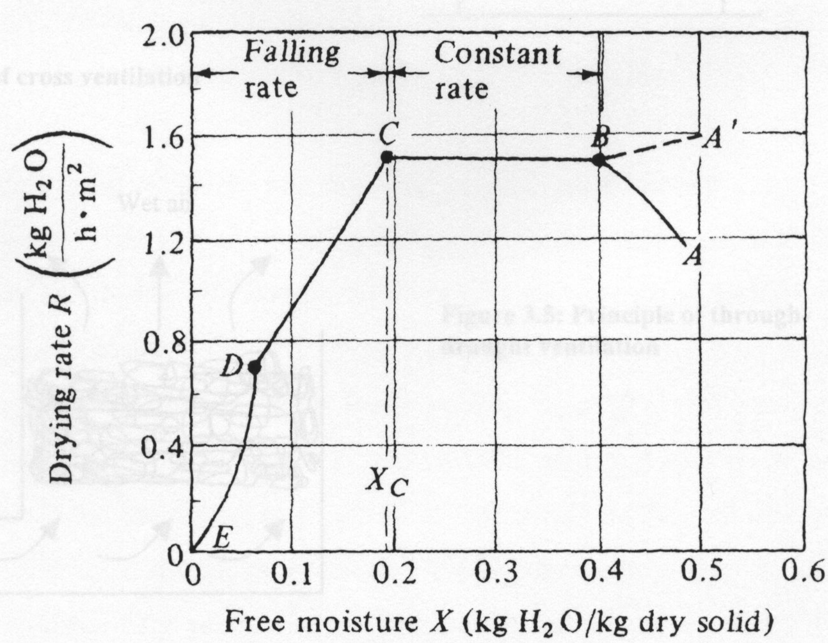


Figure 3.2: Phases of the drying process.

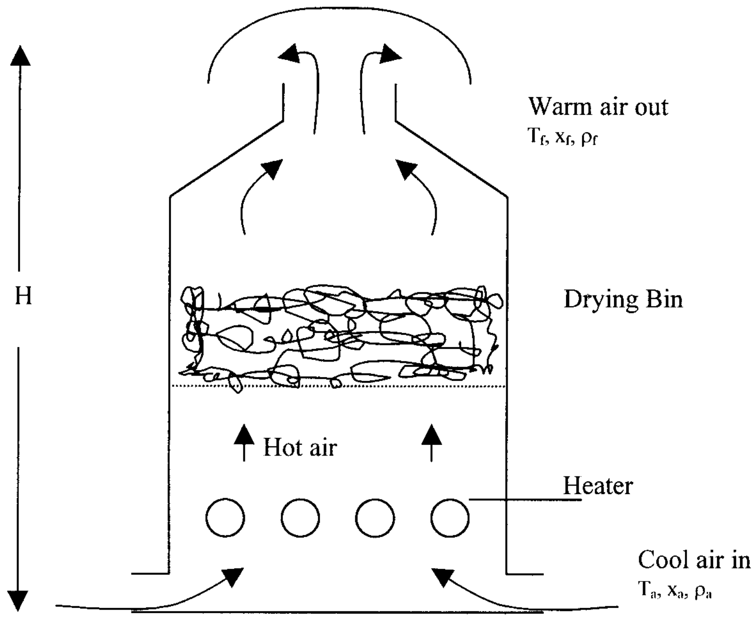


Figure 3.3: Principle of ventilation by natural convection

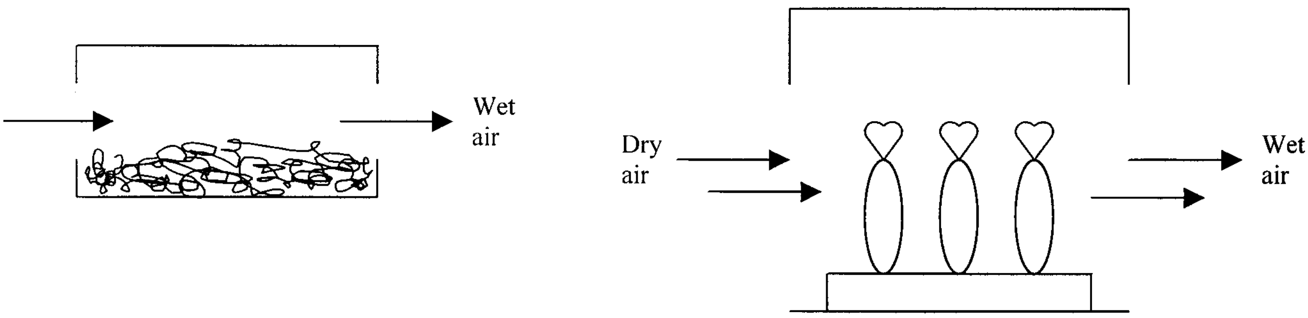


Figure 3.4: Two examples of cross ventilation

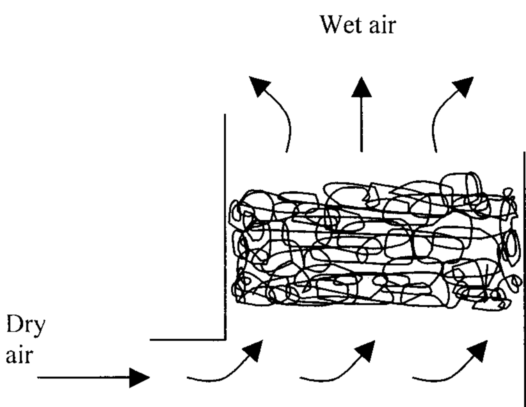


Figure 3.5: Principle of through-draught ventilation

Chapter 4
APPLICATION OF SOLAR ENERGY TO DRYING

4.1 GENERAL

It is believed that the preservation of food stuffs by drying using the sun's energy is one of the first food processing techniques used by man [25]. The application of solar energy to the drying process is still the most important present-day food-preserving technique. It plays an important role in both traditional and modern drying methods. Hence, maximum use of solar drying techniques and improved storage methods will help to ensure food self-sufficiency even in future.

This chapter describes the drying techniques associated with solar energy. Section 4.2 describes traditional drying practices used in the past and the alternatives to these methods are discussed in Section 4.3. The advantages, disadvantages and limitations of solar drying are discussed in Section 4.4. The classification and types of solar dryers, along with their advantages and disadvantages are discussed in Sections 4.5 and 4.6.

4.2 TRADITIONAL DRYING

The traditional method of drying which has been practised over the centuries throughout the world is the spreading of food products in thin layers on a flat surface in the open air, exposed to the sun. This practice may be termed as open sun drying or natural sun drying. In this technique, the product is turned over once or twice a day. Variations in the technique include hanging of the foodstuff from the eaves of buildings or trees, or gathering the product in stooks or bundles in fields.

The process of traditional sun drying is simple and does not require much money except for some labour, but suffers from many draw backs resulting in a poor quality product and hence a lower market price. There is no control over the drying rate and the product may be over-dried under hot and dry climatic conditions resulting in discoloration, loss of germination power, nutritional changes and sometimes complete damage. In an unreliable climate, losses ranging from 10 - 25% can occur during sun drying due to various reasons [28-30]. In wet or humid weather, moisture loss from the product can be intermittent and irregular, and the drying rate inhibited. This increases the risk of spoilage due to fungi and bacteria. Rain and dust storms may damage the product completely as there is no protection thus reducing the quality of the product. Considerable damage is also caused due to insect infestation and contamination by birds and animals, which may even consume part of the drying batch. These unhygienic conditions necessitate the need for extra labour to keep the pests away and to collect the material in the event of rains and storms or at the end of the day.

4.3 ALTERNATIVES TO TRADITIONAL DRYING

The food sector in many countries experiences high labour costs and increasingly stringent quality standards. One response to the problem associated with sun drying has been the development and use of large capacity, artificial drying plants capable of giving a high quality product irrespective of weather conditions. These plants are usually energy, capital and technology intensive and have a low labour requirement mainly using skilled processes and maintenance personnel. These dehydration units are relatively inflexible and are typically geared towards a large throughput of a single product. Such plants are generally not suitable for small-scale farmers in developing countries who only need to dry small quantities of several varieties of foodstuffs for short periods throughout the year [1].

In humid tropical regions where downpours are predictable and the skies are usually overcast, the potential for sun drying is limited and artificial or fuelled mechanical dryers are used. Such dryers are often associated with the so-called plantation crops such as cocoa, coffee, and copra, in which the cost of the drying operation is justified by the income generated by the product. Wood and charcoal are usually used as the fuel for the drying process. Therefore, the use of such dryers is restricted to highly forested areas where such fuels are available in abundance and the ecological damage caused by cutting the wood is minimal. In some cases, it may be possible to supplement or replace the fuel with by-products from the process such as bagasse in case of sugar or coconut shells in case of copra [22].

In arid or semi-arid regions where wood stocks are low and may already be insufficient to meet the cooking needs of the rural sector, the most suitable solution to processing problems may be to improve sun drying methods or introduce solar drying techniques [22].

4.4 SOLAR DRYING

Solar drying differs from sun drying in that parameters like air temperature, humidity, drying rate, moisture content and the air flow rate can all be controlled. The process is therefore also termed as "controlled drying". There are basically two parts of the solar drying process. First, solar radiation is captured and used to heat air, increasing its ability to hold and carry water vapour. The second part is the actual drying process during which heated air moves through, warms and extracts moisture from the product. Drying takes place in a large box called the drying chamber and the air is heated through an appropriate solar collector or through a window on the drying chamber.

4.4.1 Advantages and Disadvantages

Fuels used for most controlled drying processes of food are generally electricity, oil, natural gas or coal, which are quite capital intensive. If technology and money is applied, solar energy can be a possible solution for the dehydration of food. Although solar drying is more costly when compared with sun drying, it does have several advantages that outweigh the cost. The use of a solar collector enables higher air temperatures and consequently lower humidities which contribute to improved drying rates and a lower final moisture content of the dried product (especially in the wet season). As a result, the risk of spoilage during the actual drying process and subsequent storage is reduced as the higher air temperatures attained inhibit insect and microbial growth. Since drying is carried out in a closed chamber, the product takes up lesser space and is protected against rain, dust, insects, animals and birds. The possibility of having control on the final moisture content renders improved transportability since the product becomes lighter due to moisture loss. All these factors contribute to an improved and more consistent product quality, which ensures a better financial return.

Solar energy is also attractive for drying purposes because of the following reasons:

- Solar energy is diffuse in nature and provides low-grade heat, which is good for drying at low temperature, and high airflow rates at low temperature rise.
- The intermittent nature of solar radiation will not significantly affect the drying performance at low temperature as the energy stored in the product itself will help in removing excess moisture in periods of little sunshine.
- Solar energy is available at the site of use and saves transport costs.
- The high capital cost of solar dryers can be compensated if the dryer is used for drying a variety of products or at least put to other multiple uses such as space heating.

4.4.2 Limitations of Solar Drying

Solar drying often appears to be the ideal solution to many food drying problems on first sight as the energy source is freely available and poses no waste disposal problem. Also, the devices used are simple in construction using a significant amount of local material. However, it should be emphasised that the process is not always technically feasible, economically attractive, or socially desirable. It is therefore necessary to carry out a feasibility study in the proposed environment of use.

4.5 CLASSIFICATION OF SOLAR DRYERS

There are a large variety of solar dryers since there are many options in their design. However, the *Tropical Development and Research Institute* have found it appropriate to classify solar dryers according to the following criteria [1].

i) Whether the drying commodity is exposed to insolation or not.
ii) The mode of air flow through the dryer.
iii) The temperature of the air circulated in the drying chamber.

4.5.1 Exposure to Insolation

Based on this criterion, solar dryers can either be termed as "Direct" or "Indirect". Direct dryers are those in which the commodity is exposed to direct insolation from the sun while Indirect dryers are those in which the commodity is kept in enclosed chambers and therefore shielded from insolation. In direct dryers, heat is transferred to the drying commodity mainly by radiation whereas in indirect dryers, heat transfer mainly takes place by convection from a solar collector. While the exposure to direct sunlight may be desirable in some cases, e.g. dates for achieving the desired colour of the dried product, it may not be desirable in others due to, for example, reduction of ascorbic acid (Vitamin C) content and discoloration in several fruits.

4.5.2 Mode of Air Flow

There are two possible modes of air flow, natural convection and forced convection. Natural convection dryers rely upon thermally induced density gradients for the air flow through the dryer whereas for forced convection dryers, the air flow depends on pressure differentials generated by a fan. Because of the greater air flow in forced convection dryers, they are more suitable for dryers with large throughputs. Another advantage of these types of dryers is that the air flow is independent of ambient climatic conditions and is easily and accurately controllable for most applications. A further advantage of forced convection dryers is that of their high air flows and thus high air velocities through flat plate solar collectors, which contribute to high collector efficiencies [1].

However, the forced convection dryers pose a shortcoming in that they are capital intensive and require power for the operation of the fan except in areas where wind power and photovoltaic power generation is a feasible proposition. The capital cost of the equipment necessary to provide forced convection is high compared with the costs of natural convection dryers. Other potential disadvantages of forced convection dryers are the high running costs namely, power and mechanical maintenance and repair, and the difficulties in obtaining necessary spare parts in certain areas.

4.5.3 Circulated Air Temperature

The air entering the drying chamber of a solar dryer can either be at ambient temperature or at some higher value, which can be achieved by passing it through a solar collector prior to the drying chamber. Dryers employing a separate drying chamber and solar collector tend to have greater efficiencies as both units can be designed for optimum efficiency of their respective functions. However, a dryer with a separate collector and drying chamber can be a relatively elaborate structure whereas the combined collector and drying chamber can be compact and relatively simple.

4.6 TYPES OF DRYERS

Since two basic choices exist for each of the three criteria of classification, theoretically there could be eight different types of dryers. However, some of these have proved impractical and of the remainder, the three types that have received most attention from researchers are:

i) Direct dryers employing natural convection with a combined solar collector and drying chamber.

ii) Direct dryers employing natural or forced convection with a separate solar collector and drying chamber having a transparent cover. Such dryers are also known as mixed-mode dryers.

iii) Indirect dryers employing natural or forced convection with a separate solar collector and drying chamber.

Following, is a brief description of the main types of dryers falling in the three categories, along with their advantages and disadvantages.

4.6.1 Direct Dryers

Direct solar dryers are closed insulated boxes inside which both solar collection and drying takes place. Radiation is collected by the green house effect through a transparent glass or plastic cover in the drying chamber, which contains trays to hold the drying products, and vents through which air can enter and exit. Heated air circulates through or above the product, removing moisture, and carrying it out through the vents.

4.6.1.1 Cabinet dryers

Construction: The cabinet type of dryer shown in Figure 4.1 has a rectangular container that is insulated on the sides and bottom. The top cover is made of either glass or plastic. There are holes in the base and sides of the cabinet to allow for air circulation. The interior of the cabinet is painted black and acts as the absorber.

It is recommended that the length of the cabinet be three times its width to minimise the shading effect on the sides [1]. The top cover slope should be sufficient to allow water to run off during rainy periods.

For portable models, construction can be of wooden board, or metal for more sophisticated models. Materials such as wicker or basketwork can be used for more rudimentary models. For permanent (and larger) structures, mud, brick, stone or even concrete could be used. The insulation for the base and sides can be wood shavings, sawdust, bagasse, coconut fibre, dried grass or leaves. It is recommended that the insulation layer be at least 50mm thick for maximum internal heat retention [1]. The insulation should be sealed properly to prevent ingress of moisture, insects and dust. Gauze or mosquito netting can be used to cover the air holes in the cabinet to prevent insect infestation. The drying trays can be made from plastic mesh or netting, wicker or basketwork but preferably not metal as this would react with juices from the drying products.

Principle: Solar radiation passes through the cover and is absorbed by the blackened interior surfaces, which are thereby heated and subsequently warm the air within the cabinet. The warmed air rises by natural convection and passes through the drying trays and out of the cabinet via the upper holes while fresh air enters through the holes in the base.

Advantages: The advantages of this type of dryers are that it is relatively cheap and easy to construct, portable, and offers easy loading and unloading of the drying material as the trays are removable.

Disadvantages: The disadvantages are that very high temperatures may be attained (60 - 80°C) [26], and this may damage the drying material. This also reduces the range of materials to be dried.

Applications: The cabinet dryer can be used for drying various types of fruits and vegetables. It has also been used for drying small sizes of fish like kapenta.

4.6.1.2 Tent dryer

Construction: The tent dryer, shown in Figure 4.2, has a rigid ridge-tent frame made of bamboo poles with a clear plastic on the side facing the sun. A black plastic, which acts as the absorber, is used on the opposite side and on the ground. There are holes at the bottom and in the apex which allow air circulation by natural convection. A drying rack is positioned centrally along the full length of the tent. The plastic sheet at one end is arranged in such a way as to allow access to the rack, but is otherwise fastened shut.

Principle: The black plastic absorbs solar radiation, which heats up the incoming air. The bottom edge of the clear plastic is rolled around a pole which when raised or lowered forms a method of controlling the air flow through, and the temperature within the tent.

Advantages: The advantages of the tent dryer are that it is relatively cheap and simple in construction and operation. The drying time is also reduced by about 25% as compared to sun drying, giving a better and larvae free product [1].

Disadvantages: The disadvantages are that it is susceptible to wind damage and there is a possibility of attaining high temperatures that may damage the drying material. Drying is also not uniform since natural convection is used.

Applications: The dryer has been used for drying fish and fruits. It has also been found that the tent dryer can be used to disinfest sun-dried fish that is heavily contaminated with larvae.

4.6.1.3 Solar-Through dryer

Construction: The solar-through dryer has a half cylinder built into a wooden frame as shown in Figure 4.3. The cylinder is made of looking glass and is covered by a black gauze from the side to the centre. The half cylinder looking glass must be smooth to avoid burning spots by concentrating insolation.

Principle: The top layer of the material is dried by direct radiation from the sun, while the bottom layers are dried mainly by reflected radiation from the cylinder and looking glass to the gauze.

Advantages: The advantages of the solar through dryer are that radiation falls on both sides of the drying material resulting in an equable drying process.

Disadvantages: The disadvantages are that it is expensive because of the looking glass and also has the possibilities of attaining very high and irregular temperatures.

Applications: This dryer has been used for peaches, apricots, cocoa and cane sugar.

4.6.2 INDIRECT DRYERS

Indirect dryers have a solar collector and a drying chamber separately and it is for this reason that these dryers operate more efficiently and provide more control over the drying process than direct solar dryers. The solar collector heats up the air and forces it through the racks of drying products in the drying chamber. Such dryers are mainly suited for large volumes of product.

4.6.2.1 Oil-drum solar dryer

Construction: The oil drum solar dryer has an oil drum with openings at the front and rear as shown in Figure 4.4. The drum is covered with two layers of plastic under which the air flows. This double layer ensures that the hot air is insulated from the ambient air. The drum is painted black on the outside and white on the inside surface. A tray on which the material to be dried is kept inside the drum and drying air is circulated by natural convection through the drum via air vents made at the bottom and sides of the drum.

Principle: The drum absorbs solar radiation and heats up the air moving around it. The heated air flows through the trays and seeks its way back into the atmosphere.

Advantages: The advantage of this type of dryer is that the same amount of radiation is collected during the whole day due to the convex shaped area offered by the drum for radiation collection.

Disadvantages: The disadvantages are the non-availability of an oil drum at times, need of a metal work shop and also the high and irregular temperatures attained at times.

Applications: This type of dryer can be used for drying various food items.

4.6.2.2 Chimney dryer

Construction: The chimney dryer, as shown in Figure 4.5, has a solar collector comprising of a frame covered with clear plastic sheet, fibre glass or glass. The frame is insulated from the sides and the bottom. A black sheet made of plastic, wood or metal acts as the absorber plate.

A wooden drying chamber is placed behind the collector. The two can be connected directly or by means of an air duct. Trays on which drying material is placed can be loaded and unloaded easily through doors provided at the back of the drying chamber.

Principle: Air passes through the collector and rises by natural convection through the trays in the drying chamber. The chimney absorbs insolation, giving rise to a tall column of air that further enhances air flow in the dryer. The chimney also protects the drying material from rain, dust, insects, birds and other impurities.

Advantages: The advantages of this type of dryer are that it offers a shorter drying period during the rainy season and at the same time a better quality product. It is also possible to design the collector to a given temperature to suit the material to be dried. Hence this type of dryer can be used for drying a wide range of products. The air flow can also be increased by placing a wind driven fan at the top of the chimney [31].

Disadvantages: The disadvantages are the high cost of construction and that it is immobile. The other disadvantage is that the product does not dry uniformly in the drying chamber as the air gets cooler and moister as it rises.

Applications: The chimney dryer has been successfully used to dry fruits, rice, vegetables, herbs, fruit purees, meat and fish.

4.6.2.3 Forced - Convection dryer

The forced convection solar dryer has three basic components connected in series - a fan, a solar collector and a drying chamber as shown in Figure 4.6. It is very similar in design to the chimney type dryer, the only difference in this case being the mode of air flow. Drying air is blown through the solar collector and the drying chamber using a fan. Compared to the basic natural convection systems, the forced convection dryer is more costly due to the fan but tends to be more suitable for larger throughputs. The fan also provides a means of having more control on the drying process and is therefore suitable for drying a wider range of materials as compared to the previously described dryers.

4.6.2.4 Hybrid dryers

Hybrid dryers are dryers in which the drying air is heated using another form of energy in addition to solar energy. The system may be used in two ways. Solar energy may be used as the principle source of energy during sunny daylight hours and additional heat supplied by electricity, solid fuel etc. Alternatively, conventional energy may be used as the main means of heating during drying while solar energy is used as a supplement to cut down energy costs. This type of system is suitable for very large throughputs, and/or cases in which, continuous drying is required, in some cases at night.

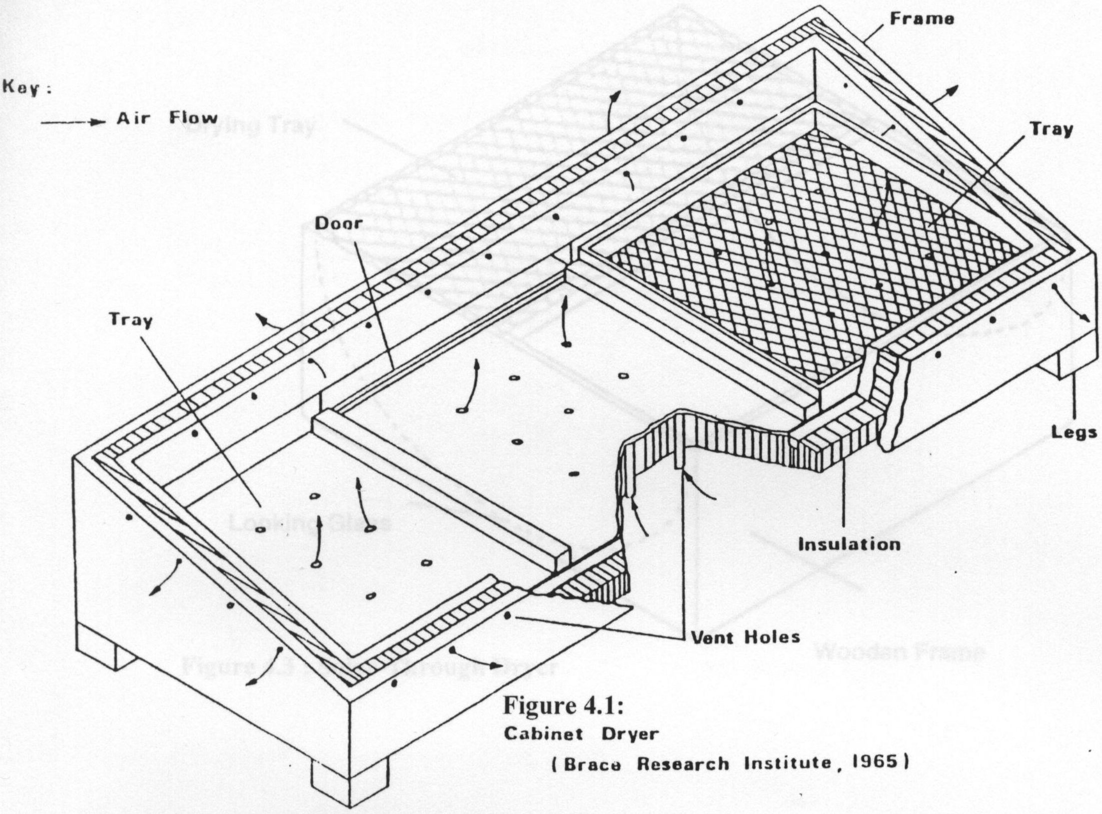


Figure 4.1:
Cabinet Dryer
(Brace Research Institute, 1965)

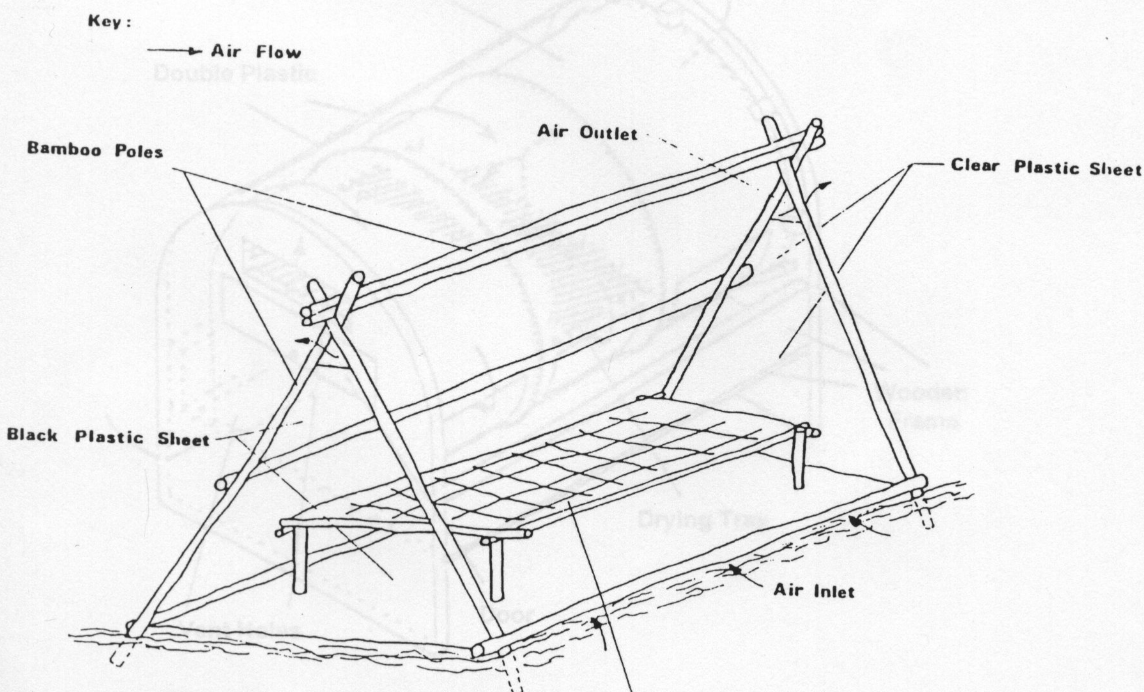


Figure 4.2 : Solar Tent
(Doe, 1979)

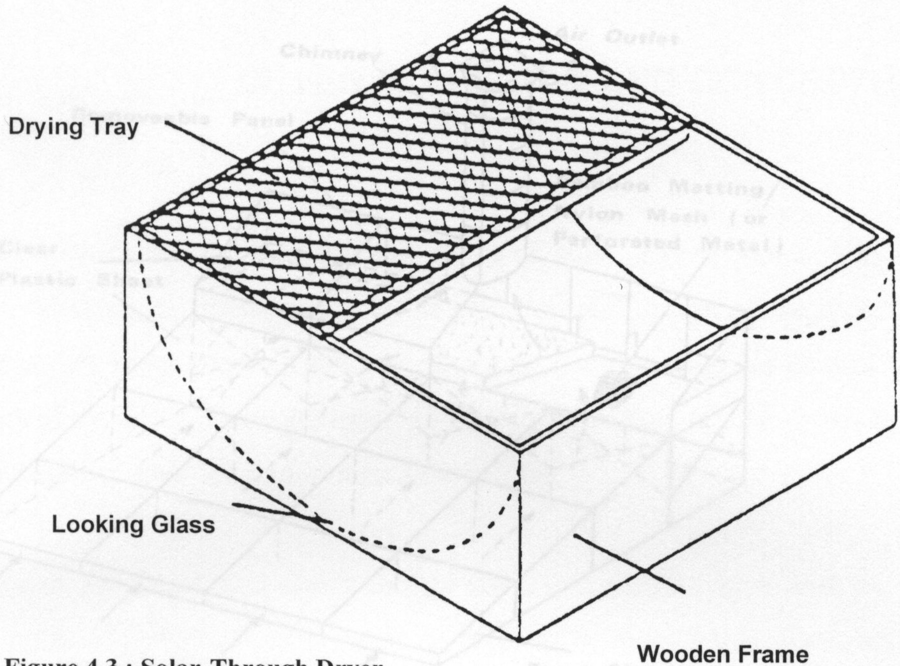


Figure 4.3 : Solar-Through Dryer

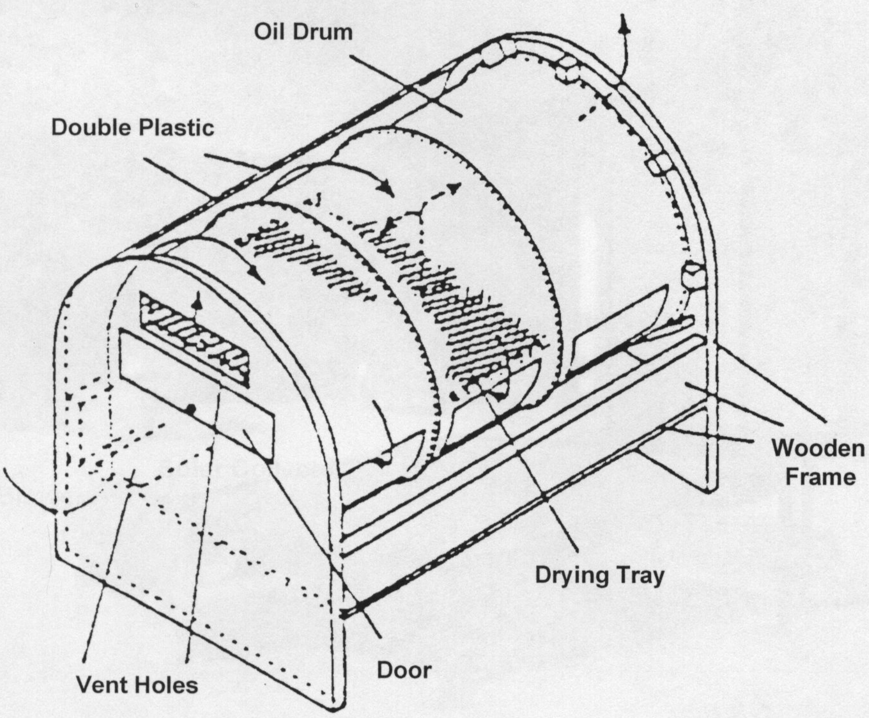


Figure 4.4 : Oil Drum solar dryer

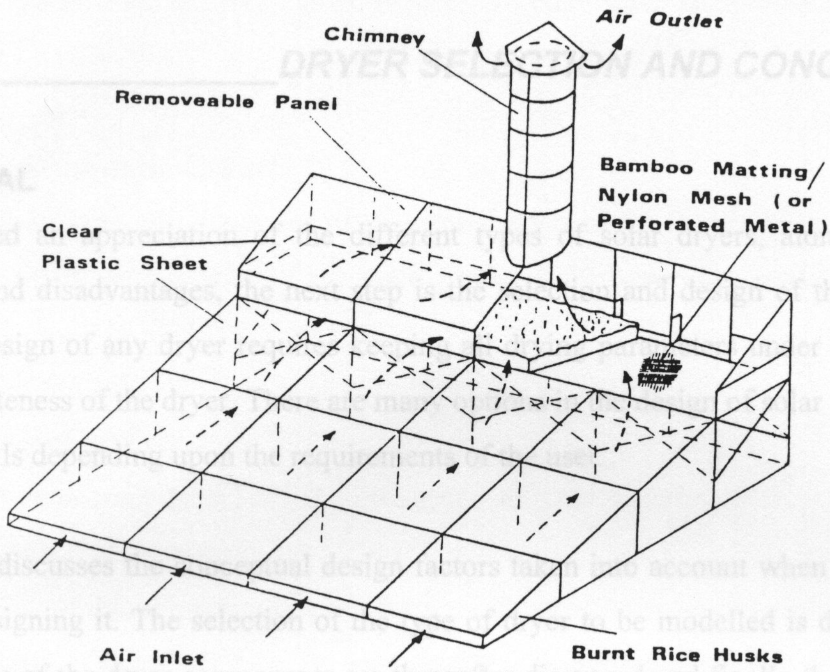


Figure 4.5: Solar Chimney Dryer (Exell, 1980)

Figure 4.6: Forced-Convection Solar Dryer (S.S. Virdy, 1996)

Chapter 5
DRYER SELECTION AND CONCEPTUAL DESIGN

5.1 GENERAL

Having gained an appreciation of the different types of solar dryers, along with their respective advantages and disadvantages, the next step is the selection and design of the most suitable type of dryer. The design of any dryer requires keeping all drying parameters under control and establishing the appropriateness of the dryer. There are many options in the design of solar dryers and hence a large variety prevails depending upon the requirements of the user.

This chapter discusses the conceptual design factors taken into account when making a selection of a dryer and designing it. The selection of the type of dryer to be modelled is discussed in Section 5.3. Design factors of the dryer components are thereafter discussed and finally the possible layouts of the dryer are presented in Section 5.9.

5.2 DRYER SELECTION

The selection and design of dryers is usually done in two stages[1]. The first stage considers the technical criteria while the second considers the socio-economic criteria.

5.2.1 Technical Criteria

The factors considered under this stage are:

- Usability of the dryer during demand periods
- Type of material to be dried
- Drying characteristics of the commodity such as maximum drying temperature, effect of sunlight on product quality etc.
- Drying capacity or Batch size in kg
- Initial and desired final moisture contents of the commodity
- Desired drying time
- Dryer Size
- Dryer materials along with their quality, durability, price and availability
- Type of labour needed to construct, operate and maintain the dryer

In any one situation, there may well be other technical factors that need to be considered and should be considered.

5.2.2 Socio - Economic Criteria

From initial considerations, estimates of the capital costs of the dryer, price of the commodity to be dried and the likely selling price of the dried product will have been made. The factors considered under this stage are:

- The owner of the dryer
- Who is to construct the dryer? The owner or a selected contractor?
- Operation and Maintenance
- Adaptation of the new technology to the present environmental situation.
- Availability of clean water on site for cleaning the commodity prior to drying
- Financial sources

Obviously there are many other socio-economic factors, particularly those of a local nature, which must be taken into account. It need not be over stressed that if these factors are not taken into account and evaluated, then an inappropriate dryer design will result. Due emphasis must be placed on both technical and socio-economic factors.

5.3 CHOSEN DRYER TYPE

After considering the advantages, disadvantages, technical factors and socio-economic criteria, of the various dryers described in Chapter 4, it was decided that the parametric modelling effort of this work would consider the forced convection type of dryer. This dryer offers shorter drying time and a better quality product during the wet season. It is also very suitable for drying fish as the fish is kept in a closed drying chamber, guarding against rain, dust, insects, birds, animals and other impurities. Since the collector and the drying chamber are separate, the dryer can be designed to suit the parameters required for fish drying such as the maximum allowable air temperature, air flow rate and air velocity in the drying chamber, and optimum fan power requirements which can be achieved by positioning the fish appropriately. The solar collector can be designed for a particular season i.e. time of the year during which the drying is to take place, to a particular efficiency, thereby giving the optimum area and slope required. Modelling of such a dryer also offers the possibility of predicting the actual drying time required for drying the specified batch size since the fan ensures a uniform air flow throughout the drying process and the collector would ensure availability of sufficient heat energy. The dryer can also be modelled to suit the requirements ranging from both small and medium-scale farmers to large-scale commercial dealers. This type of dryer may be adapted for drying commodities other than fish that have similar drying characteristics and internal parameters.

5.4 DESIGN PROCEDURE

Having selected the type of solar dryer, the next stage is the design stage. The design of the dryer involves the specification of the following:

- Batch size - Quantity of material to be dried
- Initial and desired final moisture contents
- Desired drying time
- Typical ambient conditions - particularly radiation, air temperature and humidity
- Drying temperature

The following main parameters are then determined:

- Quantity of water to be removed
- Air flow through the dryer
- Bin size and Collector area for dryers with a separate collector
- Pressure drop through the dryer and fan duty for forced convection types

It must be realised that design is an iterative process, which is started up by setting initial ideas, which are then altered as time goes on by consideration of the external factors. Given the same information, two designers will seldomly arrive at the same final design while neither will necessarily be right nor wrong. This is because different people place emphasis on different aspects. Good design therefore evolves by balancing often-conflicting requirements to produce a workable solution.

5.5 DRYER SIZING

Having established the mentioned parameters, the dryer size, the number of dryers and the expected drying time can be determined. It should be noted that a reduction in drying time will not necessarily be of financial benefit to the user especially in cases where the harvesting time gap between the first and next batch of produce is large. Also it may not necessarily be beneficial for the dryer to handle the total harvest at once. The sizing of the dryer should therefore be based on the drying load and not the total harvest.

The drying bin and the solar collector can be designed separately for the forced-convection solar dryer. The design considerations for these components are therefore described separately in the following sections starting with the drying bin.

5.5.1 The Drying Bin

The drying bin or chamber is one of the three basic components that form the forced convection solar dryer. It is basically an insulated box with a perforated base in which the material to be dried is accommodated.

Considerable research on the design and sizing of the bin chimney for the natural convection chimney dryer has been carried out and described by *Exell et al., Boothumjinda et al., and Kornsakoo* [1]. The function of the chimney on top of the drying chamber is to establish a column of warm air to enhance the draught and hence to increase the air flow rate through the dryer. This could also be achieved by placing a wind-operated fan at the top of the chimney as described by *Simate* [31].

However, in the forced convection solar dryer, the flow of air is achieved by means of a fan or blower. This requires knowledge of the required amount of air needed for the mass transfer process and the required air velocity through the dryer for the selection of the fan and hence the sizing of the bin for a particular batch size.

5.5.1.1 Design Procedure for the Drying Bin

The design of the drying bin is then carried out in the following manner:

- Determination of the amount of water to be evaporated
- Determination of the air flow rate through the dryer
- Determination of the bin size
- Determination of the fan power

5.5.2 The Solar Collector

For any solar drying system, one of the many types of solar collectors is employed for trapping the useful heat energy from the sun's radiation. The collectors can either be of the concentrating type or of the (non-concentrating) flat plate type. Flat plate solar collectors basically consist of an air duct of which one side is made into an absorbing surface, which receives insolation from the sun. Concentrating collectors use a specially shaped focusing reflector, which enables trapping of an increased amount of energy on the absorbing surface and therefore can attain higher temperatures than flat plate collectors. Concentrating collectors are therefore used for higher temperature applications such as cooking. For the purpose of fish drying, very high temperatures are undesirable as this would not only cause fast drying and crust formation on the drying surface, which inhibits the drying process, but also cook the fish. Flat plate air collectors provide the desired temperature elevation and therefore provide a more appropriate solution when compared to the more complex-concentrating collectors.

In the present research, a choice of the forced-convection type of dryer has been made. The performance of this type of dryer depends on the type and size of collector used. Over-sizing the collector area will make the system more expensive, while under-sizing will give a very slow drying rate. Therefore, in order to make effective use of the system, optimisation of the collector area is essential. A brief account of the types of flat plate collectors is given in the next section along with the factors considered when making the final selection of the collector type.

5.5.2.1 Flat Plate Solar Collectors

The simplest type of collector consists of a blackened plate (absorber) and a transparent cover above it sealed by insulated side-walls and a bottom plate. In many cases, it may also consist of clear covers placed on top of the absorber in order to prevent the trapped heat to escape back into the atmosphere, and insulation on the sides and bottom in order to reduce heat losses.

The energy from the sun's radiation is transformed to thermal energy in the drying air in two stages. Firstly, the radiation is absorbed on the absorber surface thereby heating the absorber plate. This heat is then transferred to the air either by natural or forced convection when the air comes in contact with the plate. The mode of heat transfer determines the type of collector, i.e. natural or forced convection type. Although natural convection systems have been widely used, very little detailed information is available for the temperature rise, air flow rates and the overall efficiency [1]. For forced convection applications, a fan is used to blow air through the collector and more control over these parameters is possible thereby making the design and performance of the system in relation to ambient conditions more predictable.

A. Types of flat plate collectors

The simplest type of bare plate collector for both the natural and forced convection type is the bare plate collector shown in Figure 5.1. It consists of an air duct, which has the upper most surface acting as the absorber plate. Buildings having corrugated sheet roofs are frequently converted into collectors in this manner.

The air flow in single-cover flat-plate collectors that are mainly used for forced convection systems can be made to vary in four principle ways as shown in Figure 5.1. Where a single-cover, flat plate collector cannot provide the required air temperature rise, further covers may be added to decrease the heat losses. However, more insolation is required for double or triple-covered collectors than for single cover or bare plate collectors due to the higher air temperatures attainable. The air flow is invariably below the absorber plate in order to minimize heat loss to the surroundings. Another type of collector that is worth mentioning is that with a porous high surface area absorber. The absorber surface area of this type of collector is increased by inserting blackened metallic elements e.g gauze, meshes, swarf or iron chippings. This type of absorber gives intimate contact between the air and the absorber surface and hence good heat transfer [1].

B. Factors affecting the selection of the Collector type

The choice of the type of solar collector is mainly governed by the temperature increase required. As the temperature difference between the ambient and heated air increases, the need to insulate the air duct becomes more critical. General guidelines to this choice are given in Table 5.1 [1]. At the lower end of this range, the single cover front pass collector seems to be the most suitable as it is the simplest of the single cover collectors. At the upper limit of the range, the extra insulation that is provided by the static gap above the absorber plate of the back-pass collector provides the most efficient solution. The double-pass and parallel-pass collectors are more efficient than back pass collectors in the lower part of this range but become less efficient as the temperature elevation increases. Double and parallel pass collectors are also more complex in their construction than single pass collectors.

Whereas extra covers decrease the heat losses by convection, they also decrease the amount of insolation incident on the absorber. The emissivity of the collector and the infrared transmissivity of the covers also have a great effect as the temperature of the absorber increases. The mechanical properties of the construction materials along with their durability at the elevated temperatures, which are encountered, must also be taken into account especially if plastic sheet is to be used as an inner cover.

In addition, factors such as the availability and cost of materials, and how the proposed collector fits into the available space must be considered. If the collector is to be part of an existing structure, then this will also affect the type or choice of the collector to be built.

C. Collector performance

Several factors affect the amount of energy absorbed by the solar collector. These are:

i) The level of insolation : The higher the insolation, the greater the energy absorbed. Therefore some knowledge of the typical insolation for the site under consideration is necessary. It must be noted that this parameter can vary from place to place and for different times of the year.

ii) The inclination angle: Ideally, the absorber plate should be perpendicular to the insolation. As the angle of insolation varies, with the time of the day and the year, this ideal condition cannot always be satisfied.

iii) The surface absorptivity: the greater the absorptivity of the surface, the higher the proportion of the incident radiation that will be absorbed.

iv) The cover transmissivity: The greater the transmissivity of the cover (if used), the higher the proportion of the energy which will be allowed into the solar collector.

5.5.2.2 Design Procedure for the Solar Collector

The design procedure for the flat plate solar collector consists of the following steps:

1. Choose a type of solar collector suitable for the desired application.
2. Determine the optimum collector slope.
3. Calculate the intensity of insolation on a surface of this slope.
4. Determine the required collector area.

5. Bearing in mind the effect of air velocity on collector performance, determine the dimensions (width, depth and length) of the collector.

5.6 CONSTRUCTION METHODS AND MATERIALS

Construction methods and materials may vary considerably from place to place and from the type and size of dryer being designed. It is not within the scope of this work to discuss individual local circumstances regarding the construction and material availability. However, general guidelines regarding materials and factors that must be considered are available in literature [1].

5.7 FANS

The rate and distribution of air flow, both through the solar collector and the drying chamber, is of vital importance in solar drying. Insufficient air flow rates result in undesirably long drying times, and with irregular air distribution, unevenly dried product can result. In natural convection dryers, buoyancy of warm air is used to promote the necessary air flow. This works well for cases where low flow rates are tolerable and where there is no great resistance to the air flow. However when a high velocity of the air is required and where there is considerable resistance to the flow of air as in deep bed drying of fish, the use of fans becomes necessary [1].

The air flow rate required from the fan is determined from the quantity of the commodity (in this case fish) to be dried in a certain time. This information is generally known, at least in general terms. The pressure drop produced by the air flow through a dryer is usually considered in two parts:

(i) That encountered in the drying chamber.

(ii) That produced in the solar collector and connecting ducts.

The pressure drop through the drying chamber, particularly for air flow through a deep bed, will usually be much greater than that through the collector and through the ducts. In most cases, the latter can be relatively insignificant [1]. However, for situations in which the fan is to be positioned between the collector and the drying chamber, the pressure drop in the collector, although much less, can be of equal importance. This is so because most fans are not designed to function efficiently when there is an appreciable pressure drop, say 100 to 200 Pa, on their suction side [1].

It is beyond the scope of this work to provide detailed information on fan theory, but an additional factor that should be considered is that of the air temperature. Certain electric motors can only withstand air temperatures of up to about 60°C [27]. This is however only important when the fan is placed between the collector and the drying bin.

5.7.1 Types of Fans

The smallest fans up to 50W power that are available with low voltage DC - motors, can be powered from a lead battery (or car battery). The next size comprises axial fans, which are AC powered with large capacity with regard to the air flow rate. However, the pressure does not exceed $100N/m^2$ in these types of fans.

Air pressures above $100N/m^2$ can be achieved only by radial blowers [27]. Above a capacity of about 10,000 m^3/h and 3 kW power, three phase current is necessary and such blowers are only available for three-phase current. These blowers pose no limitations on the air temperature since the motor is normally separate from the fan.

A summary of principal fan types and their suitability for various applications is given in Appendix 3.

5.7.2 Fan Selection

There is a large variety of electrical fans available on the market. Therefore when selecting a fan for a specific application, the most practical approach is to specify two parameters:

(i) The required air flow,

(ii) The total system pressure drop

The required air flow is obtained when determining the amount of air needed for the mass transfer process, and the total system pressure drop is found by simply taking the sum of the bin pressure drop and the collector pressure drop.

As is common in the design of any component for any working system, it is wise to use a factor of safety when specifying a fan or motor size. Selection of a fan with higher capabilities than required results in lower maintenance costs and longer working life.

5.8 LAYOUT OF THE DRYER

Solar drying work can be classified according to the scale of exploitation. At the lower end are the small-scale applications which involve dryers of the convective type (natural and forced), the radiative type or a combination of both, for drying various products ranging from grains, spices, fruits and vegetables to fish [32]. For large-scale applications, the solar thermal system acts as a pre-heater destined to replace or save conventional energy supplied by an auxiliary heater [32]. These types of dryers can be operated either in batch or continuous mode and find application in industrial, chemical and pharmaceutical processes. They could also be adopted for drying fish on a large scale, that may require continuous drying or for cases for which solar drying is to be adopted as a supplement to conventional energy. For these reasons, a layout of the final design of an air-based solar dryer that can be adapted for both small and large-scale applications by making appropriate changes is presented in the following section.

5.8.1 Basic Layout

The most basic layout of a forced-convection solar dryer consists of a blower, a solar collector and a drying bin connected in series as shown in Figure 5.2. The figure shows that kinetic energy is imparted into the air at ambient temperature, T_1, by means of a blower after which it enters the solar collector at point 1. The air gains heat energy in the collector and comes out at temperature T_2. The air then proceeds to the drying bin via a duct. If the air temperature is higher than that required for the drying bin, the excess energy can be dumped out of the system through the relief valve. The air then enters the drying bin where the drying process takes place during which it gains moisture and comes out as saturated air at temperature T_3. For small-scale applications, the air can be discarded to the atmosphere [32].

5.8.2 Other Possible Layouts

For larger scale applications, an auxiliary system may be incorporated as shown in Figure 5.3. The figure is similar to Figure 5.2 but has an auxiliary heater and blower added to the system. The auxiliary heater provides just enough heat energy to raise the temperature of the air coming out of the collector to the required dryer temperature during periods of low sunshine. During periods of rainfall or at night, the heater may be used to provide the entire heat load. In this configuration, the air coming out of the drying bin can either be discarded or recycled for energy economy depending on the specifications of the system. This type of configuration allows for continuous drying to take place during periods of low sunshine and also at night.

For further energy saving, a thermal storage element may be incorporated by adding a pebble bed to the system as shown in Figure 5.4. The pebble bed can at any time be charging (heating up) or discharging (energy being withdrawn), which requires the passage of air downwards or upwards through the system. This system can allow drying to proceed for several hours even after the sun goes down without necessarily activating the auxiliary heater [32].

Table 5.1: General guideline of Recommended Collector types for various temperature ranges

COLLECTOR TYPE	TEMPERATURE ELEVATION (°C)				
		10	20	30	40
Bare Plate	■	■			
Single cover front pass		■	■	■	
Single cover parallel pass		■	■	■	
Single cover double pass		■	■	■	
Single cover back pass		■	■	■	■
Double pass					■	■
Triple cover	Not generally justified for food drying purposes				
Concentrating collector	Not generally justified for food drying purposes				

(Source: Solar Dryers, 1985, pp. 44)

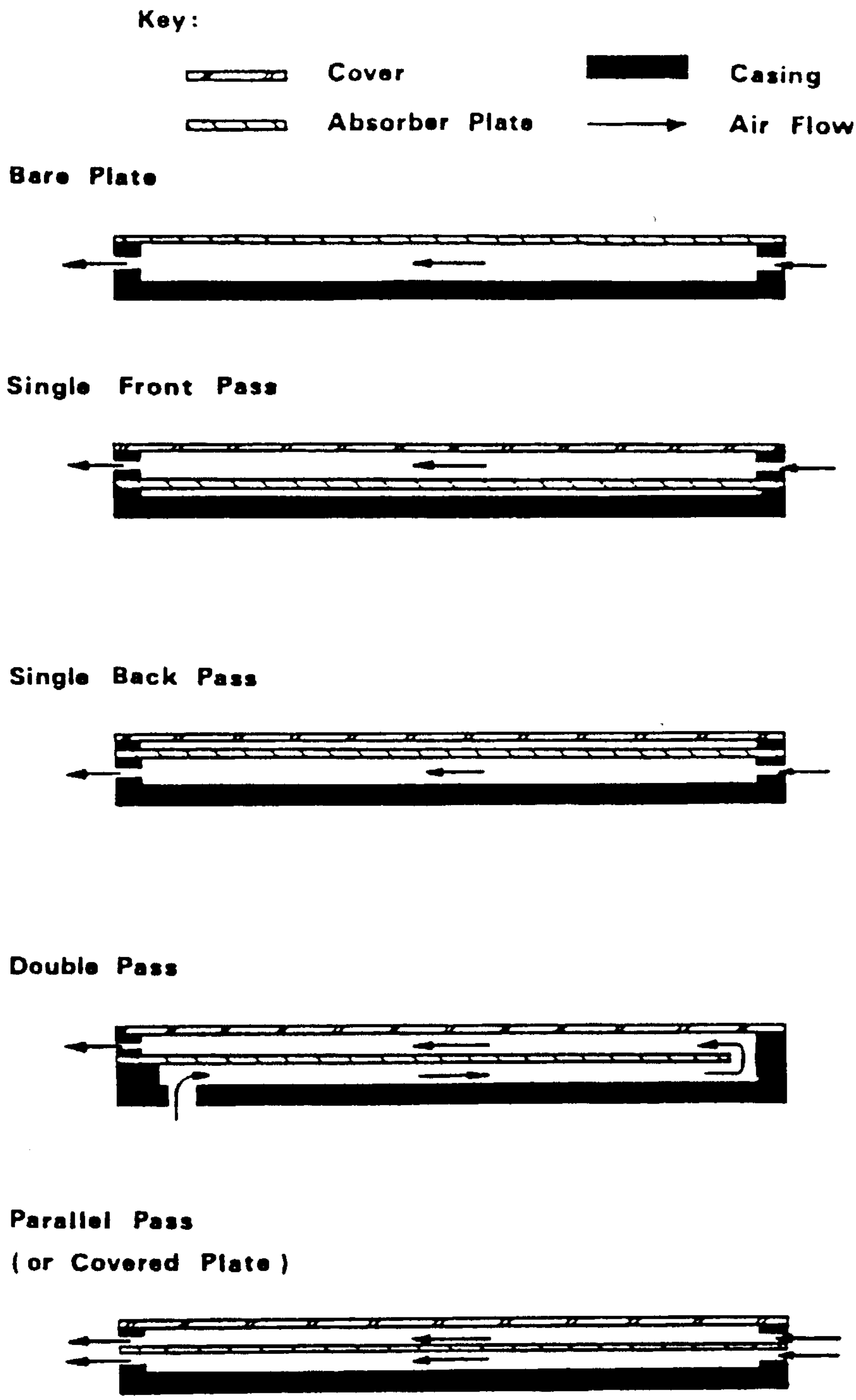
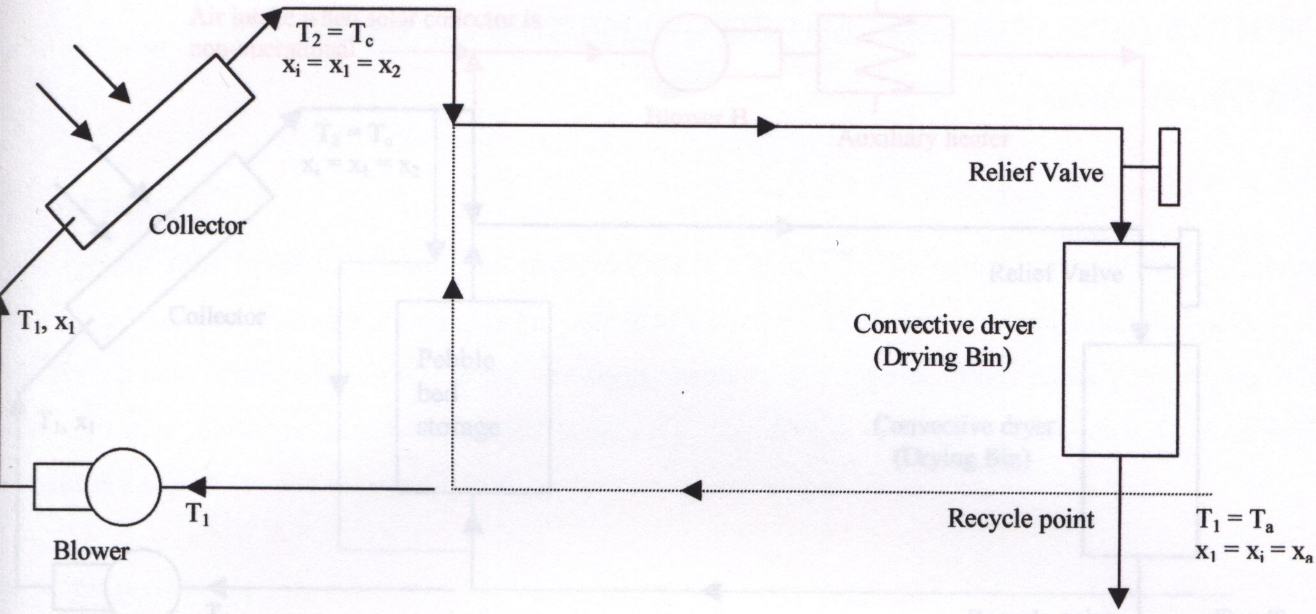
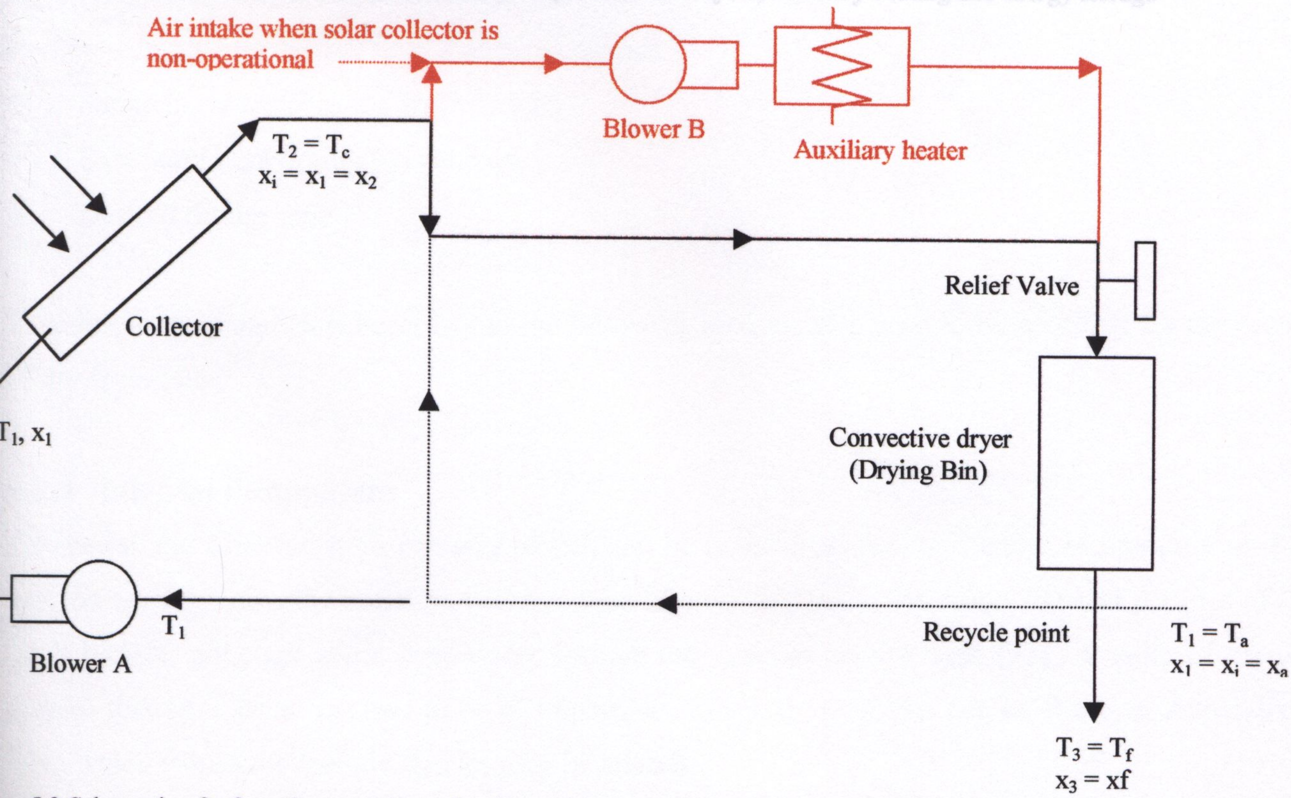


Figure 5.1: **Principal Types of Flat Plate Collectors**

(Davidson, 1980)



gure 5.2 Schematic of a forced-convection solar dryer with possible air recycles



re 5.3 Schematic of a forced-convection solar dryer with air recycle and auxiliary heating system

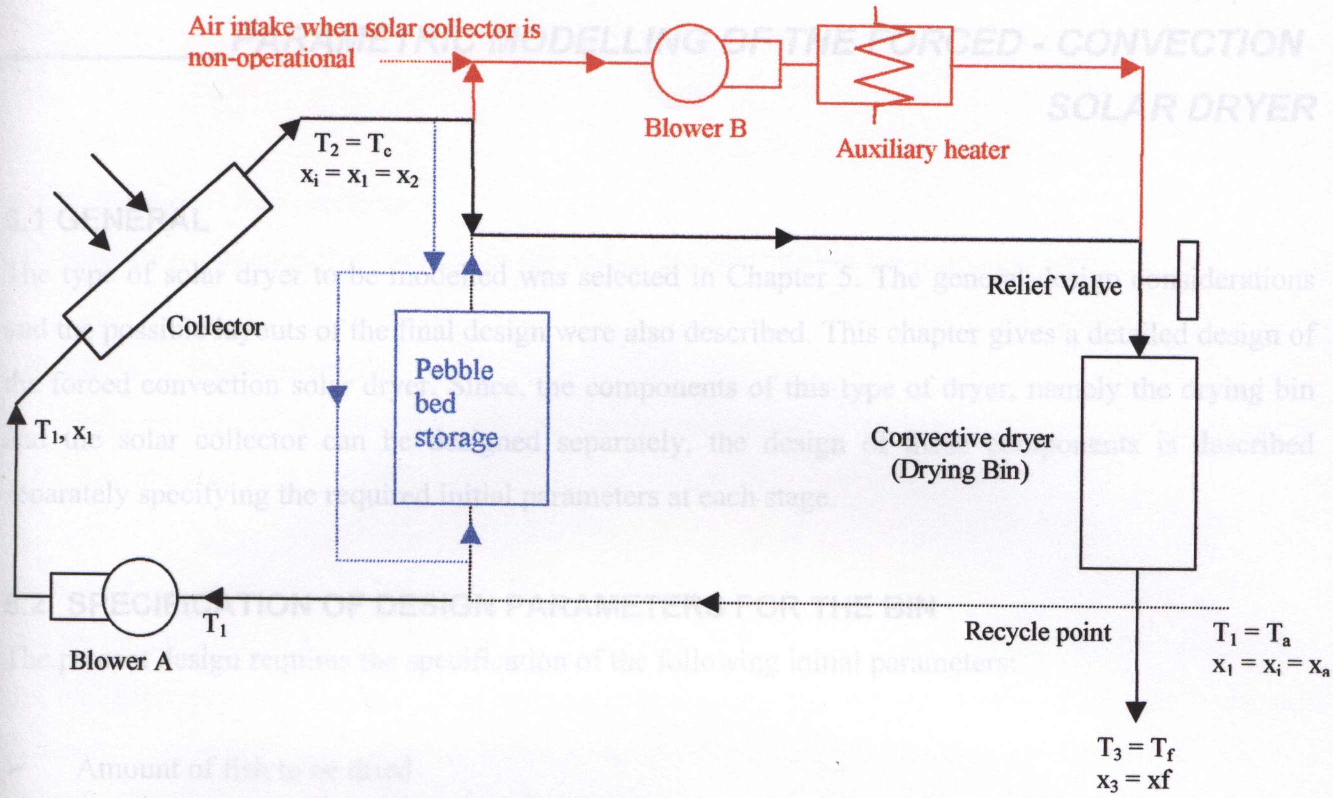


Figure 5.4 Schematic of a forced-convection solar dryer with air recycle, auxiliary heating and energy storage

Chapter 6

PARAMETRIC MODELLING OF THE FORCED - CONVECTION SOLAR DRYER

6.1 GENERAL

The type of solar dryer to be modelled was selected in Chapter 5. The general design considerations and the possible layouts of the final design were also described. This chapter gives a detailed design of the forced convection solar dryer. Since, the components of this type of dryer, namely the drying bin and the solar collector can be designed separately, the design of these components is described separately specifying the required initial parameters at each stage.

6.2 SPECIFICATION OF DESIGN PARAMETERS FOR THE BIN

The present design requires the specification of the following initial parameters:

- Amount of fish to be dried
- Dimensions of the fish to be dried
- The initial and desired final moisture contents
- Ambient air temperature and humidity
- Safe maximum drying temperature
- Desired drying time

In addition, the parameters described in the following sections also need to be specified for the design of the drying bin.

6.2.1 Internal Parameters

The initial and final moisture contents of fish can be found from standard tables in literature on fish processing. Typically, the initial moisture content of most fish lies in the range 70 to 85 per cent of the fresh weight, although some deep-water species may exceed 90 per cent [33]. A table of chosen species that have been reported to be of importance in certain locations can be found in Appendix 4 from which values for specific species may be chosen.

The final moisture content of the fish may be found from sorption isotherm curves for the particular type of fish under consideration. The final moisture content of fish is normally not less than 15 percent [25].

6.2.2 External Parameters

The external parameters that are used in the design are described in the following sections.

6.2.2.1 Temperature

Four different air temperatures are required for the calculation of the bin size. These are described in the following sections:

(i) <u>Air Temperature at the Solar Collector Inlet</u>

The air temperature at the solar collector inlet is taken to be the "average daytime" temperature, which can be determined from weather data by taking the average between the maximum and the minimum daytime temperatures. The "daytime average" temperature, which is the average between the average and the maximum day temperature, can also be used as a matter of choice during the design. However, in many cases, the minimum daytime temperature is used in order to ensure that the system performs adequately even during periods when the ambient temperature falls below the "average daytime" temperature. Therefore, in all calculations in this work, the minimum day time temperatures are used.

(ii) <u>Air Temperature at the Bin Inlet</u>

The higher the air temperature at the bin entry, the quicker will be the drying. This, however, has to be balanced against damage that could be caused due to over heating and the extra cost of a larger solar collector for increasing the temperature. In general, the initial drying temperature should not exceed 25 to 45°C. Tropical fish can withstand a higher processing temperature ranging between 35 to 45°C with no signs of heat damage as compared to temperate fish, which may not withstand temperatures higher than 25 to 30°C [34]. However, *Garg* [25] and *Scanlin* [35] have reported a safe maximum temperature for fish of 55 °C.

The safe maximum temperature mentioned is for continuos drying processes. In solar drying, the temperature varies during the drying process. As the day progresses, the ambient temperature also rises and the drying air temperature may be allowed to exceed 55 °C for certain duration of time. If this duration is too long, the drying will be very fast and crust formation may take place on the surface of fish, thus retarding further moisture transfer from the inner parts of the fish. Therefore, a value higher than 55 ^{0}C should only be allowed for a short duration of time and this is possible with solar drying as the maximum temperature is expected to occur at around midday.

(iii) Air Temperature at the Bin Outlet

The temperature of air leaving the drying bin is determined using psychrometric and equilibrium moisture content data.

(iv) Air Temperature at which the Fish will be Stored

The storage temperature is taken to be the average ambient temperature over a long period of time, say 10 years, since the storing will take place for both day and night, and wet and dry season.

6.2.2.2 Humidity

The ambient humidity is another parameter that plays an important role in both the drying process and storage of the fish. A single value of the humidity may be used through out the calculations since its fluctuation during the day and night is expected to be small for tropical regions [26]. Also, very high and low values may occur within a short period of the day e.g. a short rainfall, which are not comparable to the day's fluctuation. Therefore, the same value for the humidity can be chosen to be the storage humidity.

6.3 DETERMINATION OF PARAMETERS FOR SIZING THE DRYING BIN

Basic calculations for the bin size described by *The German Appropriate Technology Exchange* [27] proved impractical for fish drying and were modified to suit the sizing of the current bin. The following sections describe the sizing of the drying bin along with the necessary parameters and model equations.

6.3.1 Determination of the Amount of Water to be Evaporated

In order to determine the amount of water to be evaporated, the batch size, initial and desired final moisture contents of fish, and the desired drying time need to be specified. The calculation in this work requires the moisture content to be specified in dry basis values. Conversion from wet basis to dry basis can be done using equation (3.3):

The amount of water to be evaporated, m_w, is found from:

$$m_w = m_s(X_i - X_f) \quad (6.1)$$

Where:

$$m_s = m(100 - mc_i) / 100 \quad (6.1a)$$

or,

$$m_s = m / (1 + X_i) \quad (6.1b)$$

and,

$$m = M_B / t_{dr} \quad (6.1c)$$

This value is commonly known as the amount of wet material dried in one hour and significantly influences the layout of the components of the dryer. It has to be chosen carefully and slow drying should be preferred in order to cut down on installation and running costs. For fine weather conditions, fish can be dried within three days using solar drying as compared with sun drying, which would take about five days [22].

6.3.2 Determination of the Air Flow Rate through the Dryer

The capacity of the air blower (the air flow rate through the dryer) can either be calculated or determined with the help of a psychrometric chart. The air flow rate in kg/s is calculated from

$$m_l = m_w / [3600(x_f - x_i)] \quad (6.2)$$

The enthalpy of air before and after the drying process may be evaluated using the practical equation used in Psychrometry for a range of 0 to 60 °C as follows [36]:

$$h = (1.007T - 0.026) + x(2501 + 1.84T) \quad (6.3)$$

The enthalpy of air at the collector inlet will in most cases be the same as that of ambient air. Therefore the initial air enthalpy is evaluated by substituting the value for the ambient air temperature into equation (6.3). Similarly the enthalpy of air at the bed entry will be almost the same as that of the air at the collector outlet (assuming minimal heat loss through the connection duct, if any) and is evaluated by substituting the value for air temperature at the collector outlet. The enthalpy of air at the bin outlet is very often close to the value at the bin entry. This can clearly be seen when the process is represented on the psychometric chart as shown in Figure 3.1.

Point 1 on the psychrometric chart, represents the condition of air at ambient temperature or at the collector entry.

Point 2 is the condition of air at the collector outlet or at the bin entry and is found by drawing a line running horizontally from point 1 up to the line representing the desired collector outlet temperature. It should be noted that the moisture content of air remains the same during this heating process.

Point 3 is found by drawing a line parallel to the adiabatic cooling line up to the percentage saturation line corresponding to the equilibrium humidity or the design value of the air humidity at the bin outlet.

In determining the theoretical drying capacity, it is assumed that the air will follow the adiabatic cooling line and exhaust from the dryer on the saturation line. However, in practice, it is likely to follow a slightly different path and exhaust at some other point, which ideally, should be found with the help of sorption isotherm curves.

Alternatively, for cases where sorption isotherm curves are not available, the approach described by *Brenndorfer* [1] can be used. This approach suggests that whereas the theoretical outlet condition of the air from the bin is 100 per cent, a more realistic answer will be given by assuming no more than 80 per cent saturation on exhaust and base the sizing of the dryer accordingly. This approach also allows for designing a dryer, which can be used for drying a variety of fish, as it is not always necessary that a single built dryer will only be used for a single type of fish.

Oosthuizen et al., and *Preston* [19,37] suggest that a very simple model of the drying process can be adopted. In this model, it is assumed that all the water to be removed from the drying material, is held in the drying material itself in liquid form and therefore the thermal energy in the air streams entering the drying chamber is basically used to supply the latent heat required to evaporate the water from the drying material. As a result of this assumption, there will be little change in the drying material temperature during the drying process and its thermal capacity can therefore be ignored. It has also been assumed in this model that the air leaving the drying chamber will be 100% saturated and therefore point 3 will lie on the 100% relative humidity line. As a result of this assumption, the temperature of air leaving the drying chamber will only be slightly above the initial drying material temperature, which will be close to the ambient air temperature. This fact also renders the buoyancy forces in the air above the drying material negligible.

Since it is often difficult to obtain the sorption isotherm curves for any particular type of fish under consideration, it was decided to adopt the approaches described by *Brenndorfer* [1] and *Oosthuizen* [19]. However sorption isotherm curves should be made use of wherever possible.

The outlet air temperature from the bin can also be found by carrying out an energy balance for the drying chamber as follows:

$$m_1 C_p (T_2 - T_3) = m_1 (x_3 - x_1)\lambda \tag{6.4}$$

Equation (6.4) can be written more conveniently as:

$$(C_p / \lambda)\,[(T_2 - T_1) - (T_3 - T_1)] = (x_3 - x_1) \tag{6.5}$$

Because the relative humidity lines on the psychrometric chart define x_3 as a function of T_3, the outlet temperature, T_3 can also be determined from equation (6.5).

If it is further assumed that some thermal energy in the air stream is used to elevate the temperature of the drying material to the evaporation temperature of 50°C (which lies in the evaporation temperature range of 43.3 to 62.8 °C) [38], then equation (6.5) takes the form:

$$m_1 C_p (T_2 - T_3) = [m_1 (x_3 - x_1)\,\lambda] + [m C_{p,Fish} (T_1 - T_{evap})] \tag{6.6}$$

An iterative approach has to be employed in which values for the outlet temperature, T_3, and the outlet moisture content, x_3, are chosen and matched. This could be quite tedious. However substitution of values in the last term of equation (6.6) often gives a very small value compared to the first term and can be ignored.

Having found the respective enthalpies of air at the entry and exit points of the dryer, an indication of the required heater power in kW, can be estimated from the expression [27]:

$$Q = \dot{m}_l(h_f - h_i) \quad (6.7)$$

6.3.3 Determination of the Bin Size

In order to ensure that the bin accommodates the whole batch size, it is necessary to obtain the main dimensions of the bin at design stage. The main dimensions of the bin are the length, width and the height.

6.3.3.1 Determination of the bin cross sectional area

The basic cross sectional area of the bin, A_B, can be worked out from:

$$A_B = m_l / (\rho_a V) \quad (6.8)$$

The air velocity normally used for drying fish with a mechanical / cabinet drier should be between 60 and 120 meters per minute. This velocity range is thought to be a compromise between non-uniform drying and economy. A very low velocity will promote 'crusting' of the outer surface of the fish thus suppressing the drying process, while a high velocity promotes uniform drying in the dryer as the air becomes more and more saturated as it approaches the exit of the bin. However, a high velocity requires a more powerful blower. Therefore a velocity range between 1m/s and 2m/s should be used [34].

For cases where lower air velocities may suffice, the layer thickness may be found from:

$$d = V_B / A_B \quad (6.9)$$

Where the batch volume, V_B, is found from,

$$V_B = M_B / \rho_{b,Fish} \quad (6.9a)$$

The bulk density of fish, $\rho_{b,fish}$, can be obtained from existing data or can be determined experimentally. In this work, it was determined by dividing a known mass of fish by its volume. The volume of fish was found by the water displacement method. The experiment was conducted for nine samples of bream and tiger fish, and the average value for the density of fish was found to be $1080 kg/m^3$.

The height of the bin should be about 20cm more than the layer thickness, d, to accommodate other fixtures such as trays and a door [24].

This method of sizing the bin is however suitable only for certain types of items and cases where the fish is to be dried using low air velocities. It also does not take account of the space required for the air flow to take place. The above method was therefore extended in order to take care of the required air velocity in the drying bin and also to obtain the required bin height in accordance with the size of the fish to be dried.

The area obtained from equation (6.8) is the area required for air to flow through the bin, or the void area. Therefore, in order to obtain the actual bin cross sectional area, an area fraction, A_f, must be defined as follows:

Area fraction, A_f = Void Area / (Area of Void + Material Area)

$$A_f = A_v / (A_v + A_m) = A_v / A_T \qquad (6.10)$$

Now, in all drying bins, there is a false or perforated floor, which should have an open area equal to 15% or more of the total area [25]. Since, the calculated area A_B, is the open area required for air flow, the total actual area, A_T, of the material can be obtained from equation (6.10) by assuming a value for the open area. Upon obtaining the total area of the material, the area occupied by the fish can be worked out.

6.3.3.2 Determination of the Bin volume

The volume of fish to be dried can be calculated from equation (6.9a). The value obtained in this way assumes that there is a solid mass of fish, with no spaces in between. This is definitely not the case in practice.

In order to give an allowance for the spaces in between the fish, the void fraction can be defined as:

Void fraction,(ε) = Volume of Voids in the bed / Total Volume of bed (Voids + Solids)

$$\varepsilon = V_v / (V_v + V_m) = V_v / V_T \quad (6.11)$$

For most systems, values of ε range from 0.4 to 0.55 [39] although this parameter can be measured for a specific product.

The total volume of the bin can also be found from:

$$V_T = V_m / (1-\varepsilon) \quad (6.12)$$

The height of the bin can then be calculated using the following equation:

$$d_{bin} = V_T / A_T \quad (6.13)$$

The stack height of the material can be found from:

$$d_{material} = V_m / A_m \quad (6.14)$$

This value is supposed to turn out to be smaller than that obtained by equation (6.13).

6.3.3.3 Determination of the Tray size

In order to reduce the pressure drag in the drying bin, it was envisaged that the fish in the drying bin could be placed in a longitudinal manner such that it faces the direction of the air stream as shown in Figure 6.1. In this way, maximum fish surface area would be exposed to the drying air. Various means can be used to hold the fish in the desired position. One such method is to hang the fish by means of a wire. However, in order to maintain certain dryer parameters during the design stage, it was decided that a number of wire trays be employed for this purpose. The following sections describe the determination of the tray size required for a specific type of fish to be dried. If the air flow would be vertical, the fish would be placed vertically.

The area of the solid mass of material A_m, (in this case fish), can be calculated from equation (6.10). By taking actual measurements (as shown in Figures 6.2a, 6.2c and 6.2d) of a few samples of fish, the area occupied by a single fish may be obtained. The number of fish per unit area can then be found from:

No. of fish / unit area = Area of solid mass of fish / Area of one fish (6.15)

It should be noted that all the values used should be average values of measured values of the maximum width, length and thickness as shown in Figures 6.2a, 6.2c and 6.2d.

From the required material area A_m, the length and width occupied by the fish can be worked out. For a bin of square cross section, the square root of A_m, will give this length. The number of fish that can be accommodated across the length and width can then be worked out as follows:

No. of fish across bin length = Length occupied by the fish / Fish height

$$N_L = L_m / F_h \tag{6.16}$$

No. of fish across bin width = Width occupied by the fish / Fish thickness

$$N_W = W_m / F_{th} \tag{6.17}$$

The number of fish across the width also gives the number of trays required. Multiplying N_W by N_L gives a check for the number of fish per cross sectional area expressed by equation (6.15).

The calculation up to this stage assumes that there is no gap between the fish. This is obviously both undesirable and impractical. Therefore, the bin void length and width have to be calculated and divided accordingly. The bin void length can be found simply by taking the difference between the total bin length and the length occupied by the fish as follows:

$$L_v = L_T - L_m \tag{6.18a}$$

The void width is obtained in a similar manner:

$W_v = W_T - W_m$ (6.18b)

The gap between the fish along the length of the bin is calculated as follows:

Gap along the length = Available length (m) / No. of fish along the length + 1

$G_L = L_v / N_L + 1$ (6.19)

The gap along the width:

Gap along the width = Available Width (m) / No. of fish along the width + 1

$G_W = W_v / N_W + 1$ (6.20)

The tray size can now be found:

Tray thickness = Fish thickness + Gap along the width

$T_{th} = F_{th} + G_W$ (6.21)

Tray length = Length of side of section of the bin

$T_L = L_T$ (6.22)

Tray width = Length of the fish

$T_W = F_L$ (6.23)

A number of parameters may have to be "rounded off" during the course of the calculation if it is done by hand. Therefore, it is necessary to make a check on the final void area in order to ensure sufficient air flow.

1. Void area along the length = Space between trays * Tray length * No. of gaps between trays

$A_{vL} = G_W * T_L * (N_W + 1)$ (6.24)

2. Void area along width

= Space between fish * Tray thickness * No. of gaps between fish * No. of gaps between trays.

$A_{vW} = G_L * T_{th} * (N_L + 1) * (N_W + 1)$ (6.25)

The total void area is obtained by adding equations (6.24) and (6.25). It also gives a check for the required void area for air flow.

The actual void area is expected to be greater than the assumed value since the values used for calculating the fish area were the maximum dimensions of the length, width and thickness of the fish. The calculation also assumes that the fish has a rectangular shape. This is obviously not true in practice but is desirable for design purposes as it helps to ensure that all the fish will fit in. It also helps in providing a design allowance in calculating the required fan power to blow the air through the bin.

The number of fish that fit into a single tray is found as:

Number of fish / tray = Number of fish along the length

$N_T = N_L$ (6.26)

Number of trays = Number of fish across the width

$T_N = N_W$ (6.27)

Number of fish/ bin cross section = Number of fish per tray * Number of trays

$N_c = N_L * N_W$ (6.28)

Mass per Cross Section = Average mass of a single fish * Number of fish / cross section

$W_{F,c} = W_F * N_c$ (6.29)

Having found the mass of fish that can be taken up by a single cross section of the bin, the number of such cross sections required to accommodate the whole batch size can be found. This is also equal to the number of trays to be placed vertically.

Number of trays placed vertically = Total batch size / mass per cross section

$T_v = M_B / W_{F,c}$ (6.30)

Finally,

Bin height = Tray width * Number of trays placed vertically

$H = T_W * T_v$ (6.31)

The calculation procedure described in this section is likely to give a more practical indication of the required size of the bin than the one described by the *German Appropriate Technology Exchange* [27]. As seen in the calculation, the air velocity is also taken care of by giving an allowance for the required cross-sectional area for the bin. Equal exposure of the fish to the drying air is also ensured by calculating the gap between the fish, both along the bin length and width and keeping these gaps the same in the respective directions.

The value for the bin height obtained by equation (6.13) is compared to that obtained by equation (6.31) and the greater of the two should be chosen. It should be noted further that the dimensions obtained for both the bin and the trays are the basic dimensions and do not take into account the necessary tolerances required for manufacturing. This aspect should therefore be taken into account during manufacturing.

6.3.4 Determination of the Bin Fan Power

Having established the required air flow rate through the dryer and the bin dimensions, the required fan power for blowing the air can be evaluated. This is a necessary parameter, as it is known that the greatest pressure drop in any forced convection dryer system takes place in the drying bin. The size of the chosen blower is also critical, as it constitutes a major proportion of the total cost of the dryer.

6.3.4.1 Bin pressure drop

The pressure drop in the bin depends on the specific air resistance, thickness of the layer of fish and the air velocity. It is expressed as a pressure difference, ΔP_B, which the blower must be able to subdue. The relation between ΔP_B, layer thickness, d and air velocity, V is given by the equation [27]:

$$\Delta P_B = \omega d \rho_a V^2 / 2 \tag{6.32}$$

In order to obtain the total pressure drop in the bin, the layer thickness d, in equation (6.32) has to be replaced by the total bin height, H, giving:

$$\Delta P_B = \omega H \rho_a V^2 / 2 \tag{6.33}$$

A. Drag coefficient

The air resistance can be determined from the drag coefficient, which can be measured experimentally. Also by measuring the pressure drop directly across a few samples of fish, the air resistance can be calculated from either equation (6.32) or (6.33). In this work, attempts to measure the drag coefficient experimentally for fish and maize proved unsatisfactory and this option was therefore discarded. However, the experiments revealed that the pressure drag is minimum when the fish is kept in the positions shown by Figures 6.2a, 6.2b, and 6.2d. The maximum pressure drag occurs when the fish is kept in the position shown by Figure 6.2c.

B. Particle diameter

Since the air resistance also depends on the particle diameter of the drying product, it was decided to obtain the particle diameter of fish and maize cobs as described by *Geankoplis* [24], and thereafter compare the values with those of other materials in Table 6.1. The value of the air resistance, ω, would then be estimated as suggested by [27].

The particle diameter of each of the materials in Table 6.1 was obtained experimentally and compared with that of fish. Calculation of the particle diameter was carried out as follows [24]:

$$D_p = 6 / a_v \tag{6.34}$$

Where the specific surface of a particle, a_v, is found as:

$$a_v = S_p / V_p \tag{6.35}$$

The surface area, S_p, and the volume, V_p, of the particles were obtained by taking actual measurements of a few samples using a pair of callipers. The particle diameter for fish was also determined from actual measurements. The obtained values were then tabulated and compared with the values in Table 6.1. This comparison is done in Table 6.2.

From the results, it was seen that the average particle size of fish compared well with that of maize cobs. An extrapolation using the *Langrange polynomial* [40] gave a value of 1417/m. Therefore, upon comparison from Table 6.2, the estimated value would turn out to be 1500/m. However, since the water content of fish is much more than that of maize cobs, it is more likely that the surface of fish will remain wet for a longer period of time as compared to that of maize. Hence, for design purposes, a value of 2000/m was used to evaluate the pressure drop through the bin.

6.3.4.2 Fan power

The electrical power of the blower, P_B can then be obtained by specifying the efficiencies of the blower and motor in the equation:

$$P_B = m_l \Delta P_B / (\rho \eta_{B,M}) \quad (6.36)$$

A safety factor of 20 per cent may be added to the result as it is always better to specify a fan which is little over sized rather than an under sized fan. In addition, this offers a lower maintenance cost and longer working life.

6.4 SPECIFICATION OF DESIGN PARAMETERS FOR THE SOLAR COLLECTOR

The Design of the solar collector requires the specification of the following initial parameters.

- Month in which drying is to take place
- Latitude angle of the site of location
- Insolation data of the site of location
- Average ambient temperature during the drying season
- Air flow rate through the collector
- Desired temperature rise through the collector

6.5 DETERMINATION OF PARAMETERS FOR SIZING THE SOLAR COLLECTOR

The following sections describe the sizing of the solar collector along with the necessary parameters and model equations.

6.5.1 Determination of the Collector Orientation and Slope

The insolation on any collector will vary over the period it is being used irrespective of its slope or orientation. In order to maximise the trapped insolation, solar collectors are generally designed such that they face perpendicular to the insolation at solar noon on the day selected as representing the peak of the drying season. Also, depending on the time of the year and location, the collector should ideally be made to face either directly south or directly north.

The collector slope angle varies for each day and is calculated from the following expression [1,41],

$$\beta = \varphi - \delta \tag{6.37}$$

Where, φ is the latitude angle of the place under consideration and the declination angle, δ is calculated by specifying the day number from January 1, n, in the equation [1,41]:

$$\delta = 23.45 \text{ Sin } [0.9863(284 + n)] \tag{6.38}$$

According to the sign convention for equation (6.37), a POSITIVE value of β means that the collector should face SOUTH and a NEGATIVE value indicates that the collector should face NORTH. Also, when the declination angle, δ, in equation (6.38) is POSITIVE, the sun is NORTH of the collector and when it is NEGATIVE, the sun is SOUTH of the equator. Therefore, a collector placed at a certain location relative to the equator should be oriented towards the sun accordingly. It can be seen from equation (6.38) that the declination angle is unique for each day of the year. It must be emphasised that this approach is only valid for determining β, the angle of incidence, at solar noon and for a collector facing either due North or South. However, in practice, variations of a few degrees will not make much difference in collector performance [1].

6.5.2 Solar Radiation Calculations

When designing and predicting the performance of solar dryers and collectors, it is often necessary to have precise knowledge of the direction of insolation in relation to the slope of the collector or dryer. Insolation data are most often gathered from instruments measuring the intensity of radiation on a horizontal surface. This is obviously not the same as the intensity falling on a sloping surface.

6.5.2.1 Determination of the Intensity of insolation on a collector surface

Due to variation in intensity of insolation, with climatic conditions, precise prediction of the intensity of insolation on the collector surface is not possible. Consequently, the heat output of the collector will vary. Since the heat output of the fixed collector must be matched to the drying load, the question arises as to what value of insolation to use in determining the size of the collector. Whatever value is selected, it is obviously a compromise between an excessively large collector on one hand and the risk of not generating enough heat on the other. Therefore, a good rule of thumb is to base the design on the peak of the season [1]. A useful concept in this regard is that of the *average day* of the month. This is defined as the day for which the extra-terrestrial radiation is closest to the average for that month. A list of average days for each month along with their day numbers from January 1 is given in Table 6.3.

Whilst this method will in some cases give an over sized collector for a large part of the season, it does ensure that sufficient energy is available when it is most needed. Hence the collector is designed such that it is perpendicular to the insolation at solar noon on the day selected as representing the peak of the season. Therefore, to provide data for sizing the solar collector, an average value for the insolation has to be estimated. The procedure here is as follows:

(i) Calculate the intensity of insolation on a horizontal surface ;

(ii) Then, calculate the intensity of insolation upon the inclined collector surface.

A <u>Determination of the Intensity of Insolation on a Horizontal Collector</u>

The insolation data available is the total amount of insolation over the whole day on a horizontal surface. The angle of incidence of beam radiation on a surface, θ, placed at a specified latitude, φ, sloping at a certain angle, β, and at a specified time of the year is calculated for any time of the day from the following equation [1,41]:

$$\cos\theta_t = \sin\delta.\sin\varphi.\cos\beta - \sin\delta.\cos\varphi.\sin\beta.\cos\gamma + \cos\delta.\cos\varphi.\cos\beta.\cos\varpi + \cos\delta.\sin\varphi.\sin\beta.\cos\gamma.\cos\varpi + \cos\delta.\sin\beta.\sin\gamma.\sin\varpi \quad (6.39)$$

Equation (6.39) is valid for the following conditions:

Latitude angle, φ: $-90^o \leq \varphi \leq 90$
(North is positive and South is negative)
Slope angle, β: $0^o \leq \beta \leq 180^o$
($\beta > 90^o$ means that surface has a down ward-facing component)
Surface azimuth angle, γ: $-180^o \leq \gamma \leq 180^o$,
(Zero is due South, East is negative, and West positive)
Hour angle, ϖ, -90^o (in the morning) $\leq \varpi \leq 90^o$ (in the evening).
(It changes 15^o per hour and is Zero at Solar noon)

Definitions of the angles are given in Appendix 1.

Since for a horizontal surface, the slope angle, β, is zero, equation (6.39) reduces to:

$$\cos\theta_{h,t} = \sin\delta.\sin\varphi + \cos\delta.\cos\varphi.\cos\varpi \quad (6.40)$$

A reasonable estimate of the mean value of the angle of incidence of beam radiation, θ_h, over the day can be made by assuming a 12-hour day and dividing it into 3-hour periods and calculating θ_h for each period. For a 12-hour drying day starting at 06:00hrs, the hour angle, ϖ, varies from -90^o at 06:00 hours to $+90^o$ at 18:00 hours. For the first three-hour period, i.e.06:00 hours to 09:00 hours, the mean value of ϖ is -67.5^o since ϖ changes by 15^o every hour and occurs at 07:30 hours. Other values are calculated in a similar way [1]. The procedure is repeated up to 12:00 hours (noon) after which the calculated values of radiation for the morning are assumed to be symmetrical to those after 12:00 hours. For example, θ_h for 06:00 to 09:00 hours is identical to the period from15:00 to 18:00 hours and θ_h for 09:00 to 12:00 hours is identical to the period from 12:00 to 15:00 hours. For more accuracy, these values can be calculated for every hour. The hour angle in this case will assume values corresponding to the middle of each hour being considered. For this case, the value for 06:00 hours to 07:00hours will correspond to the period from 17:00 hours to 18:00 hrs and so on.

Having determined the angle of incidence for the beam radiation on a horizontal surface for each hour, the insolation falling on a horizontal solar collector over any hour period can be calculated by specifying the total radiation available for the whole day from the expression [1]:

$$I_{h,t} = I_T \cos\theta_{h,t} / [\cos\theta_{h(06:00-07:00)} + \cos\theta_{h(08:00-09:00)} + \ldots\ldots\ldots\ldots + \cos\theta_{h(17:00-18:00)}] \quad (6.41)$$

Measured values of the available total radiation, I_T, for any place can be obtained from any reliable weather station situated close to the location under consideration.

B. Determination of the Intensity of Insolation falling on an Inclined Collector

The values from equations (6.39) to (6.41) can be used to obtain the intensity of insolation received by an inclined collector surface over any one hour period using the following equation [1,41],

$$I_{c,t} = I_{h,t} \mathrm{Cos}\theta_t / \mathrm{Cos}\ \theta_{h,t} \quad (6.42)$$

Whereas equation (6.42) can give a good estimate of the radiation falling on an inclined surface, it does not take into account the status of the atmosphere. The effects of the atmosphere in scattering and absorbing radiation are variable with time as atmospheric conditions and air mass change. The occurrences of periods of various radiation levels e.g. good and bad days are also of interest during the design of any solar system.

Numerous models for calculating the hourly average radiation falling on a tilted surface have been developed. However, the method developed by *Liu* and *Jordon*, and extended by *Klein* [41], has gained much popularity in this respect. The method basically consists of the determination of the following parameters:

(i) The Hourly Extra-Terrestrial Radiation

(ii) The Hourly Clearness Index

(iii) The Diffuse Ratio

(iv) Angle of incidence upon the collector

(v) The Geometric factor

(vi) Insolation on the tilted collector surface

(i) Determination of the hourly extra-terrestrial radiation

The extra-terrestrial radiation is the theoretically possible radiation that would be available if there were no atmosphere. With the absence of the atmosphere, all the solar radiation would be beam radiation. The extra-terrestrial radiation, G_o, received by a horizontal surface at any time between sunrise and sunset is given by:

$$G_o = G_{sc}\,[1+ 0.033\cos(360n/365)]*(\cos\delta\cos\varphi\cos\varpi + \sin\delta\sin\varphi) \qquad (6.43)$$

Where G_{sc}, is the solar constant and is taken to be 1367 W/m^2 in this report [41]. For most engineering calculations however, it is necessary to have the integrated daily, H_o, or the hourly, I_o, extraterrestrial radiation on a horizontal surface, as in the present case. Equation (6.43) can be integrated over a period from sunrise to sunset to obtain H_o as:

$$H_o = 24 * 3600 * G_{sc}(1/\pi)[1+ 0.033\cos(360*n/365)] \\ *[\cos\delta\cos\varphi\sin\varpi_s + (\pi\varpi_s / 180) \sin\delta\sin\varphi] \qquad (6.44)$$

Where ϖ_s in equation (6.44) is the sunset hour angle calculated from:

$$\cos\varpi_s = (\sin\delta \sin\varphi / \cos\delta \cos\varphi) = -\tan\delta \tan\varphi \qquad (6.44a)$$

The same can be done for a period between two hours to obtain I_o as:

$$I_o = 12 * 3600 * G_{sc}(1 / \pi)[1+ 0.033*(\cos360n /365)] \\ *\{\cos\delta \cos\varphi (\sin\varpi_2 - \sin\varpi_1) + [\pi(\varpi_2 -\varpi_1) / 180] \sin\delta \sin\varphi\} \qquad (6.45)$$

Where ϖ_1 and ϖ_2 are the hour angles of the two respective hours over which the calculation is being done. Note that ϖ_2 is always greater than ϖ_1.

Equation (6.45) has been adopted for the calculation of the hourly extra-terrestrial radiation in the present model.

(ii) <u>*Determination of the hourly clearness index*</u>

The clearness index is the ratio of the average radiation falling on a horizontal surface to the average extra-terrestrial radiation. The index can be defined as monthly, daily or hourly. The daily clearness index, K_T, is defined as the ratio of the radiation of a particular day to the extra-terrestrial radiation of that day. The hourly index, k_T, is also defined in a similar manner:

$$K_T = H_R / H_o \tag{6.46a}$$

$$k_T = I / I_o \tag{6.46b}$$

H and I are obtained from actual measurements of solar radiation on a horizontal surface whereas H_o and I_o can be calculated from equations (6.44) and (6.45) respectively. For the present model however, only equation (6.46b) is relevant.

(iii) <u>*Determination of the Diffuse Fraction*</u>

Many applications require that the diffuse and beam components from the measured total radiation be separated. The split of total radiation on a horizontal surface into its diffuse and beam components is of interest since the methods used for calculating the total radiation on surfaces of other orientation from data on a horizontal surface require separate treatments of the two components. Also, estimates of the long-time performance of most concentrating collectors must be based on estimates of availability of beam radiation.

The usual approach for determining the two components is to correlate I_d / I, the fraction of the hourly radiation which is diffuse, with k_T, the hourly clearness index. A k_T value of 0.5 may result from skies with thin cloud cover, resulting in a high diffuse fraction, or by skies that are clear for part of the hour and heavily clouded for the other part of the hour, leading to a low diffuse fraction. Thus the correlation may not represent a particular hour accurately, but adequately represents the diffuse fraction over a large number of hours.

Of the various methods available, the *Orgill* and *Hollands* correlation, and those of *Erbs et al.* have been widely used and found to produce results that are practical [41]. The *Orgill* and *Hollands* correlation is represented by the following equations:

$$I_d / I = \begin{cases} 1.0 - 0.249k_T & \text{for } k_T < 0 \\ 1.557 - 1.84\, k_T & \text{for } 0.35 < k_T < 0.75 \\ 0.177 & \text{for } k_T > 0.75 \end{cases} \qquad (6.47)$$

The *Erbs et al.*, correlation is represented by:

$$I_d / I = \begin{cases} 1.0 - 0.09k_T & \text{for } k_T \leq 0.22 \\ 0.9511 - 0.1604k_T + 4.388k_T^2 - 16.638\, k_T^3 + 12.336k_T^4 & \text{for } 0.22 < k_T \leq 0.80 \\ 0.165 & \text{for } k_T > 0.80 \end{cases} \qquad (6.48)$$

There is very little data for values of k_T greater than 0.8. Some of the available data show an increasing diffuse fraction as k_T increases above 0.8. This apparent rise in diffuse fraction is probably due to the reflection of radiation from the clouds during times when the sun is unobscured but when there are clouds near the path from the sun to the observer. A diffuse radiation of 0.165 is recommended in this range.

Since the *Erbs et al.*, correlation covers a wider range of values for k_T without much discontinuity between the ranges, it has been adopted for the present model.

(iv) *Determination of the angle of incidence on the collector*

The angle of incidence of beam radiation on the solar collector can be calculated from equation (6.39) described earlier.

(v) Determination of the Geometric Factor

The Geometric factor, R_b, is the ratio of beam radiation on a tilted surface to that on a horizontal surface at any time and can be calculated exactly by appropriate use of equations (6.39) and (6.40) as follows:

$$R_b = \cos\theta / \cos\theta_h \tag{6.49}$$

Other relations for obtaining the value of R_b have also been developed specifically for the Northern and the Southern Hemispheres by *Hottel* and *Woertz* [41]. They also showed a graphical method for solving these equations, which was revised by *Whillier* and is presented in Appendix 5. In the present model, equation (6.49) is used.

(vi) Determination of the Insolation on a Tilted Collector surface

Having obtained all the parameters described, the mean solar radiation falling on an unshielded tilted surface over a period of one hour is calculated from the expression [41]:

$$I_{c,t} = I_{h,t}\,[1 - (I_d/I_h)_t]R_{b,t} + I_{h,t}(I_d/I_h)_t[(1 + \cos\beta)/2] + I_{h,t}\rho_g[(1 - \cos\beta)/2] \tag{6.50}$$

where ρ_g, is the diffuse reflectance from the surroundings or the ground reflectance. With ground reflectances normally of the order of 0.2 and low collector slopes, the contributions of the ground-reflected radiation are small. However, for ground reflectances of 0.6 to 0.7, typical of snow and for high slopes, the contribution of the reflected radiation of the surfaces may be substantial [41].

The *Liu and Jordon Method* for obtaining the radiation falling on a tilted surface ends at equation (6.50). What remains is to determine the average radiation falling on the collector surface over the whole day. Since the insolation falling on a tilted surface can be calculated for every hour from equation (6.50), for a 12-hour drying day starting at 06:00hrs and ending at 18:00 hrs, the average value of the radiation is found as follows:

$$I_{c,ave} = (I_{c\,(06:00-07:00)} + I_{c\,(07:00-08:00)} + \ldots\ldots + I_{c\,(16:00-17:00)} + I_{c\,(17:00-18:00)}) / 12\text{ hrs} \tag{6.51}$$

The value obtained from equation (6.51) is then used for sizing the solar collector.

6.5.3 Determination of the Solar Collector Area

The collector area has to be chosen according to the heat required to evaporate the moisture. This can be calculated as the power of the heater Q, using equation (6.7). The collector area for the dryer can be found from the expression:

$$A_c = 1000^*Q / (\eta_c I_{c,\,ave}) \tag{6.52}$$

The collector area can also be found from the definition of the collector efficiency as:

$$A_c = v_1 \rho \Delta T C_p / (\eta_c I_{c,\,ave}) = m_1(T_c - T_a)C_p / (\eta_c I_{c,\,ave}) \tag{6.53}$$

There are two options for obtaining the collector area at this stage. The first is to assume a value for the collector efficiency from standard available data and the second is to calculate it using certain selected collector properties. For the design process, the second option was deemed more suitable as it gives an idea of the collector properties.

6.5.3.1 Determination of the Collector Efficiency

Considerable research has been carried out on forced convection solar collectors and some researchers have developed empirical relations based on principles of heat transfer for predicting the collector performance.

Buelow [1] developed empirical equations for predicting the temperature rise for bare plate collectors and also for parallel-pass single-cover collectors. The equations were also represented graphically. By combining these equations with the equation for calculating the efficiency for a solar collector, predictions of collector efficiency can be made. However the equations are strictly valid only for the range of air flow rates investigated by *Buelow*. Another equation that can be used to predict the collector efficiency is that proposed by *Whillier* [1]. This equation is more flexible than *Buelow's* as it offers the possibility to design collectors having air flow rates, absorber emissivity, cover transmissivity, heat losses and heat transfer coefficients other than those used by *Whillier*. It was therefore decided to use *Whillier's* approach for the present work.

A Whillier's approach for collector efficiency

The collector efficiency according to *Whilliers'* equation is determined from :

$$\eta_{W,c} = [1 / (1+ U_L/h)]*[(1- \exp(U_o/G_aC_p)]*(G_a.C_p / U_o)f_{ca} \qquad (6.54)$$

Where, the collector heat loss coefficient, U_L, is the sum of the front, back and side heat loss coefficients respectively:

$$U_L = U_o + U_b + U_s \qquad (6.54a)$$

The front heat loss coefficient U_o, can either be calculated or estimated graphically as described by *Duffie and Beckman* [41].

By knowing the thermal conductivity k_i, and the thickness t_i, of the insulation used in the collector, the collector back loss coefficient U_b, can be estimated as follows:

$$U_b = (k_i / t_i) \qquad (6.54b)$$

For most collectors, the evaluation of side losses is complicated. However, in a well-designed system, the side loss should be small so that it is not necessary to predict it with great accuracy. *Tabor* [41] recommends that the side insulation be about the same thickness and type as the bottom insulation. Assuming one-dimensional sideways heat flow around the perimeter of the collector system, and by knowing the thermal conductivities and thicknesses of the side plate material and insulation, the side losses can be estimated by using the following expression :

$$U_s = (A_s / A_c)\{1/[(t_m/k_m) + (t_i/k_i)]\} \qquad (6.54c)$$

For situations where the side plate material thickness is very small and of high thermal conductivity, equation (6.54c) reduces to:

$$U_s = (A_s / A_c)[1/ (t_i/k_i)] \qquad (6.54d)$$

However, equations (6.54a) through (6.54d) could not be used in this work as the collector dimensions were unknown at this stage.

The data required to use equation (6.54) are provided in Tables 6.4, 6.5 and 6.6 and the assumptions made in determining the values are:

- Heat transfer coefficient between absorber and flowing air, h = $22.7 W/m^2K$
- Mass flow rate per unit collector area, $G_a = 40.8 * 10^{-3} kg/m^2s$
- Specific heat of air, $C_p = 1.005 kJ/kgK$
- Effective transitivity-absorptivity product at normal incidence, $f_{ca} = \tau\alpha = 0.85$ (from Table 6.2)
- Rear and edge heat losses are 10% of upward heat loss.
- Sky temperatures are taken approximately as 5°C below ambient
- Wind speed is taken to be 2.2m/s (5 mph)
- Glass thickness = 2.5mm
- Tedler thickness (Type of clear plastic used as collector cover) = 0.1mm

The values stated are for a specific air mass flow rate and heat transfer coefficient for *Whillier's* experimental conditions. These values are used for calculating the *Whillier's* efficiency, which is substituted into equation (6.53) to obtain the collector area.

The mass flow rate of air per unit collector area is then determined from:

$$G_a = v_1 \rho / A_c = m_1 / A_c \tag{6.55}$$

In order to obtain efficiencies for different mass flow rates and heat transfer coefficients to suit the present designer's (or desired) conditions, the correction factors given in Tables 6.5 and 6.6 are used [1]. Equation (6.55) gives the air flow rate per unit collector area, required for the situation at hand. A correction factor for the air flow, k_1, is then obtained by linear interpolation from Table 6.5. For cases where the collector is being designed for a heat transfer coefficient other than the one used by *Whillier*, the correction factor for the heat transfer coefficient, k_2, is determined by linear interpolation from Table 6.6. These correction factors are then multiplied by the *Whillier's* efficiency to get the corrected efficiency.

Finally, the actual, corrected collector area can be determined as follows:

$$A_{c,c} = m_1(T_c-T_a)C_p / (k_1 k_2 \eta_{W,c} I_{c,\,ave}) \quad (6.56)$$

6.5.4 Determination of the Solar Collector Dimensions

Once the collector area has been obtained, the next step is to find the actual dimensions of the solar collector. These include the actual collector length, $L_{a,c}$, collector width, $W_{a,c}$, and the collector depth, $d_{a,c}$. Referring to Figures 6.3 and 6.4, which is a schematic representation of a basic air collector configuration, the problem is to determine the spacing (or depth), $d_{a,c}$, the number of bays, *N*, for a given value of bay width, W_c. In such cases, heat transfer and pressure drop analysis like that of *Malik* and *Buelow* [32] would have to be resorted to. Such analyses however require the knowledge of the formulae for the heat transfer and the pressure drop specifically meant for the duct configurations in question. Such formulae are more often than not unavailable and can only be determined by experimentation after which the design analysis can be carried out [42].

Theoretically, the highest air temperatures would be achieved when the collector depth, d_c, is close to zero. However, in practice if the collector depth is too small, the air significantly cools down when it reaches the crop bin because of the available large volume for expansion. Further more, as the collector depth is reduced, the airflow pattern changes thereby causing a drop of air temperature. This means that there is a minimum collector depth below which overall heat losses increase so fast that efficiency drops. It has been reported by *Herick Othieno* that *Macedo* and *Altermani*, *Grainger et.al.*, and *Grainger* suggest that this minimum depth should be about 5cm [43].

Other available guidelines [27] when designing or sizing a collector are:

(i) Length of collector, $L_{a,c}$, must be made at least 20 times the collector depth $d_{a,c}$

(ii) The width can then be calculated by dividing the collector area by the length.

(iii) Other dimensions may be chosen arbitrarily.

It has also been reported that the collector width is determined by the total amount of energy required to dry the material within the desired drying time [43]. The collector length, on the other hand, is determined by the velocity of air passing through it and the maximum air temperature required for the drying process.

Another approach described by *Werecko-Brobby* [1], involves an iterative procedure in which the dimensions are chosen after which factors such as the pressure drop and the heat transfer coefficients are considered. If these prove suitable, then the chosen dimensions can be used. If not, a new set is chosen.

This iterative approach involves the recalculation of the heat transfer coefficient used in calculating *Whillier's* collector efficiency determined by equation (6.54). The recalculation is performed by assuming dimensions of the cross-sectional opening of the collector duct and choosing a friction factor from the Moody Diagram according to the *Petukhove* approach [44]. Once the recalculated value converges to the one used in the efficiency equation (within a chosen error limit), the chosen dimensions are taken to be the dimensions of the solar collector. This approach has been adopted for the present model, the error limit for convergence being about ±0..1% of the chosen value.

6.5.4.1 Determination of the Heat Transfer Coefficient

The rate at which the energy absorbed by the absorber is transferred to the air is controlled by the air flow pattern over, below or around the absorber plate. At low velocities as in natural convection, the air flow will be laminar resulting in poor heat transfer between the absorber plate and the air. As the air velocity increases, the flow becomes more turbulent and the heat transfer improves. Therefore, for high collection efficiencies, high volumetric flow rates in narrow ducts are recommended.

The volumetric flow rates and the duct depth are however limited by two factors. Firstly, high volumetric flow rates, although giving good collection efficiency, will also lead to low temperature increases and secondly, will result in high pressure drops.

The approach used to calculate the heat transfer coefficient in this work proceeds in the following four steps:

(i) Determination of the Air velocity through the collector

(ii) Determination of the Reynold's number

(iii) Determination of the Nusselt number

(iv) Determination of the heat transfer coefficient

(i) Determination of the air velocity

The air velocity in the collector is determined from the basic continuity equation for fluid flow in ducts from Fluid Mechanics. For a solar collector it can be found from:

V_c = Volumetric Air Flow / Cross Sectional Area of flow

$$V_c = m_l / \rho \, d_c W_c \tag{6.57}$$

A higher value of the air velocity should be used for bare plate collectors in order to have good heat transfer between the air in the duct and the absorber plate as the heat losses from the absorber plate in these types of collectors can be quite considerable. A value of 5m/s is recommended by *Preston* [1] for bare plate collectors. Higher values will lead to higher pressure drops requiring more powerful fans. For single or multiple cover collectors, the air velocity should be in the range of 2.5 to 5m/s in order to reduce vibrations and noise [1].

(ii) Determination of the Reynold's number

The Reynolds number is a dimensionless number in Fluid Mechanics that is used to define the type of flow taking place on an external surface or in a duct. For flow in a solar collector, the Reynolds number is calculated by [1]:

$$Re = V_c \rho_a D_{hyd} / \mu \tag{6.58}$$

Where, the hydraulic diameter, D_{hyd}, for the collector duct is calculated as:

D_{hyd} = 2(Depth * Width) / (Depth + Width)

$$D_{hyd} = 2 d_c W_c / (d_c + W_c) \tag{6.59}$$

(iii) Determination of the Nusselt number

The Nusselt number provides a measure of the convection heat transfer occurring at a particular surface. From knowledge of the Nusselt number, the local convection coefficient h, may be found.

There are a number of empirical correlations for the prediction of this number for both external flow and internal flow taking place as free or forced convection, for different ranges of the Grashof, Reynolds and Prandtl numbers. Definitions of these numbers are given in appendix 1.

For situations where the effects of free and forced convection are comparable, it would be inappropriate to neglect either process and heat transfer correlations of the form Nu = f(Re,Gr,Pr) would be expected. Such situations are termed as combined free and forced (or mixed) convection regimes. Values for heat transfer coefficients for both free and forced convection are calculated separately and the greater of the two is applied [44].

For such situations, an external flow is superposed on the bouyancy–driven flow and there exists a well defined forced convection velocity. Generally, the combined effects of free and forced convection must be considered when $(Gr/Re^2) \approx 1$. If the inequality $(Gr/Re^2) \ll 1$, is satisfied, free convection effects may be neglected and Nu = f(Re,Pr). Conversely, if $(Gr/Re^2) \gg 1$, forced convection effects may be neglected and Nu = f(Gr,Pr) [44].

In the strict sense a free convection flow is one that is induced solely by bouyancy forces, in which case there is no well defined forced convection velocity and $(Gr/Re^2) = \infty$. It should also be noted that although bouyancy effects can significantly enhance heat transfer for laminar forced convection flows, enhancement is typically negligible if the forced flow is turbulent [44].

Since the present design involves a forced convection system, involving a well-defined forced convection velocity, the flow is more likely to be turbulent and effects of free convection have therefore been neglected.

A classical expression for computing the local Nusselt number for fully developed turbulent flow in a smooth circular tube (or ducts), is obtained from the *Chilton-Colburn* analogy as [44]:

$$Nu = 0.023\, Re^{4/5} Pr^{1/3} \tag{6.60}$$

For a solar collector, the hydraulic diameter of the collector opening should be used in calculating the Reynolds number. For the temperatures encountered for drying purposes, the value of the Prandtl number does not change much and can safely be taken as 0.7 as seen from standard tables showing thermophysical properties of air at atmospheric pressure [44].

Although equation (6.60) can be applied easily and satisfactorily, it is only meant for flow in smooth pipes (or ducts) and allows for the calculation of the heat transfer coefficient by varying the hydraulic diameter of the collector opening only. This means that only two parameters can be varied. These are the collector width W_c, and the collector depth d_c. Also, errors as large as 25% may arise in the use of this equation [44].

A more recent correlation which is widely used, but generally more complex is that attributed to *Petukhove, Kirillov*, and *Popov*, and is of the form [44]:

$$Nu = (f / 8)RePr / [1.07 + 12.7(f / 8)^{1/2}(Pr^{2/3} - 1)] \qquad (6.61)$$

Valid for: $\{0.5 < Pr < 2000 \text{ and } 10^4 < Re < 5*10^6\}$

The friction factor, f, may be obtained from the Moody diagram for smooth ducts, from the expression:

$$f = (1.82\log_{10}Re - 1.64)^{-2} \qquad (6.61a)$$

This expression allows for the varying of an additional parameter, the friction factor f, during the design, thus giving an extra and at the same time important option. This option is necessary because a rougher surface enhances turbulence, thus increasing the heat transferred from the absorber plate to the air.

In order to obtain agreement with smaller Reynold's numbers, *Gnielinski* modified the correlation [44] and proposed an expression of the form:

$$Nu = (f / 8)(Re - 1000)Pr / [1 + 12.7(f / 8)^{1/2}(Pr^{2/3} - 1)] \qquad (6.62)$$

Valid for $\{0.5 < Pr < 2000 \text{ and } 2300 < Re < 5*10^6\}$

Where for smooth tubes, the friction factor is given by the following expression:

$$f = (0.79 \ln Re - 1.64)^{-2} \qquad (6.62a)$$

Equation (6.62) is more versatile in terms of the range of the Reynold's number. The friction factor for the duct can also be selected from the Moody diagram thus allowing three parameters (hydraulic diameter of the collector opening, air velocity and the friction factor) to be varied during the design. Equation (6.62) was therefore chosen for calculating the Nusselt number in the model.

(iv) Determination of the Heat Transfer Coefficient

The Nusselt number relates to the heat transfer coefficient through the expression:

$$Nu = hL / k \qquad (6.63)$$

Where the characteristic dimension L, is replaced by the hydraulic diameter of the solar collector duct. The heat transfer coefficient for the solar collector absorber plate can then be determined as:

$$h = Nuk_a / D_{hyd} \qquad (6.63a)$$

Where, k_a is the thermal conductivity of air. It should also be noted that the calculated heat transfer coefficient is based on the temperature difference between the absorber plate and the ambient air, and the frontal area of the collector.

The calculated value from equation (6.63) is compared with the value used for calculating *Whillier's* efficiency. If these two values match, the chosen dimensions can be taken as the dimensions of the collector. If not, the friction factor in equation (6.62) is varied. If this still does not give an acceptable value, new dimensions should be chosen and the procedure repeated until the value converges within 0.1% of the chosen value of the heat transfer coefficient.

In some cases, the chosen set of dimensions may have the iteration converge to a higher value of the heat transfer coefficient, than that used in *Whillier's* equation. If these values are acceptable, the iteration may be terminated.

It should be noted that the flow passage obtained using the present method is such that high turbulence is created at the collector entry and at the exit, thus often leading to increasingly large collector lengths and very small widths. Therefore, the dimensions obtained are dimensions of the flow passage as shown in Figure 6.3. In order to obtain the actual dimensions of the collector, an optimisation is carried out which helps to cut down the overall outer collector length by making the air to flow in a serpentine manner inside the collector as shown in Figure 6.4a. This can be done by dividing the length obtained by the number of allowable passes the air will make in the collector. Therefore for N number of passes, the new (or actual) length is given by:

$$L_{a.c} = L_c / N \qquad (6.64)$$

And the width,

$$W_{a,c} = N^* W_c \qquad (6.65)$$

This will help maintain the required air path length for the required temperature rise, the collector area, as well as reducing the overall perimeter of the collector as shown in Figure 6.4a. In so doing, minor losses will occur at the corners at which the air changes its direction.

6.5.5 Determination of the Collector Fan Power

In order to calculate the fan power required to blow the air through the collector, the pressure drop though the collector has to be calculated. This requires knowledge of the total length travelled by the air in the collector as well as the final outer dimensions of the collector. The pressure drop through a solar collector is given by *Brenndorfer* [1]as:

$$\Delta P_c = (f L_c G_d^2 / \rho D_{hyd}) \qquad (6.66)$$

Equation (6.66) was extended to obtain the pressure drop through a solar collector sloping at an angle β along its length, and having a number of air-direction changes as:

$$\Delta P_c = (f L_c G_d^2 / \rho D_{hyd}) + \rho g L_{a,c} \mathrm{Sin}\beta + [K(\rho V_c^2 / 2)^* 2(N-1)] \qquad (6.67)$$

Where the fanning friction factor, f is the same as that chosen for equation (6.62), $L_{a,c}$ is the final actual collector length obtained after optimisation, and K is the loss coefficient which ranges from 0.5 to 0.75 for sharp 90^o bends [45].

The second term on the right hand side of equation (6.66) takes account of the pressure drop due to height difference between the inlet and outlet of the collector, while the third term takes account of the minor losses incurred at the sharp edges when the air changes direction. However, since the cross sectional area of the flow duct does not change these losses are quite small compared with the overall pressure drop in the collector and can be ignored. Also, in general, minor losses may be neglected when, on the average, there is a length of 1000 diameters between each minor loss [45].

The mass flow rate per unit duct area, G_d, is obtained as:

$$G_d = m_l / W_c d_c \tag{6.67a}$$

The electrical power of the blower can then be found from:

$$P_{B,c} = m_l \Delta P_c / \rho \, \eta_{B,M} \tag{6.68}$$

Having found the parameters described up to this stage, the solar collector would have been adequately sized.

6.6 TOTAL SYSTEM FAN POWER

In order to select a suitable fan or blower, the required air flow is obtained from equation (6.2) and the total system pressure drop is found by simply taking the sum of the bin pressure drop and the collector pressure drop obtained by equations (6.33) and (6.67) respectively as follows:

$$\Delta P_T = \Delta P_B + \Delta P_c \tag{6.69}$$

The total system fan power is then found from:

$$P_T = \Delta P_T \, m_l / \rho \, \eta_{B,M} \tag{6.70}$$

6.7 CONCLUDING REMARKS

The bin parameters obtained in this chapter are sufficient to specify the required size of the drying chamber for a certain fish batch size. However, the dimensions obtained are basic dimensions and tolerances should be applied wherever necessary during manufacture. The value for the air resistance is an estimate and should be used cautiously.

The methodology for determining the required size and dimensions of the solar collector has also been developed in this chapter. However, the dimensions are basic and the necessary tolerances should be applied wherever necessary during manufacture. The thickness of the insulation on the sides and the bottom of the collector has not been addressed. This parameter is often necessary to predict the performance of a particular designed collector and to optimise heat loss through the collector. Also, since the current research is only confined to determining the size of a solar dryer, carrying out performance calculations for every collector designed is beyond the scope of this work. However a number of models for doing this are readily available. The parameters can therefore be decided upon at manufacturing stage depending on the size and type of the designed collector and also the type of insulation available.

Table 6.1 Air resistance of certain materials

MATTER	SPECIFIC AIR RESISTANCE ($1000m^{-1}$)
Paddy	60
Maize grain	33
Cocoa bean	60, wet ; 27, dry
Ground nuts	10
Ground nuts in shells	2.5
Ear corn (maize cobs)	1.5

(Source: Devices for drying – State of energy report on intermediate solutions for rural application, 1979, pp. 9)

Table 6.2 Comparison of Particle Diameter and Air Resistance

MATTER	PARTICLE DIAMETER (m)	AIR RESISTANCE ($1000m^{-1}$)
Paddy	-	60
Maize grain	0.0066	33
Ground nuts	0.0127	10
Ground nuts in shells	0.0178	2.5
Ear corn (maize cobs)	0.04295	1.5
Fish	0.0429	(Desired)

Table 6.3 Recommended average days for months & values of n by Months

Month	n, for i^{th} Day of Month	Date	n, Day of year
January	i	17	17
February	$31 + i$	16	47
March	$59 + i$	16	75
April	$90 + i$	15	105
May	$120 + i$	15	135
June	$151 + i$	11	162
July	$181 + i$	17	198
August	$212 + i$	16	228
September	$243 + i$	15	258
October	$273 + i$	15	288
November	$304 + i$	14	318
December	$334 + i$	10	344

(Source: Solar Engineering of Thermal Processes, 1991, pp. 14)

Table 6.4 Data for prediction of collector performance *(Whillier, 1964)*

Collector type	f_{ca}	U_L	U_o	U_o / GC_p
No cover	0.9	22.2	11.2	0.274
Single cover glass (k = 0.2)	0.88	6.99	5.3	0.131
Single cover glass (k = 0.6)	0.83	6.99	5.3	0.131
Single tedler cover	0.82	8.12	6.0	0.146
Double cover glass (k = 0.2)	0.78	4.43	3.7	0.91
Double cover glass (k = 0.6)	0.74	4.43	3.7	0.091
Double cover one glass (k = 0.2) over one Tedler	0.79	5.25	4.3	0.103
Double cover Tedler	0.84	5.44	4.4	0.107

(Source: Solar Dryers, 1985, pp. 47)

Table 6.5 Correction factors for varying air flow rates, k_1 *(Whillier, 1964)*

Mass flow rate, G_a (10^{-3}kg/m^{2}s)	1.36	6.80	13.60	40.80	68.00	136
No cover	0.14	0.57	0.78	1.00	1.06	1.10
One cover	0.26	0.73	0.88	1.00	1.03	1.05
Two covers	0.34	0.79	0.91	1.00	1.02	1.03
Three covers	0.42	0.84	0.93	1.00	1.01	1.02

***To obtain the corrected value for efficiency, multiply the efficiency as determined from equation 6.54 by the correction factors above. (Source: Solar Dryers, 1985, pp. 48)**

Table 6.6 Correction factors for varying the Heat Transfer Coefficient, k_2*(Whillier, 1964)*

Heat transfer coefficient, h-W/m^{2}K	11.4	22.7	34.1	45.4	68.2	90.9
No cover	0.67	1.00	1.20	1.33	1.49	1.59
One cover	0.80	1.00	1.09	1.14	1.20	1.23
Two covers	0.85	1.00	1.06	1.10	1.13	1.15
Three covers	0.88	1.00	1.04	1.07	1.10	1.11

***To obtain the corrected value of efficiency, multiply the efficiency as determined from equation 6.54 by the correction factors above. (Source: Solar Dryers, 1985, pp. 48)**

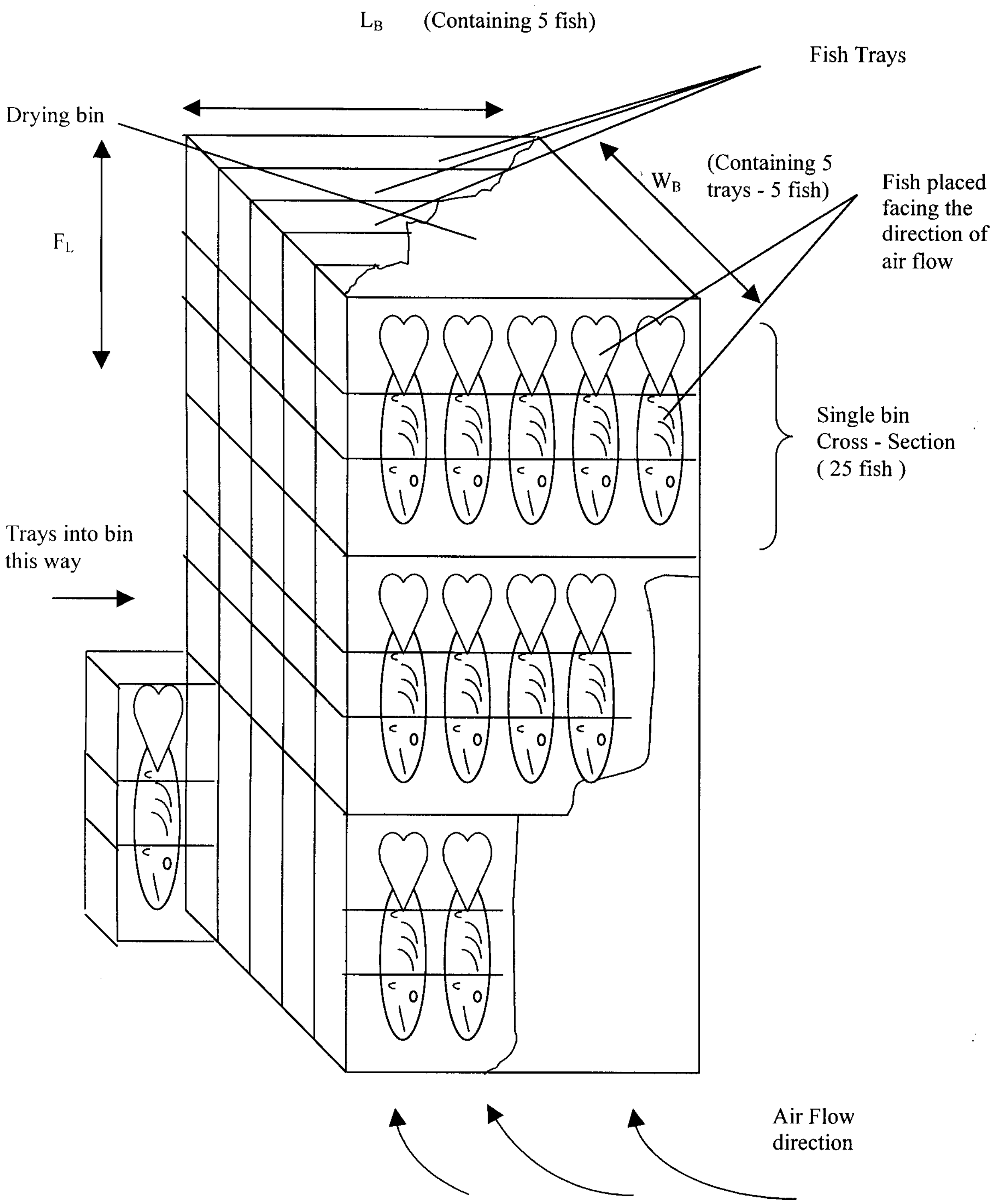


Figure 6.1: Sketch showing intended positioning of fish in drying bin

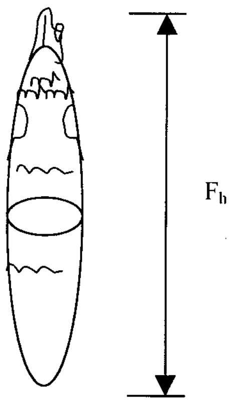


Fig 6.2a Vertical-longitudinal position

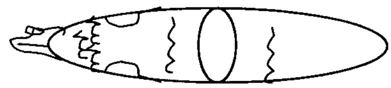


Fig 6.2b Horizontal-Longitudinal Position

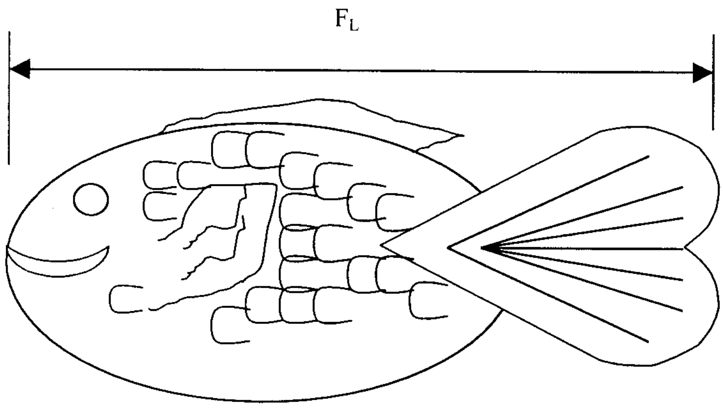


Fig 6.2c Vertical- Transverse position

Note: The direction of air flow is into plane of the page in all cases

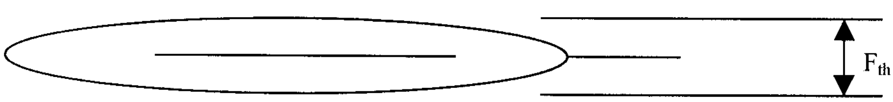


Fig 6.2d Horizontal-Transverse

Figure 6.2: Positions of fish investigated for obtaining minimum pressure drop. Also shown are the fish dimensions used for tray sizing.

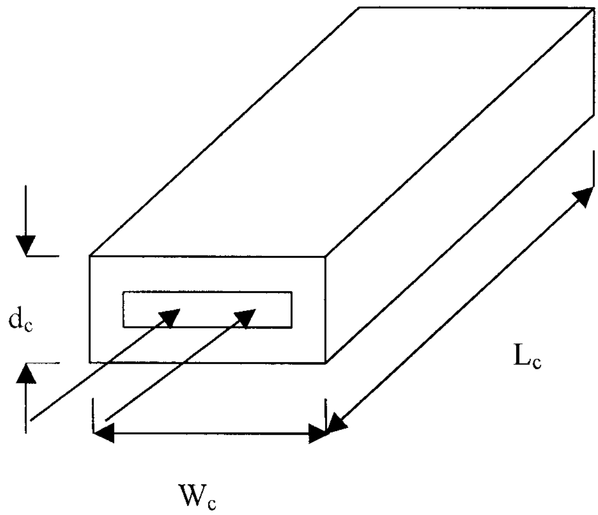


Figure 6.3 Schematic representation of a flat plate air heater showing flow duct dimensions

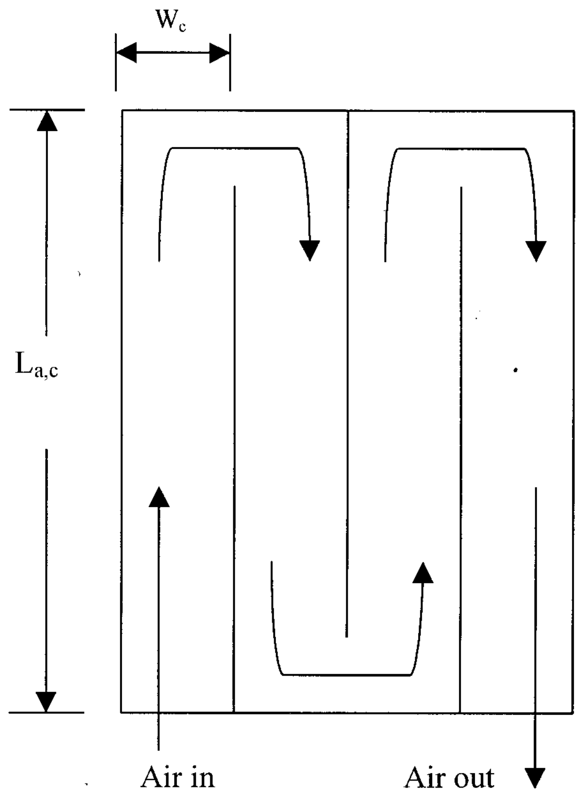


Figure 6.4a Plan view

Figure 6.4 Plan and front views of collector showing Actual dimensions after optimization

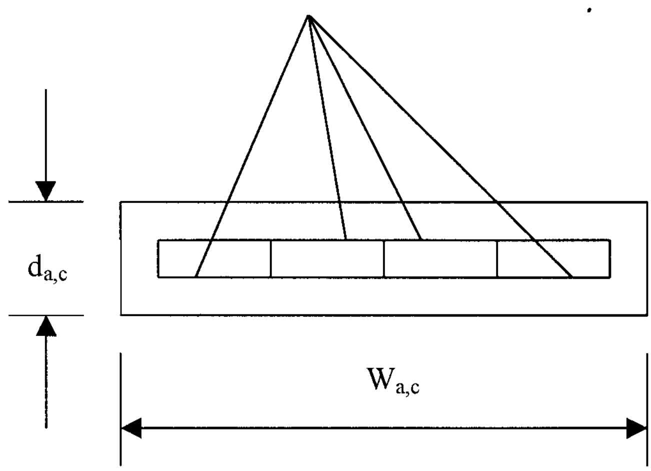


Figure 6.4b Front view

Chapter 7

DRYING TIME MODELLING

7.1 GENERAL

Once the solar dryer has been sized, a very important parameter that needs to be calculated is the drying time for the batch size to be dried under the specified weather conditions. Equation (3.8) could not be used for this purpose since values for the drying constant *K*, for fish could not be found in literature. It should be noted that the calculated drying time is not the same as that specified in equation (6.1c).

7.2 DRYING TIME MODEL EQUATIONS

In the actual computation, the moisture content of the fish at any time t, after the drying process has started can be determined from a simple finite difference approximation using the equations described in the previous chapters. The moisture content at any time can be obtained from the following expression [19]:

$$M(t+\Delta t) = M_t - (dM / dt)_t \Delta t \quad (7.1)$$

where the drying rate at any time $(dM/dt)_t$ is found by considering the drying process on the psychrometric chart as shown in Figure 7.1. If the air leaving the collector and entering the drying bin is at a temperature indicated by a point such as b, then the available sensible heat of the incoming air will limit the drying rate, i.e. the air leaving the bin will be at the fish-bed temperature and not fully saturated. The available sensible heat in the air stream for this condition will therefore be equal to the energy it gains in the solar collector as expressed by:

$$M_B (dM / dt)_t \lambda = \eta_{W,c} I_{c,t} A_{c,c} \quad (7.2)$$

The right hand side of equation (7.2) represents the net rate at which solar energy is absorbed by the collector and transferred to the air passing through the dryer. The left-hand side represents the rate at which latent heat is supplied to the fish bed in the bin. The drying rate for this situation will therefore be:

$$(dM / dt)_t = \eta_{W,c} I_{c,t} A_{c,c} / (M_B \lambda) \qquad (7.2a)$$

If on the other hand, the air leaving the collector is at a point such as c, the drying rate will be limited by the fact that the air leaving the bed will be saturated (i.e. the point c' will lie on the 100% relative humidity line). In this case, the drying rate is determined by noting that the energy balance for the collector gives:

Energy into the solar collector from the sun = Energy into the air from the collector

$$\eta_{W,c} I_{c,t} A_{c,c} = m_1 C_p (T_2 - T_1)_t \qquad (7.3)$$

Since values for the insolation falling on the collector surface, I_c, are calculated for every hour, the temperature rise of the air in the solar collector can be evaluated for any hour from:

$$(T_2 - T_1)_t = \eta_{W,c} I_{c,t} A_{c,c} / (m_1 C_p) \qquad (7.3b)$$

The energy balance for the fish bed requires that:

Energy in the air = Energy used to evaporate water from the bed

$$m_1 C_p (T_2 - T_3)_t = m_1 (x_3 - x_2) \lambda \qquad (7.4)$$

The amount of moisture gained by the air between the inlet to the drying bed and the outlet, at any time, t, is found by re-writing equation (7.4) as follows:

$$(x_3 - x_2)_t = (C_p / \lambda)[(T_2 - T_1)_t - (T_3 - T_1)] \qquad (7.4a)$$

The saturation line on the psychrometric chart defines x_2 as a function of T_3, which enables the determination of T_3 and x_3 from equations (7.3) and (7.4) for any value of the insolation, $I_{c,t}$. The drying rate is then obtained by considering a moisture balance for the fish bed that gives:

$$(dM / dt)_t = m_1 (x_3 - x_2)_t / M_B \qquad (7.5)$$

Repeated use of these expressions for the next time step Δt, gives the variation in moisture content of the fish for any time after the drying process has started and a curve of moisture content against time (the drying curve) can be plotted. The value of the time step is taken to be one hour since the model only calculates insolation values for every hour.

This model of the drying process is only applicable as long as the moisture content of the fish remains well above the equilibrium moisture content for ambient conditions. Once the moisture content drops to nearly the equilibrium moisture content, the drying rate will start to be limited by the moisture diffusion rate within the flesh of the fish as well as by the energy considerations and a much more complex drying model should be adopted. However, because drying can be regarded as complete when the equilibrium moisture content is reached, this is not a serious limitation [19]. In the model, this procedure is performed until the moisture content M, has dropped to the equilibrium moisture content, at which it is assumed to remain constant. The drying curve can also be very useful in selecting the best drying period of the day.

7.3 CONCLUDING REMARKS

A method to determine the drying time of the material in the designed dryer, taking the weather conditions into account has been described. As the method does not require the properties of the particular product, it can be adopted for other commodities as well.

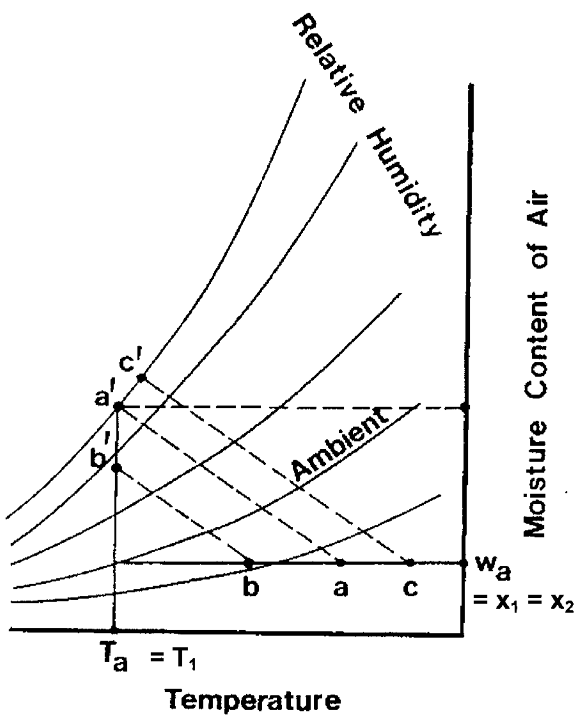


Figure 7.1 Possible changes in temperature and humidity in the fish bed.

Chapter 8

DRYER COST ANALYSIS

8.1 GENERAL

In the previous chapters, sizing of the forced-convection solar dryer has been described. In any such study, the cost of solar equipment plays a significant role in their marketing. Hence the cost-benefit ratio is an important aspect. Unfortunately, rich literature is not available on the design of solar dryers that keeps the cost-effectiveness in view. In the present work, a detailed theoretical analysis of the drying bin coupled to a single-pass-flat plate collector and a fan has been developed. The dryer system has been broken down into three main parts namely, the drying bin, fish trays, and the solar collector, which are costed separately.

This chapter describes in detail, the method developed to determine the cost of the designed dryer. Determination of the cost of running dryers for different batch sizes and the cost per unit of evaporated moisture has also been described.

8.2 COST OF THE DRYING BIN

In the computation, a drying bin of the type shown in Figure 8.1 is considered. The drying bin is broken down into three basic parts, which are the bin framework, the covering sheet, and the bin insulation. The following sections describe the costing of the bin in detail.

8.2.1 Cost of the Bin Frame

The total bin frame length is found from:

Bin frame length = Total length of the bin skeleton

Bin frame length = (4*Bin length + 4*Bin width + 4*Bin height)

$$L_{Bf} = 4(L_B + W_B + H_B) \tag{8.1}$$

By specifying the standard length of the available frame material, the number of standard lengths required can be found from:

Number of standard lengths = Total frame length / Length of a single standard piece

$N_{SLB} = L_{Bf} / L_{SBf}$ (8.2)

The cost of the bin frame is then found from:

Cost of bin frame = Number of standard lengths of frame material * Cost per length

$C_{Bf} = N_{SLB} * C_{Length}$ (8.3)

8.2.2 Cost of the Bin Insulation

The total area of the insulation required to insulate the bin from all sides has to be evaluated. Depending on the bin configuration, if the air is made to flow into the bin from the bottom, it may not be absolutely necessary to insulate the bin from the bottom. However, it is always safer to work out a value larger than that required and therefore it is assumed that the air will enter the bin from one side, thereby making it necessary to insulate the bottom side.

The total area of the required insulation is then found as:

Required area of bin insulation

= Area of insulation on the sides + Area of insulation for the top & bottom

Required area of bin insulation = [2*(Bin height * Bin width) + 2*(Bin height * Bin length) + 2*(Bin width * Bin length)]

$A_{BI} = 2[(H_B*W_B) + (H_B*L_B) + (W_B*L_B)]$ (8.4)

By specifying the standard area of the available bin insulation, the number of pieces of insulation can be found from:

Number of standard pieces required

= Total area of bin insulation / Area of standard piece of bin insulation

$N_{SBI} = A_{BI} / A_{SBI}$ (8.5)

The cost of the bin insulation can then be found from:

Cost of bin insulation = Number of standard pieces of bin insulation * cost per piece

$$C_{BI} = N_{SBI} * C_{Insulation} \quad (8.6)$$

8.2.3 Cost of the Bin Covering Sheet

In calculating the area of sheet required, it is assumed that the bin is covered from all four sides, the top and the bottom. At the same time, all sides are double layered, having the insulation 'sandwiched' in between the covering sheets as shown in Figure 8.1.

The total area of the covering sheet for the bin is found as:

Area of required covering sheet = 2[2*(Bin height * Bin width) + 2*(Bin length * Bin height) + 2*(Bin length * Bin width)]

$$A_{sh} = 2[2(H_B*W_B) + 2(L_B*H_B) + 2(L_B*W_B)] \quad (8.7)$$

By specifying the standard area of the available sheet material, the number of standard sheets required can be found from:

Number of standard covering sheets = Total area of required sheet / Area of a single standard sheet

$$N_{Ss} = A_{sh} / A_{Ss} \quad (8.8)$$

The cost of the bin-covering sheet is then found from:

Cost of bin covering sheet = Number of standard sheets required * Cost per sheet

$$C_{sh} = N_{Ss} * C_{Sheet} \quad (8.9)$$

8.2.4 Cost of the Drying Bin

The cost of the drying bin is found by adding the cost of the bin frame, bin insulation and the bin covering sheet as follows:

$C_{Bin} = C_{Bf} + C_{BI} + C_{sh}$ (8.10)

8.3 COST OF TRAYS

The type of tray considered for the present work is shown in Figure 8.2. This type of tray consists of a wire frame supported by three extra wires running across, both along the length and the width in order to provide structural stability of the frame. The thickness of the wire will depend on the size and weight of the fish to be dried. A mesh is fixed around the tray to ensure that the fish is kept in place during the drying and all sides are equally exposed to the air. A provision for opening and closing the tray may be kept on one side.

8.3.1 Cost of the Tray Frame

The total length of the wire used for the frame is obtained from:

Length of wire for the tray frame = [(10*Tray length) + (10*Tray width) + (10*Tray thickness)]

$L_{Twr} = [(10*L_B) + (10*F_L) + (10*F_{th})]$ (8.11)

By specifying the standard length of the available wire, the number of standard lengths required can be found from:

Number of standard wire lengths required

= Total length of frame wire / Length of standard available wire

$N_{Swr} = L_{Twr} / L_{Swr}$ (8.12)

The cost of the wire is then found from:

Cost of wire = Number of standard lengths of wire required * Cost per length

$C_{wr} = N_{Swr} * C_{Wire}$ (8.13)

8.3.2 Cost of the Mesh

The total area of the mesh required is found by adding the area required for the top, bottom and the sides of the tray. This is done as follows:

Area of mesh = [2(Tray length *Tray width) + 2(Tray length * Tray thickness) + 2(Tray width * Tray thickness)]

$$A_{msh} = [2(F_L*L_B) + 2(L_B*F_{th}) + 2(F_L*F_{th})] \quad (8.14)$$

By specifying the standard area of wire mesh available, the number of standard units of mesh required can be found from:

Number of standard units of mesh = Total area of mesh required / Area of standard available mesh

$$N_{Smsh} = A_{msh} / A_{Smsh} \quad (8.15)$$

The cost of the mesh is found from:

Cost of mesh = Number of standard pieces of mesh required * Cost per piece

$$C_{msh} = N_{Smsh} * C_{Mesh} \quad (8.16)$$

8.3.3 Cost of the Tray

The total cost of the tray is found by summing the individual costs of the frame and the mesh as follows:

Cost of tray = Cost of the frame + Cost of the mesh

$$C_{Tray} = C_{wr} + C_{msh} \quad (8.17)$$

The total cost of the trays is then found by multiplying the cost of each tray by the number of trays t, required in the dryer as follows:

$$C_{Trays} = C_{Tray} * N_t \quad (8.18)$$

8.4 COST OF THE SOLAR COLLECTOR

In the computation, a solar collector of the type shown in Figure 8.3 is considered for the costing. The collector is broken down into five basic components comprising the collector framework, the absorber plate, the back and side plates, the insulation and the cover. The following sections describe the cost calculation of the collector in detail.

8.4.1 Cost of the Collector Frame

In order to obtain the cost of the collector frame, the total length of material used is required. The total length of the frame is obtained as:

Length of collector frame = (4*Collector length + 4*Collector width + 4*Collector depth)

$$L_{c,f} = (4L_{a,c} + 4W_{a,c} + 4d_{a,c}) \tag{8.19}$$

By specifying the standard length of the frame material available, the number of frame lengths can be found from:

Number of standard lengths = Length of collector frame / Standard length

$$N_{Scf} = (4L_{a,c} + 4W_{a,c} + 4d_{a,c}) / L_{scf} \tag{8.20}$$

The cost of the frame is then found as:

Cost of frame = Number of required frame lengths * cost per length

$$C_{cf} = N_{Scf} * C_{Length} \tag{8.21}$$

A number of materials can be used for fabricating the frame. However, if a metal frame is desired, an appropriate size of channel will give the advantage of both holding the insulation and providing extra strength.

8.4.2 Cost of the Absorber Plate

The cost of the absorber plate is found as follows:

The area of the absorber plate is found from:

Area of absorber plate = (Collector length * Collector width)

$$A_{ap} = L_{a,c} * W_{a,c} \tag{8.21}$$

By specifying the standard area of the available plate material, the number of standard plates required can be found from:

Number of standard plates = Absorber plate area / Area of standard plate

$N_{spt} = A_{ap} / A_{Sp}$ (8.22)

The cost of the absorber plate is then found as:

Cost of absorber plate = Number of standard plates * cost per plate

$C_{ap} = N_{Spt} * C_{Plate}$ (8.23)

8.4.3 Cost of the Back and Side Plates

The cost of the collector back and side plates is found by calculating the total area of the plate required as follows:

Area of back and side plates = 2[(Collector length * Collector depth)
+ (Collector width * Collector depth)]+ (Collector length * Collector width)

$A_{BSp} = 2[(L_{a,c} * d_{a,c}) + (W_{a,c} * d_{a,c})] + (L_{a,c} * W_{a,c})$ (8.24)

By specifying the standard area of the available material for the back and side plates, the number of plates needed can be found from:

Number of plates needed = Total area of Back and Side plates / Area of Standard plate

$N_{BSp} = A_{BSp} / A_{SBSp}$ (8.25)

The cost of the back and side plates is then found from:

Cost of Back and Side plates = number of standard plates required * Cost per plate

$C_{BSp} = N_{BSp} * C_{Plate}$ (8.26)

8.4.4 Cost of the Collector Insulation

The cost of the insulation is found by evaluating the amount of insulation required to insulate the sides and the bottom of the collector. If the insulation is in the form of a blanket (e.g. glass wool) or straight sheet (e.g. asbestos), then the area of insulation required is found from:

Area of required Insulation = (Area of insulation on the sides + Area of insulation at the bottom)

Area of required Insulation = [2(Collector length * Collector depth)

+ 2(Collector width * Collector depth) + (Collector length * Collector width)]

$A_{cI} = [2*(L_{a,c} * d_{a,c}) + 2*(W_{a,c} * d_{a,c}) + (L_{a,c} *W_{a,c})]$ (8.27)

By specifying the standard area of the available insulation, the number of standard pieces required can be evaluated from:

Number of standard pieces required

= Total area of required insulation / Area of available standard piece

$N_{ScI} = A_{cI} / A_{ScI}$ (8.28)

The total cost of the collector insulation is then found from:

Cost of insulation = Number of standard pieces required * Cost per piece

$C_{cI} = N_{ScI} * C_{Insulation}$ (8.29)

8.4.5 Cost of the Collector Cover

The cost of the collector cover is determined by first evaluating its area as follows:

Area of collector cover = Collector length * Collector width

$A_{cc} = (L_{a,c} *W_{a,c})$ (8.30)

The number of standard covers needed can be found by specifying the standard area of a single cover as follows:

Number of standard covers = Required cover area / Area of standard cover

$N_{Scc} = (A_{cc} / A_{Scc})$ (8.31)

The cost of the collector cover is then found as:

Cost of cover = Number of standard covers needed * Cost per cover

$C_{cc} = N_{Scc} * C_{Cover}$ (8.32)

8.4.6 Cost of the Collector

The cost of the collector is found by adding the cost of the collector frame, absorber plate, back and side plates, insulation and the cover, as follows:

$C_{Collector} = C_{cf} + C_{ap} + C_{BSp} + C_{cI} + C_{cc}$ (8.33)

8.5 TOTAL DRYER COST

The total cost of the dryer (without the fan) is obtained by adding the cost of the drying bin, trays and the solar collector, as follows:

$C_{Dryer} = C_{Bin} + C_{Trays} + C_{Collector}$ (8.34)

8.6 DAILY RUNNING COST OF THE DRYER

In order to calculate the daily running cost of the dryer, different cost factors are calculated. These are described in the following sections.

8.6.1 Daily Pumping Cost

Since the dryer will employ a fan to pump the air through the system, there will be a cost incurred for this pumping if electricity is used. The daily pumping cost is calculated as follows [20]:

$DPC = (m_1 \Delta P_T / \rho_a)\theta_{op}C.E.$ (8.35)

Where ρ_a is the density of air, θ_{op} is the operating time in hours from the start of the drying process and CE is the cost of electricity. The air mass flow rate and the total pressure drop through the system can be found from equations (6.2) and (6.69) respectively.

8.6.2 Daily Salvage Value

The daily salvage value of a system is the value that remains after the system has been used for a certain period of time. The daily salvage value is calculated from [20]:

$$DSV = (SFF * SV) / \text{Number of operating days} \tag{8.36}$$

Where the salvage fund factor, SFF, is found from:

$$SFF = [\, i / (i+1)^n - 1] \tag{8.37}$$

Where n is the life of the device and is often specified in years. The salvage value is taken to be about 10% of the capital investment [20].

$$SV = 0.1(CI) \tag{8.38}$$

8.6.3 Capital Investment

The total capital investment of the system is calculated by adding to the dryer cost C_{Dryer}, obtained in equation (8.34), the cost of the ducting, the blower cost, paint cost and the labour (or fabrication) cost. Since for different systems and configurations, the type and size of the ducting and fan used may differ, the cost of these items will have to be specified separately in the model. Also since different types of paints may be used, and the labour rates vary from place to place, these costs will also have to be specified in the model. The capital investment cost can then be found as [20]:

$$\text{Capital investment} = \text{Dryer cost} + \text{Cost of air duct} + \text{Blower cost} + \text{Paint cost} + \text{Fabrication cost} + \text{Miscellaneous cost} \tag{8.39}$$

The daily running cost of the system is then found by subtracting the daily salvage value from the daily pumping cost as follows:

$$DRC = DPC - DSV \tag{8.40}$$

8.7 COST PER UNIT OF EVAPORATED MOISTURE

The cost per unit of moisture evaporated is found from dividing the daily running cost by the amount of moisture, M, evaporated during the operating time, θ_{op}, which can be obtained from the equations described in Section 7.4. The cost per percentage of moisture evaporated over any time period can be found as follows [4]:

$$C_{Evaporated\ Moisture} = DRC / (M_i - M_t) \quad (8.41)$$

Whereas the cost per unit mass of moisture evaporated over any time period can be found from:

$$C_{Evaporated\ Moisture} = DRC / \{[(M_i - M_t)/100]m_w\, t_{dr}\} \quad (8.42)$$

8.8 CONCLUDING REMARKS

In any design, it is always economical to adopt dimensions of the system to be manufactured keeping in mind the standard dimensions of the materials to be used. Therefore in the calculation of the number of standard units required in all cases, the figures obtained should be 'rounded off' to suit the nearest standard dimension. For example, if the required length of a solar collector is found to be 1.1m and the available standard length of the frame material is 1m, then a length of 1m must be adopted. The same goes for the bin, and the tray design.

It should also be noted that the model does not take into account the costing of extra items such as the stand for the collector and bin as these depend on the size of the system and also its location e.g. how high the system should be off the ground. Such costs along with the cost of other small items such as nails, hinges, handles, and other fixtures may be included as miscellaneous costs when evaluating the capital investment.

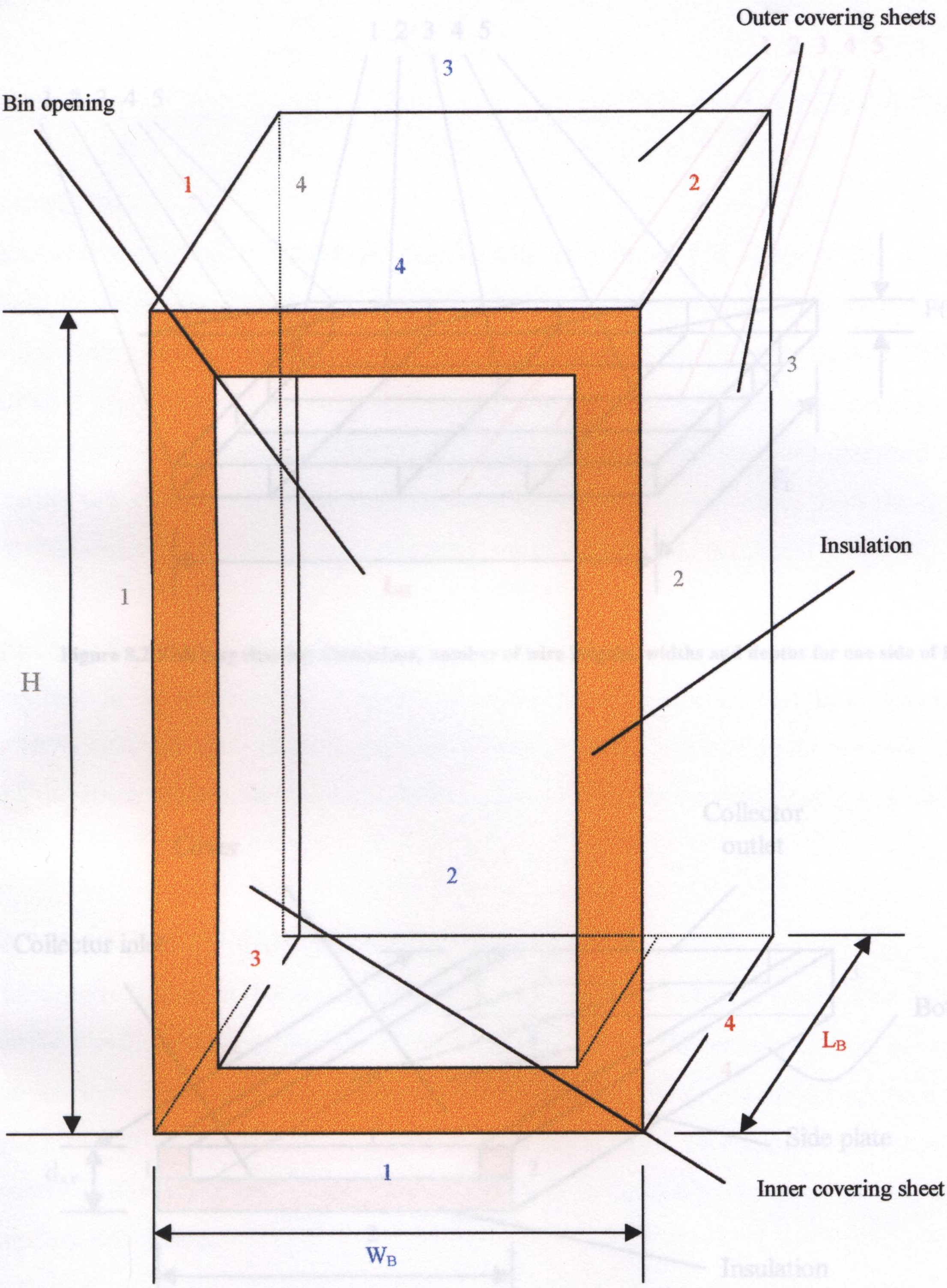


Figure 8.1 Drying bin showing dimensions, number of lengths, widths and heights of frame.

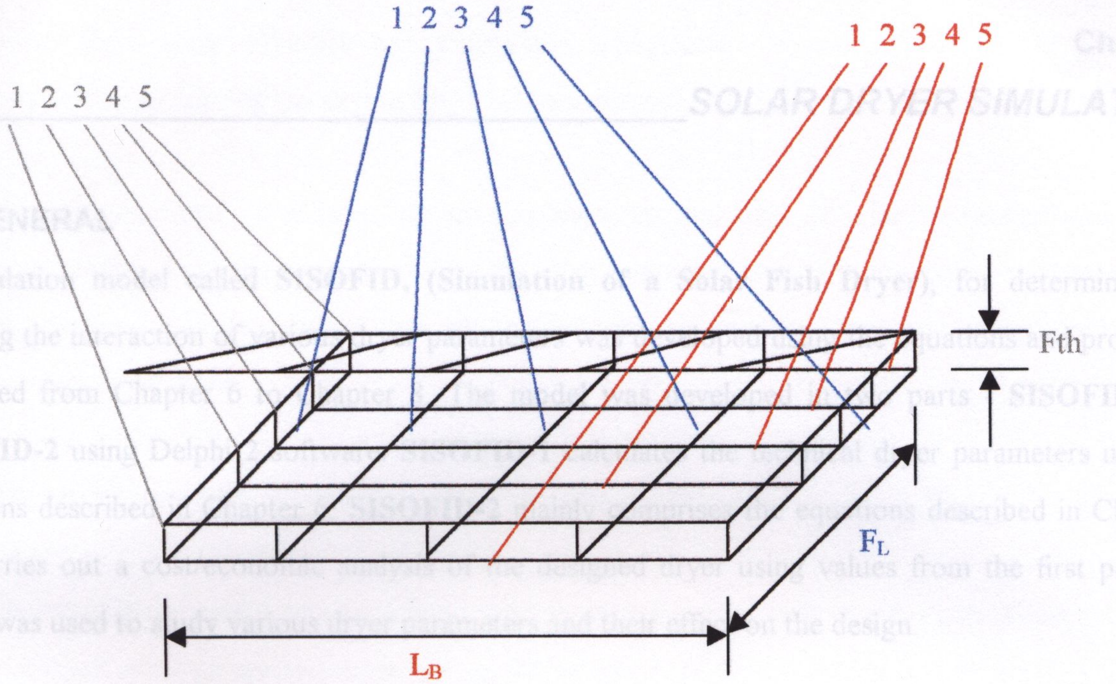


Figure 8.2 Fish tray showing dimensions, number of wire lengths, widths and depths for one side of frame.

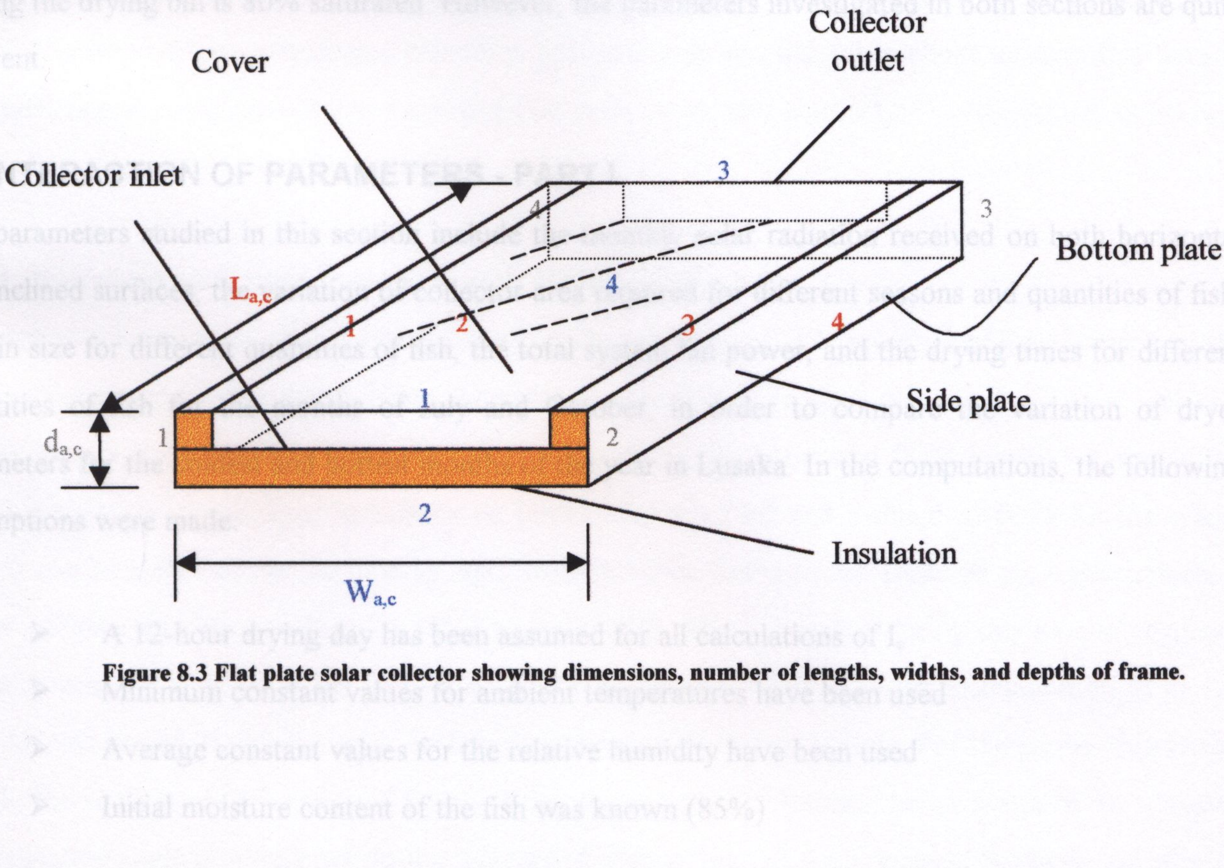


Figure 8.3 Flat plate solar collector showing dimensions, number of lengths, widths, and depths of frame.

Chapter 9
SOLAR DRYER SIMULATIONS

9.1 GENERAL

A simulation model called **SISOFID, (Simulation of a Solar Fish Dryer)**, for determining and studying the interaction of various dryer parameters was developed using the equations and procedures described from Chapter 6 to Chapter 8. The model was developed in two parts - **SISOFID-1** and **SISOFID-2** using Delphi 2 software. **SISOFID-1** calculates the technical dryer parameters using the equations described in Chapter 6. **SISOFID-2** mainly comprises the equations described in Chapter 8 and carries out a cost/economic analysis of the designed dryer using values from the first part. The model was used to study various dryer parameters and their effect on the design.

The results and discussion of the interaction of various dryer parameters are presented in this chapter in two sections. In the first section, the dryer is simulated on the assumption that the air leaving the drying bin is 100% saturated while in the second section, the simulation is based on the assumption that the air leaving the drying bin is 80% saturated. However, the parameters investigated in both sections are quite different.

9.2 INTERACTION OF PARAMETERS - PART I

The parameters studied in this section include the monthly solar radiation received on both horizontal and inclined surfaces, the variation of collector area required for different seasons and quantities of fish, the bin size for different quantities of fish, the total system fan power, and the drying times for different quantities of fish for the months of July and October, in order to compare the variation of dryer parameters for the coldest and hottest months of the year in Lusaka. In the computations, the following assumptions were made:

- A 12-hour drying day has been assumed for all calculations of I_c
- Minimum constant values for ambient temperatures have been used
- Average constant values for the relative humidity have been used
- Initial moisture content of the fish was known (85%)

- Re-wetting of the fish during night time is neglected
- The air leaving the drying bin is 100% saturated

Using these assumptions, predictions of various parameters and sizes of solar dryers performing under different conditions have been made. Among the most important factors in the drying process are solar radiation, air flow, available surface area, air temperature, air humidity, moisture content and porosity of the product to be dried.

The initial results have been classified in three categories as follows:

A. Variation of dryer parameters for a fixed quantity of fish and varying weather conditions,
B. Variation of dryer parameters with varying fish quantity and fixed weather conditions,
C. Variation of drying time with moisture content and fish quantity.

A.1 Variation of Dryer Parameters with Constant Fish Quantity

The simulation carried out for this set of results was for a fixed fish quantity of 500kg to be dried in 48hrs. This desired time was chosen since it is generally said that fish takes about three to five days to dry under fine weather conditions. Assuming that each drying day consists of twelve hours, an average value of four days i.e. 48 hours was chosen.

A.1.1 Variation of Solar Insolation with Month of the Year

In order to enhance any solar drying process at a certain location, it is essential to have an idea of the solar radiation received at that location. It is also known that the energy received by a solar collector can be increased by inclining the collector at an angle to the horizontal [41]. Figure 9.1 shows the variation of radiation received in Lusaka on both horizontal [46] and inclined surfaces for the whole year. It can be seen that for the months April to September, the radiation received by a solar collector can be considerably increased (up to 30%) by inclining it. This is because during this time of the year, the sun's position relative to the earth is North of the equator. Therefore the inclination angle is also large for this period of the year with the largest inclination occurring in June. For the period October to March, the sun's relative position is South of the equator and for Lusaka, being South of the equator, the inclination angle is quite small during this period. Hence, the radiation received is almost the same as that received by a horizontal surface. Another reason for the higher gain in radiation for the period April to September, could be that the diffuse fraction of radiation I_d/I_h, for this period is much lower since the days are much clearer (less cloudy). This can be confirmed by the relatively lower values for the diffuse fraction shown in Table 9.1 during this period. The higher gain is also confirmed by the calculated values for the clearness index, K_T, shown in Table 9.1, which turn out to be relatively high during the same period.

The graph also underpins the importance of rightly facing the solar collector i.e. due North or due South. It can be seen that considerable amount of radiation can be lost (up to 55% for the case of June) if the collector is made to face South during the period April to September.

A.1.2 Variation of Solar Collector Area with Month of the Year

Figure 9.2 shows the variation in the solar collector area for three situations required to dry 500kg of fish in each month throughout the year. The three situations are: (i) Correctly faced inclined collector, (ii) wrongly faced inclined collector, and (iii) horizontal collector.

The plot shows that for a correctly faced and inclined collector, the required solar collector area does not vary much for most of the year except for the months of January and February when the received insolation is quite low, possibly due to heavy cloud cover. The minimum solar collector area occurs in the month of October when the received insolation and ambient temperatures are both high. It can also be seen that the solar collector area in June is lower than that for February although the ambient temperature in June is lower. This is because of the much higher gain in radiation in June due to the inclination effect or high value for the Geometric factor, R_b, as shown in Table 9.1.

The importance of rightly facing the collector i.e. facing North, during the period March to October can be clearly seen from the plot. A considerably large collector area will be required to provide the same amount of energy if the collector is facing South with the largest area occurring in the month of June when both the ambient temperature and the received radiation are low. Also, at this time of the year, the sun is in the Northern Hemisphere as mentioned before. For the period from October to March, the variation of the solar collector area is comparatively low, and although for this period the collector should be facing South, this condition is not so critical.

For the third situation, i.e. collector placed horizontally, the required collector area for the period March to October, is greater than that if the collector were inclined and facing North. The increase is however not as much as when the collector is inclined but facing South. For the period from October to March, the required solar collector area does not change much for this situation either, since the sun is in the Southern Hemisphere during this time of the year.

From this result, it can be deduced that for a solar collector mounted in Lusaka, the optimum condition is to make it face North, while the second option is to place it horizontally. For the period between October and March, the orientation of a collector mounted in Lusaka is not so critical. Although, the optimum angle of collector inclination β, for the whole year is found by taking the average of the values obtained for each month (in Table 9.1, the average value for fixed collector mounting turns out to be 18^o), where possible, the mounting should be made such that the inclination angle is adjustable if a fixed collector area is employed for drying to take place all year round.

A.1.3 Variation of Collector Area with Radiation

The variation of the solar collector area (for a 500 kg dryer) with radiation is shown in Figure 9.3. The collector area was calculated using the equations and procedures described in Section 6.5.3. The values for the ambient temperature, radiation and the air flow rate, used in calculating the collector areas are shown in Table 9.2. During the design process, a compromise must be made between a collector having the 'best' properties, (which can be quite expensive) and that which would have a low cost but have excessively long drying times. Therefore, for the present calculations, the heat transfer coefficient between the absorber plate and the flowing air is taken to be $22.7W/m^2K$, while the effective transmissivity-absorptivity product of the glass and absorber was taken as 0.85 and the desired collector outlet temperature T_2, was taken to be 55^oC. The plotted curves are for the required collector areas for the three different situations, described in Section A.1.2. The curves obtained in all cases are as expected and indicate that the solar collector area reduces with increasing radiation. It can also be noted from the plot that although the ambient temperature and air flow rate do play a part in the calculation of the solar collector area according to equation (6.53), it is not as significant as the total amount of radiation received. The plot also shows that a much larger collector area would be required to provide the same amount of energy if the collector is wrongly faced.

Another feature that can be seen from Table 9.2 is that the required air flow rate does not stay the same for every month. This variation is due to the variation in ambient relative humidity for the different months of the year. For periods when the ambient relative humidity is high i.e. from November to April, more air is required for drying the same amount of fish since the capacity of the drying air to absorb moisture is lower during this period.

B.1 Variation of Dryer Parameters with Varying Fish Quantity

The following predictions were made for fixed weather conditions for the month of July and a constant drying time of 48 hours as in section A.1.

B.1.1 Variation of Collector Area and Bin Cross - Sectional Area with Fish Quantity

Figure 9.4 shows the variation of the required solar collector area and the required bin cross- sectional area for drying a given quantity of fish. The collector area was evaluated using the procedures described in Section 6.5.3 while the bin cross-sectional area was obtained using the procedure described in Section 6.3.3. Values of 20% for the area fraction A_f, and 1.5m/s for the air velocity (as suggested by *Garg* [25] and *Clucas* [33] respectively) have been taken for the drying bin in all cases, while for the fish, a length of 0.3m, a height of 0.09m and a thickness of 0.003m has been taken. The values for the dimensions of fish were found from physical measurements of few samples of fish. From the plot, it can be seen that the required solar collector area varies linearly with varying fish quantity. This is due to the fact that the air mass flow rate required for transferring the evaporated water from a given amount of fish is found to increase linearly with increasing amount of fish as shown in Figure 9.4, and this is the only parameter changing in the expression for determining the collector area. This fact can be seen from equations (6.1c) and (6.53). The desired temperature rise, insolation, and collector efficiency all remain constant.

The bin cross-sectional area on the other hand does not vary linearly. This could be because the sizing of the bin was performed by considering the physical dimensions of the fish along with specified values of the air velocity and area fraction A_f, through the bin, which were kept constant at 1.5m/s and 20% respectively in this investigation. Such an approach would not be expected to yield a linear relationship.

Since the required amount of air for a small quantity of fish is small, the cross sectional area of the bin becomes small according to the continuity equation of Fluid Mechanics (equation 6.8). For practical purposes, therefore, two options for sizing for small quantities are possible. One way is to increase the mass flow rate by providing a larger fan motor than the one calculated. This would allow one to increase the cross-sectional area, but will obviously cost more. The other way is to divide the height of the bin into a number of parts and passing the air through a series of channels of the same cross-sectional area. In this way, the height of the bin is reduced thereby giving a more cost-effective solution. Also, since the number of fish placed along the length, width and height of the bin varies for different batch sizes, the total cross-sectional area is bound to vary. The numerical model gives an indication of the number of fish to be placed along the length, width and height of the bin taking into account the required gap for air flow between the fish as can be seen from a sample print out in Appendix 8.

B.1.2 Variation of the required Air flow rate and Heater power with Fish Quantity

Figure 9.5 shows the variation of the required air flow rates and the heater power for various quantities of fish. In both cases, the curves obtained show a linear relationship with increasing fish quantity.

The linear relation between the air flow rate and the quantity of fish to be dried is apparent from the procedure for obtaining the required air flow for a specific amount of fish, described in section 6.3.1. From the equations, it can be seen that the determination of the air flow rate for drying under specified weather conditions is dependent on the amount of water to be evaporated. In determining the amount of water to be evaporated, for specified initial and final moisture content levels during a specific desired drying time t_{dr}, the only parameter changing in the calculation is the quantity of fish to be dried. Since this parameter appears in the numerator in the whole procedure, the result is expected to be linear.

Equation 6.7 was used to evaluate the heater power. From the equation it can be seen that the heater power depends on the air flow rate and the enthalpy change of the drying air between the entry point into the collector and exit point out of the drying bin. For a specified reduction in moisture content under the same weather conditions, the enthalpy change of the air remains the same regardless of the quantity of fish to be dried as can be seen from the process represented on the psychrometric chart in Figure 3.1. Therefore, since the air flow rate changes linearly, the effect is reflected in this equation thus causing the required heater power to assume a linear relationship.

This information could be used in selecting a fan for the drying process as well as selecting an auxiliary heater to be installed in the system for periods of low or no sunshine.

B.1.3 Variation of Collector, Bin and Total System Fan Power with Fish Quantity

Figure 9.6 shows a plot of the required collector fan power, bin fan power and the total system fan power for increasing quantity of fish for a fixed bin height of 2.02m.

The plot shows a linear relation between bin power (which is directly proportional to the pressure drop in the bin) and fish quantity. The only parameter changing in this case is the air mass flow rate, which as shown before, changes linearly with increasing fish quantity. As expected, the plot indicates that the larger amount of power is required in blowing air through the drying bin. This arises from the fact that the air experiences the maximum frictional loss as it comes into contact with the fish.

The variation of the collector fan power with fish quantity on the other hand does not follow a definite pattern. This could be due to the iterative procedure involved in obtaining the solar collector dimensions. In this case, the length of the air path in the solar collector, the cross-sectional opening of the collector duct, and the friction factor all change during the iteration in recalculating the heat transfer coefficient using *Whillier's* approach. Since it is for the designer to decide on the balance between these parameters, the trend of the collector fan power curve cannot be definite and will vary for each design. However, the collector fan power required is much lower than the bin fan power.

The total system fan power required is obtained by simply summing the values obtained for the bin and collector fan power. It is therefore not surprising that the total system fan power curve closely follows the bin fan power curve.

C.1 Drying Curve

The procedure outlined in Chapter 7 was used to plot the drying curves in Figure 9.7 for various quantities of fish. A fixed dryer size having a solar collector area of 25m^2 designed to dry a batch capacity of 500kg in the month of July from an initial moisture content level of 85% to a final moisture content level of 15% was used. It was also assumed that drying was to take place from 06:00 hrs to18:00 hrs in all cases.

The plots indicate that it would take about 53 drying hours to dry this batch in July while it would take about 41 drying hours to dry the same batch in October. The drying curve for July shows a slight increase in moisture content at the start and towards the end of the drying process for each day. This is a sign of moisture gain of the fish from the air (re-wetting), due to the high humidity level in the air during the night hours of the days in July. The effect is overcome by the increase in ambient temperature as the day progresses. The effect does not occur in October simply because the humidity is much lower and the average ambient temperature is much higher during this month. This curve gives some guidelines in determining the optimum period in which to dry during each day. For example, the drying process could be started an hour later and stopped an hour earlier each day for the month of July thus decreasing the drying time to 45 hours. It should be noted that the desired final moisture content would still be achieved, as the dryer will not have to remove the extra moisture gained by the fish from the air. Also, in so doing, the running cost of the dryer may also be reduced.

The effect of drying smaller batches on the drying times for the same dryer was also studied. It is seen from Figure 9.7 that the drying times for a 300 kg and a 100 kg batch size are 23 hours and 7 hours respectively in the month of October. These plots give an indication of the caution that must be taken against drying smaller batches of fish for longer than is necessary.

9.3 INTERACTION OF PARAMETERS - PART II

In order to study the effect of the heat transfer coefficient on the dryer parameters, calculations for studying the variations of various dryer parameters with the heat transfer coefficient were carried out for the month of October for which the value for the radiation falling on a horizontal surface was taken as 23MJ [46]. Each calculation was carried out for three batch sizes of 100kg, 300kg and 500kg as this range forms a compromise between very small-scale users and very large scale dealers. The variation of the parameters can also be seen clearly for this range and the trend for other ranges may be deduced. The parameters were investigated for values of heat transfer coefficients ranging from 11.4W/m^{2}K to 90.9W/m^{2}K since the correction factors for the air flow rate and the heat transfer coefficient could only be found from *Whillier's* tables for this range [1]. The following assumptions were made during the computations:

- A 12 hour drying day
- Ambient temperature taken as 18°C
- Relative humidity taken as 47%
- Re-wetting of the fish at night is neglected
- The air leaves the drying bed at 80% saturation

The results have been further classified into three sets as follows:

A. Variation of the dryer parameters with the heat transfer coefficient,
B. Variation of the drying time with varying fish quantity and various moisture content levels,
C. Typical Dryer Economics

A.2 Effect of the Heat Transfer Coefficient on Dryer parameters

In this section, the effect of the heat transfer coefficient on various dryer parameters has been studied.

A.2.1 Variation of Collector Area with Heat Transfer Coefficient

Figure 9.8 shows the variation of the required solar collector area with the heat transfer coefficient for three batch sizes of fish. From the graph, it can be seen that the collector area decreases exponentially as the heat transfer coefficient is increased. When the value for the heat transfer coefficient is low, a larger collector area is required compared to that required when it is high, for drying the same quantity of fish. The additional area is required to "make up" for the heat required for the drying process since less heat is transferred to the drying air when the heat transfer coefficient is low. Although a much smaller collector area is required when the value of the heat transfer coefficient is increased, the reduction in the required collector area is not significant beyond a value of 68.2W/m^{2}K. This is seen from *Whillier's* relation, expressed by equation (6.54), which shows that the effect of the heat transfer coefficient on *Whillier's* efficiency is small for large values of the heat transfer coefficient and larger for smaller values of the heat transfer coefficient. Therefore, since the collector area depends upon the collector efficiency, as seen from equation (6.53), the collector area reduces as the efficiency increases. Also, the reduction in collector area as the heat transfer coefficient is increased is more significant as the batch size is increased. For example, a reduction of 9.26m^2 is achieved for a batch size of 500kg by increasing the heat transfer coefficient from 11.4W/m^{2}K to 90.9W/m^{2}K whereas a reduction of only

$1.86m^2$ is achieved for a batch size of 100kg over the same range of values for the heat transfer coefficient. This is so since the required collector area is directly proportional to the batch size as discussed in B.1.1. Although the percentage reduction is almost the same (33.2 %), the actual area reduction could greatly contribute to the cost of the solar collector as the batch size is increased.

A.2.2 Variation of Collector Length and Width with Heat Transfer Coefficient

The variation of the collector length with the heat transfer coefficient is shown in Figure 9.9. For each case, the procedure outlined in Section 6.5.4 was followed. The graph shows that the collector length increases linearly with increasing heat transfer coefficient. This is so because the air velocity in the collector increases for higher values of the heat transfer coefficient and the air therefore needs more contact time with the absorber plate in order to attain the required temperature rise. The curve also suggests that the increase in collector length is similar for all three batch sizes because the required collector length designed for a particular temperature rise, surface temperature and heat transfer coefficient remains the same for any batch size.

The plot of the collector width against the heat transfer coefficient (secondary axis) shows that the collector width decreases exponentially with increasing heat transfer coefficient. The required collector width increases with increasing batch size, but the magnitude of the increase is not the same for different batch sizes. It can therefore be seen that the heat transfer properties of the solar collector absorber plate can be increased by reducing the collector width. This is because the air speed in the collector is increased thus increasing the air turbulence (Reynolds number) which enhances heat transfer. The reduction in the collector width is much more pronounced for lower values of the heat transfer coefficient than for the higher values. This could be attributed to the nature in which the collector area reduces with increasing heat transfer coefficient as explained before. Since the collector length remains the same, the width reduces exponentially.

In the final design, it is desirable to have the shortest possible collector length, a reasonable width and a relatively large heat transfer coefficient keeping the required collector area constant. Choosing a large width will give a shorter length but a lower value for the heat transfer coefficient. Therefore a compromise is necessary.

A.2.3 Variation of Collector Hydraulic Diameter with Heat Transfer Coefficient

Figure 9.10 shows the variation of the collector opening hydraulic diameter, with the heat transfer coefficient for the three batch sizes. The collector depth was kept constant at 0.05m in all cases as it has been found to be the optimum duct spacing for air solar collectors by *Reddy et al.* [42] and *Othieno* [43]. The figure suggests an exponential decrease in hydraulic diameter in all three cases although for larger batch sizes, an approximately linear relation is seen. This is because in the design of solar collectors for all cases, an air velocity of 5m/s in the solar collector was aimed for in the iteration approach outlined in Section 6.5.4. Since for smaller batch sizes, the amount of air required is less, a smaller collector opening is required to obtain the required air velocity as can be seen from equation (6.67a). As the batch size is increased, the required air also increases and the collector opening need not be very small to obtain the required air velocity. Therefore, as the batch size gets larger and larger, the reduction in the collector opening gets smaller and smaller even at high values of the heat transfer coefficient.

This information could also act as a useful guide in aiming for the hydraulic diameter for obtaining the required Reynolds number, prior to finding the Nusselt number and the Heat Transfer coefficient in the collector, to a designer using **SISOFID-1** for designing a solar collector for the first time.

A.2.4 Variation of Collector Efficiency and Drying Time with Heat Transfer Coefficient

The variation of collector efficiency, η_c, and the drying time with the heat transfer coefficient is plotted in Figure 9.11. In calculating the collector efficiency, a value for the effective transmissivity-absorptivity product of 0.85 has been assumed. The plot shows an exponential increase in collector efficiency with increasing heat transfer coefficient. The increment is greater at lower values of the heat transfer coefficient and reduces as the heat transfer coefficient attains larger values. The increment of the collector efficiency is however not much beyond 68.2W/m^{2}K since the effect of the heat transfer coefficient becomes smaller and smaller on the collector efficiency as the heat transfer coefficient is increased. This can be seen from the *Whillier's* relation given by equation (6.54). The collector efficiency remains the same for all three batch sizes since the calculated collector area for each batch changes proportionally with the air flow rate required for a particular batch size. Since both these parameters increase or decrease proportionally, the collector efficiency remains constant as seen from equation (6.53). Also, the calculations carried out assume uniform climatic conditions for all cases.

From the variation of the drying time with the heat transfer coefficient (secondary axis), as expected, it is seen that the drying time for each batch size decreases exponentially with increasing heat transfer coefficient. This is so because the same designed solar collector area would for higher values of the heat transfer coefficient, work more efficiently and provide more heat to the drying air than for lower values. The collector efficiency increases exponentially with the heat transfer coefficient as seen before, thus extending the same effect to the drying time according to equations (7.3) to (7.5). There is however not much reduction in the drying time when the heat transfer coefficient is increased beyond $68.2 W/m^2K$ for all the three cases for the reasons given earlier.

A.2.5 Variation of Collector Fan Power with Heat Transfer Coefficient

Figure 9.12. shows a plot of the variation of the required collector fan power with the heat transfer coefficient. In this calculation, a value of 0.07 for the friction factor in equation (6.67) was adopted from the Moody diagram. From the plot, it can be seen that the collector fan power increases parabolically with increasing heat transfer coefficient, since the collector fan power is dependent on both the collector length and width which are used in calculating the hydraulic diameter of the collector opening in equation (6.59). As the collector length increases, the width reduces thus giving a higher value of the pressure drop in the collector. The increase is however not substantial at lower values of the heat transfer coefficient. This is because the collector width at lower values of the heat transfer coefficient is relatively larger thus reducing the collector air velocity and hence the pressure drop in the collector. The increase in collector fan power becomes more prominent for higher values since the collector width is smaller and air turbulence is high which induces a high pressure drop in the collector. Also, since the air required for the mass transfer process for larger batch sizes is more, the selection of a fan becomes more critical for dryers designed for larger batch sizes and high values of the heat transfer coefficients since the required fan power becomes quite large according to equations (6.36) and (6.68).

B.2 Variation of Drying Time with Fish quantity to various Moisture Content levels

This section describes the variation of the drying time for various quantities of fish dried down to various final moisture content levels.

B.2.1 Variation of Drying Time with Batch size

Figure 9.13 shows a plot of the drying time required for drying fish from an initial moisture content of 85% down to various moisture content levels including the final moisture content of 15%. The calculations are based on a fixed dryer size of 500kg capacity, designed for the month of October, having a collector area of 22.58m^2. The plot suggests a linear relationship between the drying time and the batch size. The drying time is less for a smaller quantity of fish since the energy provided by the solar collector for smaller batch sizes is more than sufficient to evaporate the water. As the quantity is increased, there is more water to be evaporated by the same amount of energy. Hence, the drying time is prolonged. The points on the graph do not appear in the same line because every value of the moisture content is time dependent in the calculation of the drying time and the drying rate changes with the time of the day, the maximum value occurring just before and just after noon. This aspect can be observed by applying equations (7.3) to (7.5). The curves give an indication of how long it would take for the fish moisture content to reach a certain value and thus caution one as to when to retrieve the fish from the dryer.

This information could be useful in cases where the fish is to be transported. By reducing the moisture content of the fish to a certain level, the weight of the fish could be reduced thus reducing the transport cost.

C.2 Typical Dryer Economics

The equations described in Chapter 8 were used to carry out a cost / economics analysis of dryers designed for the three batch sizes. The assumptions for material costs made in this section are given in Table 9.3. All assumptions and material costs are based on prevailing rates as at September 1999.

The blower cost was taken to be K1,000,000; cost of ducting K100,000; the labour cost K200,000; and the cost of electricity was taken to be K100 / kWhr (ZESCO rate as at September 1999). The rate of interest i, was assumed as 55% and the life of the device n, as 10 years [20]. The operational time is considered as 300 days/year and 12 hours/day.

The values cited above along with values obtained from SISOFID-1 were fed into SISOFID-2 and the following parameters were studied.

C.2.1 Variation of Daily Running Cost and Evaporated Moisture with Operating Time

The daily running cost curves for dryers of three batch sizes and the respective amounts of the evaporated moisture are plotted in Figure 9.14. From the curves it can be seen that the daily running cost of any dryer increases linearly, with the operating time θ_{op}, in the day which is taken on an hourly basis. As expected, the daily running cost is greater for dryers of bigger batch size capacity. This is because larger dryers incur a greater pressure drop in the collector and drying bin therefore consuming more fan power. Also, since the sizes of dryers required for bigger batch sizes are greater, the total investment cost is more. The cumulative moisture removal also increases as the day progresses with the maximum rate of removal being at around mid day and then decreasing thereafter as the sun starts setting.

C.2.2 Variation of Daily Drying Cost with Operating Time

Figure 9.15 shows the cost per percentage of moisture evaporated. From the curve, it can be seen that the cost per percentage of evaporated moisture is the highest for the 500kg dryer and the lowest for the 100kg dryer. This is so because the capital investment and the blower power are both high for larger dryers. The cost per kg-percentage of moisture on the other hand turns out to be the same for all dryers designed using the model. This is because the desired drying time for all three dryers to dry the different amounts of fish was kept constant at 48hours. This meant that the percentage of moisture evaporated for the smaller dryers per unit time turned out to be proportionately more. Also, the amount of water to be evaporated changes proportionally with the quantity of fish to be dried. Therefore when each of the curves in Figure 9.15 are divided by their respective amounts of water to be evaporated, the curve in Figure 9.16 is obtained suggesting that the cost per kg-% of moisture evaporated is the same in all cases.

Figure 9.16 shows the variation of the daily drying cost with the operating time in the day for all the three cases. From the curve it can be seen that the cost per unit moisture evaporated decreases as the day progresses to a minimum value of Daily Cost / kg of Moisture Evaporated at around 15:00 hrs assuming that the drying process began at 06:00 hrs. This is a useful indicator for drying items that require short drying times and would be the most economical time to use the dryer.

For drying later in the day, although the ratio of Daily Cost / kg of Moisture Evaporated increases for the period 15:00hrs to 18:00hrs, the increase is only by K18.78 / kg Moisture evaporated. The curve also shows that the cost per unit moisture evaporated is very high at the start of the drying process. This is because of the limited available heat for the drying process during the early hours of the day. Similarly, during the later part of the day, the available solar energy for the drying process begins to reduce therefore increasing the cost per unit evaporated moisture. The cost does not rise to as much as that at the start of the drying process since the cumulative moisture evaporated is more during the later part of the day as seen from Figure 9.14. However, further drying would definitely raise the cost appreciably.

Table 9.1 Calculated values for Geometric factor, Clearness index, Diffuse fraction, Declination angle, and Collector inclination angle for each month of the year.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
R_b	1.020	1.000	1.040	1.198	1.429	1.580	1.510	1.282	1.092	1.008	1.012	1.031
K_t	0.438	0.395	0.494	0.532	0.618	0.639	0.619	0.645	0.602	0.600	0.522	0.492
I_d/I_h	0.778	0.847	0.671	0.590	0.399	0.354	0.397	0.344	0.435	0.439	0.612	0.674
δ	-20.9	-12.9	-2.4	9.4	18.79	23.1	21.2	13.5	2.2	-9.6	-18.9	-23.3
β	5.9	2.0	12.8	24.4	33.8	38.1	36.2	28.5	17.2	5.4	3.9	8.3

Table 9.2 Values of Minimum ambient temperature (°C), calculated Radiation on inclined collector (W/m²), and calculated Air flow rate (m³/s), for each month of the year used in equation (6.53).

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
T_{amb}	17.0	17.3	16.5	15.7	13.0	10.0	10.5	12.0	15.0	18.0	18.7	17.5
$I_{c,ave}$	412	363	430	430	497	514	490	536	515	540	487	465
v_1	0.170	0.168	0.170	0.168	0.161	0.158	0.156	0.156	0.158	0.161	0.165	0.168

Table 9.3 : Assumptions made for material costs

SOLAR COLLECTOR			
Component	Material Specification	Standard Unit	Cost (K)
1. Frame	40 x 40 x 3 Mild Steel angle	6m	21,306
2. Absorber plate	2130 x 920 x 1.05 C/rolled	1.96m²	37,074
3. Insulation	50000 x 2400 Glass wool	120m²	250,000
4. Back / Side plate	2130 x 920 x 1.05 C/rolled	1.96m²	37,074
5. Cover	1830 x 1220 x 4 Glass	2.23 m²	62,000
DRYING BIN			
Component	Material	Standard unit	Cost (K)
1. Frame	50 x 50 x 5 Mild Steel angle	6m	44,010
2. Covering sheet	1200 x 2400 x 18mm Plain particle board	2.88 m²	34,000
3. Insulation	50000 x 2400 Glass wool	120 m²	250,000
TRAYS			
Component	Material	Standard unit	Cost (K)
1. Frame	4mm Galvanised wire	300m	132,000
2. Covering	50000 x 2400 Industrial mesh	120m²	550,000

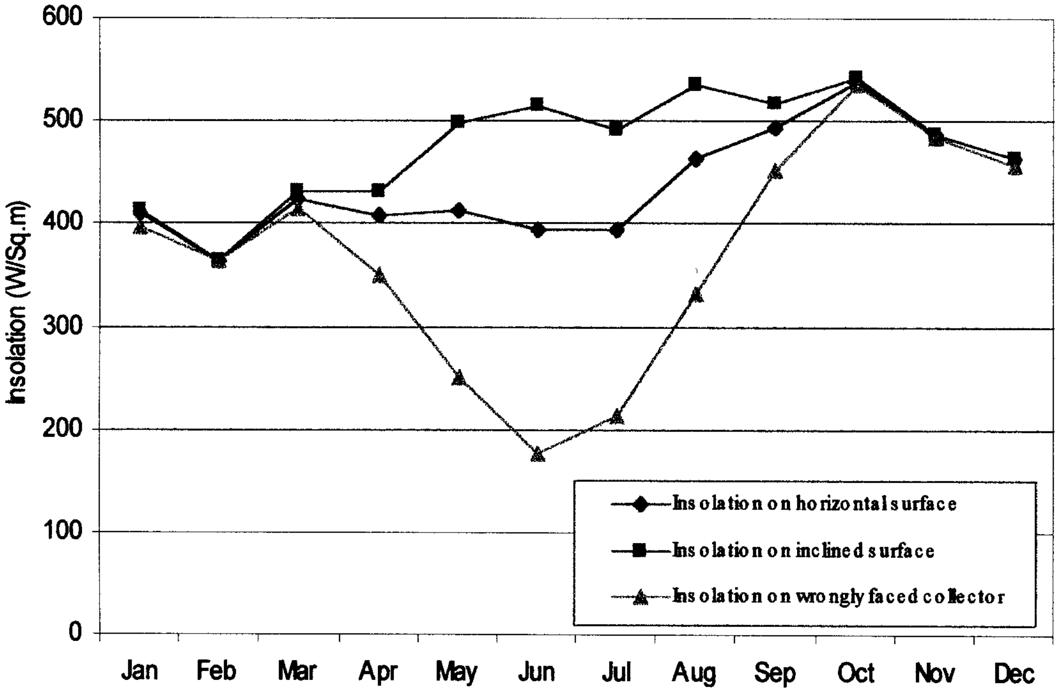


Figure 9.1 SOLAR INSOLATION Vs MONTH of YEAR

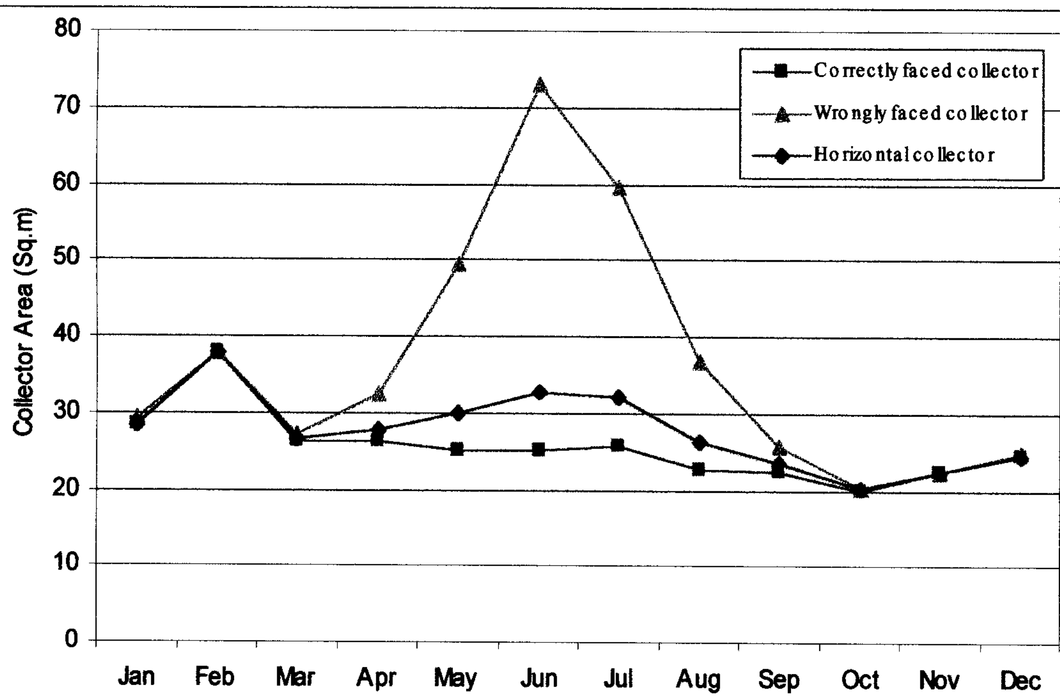


Figure 9.2 SOLAR COLLECTOR AREA Vs MONTH of YEAR

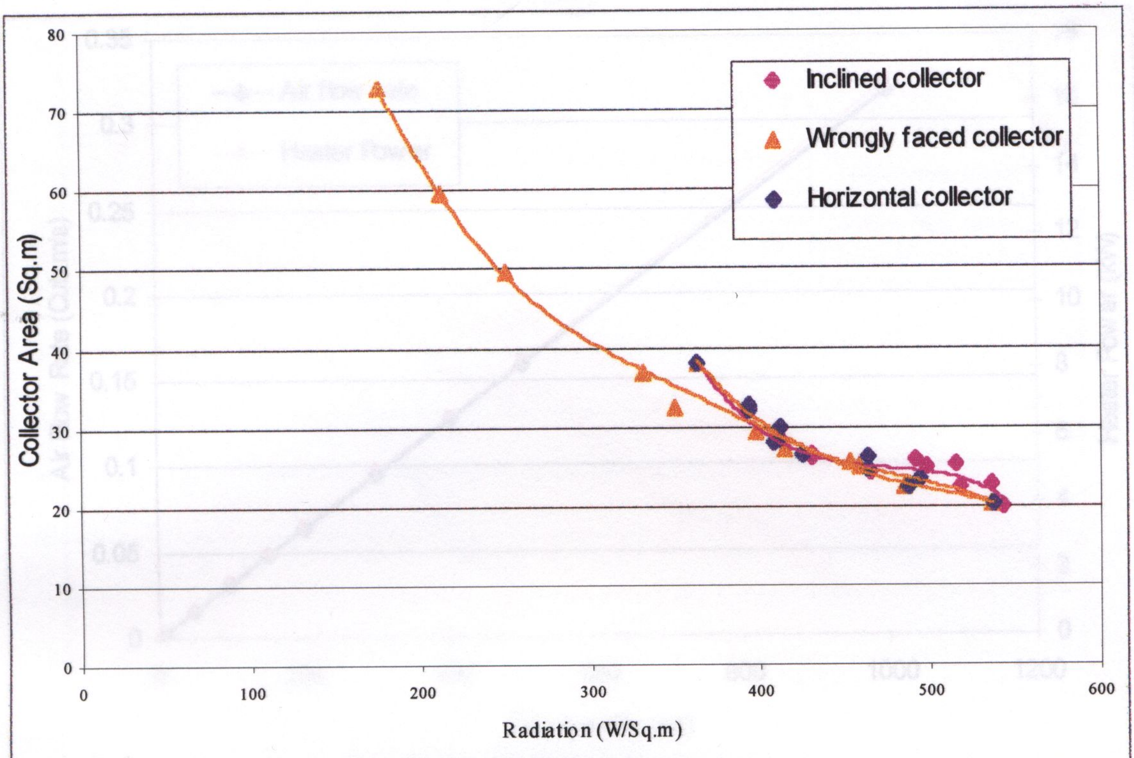


Figure 9.3 SOLAR COLLECTOR AREA Vs RADIATION

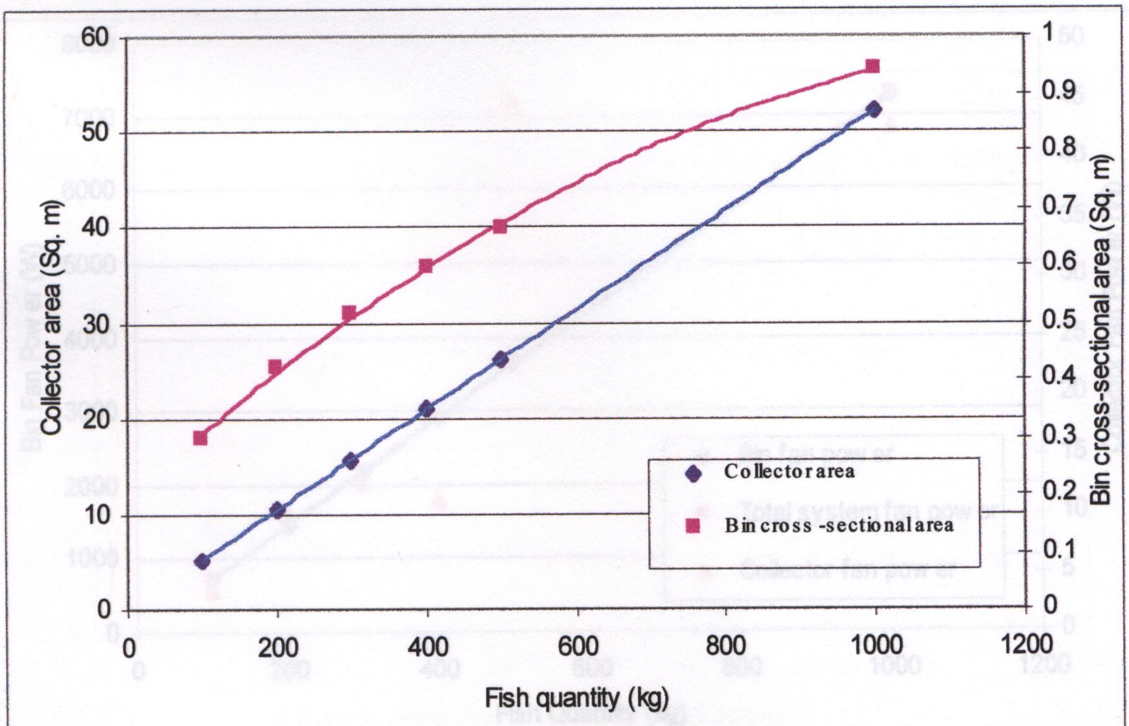


Figure 9.4 SOLAR COLLECTOR AREA & BIN CROSS-SECTIONAL AREA Vs FISH QUANTITY

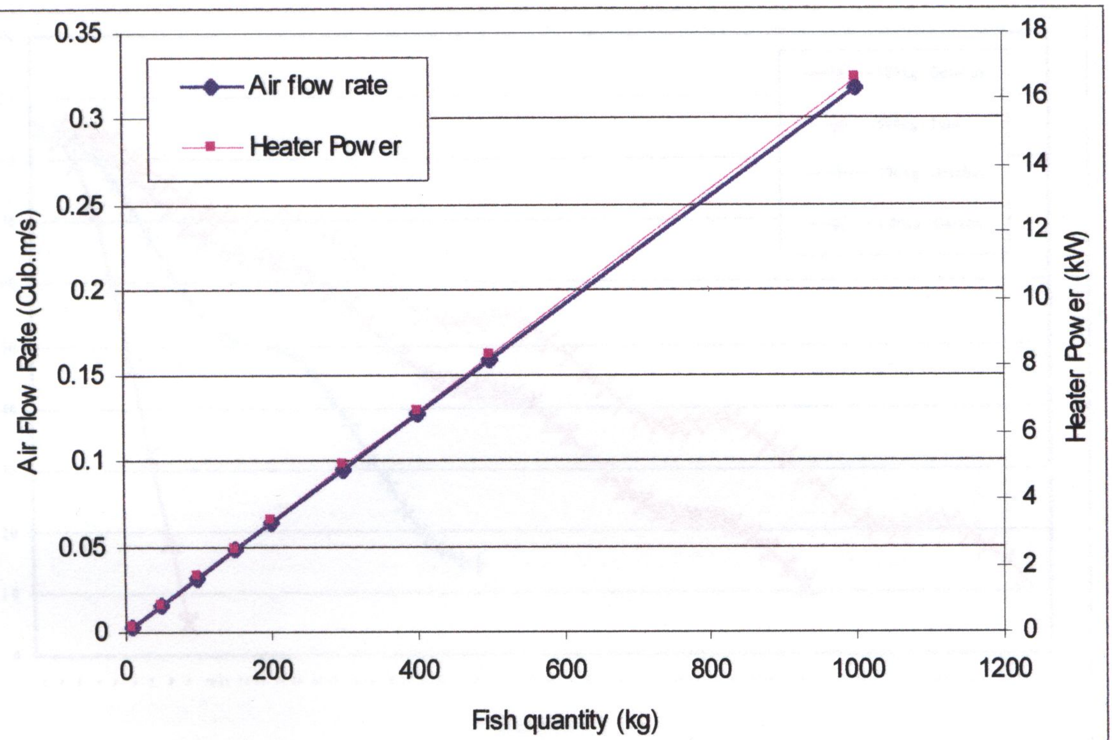


Figure 9.5 AIR FLOW RATE & HEATER POWER Vs FISH QUANTITY

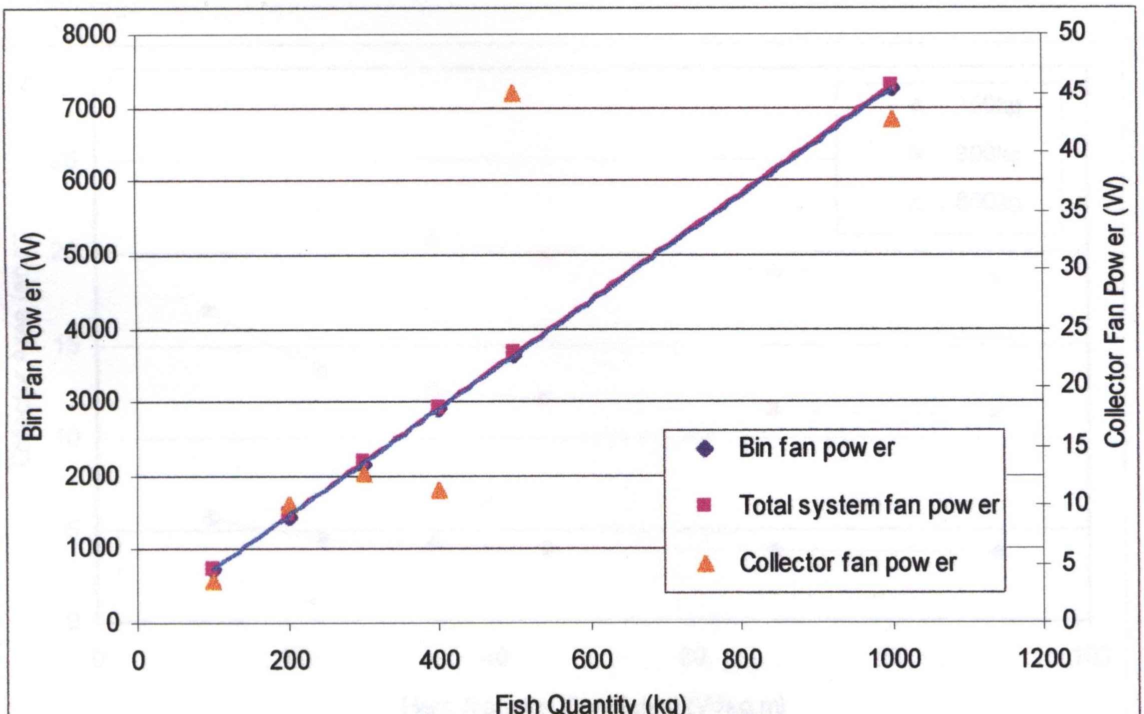


Figure 9.6 COLLECTOR, BIN & TOTAL SYSTEM FAN POWER Vs FISH QUANTITY

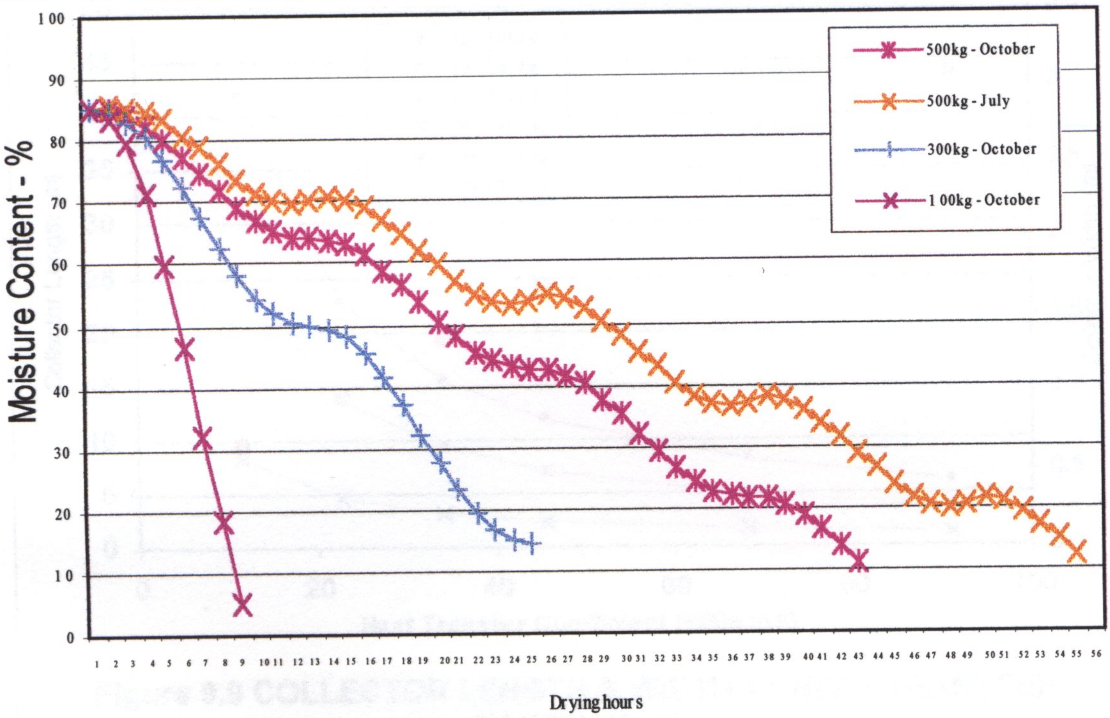


Figure 9.7 DRYING CURVE - MOISTURE CONTENT Vs DRYING TIME

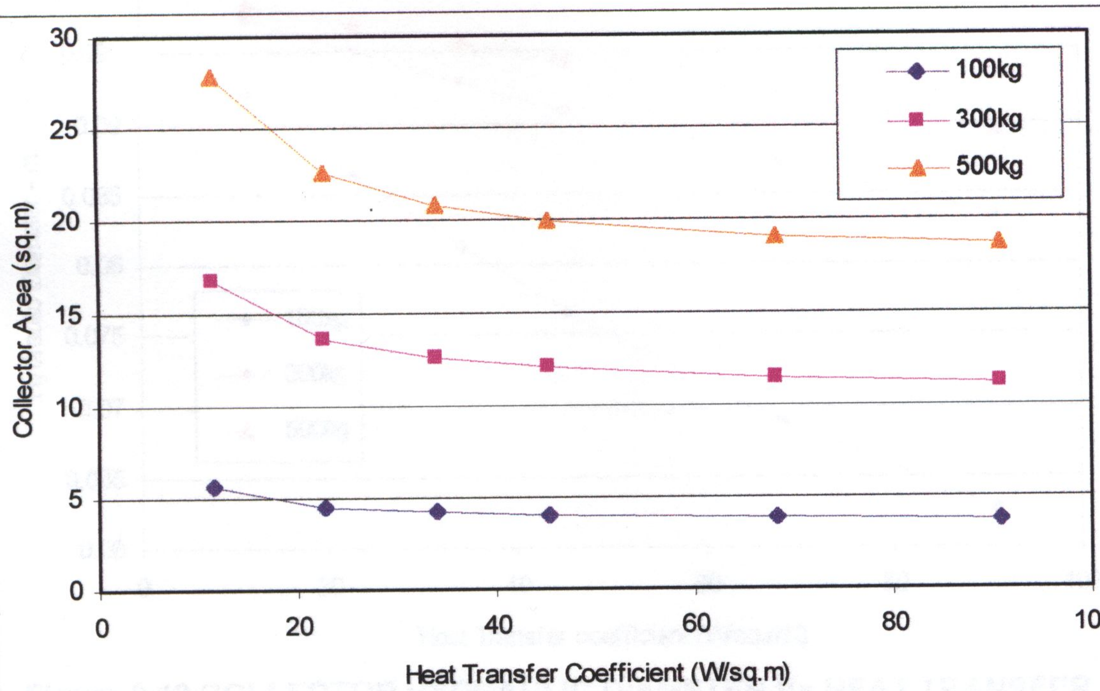


Figure 9.8 COLLECTOR AREA Vs HEAT TRANSFER COEFFICIENT

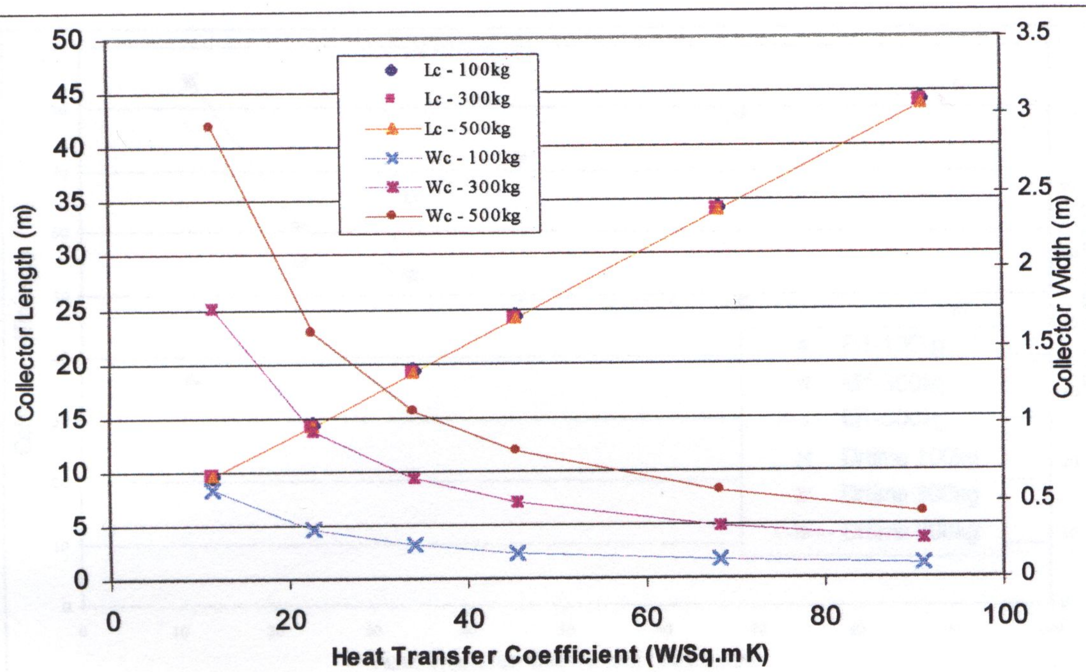


Figure 9.9 COLLECTOR LENGTH & WIDTH Vs HEAT TRANSFER COEFFICIENT

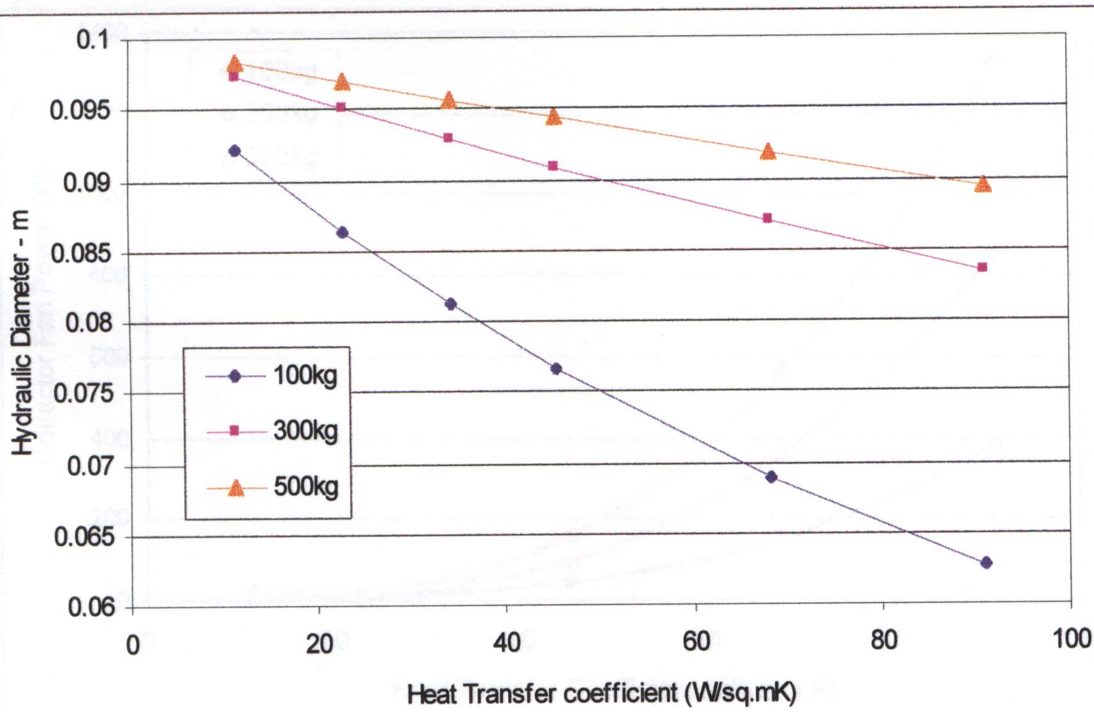


Figure 9.10 COLLECTOR HYDRAULIC DIAMETER Vs HEAT TRANSFER COEFFICIENT

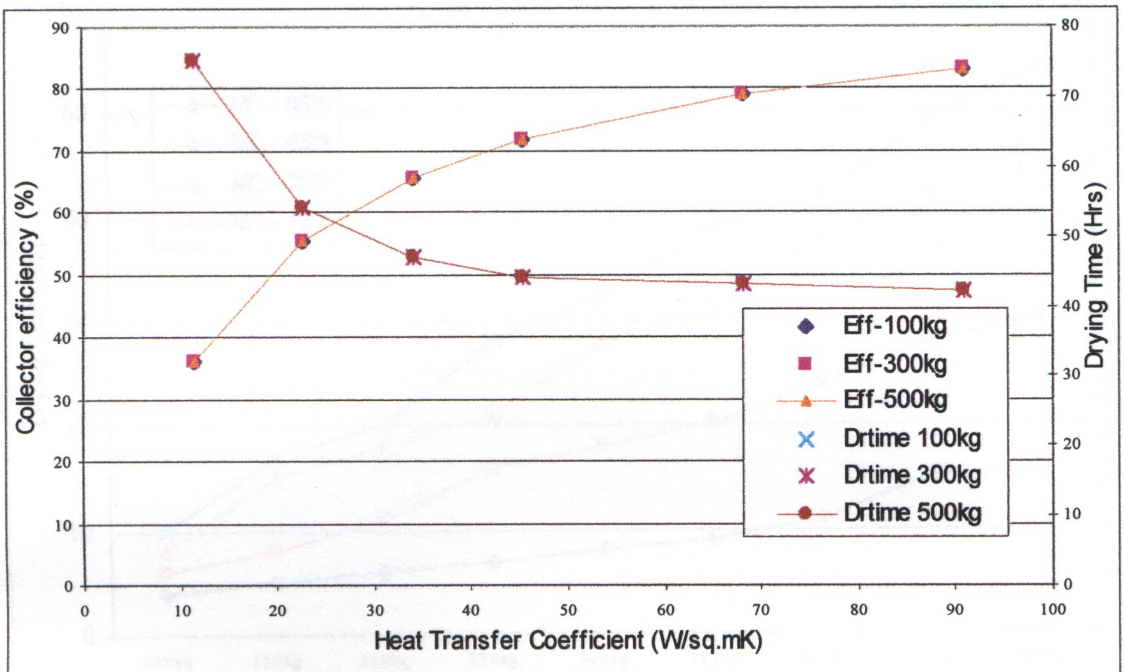


Figure 9.11 COLLECTOR EFFICIENCY & DRYING TIME Vs HEAT TRANSFER COEFFICIENT

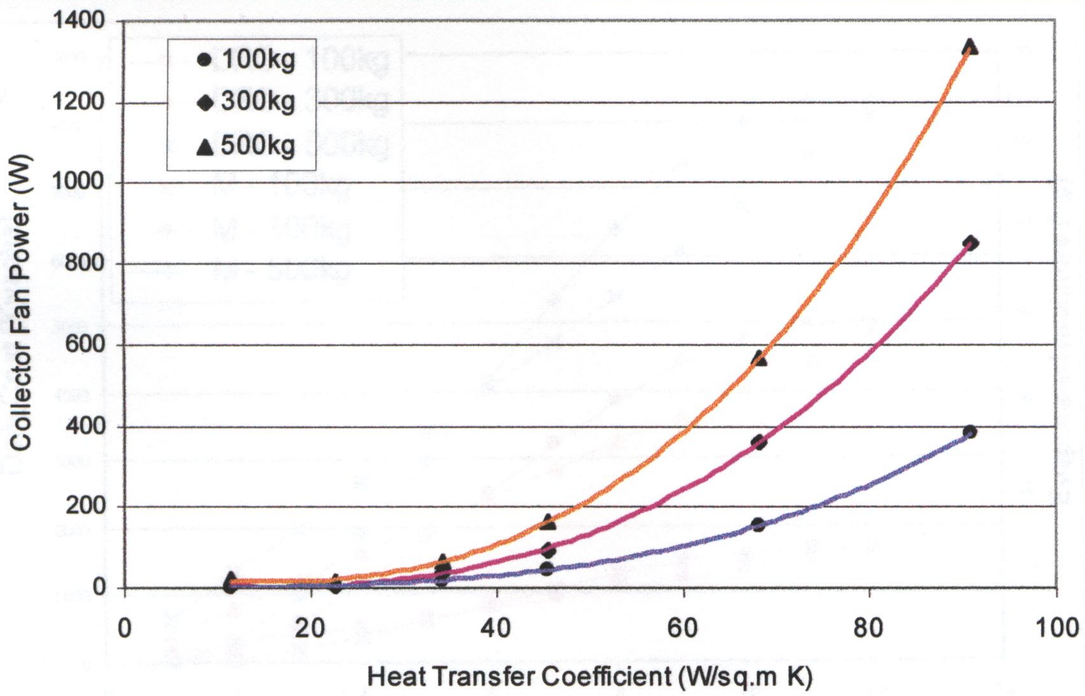


Figure 9.12 COLLECTOR FAN POWER Vs HEAT TRANSFER COEFFICIENT

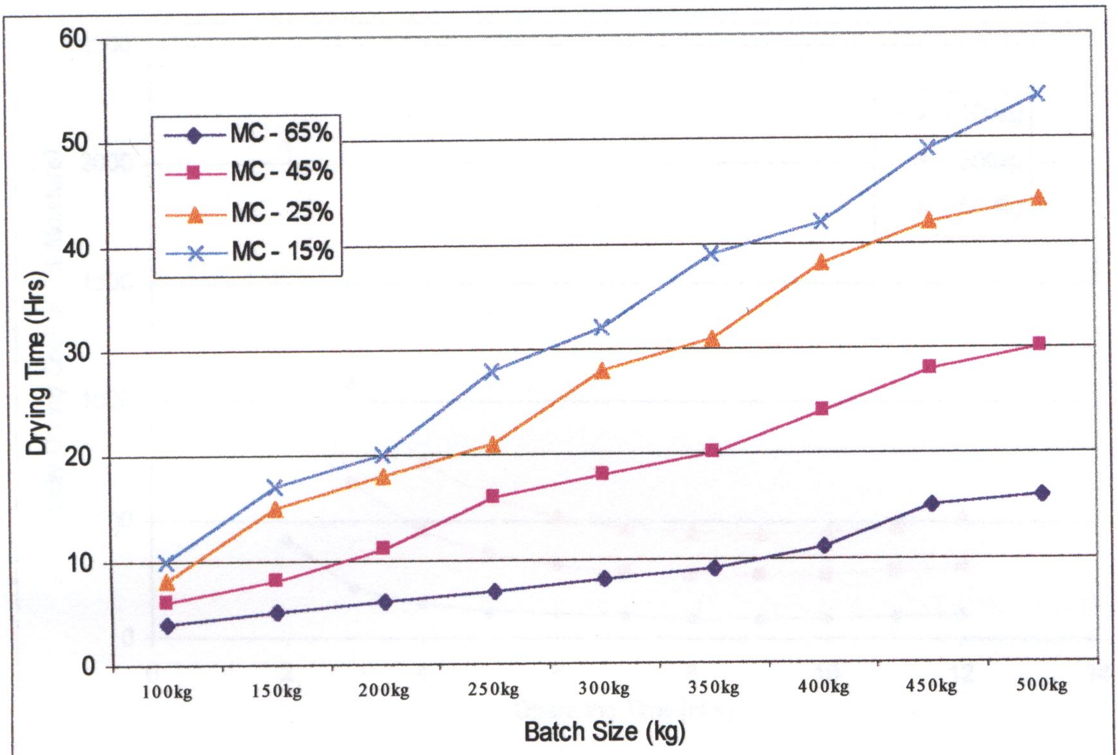


Figure 9.13 DRYING TIME Vs BATCH SIZE

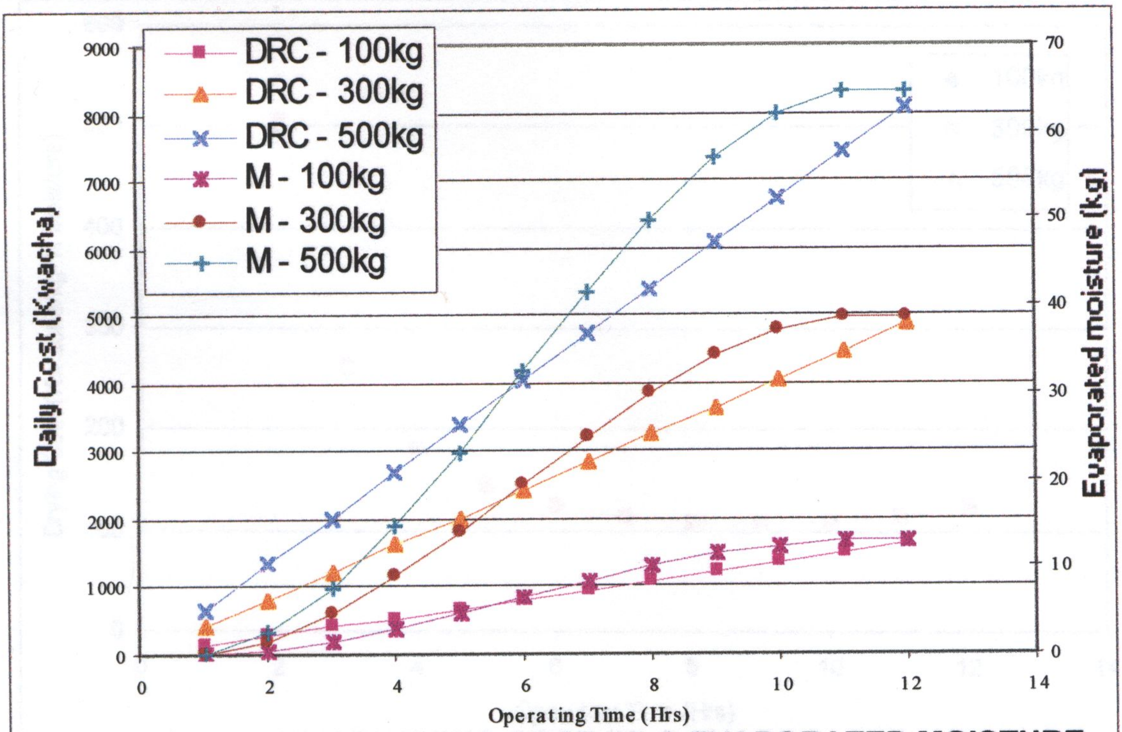


Figure 9.14 DAILY RUNNING COST (K) & EVAPORATED MOISTURE Vs OPERATING TIME

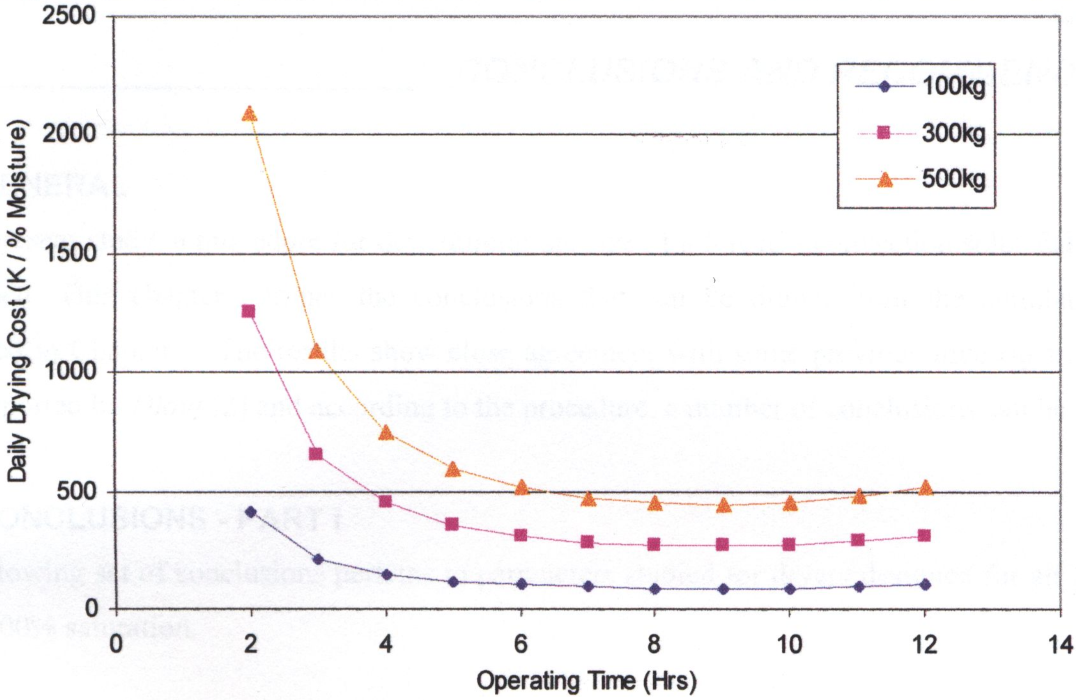


Figure 9.15 DAILY DRYING COST Vs OPERATING TIME

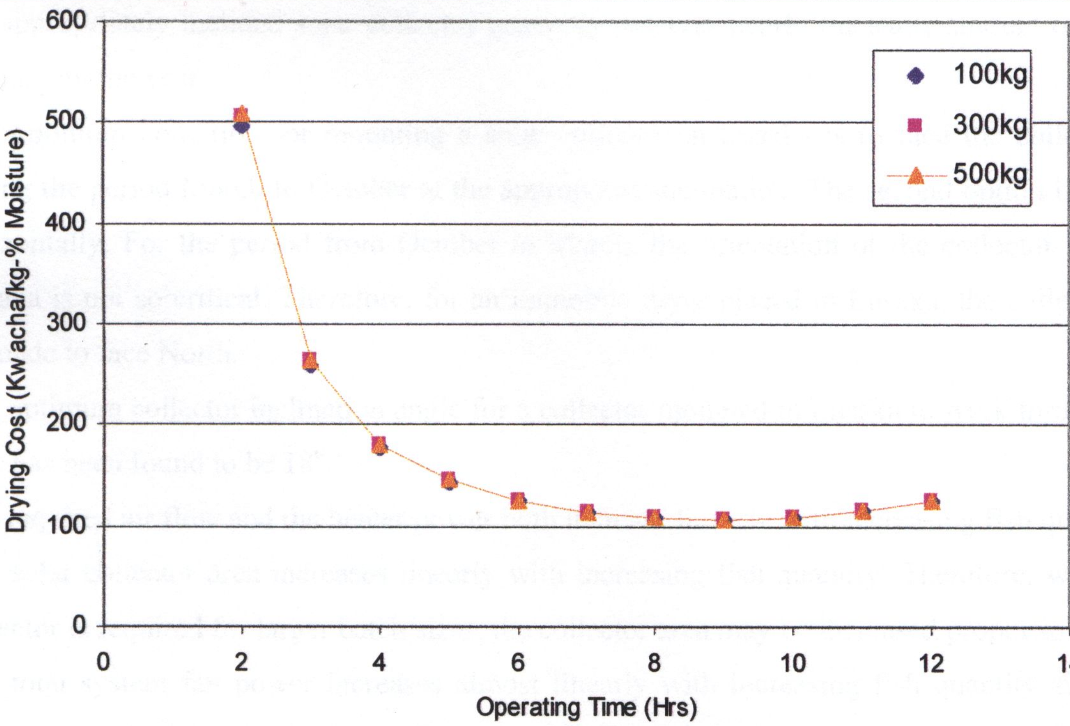


Figure 9.16 DAILY DRYING COST Vs OPERATING TIME

Chapter 10
CONCLUSIONS AND RECOMMENDATIONS

10.1 GENERAL

In the present study, a procedure for determining the size of a forced - convection solar fish dryer was developed. This chapter outlines the conclusions that can be drawn from the simulation results described in Chapter 9. The results show close agreement with some previous investigations such as those reported by *Diouf* [2] and according to the procedure, a number of conclusions can be made:

10.2 CONCLUSIONS - PART I

The following set of conclusions pertains to parameters studied for dryers designed for air leaving the bin at 100% saturation.

1. The solar intensity received by a solar collector stationed in Lusaka can be increased considerably by inclining the collector at its optimum angle and facing it due North for the months April to September.
2. An appropriately inclined solar collector generally receives nearly the same amount of insolation throughout the year.
3. The optimum condition for mounting a solar collector in Lusaka is to face the collector North during the period March to October at the appropriate inclination. The second option is to place it horizontally. For the period from October to March, the orientation of the collector mounted in Lusaka is not so critical. Therefore, for an immobile dryer placed in Lusaka, the collector should be made to face North.
4. The optimum collector inclination angle for a collector mounted in Lusaka to work through out the year has been found to be 18^{o}.
5. The required air flow and the heater power both increase linearly with increasing fish quantity.
6. The solar collector area increases linearly with increasing fish quantity. Therefore, when a solar collector is required for larger batch sizes, the collector area may be increased proportionally.
7. The total system fan power increases almost linearly with increasing fish quantity since the air flow rate required for the mass transfer process also increases proportionally.

8. The drying curve can be used to deduce optimum drying periods since periods during which the fish gains humidity from the drying air can be clearly seen. This can help in cutting down the running time of the dryer and hence cut down on the running costs of the dryer, while maintaining the final desired moisture content.

10.3 CONCLUSIONS - PART II

The following set of conclusions pertains to parameters studied for dryers designed for air leaving the bin at 80% saturation.

1. The solar collector area decreases exponentially as the heat transfer coefficient is increased from 11.4 W/m^2K to 90.9 W/m^2K. The decrease is however not significant beyond a value of 68.2 W/m^2K.
2. The collector length that is required for any batch size designed for a particular heat transfer coefficient remains the same. The collector width however decreases exponentially with increasing heat transfer coefficient. Therefore, only the width needs to be changed in designing a solar collector with the same heat transfer coefficient for a different batch size.
3. The relationship between the collector opening hydraulic diameter shows an exponential decrease with increasing heat transfer coefficient. The decrease is more substantial for smaller batch sizes than for larger batch sizes. For larger batch sizes, the relationship tends to become approximately linear.
4. The collector efficiency increases exponentially with increasing heat transfer coefficient. The increase is however not considerable beyond a value of 68.2W/m^2K.
5. The collector fan power increases parabolically with increasing heat transfer coefficient and reducing collector width. The selection of a fan is therefore more critical for larger batch sizes and high heat transfer coefficient.
6. The drying time for any particular batch decreases exponentially with increasing heat transfer coefficient. The decrease is however not substantial beyond 68.2 W/m^2K. On the other hand, the drying time increases linearly with increasing batch size.
7. The daily running cost for any dryer increases linearly with the operating time and the cost per unit moisture evaporated decreases to a minimum at around 15:00 hrs Zambian time, in the month of October, after which it starts to rise up again. The rise is however not substantial. Thus 15:00 hrs is the optimum drying time in Lusaka.

8. The analysis allows for the deduction of the optimum heat transfer coefficient and the optimum drying times with respect to cost.

10.4 RECOMMENDATIONS

In view of the results, discussion and conclusions presented in this dissertation, it is necessary to make critical remarks about the research, which can be taken as a guide for continued research in the subject in future.

1. From the foregoing, it can be seen that **SISOFID** generates enough data for the construction of a solar fish dryer. However, before the model can be used with any confidence to design a dryer, its ability to adequately predict the dryer parameters must be proven, i.e. the model must be validated. This has been done to some extent by comparing certain obtained values to those obtained by various researchers. Although good agreement was accomplished in some cases like the dimensions obtained for the solar collector, other parameters such as the material moisture contents and the drying times can only be verified through accurate experimentation. Also, the comparisons made were with research work carried out in different parts of Africa other than Zambia. It is therefore strongly recommended that the next step in this research should be the construction of a prototype to be experimented upon under Zambian conditions. This would generate two advantages:

   I. Provide solid information for model validation;

   II. Provide a sound foundation for parties interested in the subject. This is important as the subject of the materials, cost and performance raised much interest during two local Engineering conferences held during the period of the research.

2. For more fundamental results about the solar drying process, the calculations and experiments will have to be performed with a more accurate value for the specific resistance of fish. The experimental rig may have to be enlarged to enable accurate determination of this value.
3. All the results concerning the average daily solar radiation components and the daily distribution of the beam and diffuse components are based on calculation models using values of the total solar radiation obtained from the local weather station. In order to get more reliable data for further design and experimentation, it is recommended to measure not only the hourly total solar radiation

but also the hourly diffuse solar radiation. It also goes without saying that measurements should be taken all year round.

4. An extension to **SISOFID-1** would be to include simulation of the drying process once the dryer parameters and dimensions have been obtained. This would involve carrying out heat and mass balances for both the collector and the drying bin, and would give further validation in performance prediction. For example, the heat and fluid flow patterns can adequately be studied using a computational Fluid Dynamics software such as **PHOENICS**. A number of models for various types of collectors and dryers are available in literature.

5. In some cases the solar or sun drying processes stop almost directly when the solar radiation drops below a critical level. One possibility of improving this discrepancy is to provide an energy accumulator in the system. In this way, the stored energy can be used to heat up the drying air when the radiation is below the critical level. For low cost, it is possible to put stones in the collector or to place a bed of stones in the dryer line as described in Chapter 7. In general, a material with high relative specific heat and thermal conductivity should be chosen for this purpose. This can help in extending the drying period of the dryer and can also be a good extension to **SISOFID-1** if simulated.

6. Since the procedure for determining the dryer parameters is not material specific, **SISOFID-1** and **SISOFID-2** can be used for sizing dryers for other agriculture and industrial applications by making valid assumptions and minor adjustments in the code.

7. Although **SISOFID-2** provides a good estimate of the cost of the dryer, it should be used carefully in carrying out the cost analysis as it does not offer the provision to round off values obtained for the amounts of units of the standard materials required. The analysis is carried out for the exact amount of material required while in practice it is always necessary to purchase a standard unit of material.

It goes without saying that since solar energy is gaining increasing importance globally, any further rigour put into researching the subject will certainly be beneficial.

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APPENDIX 1: USEFUL DEFINITIONS

1. HUMIDITY

The humidity of an air - water mixture is defined as the kg of water vapor contained in 1 kg of air. The humidity so define depends only on the partial pressure, p_A of water vapor in the air and on the total pressure P (taken as 101.325 kPa, 1.0 atr abs, or 760 mm Hg). Using the molecular weight of water (A) as 18.02 and of air as 28.97, the humidity H in kg H_2O / kg dr air is found to be:

$$H = 18.02\, p_A / 28.97\, (P - p_A) \tag{A1.1}$$

Saturated air is air in which the water vapor is in equilibrium with liquid water at the given conditions of pressure an temperature. In this mixture, the partial pressure of the water vapor in the air-water mixture is equal to the vapor pressure p_{AS} o pure water at the given temperature. Hence the saturation humidity H_S is :

$$H_S = 18.02\, p_{AS} / 28.97\, (P - p_{AS}) \tag{A1.2}$$

2. PERCENTAGE HUMIDITY

The percentage humidity is defined as 100 times the actual humidity H of the air divided by the humidity H_S if the air were saturated at the same temperature and pressure.

$$H_P = 100\, H / H_S \tag{A1.3}$$

3. PERCENTAGE RELATIVE HUMIDITY

The amount of saturation of an air-water vapor mixture is also given as percentage relative humidity H_R using partial pressures.

$$H_R = 100\, p_{AS} / p_{AS} \tag{A1.4}$$

Note that $H_R \neq H_P$ since H_P expressed in partial pressures by combining equations. (3.1), (3.2) and (3.3) is:

$$H_P = p_A\, (P - p_{AS}) / p_{AS}\, (P - p_A) \tag{A1.5}$$

4. TOTAL ENTHALPY OF AN AIR-WATER VAPOR MIXTURE

The total enthalpy of 1kg of air plus its water vapor is h_T J/kg or kJ/kg dry air. If T_o is the datum temperature chosen for both components, the total enthalpy is the sensible heat of the air-water vapor mixture plus the latent heat λ_o in J/kg or kJ/kg water vapor of the water vapor at T_o. If the total enthalpy is referred to a base temperature T_o of 0°, then the equation for h_T becomes:

$$h_T \text{ (kJ/kg dry air)} = (1.005 + 1.88H)(T^o\text{C} - 0) + 2501.4H \tag{A1.6}$$

5. DRY AND WET BULB TEMPERATURE

The dry bulb temperature is the air temperature measured using a thermometer having a dry bulb. The wet bulb temperature is measured using a thermometer with a soaked wick wrapped around its bulb. The temperature measured is the air temperature minus the temperature drop caused by the evaporation of the water from the wick. In saturated air, both temperatures are the same.

6. LATITUDE ANGLE

The Latitude angle is the angular location north or south of the equator, north positive;
$-90^o \leq \varphi \leq 90^o$

7. DECLINATION ANGLE

The Declination angle is the angular position of the sun at solar noon (i.e. when the sun is on the local meridian) with respect to the plane of the equator, north positive; $-23.45° \leq \delta \leq 23.45°$

8. SLOPE ANGLE

The Slope angle is the angle between the plane of the surface in question and the horizontal; $0 \leq \beta \leq 180°$. ($\beta > 90°$ means that the surface has a downward facing component).

9. SURFACE AZIMUTH ANGLE

The Surface Azimuth angle is the deviation of the projection on a horizontal plane of the normal to the surface from the local meridian, with zero due south, east negative, and west positive; $-180° \leq \gamma \leq 180°$.

10. HOUR ANGLE

The Hour angle is the angular displacement of the sun east or west of the local meridian due to rotation of the earth on its axis at 15° per hour, morning negative, afternoon, positive.

11. ANGLE OF INCIDENCE

The Angle of Incidence is the angle between the beam radiation on a surface and the normal to that surface.

12. GRASHOF NUMBER

Dimensionless number defining ratio of the buoyancy to viscous forces. Plays the same role in natural convection that Reynold's number plays in forced convection.

$$Gr = g\beta(T_s - T_\infty)L / \nu^2 \qquad \text{(A1.7)}$$

Where : L = characteristic length (m); T_s = Surface temperature (K); T_∞ = Air temperature (K); β = Volumetric thermal expansion coefficient $\approx 1/T$ (K^{-1}); T = absolute temperature (K); g = acceleration due to gravity (m/s^2); ν = Kinematic viscosity (m^2/s).

13. PRANDTL NUMBER

Dimensionless number defining the ratio of momentum and thermal diffusivities.

$$Pr = C_p\mu / k = \nu / \alpha \qquad \text{(A1.8)}$$

Where: α = Thermal diffusivity (m^2/s)

14. REYNOLDS NUMBER

Dimensionless number difining ratio of the inertia and the viscous forces.

$$Re = VL / \nu \qquad \text{(A1.9)}$$

Where: L = Characteristic length (m)

APPENDIX 2: SORPTION ISOTHERM CURVES

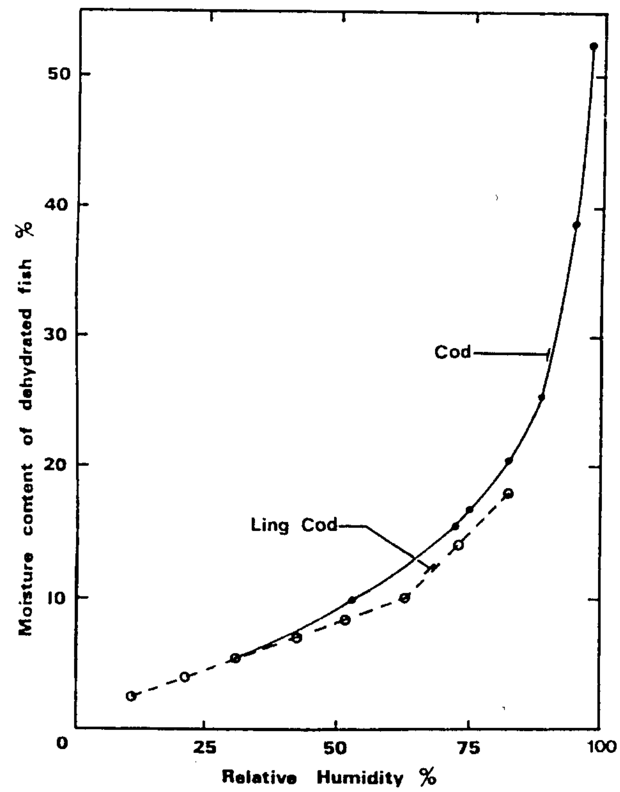

Figure A2.1 Equilibrium Moisture Contents of Dehydrated Cod and Ling Cod

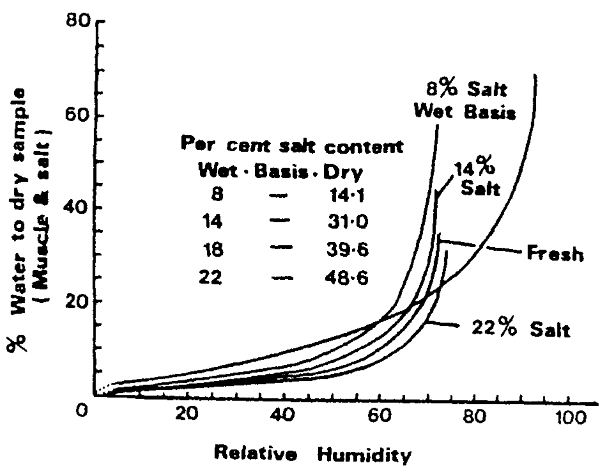

Figure A2.2

Equilibrium Water Content of Salt and Fresh Cod

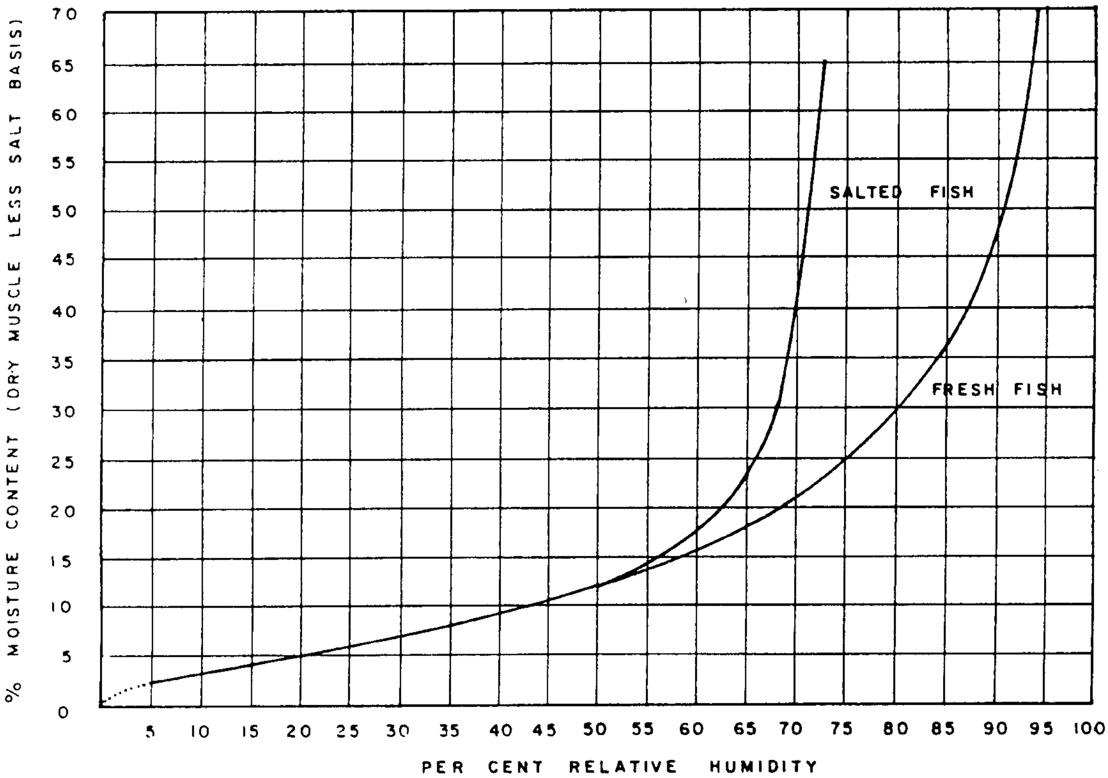

Figure A2.3 Equilibrium moisture content of salt and fresh cod (Source. Cooper and Noel, 1966).

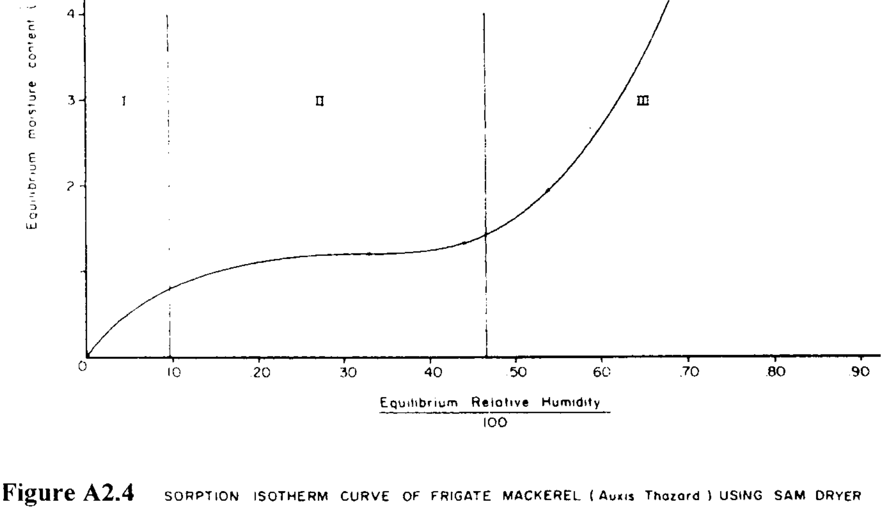

Figure A2.4 SORPTION ISOTHERM CURVE OF FRIGATE MACKEREL (Auxis Thazard) USING SAM DRYER

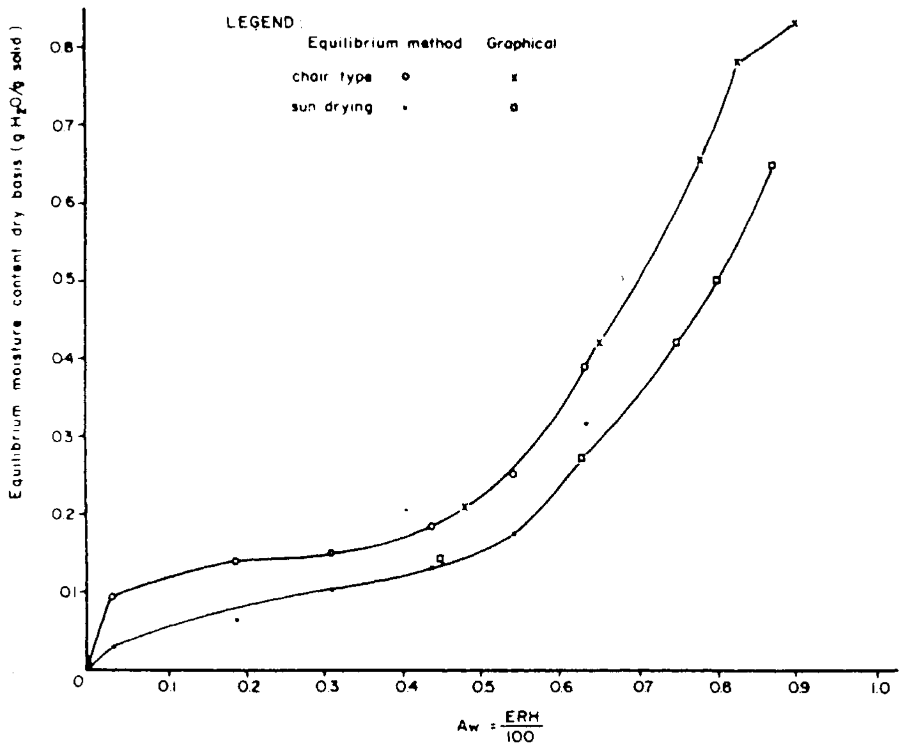

Figure A2.5 SORPTION ISOTHERM CURVES OF DRIED MUSSELS USING DIFFERENT DRYERS

APPENDIX 3: TYPES OF FANS

Fan type	Fan static efficiency	Advantages	Disadvantages	Applications
1.Axial flow (without guide vanes)	60 - 65 %	Very compact, Straight through flow. Suitable for installing in any position in line of ducting.	High tip speed. Relatively high sound level comparable with 5. Low pressure development	All low pressure, atmospheric air applications
2.Axial flow (with guide vanes)	70 - 75 %	Straight-through flow. Eminently suitable for vertical axis.	Same as 1 but to lesser extent.	As for 1 and large ventilation scheme applications.
3.Forward vane or multi vane centrifugal	50 - 60 %	Operates with low peripheral speed. Quiet and compact	Severely rising power characteristic, requires large motor margin.	All low and medium pressure atmospheric air and ventilation plants.
4.Straight or paddle-bladed centrifugal	45 - 55 %	Strong simple impeller, least clogging, easily cleaned and repaired	Inefficiency, rising power characteristic.	Material transport systems and any application where dust burden is high.
5.Backwards-curved or backwards inclined centrifugal	70 - 75 %	Good efficiency. Non overloading power characteristic.	High tip speed. Relatively high sound level compared with 3.	Medium and high pressure applications such as high velocity ventilation schemes.
6.Aerofoil bladed centrifugal	80 - 85 %	Highest efficiency of all fans. Non-overloading characteristic.	Same as 5.	Same as 5 but higher efficiency justifies its use for higher power applications.
7.Propeller	Less than 40 %	Low cost and ease of Installation.	Low efficiency and very low pressure development.	Mainly non-ducted low pressure atmospheric air applications. Pressure development can be increased by diaphragm mounting.
8. Mixed flow	70 - 75 %	Straight through flow. Suitable for installing in any position in a run of ducting. Can be used for higher-pressure duties than 2. Lower speeds than 1 and 2 hence, less noise.	Stator vanes are generally highly loaded due to higher-pressure ratios. Maximum casing diameter is greater than either inlet or outlet diameters.	Large ventilation schemes where higher pressures and lower noise give advantage over 2.
9. Cross-flow or tangential flow	40 - 50 %	Straight across flow. Long narrow discharge.	Low efficiency. Very low pressure development.	Fan-coil units. Room conditioners, domestic heaters, small dryers

(Institute of Heating and Ventilating Engineers (1972))

APPENDIX 4: VALUES FOR WATER, FAT & PROTIEN CONTENT FOR DIFFERENT TYPES & SPECIES OF FISH

Proximate composition of some fish from tropical areas*

Species	Composition (by percentages)†		
	Water	Fat	Crude Protein
Africa			
Bream (*Tilapia mossambica*)	74.5 – 83.7	0.1 – 8.4	14.0 – 20.6
Mudsucker (*Labeo congoro*)	75.1 – 83.6	0. – 6.1	15.2 – 21.2
Tiger fish (*Hydrocyon vittatus*)	74.7 – 80.2	0. – 3.5	18.5 – 23.4
Barbel (*Clarias mossambicus*)	75.2 – 84.6	0.2 – 6.3	13.0 – 18.5
Barracouda (*Sphyraena jello*)	76.5	0.7	20.0
Bonga (*Ethmalosa dorsalis*)	68.3 – 71.2	2.3 – 7.5	19.8 – 20.8
Sea bream (*Pagelus caupei*)	74.8	2.3	17.9
Bumper (*Chloroscombrus chryșurus*)		3.1	
Bluefish (*Pomatomidae* sp.)	69.0 – 81.4	2.1 – 4.8	20.4 – 21.6
Philippines			
Alumahan (*Rastrelliger chrysozomus*)	78	1	17
Bambangin (*Lutjanus fulvus*)	70	0.4	20
Tulingan (*Auxis thazard*)	72	1	23
Parang (*Chirocentrus dorab*)	75	1	20
Dapang (*Cynoglossus puncticops*)	80	2	18
Banak (*Mugil vaigiensis*)	73	2.5	20
Bisugo (*Nemipterus taenipterus*)	78	1	18
Sri Lanka			
Goatfish (*Parapeneus malabaricus*)	70.0	1.2	21.0
Trevally (*Caranx* sp.)	77.0	1.5	21.4
Grouper (*Epinephalus undulosus*)	77.0	0.8	16.4
Triggerfish (*Balistes viridescens*)	80.5	2.0	16.1
India			
Carp (*Cirrhina mrigala*)	75.0 – 79.8	0.2 – 4.0	18.1 – 19.6
Mackerel (*Scomberomorus guttatus*)	63.0 – 82.1	0.2 – 14.4	15.9 – 22.4
Lobster (*Panulirus* sp.)	71.5 – 81.2	0.6 – 1.9	16.2 – 21.6
Mackerel (*Rastrelliger* sp.)	73.3 – 79.3	0.5 – 4.1	16.6 – 21.4
Sardine (*Sardinella longiceps*)	75.3 – 76.0	1.9 – 4.6	17.7 – 21.0
Drum (*Sciaenidae* sp.)	69.7 – 80.2	1.0 – 8.4	18.1 – 20.1
Samson crab (*Scylla serrata*)	75.1 – 83.9	0.7 – 4.0	11.8 – 20.1
Carp (*Barbus* sp.)	70.3 – 79.1	2.3 – 3.1	16.0 – 25.2
Japan			
Rockfish (*Sebastes* sp.)	75.1 – 80.0	0.2 – 2.4	17.2 – 20.8
Sandlance (*Ammodytes* sp.)	78.0	1.5	17.9
Pink salmon (*Onchorhynchus gorbuscha*)	69.0 – 78.3	2.0 – 9.4	17.2 – 20.6
Pacific mackerel (*Pneumatophorus japonicus*)	72.3	1.6 – 9.5	21.2
Soles (*Limanda* sp.)	80.0 – 82.7	0.1 – 1.3	17.0 – 19.2
Puffer (*Sphaeroides* sp.)	74.2	0.7	23.2

*Species chosen have been reported of commercial importance in the area indicated.

†Where possible a range of values are quoted but these do not necessarily cover the complete seasonal variations.

APPENDIX 5: GRAPHICAL REPRESENTATION OF GEOMETRIC FACTOR, R_B

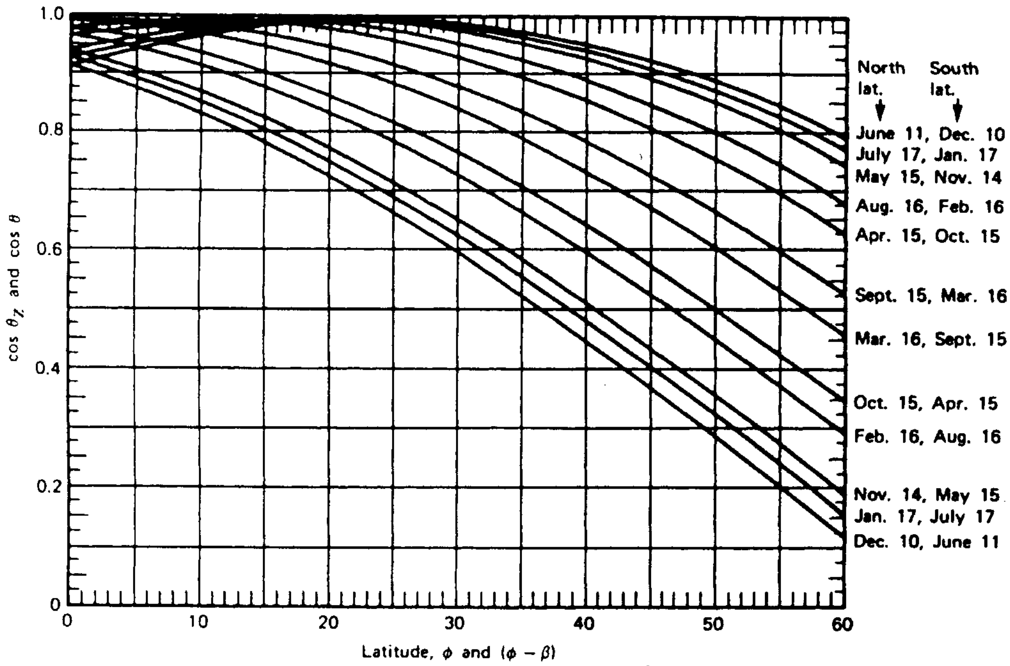

Figure A5.1 Cos θ vs. $(\phi - \beta)$ and cos θ_z vs. ϕ for hours 11 to 12 and 12 to 1 for surfaces tilted toward the equator. The columns on the right show dates for the curves for north and south latitudes. In south latitudes, use $|\phi|$. Adapted from Whillier (1975).

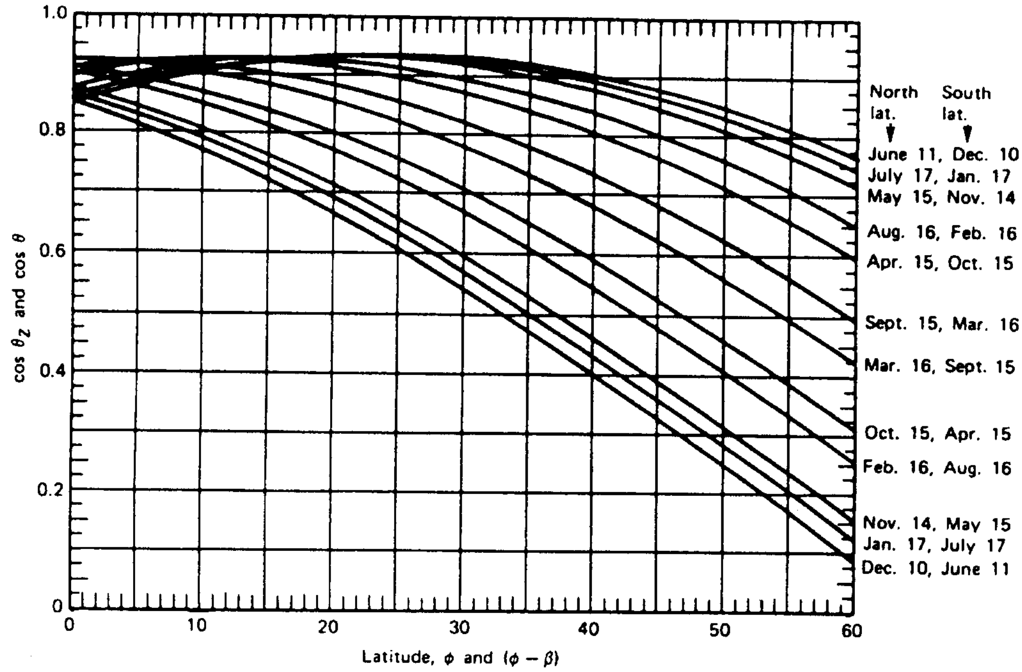

Figure A5.2 Cos θ vs. $(\phi - \beta)$ and cos θ_z vs. ϕ for hours 10 to 11 and 1 to 2.

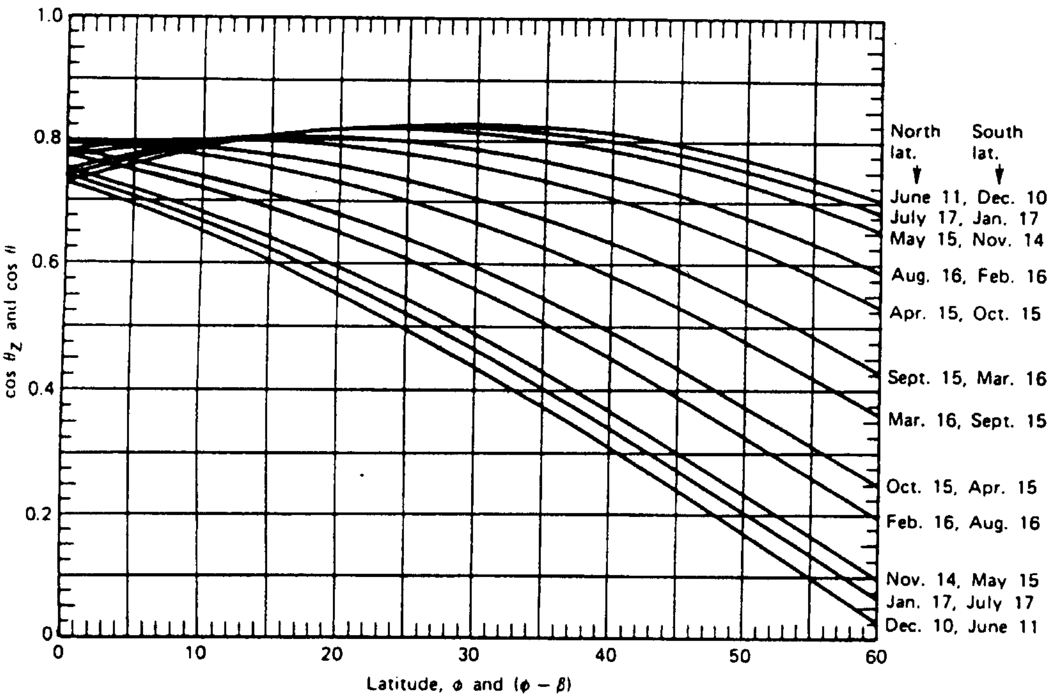

Figure A5.3 Cos θ vs. $(\phi - \beta)$ and cos θ_z vs. ϕ for hours 9 to 10 and 2 to 3.

Ratio of Beam Radiation on Tilted Surface to That on Horizontal Surface

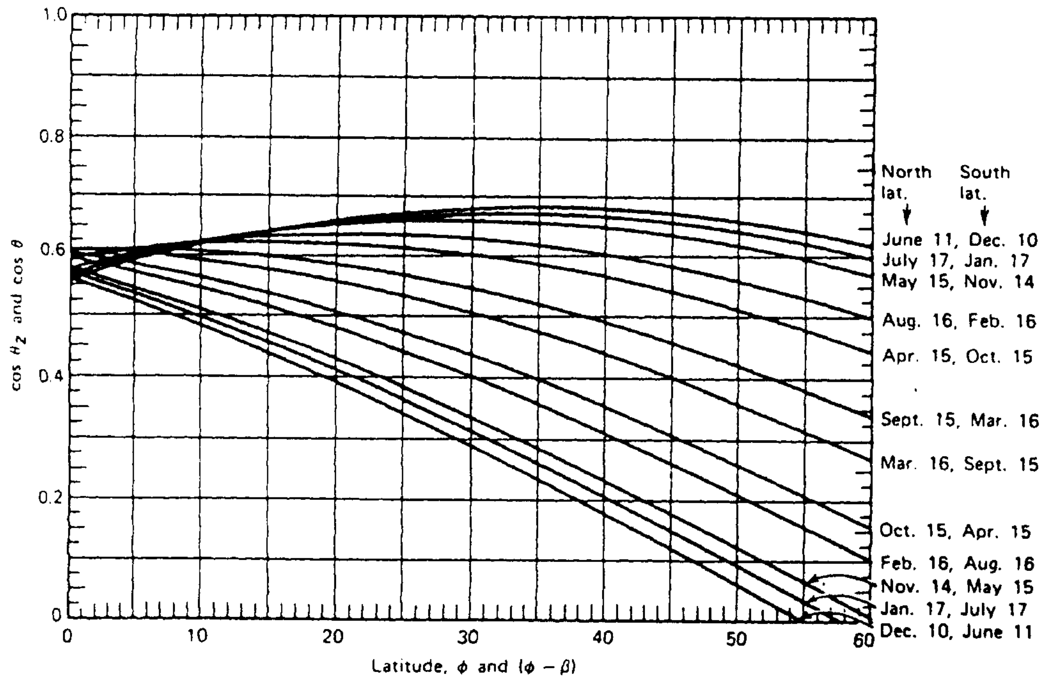

Figure A5.4 Cos θ vs. $(\phi - \beta)$ and cos θ_z vs. ϕ for hours 8 to 9 and 3 to 4.

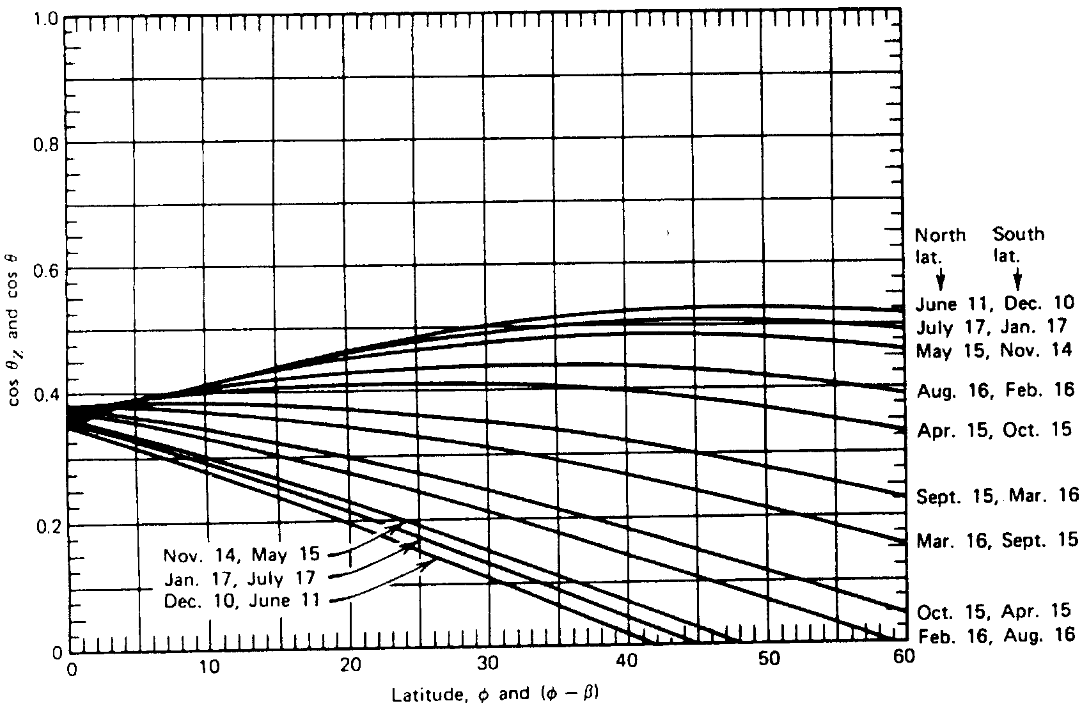

Figure A5.5 Cos θ vs. $(\phi - \beta)$ and cos θ_z vs. ϕ for hours 7 to 8 and 4 to 5.

APPENDIX 6: SISOFID USER MANUAL

1 INTRODUCTION

1.1 WHAT IS *SISOFID*

SISOFID - **Simulation of a Solar Fish Dryer**, is an engineering tool that helps one to simulate the size of a flat-plate forced-convection solar fish dryer for a given quantity of fish to be dried under certain weather conditions. It allows for analysis and post processing in one environment. The software is divided into two parts. These are *SISOFID-1*, which calculates the technical dryer parameters, and *SISOFID-2*, which carries out a cost analysis of the designed dryer.

1.2 THE STRENGTH OF *SISOFID*

1.2.1 Cost effective and time efficient

SISOFID allows an engineer to subject a computer model of a forced-convection solar-fish dryer to various climatic conditions, collector and drying bin properties, (such as airflow rate, heat transfer, and materials) and determine the resulting effect on the design. *SISOFID* enables one to quickly model, analyze, change design, check for feasibility, and re-design. The greatest advantage of using *SISOFID* is that it can reduce cost and save tremendous amount time involved in building, testing, re-designing and re-testing prototypes until optimized.

1.2.2 User friendly

SISOFID is easy to learn and use. The user can easily simulate and solve his problems by following the instructions laid out in this manual. It does not require the user to remember any commands.

1.3 THE MINIMUM SYSTEM REQUIREMENTS

The minimum requirements for running *SISOFID* are:

- An IBM compatible PC (486 or higher)
- Windows 95 or higher loaded with Office 95 or higher
- DELPHI 2 software
- Microsoft compatible series mouse
- Psychrometric chart
- Moody diagram

1.4 INSTALLATION

- Place the key (installation) disk in your floppy drive A.
- Follow the Windows 95 procedures for copying files from drive A to any destination folder on the hard drive of the PC.

Click ***Start*** button
Click ***programmes***
Click ***Windows Explorer***
Double Click ***Floppy (A:)***
Click ***Edit***
Click ***Select all***
Click ***Copy***
Double click the CREATED ***"Destination"*** folder (named SISOFID 1)
Click ***Edit***
Click ***Paste***
Do the same for Disk 2 to complete loading of SISOFID-1

The same procedure is carried out for loading SISOFID-2 into another separately created folder (named SISOFID 2).

A similar procedure is followed when copying from CD.

1.5 RUNNING *SISOFID*

SISOFID-1 can be run from Windows explorer by clicking on ***SISOFID-1*** and then double clicking on the file named "***compmodel***".

SISOFID-2 can be run from Windows explorer by clicking on ***SISOFID-2*** and then double clicking on the file named ***"Dryer costing".***

The appropriate starting screen will appear. This will require the user to type in a password. For this version, type in "sisofid" in order to start modelling with both *SISOFID-1,* or *SISOFID-2.*

1.6 SIMULATION PROCEDURE

Simulation of the solar dryer is carried out by specifying the parameters grouped as "inputs" on the form that appears. "Output" parameters are obtained by simply clicking the ***"Calculate"*** button.

A message reading "Would you like to proceed?" will appear on the form. Click the appropriate button - ***"Yes"***, if the calculation seems to be going in the right direction, or ***"No"*** if any input parameter needs to be changed.

Make any changes, if necessary, and proceed in the same manner.

1.7 SAVING THE CALCULATED DATA

In order to store the input and out put parameters for any run, simply click on the ***"save"*** button on the last form of either programme. The data is then sent to an in-built database and can be printed.

1.8 EXITING *SISOFID*

In order to exit *SISOFID*, simply click on the ***"Exit"*** button of the last screen for either programme. The then programme stops running.

2 MODELLING WITH SISOFID-1

A detailed demonstration of the modelling procedures for SISOFID-1, which determines the technical parameters of the solar dryer, is given in this part.

2.1 DETERMINATION OF EVAPORATED WATER

In order to determine the amount of water to be evaporated, type the following input parameters in the section reading ***"User Inputs"***:

1. Type of drying material
2. Initial moisture content in percentage, e.g. 85%
3. Final moisture content in percentage, e.g. 15%
4. Maximum allowable drying temperature, (Degrees Centigrade)
5. Ambient air temperature, (Degrees Centigrade)
6. Ambient air moisture content, (kg/kg)
7. Ambient relative humidity in percentage, e.g. 50%
8. Batch capacity, (kg)
9. Desired drying time, (Hours)
10. Drying season (Month(s) in which drying is to take place)
11. The ***"RUN"*** number, e.g. 1for the first run, 2 for the second, 3 for the third,....etc

Click on the ***"Calculate"*** button to obtain the amount of water to be evaporated in kg/hr.

The answer is displayed in the section reading ***"Output"***.

A message reading *" Do you wish to proceed with calculation of the airflow rate and heater power?"* appears on the screen. Click ***"Yes"*** to proceed, or ***"No"*** if there is need for changing any input parameters.

2.2 DETERMINATION OF THE AMOUNT OF AIR AND THE HEATER POWER

In order to obtain the required airflow rate and the heater power, a quick representation of the drying process is made on the psychrometric chart.

2.2.1 Representation of the Drying Process on the Psychrometric Chart

Refer to Figure 1

1. Plot *point 1* on the psychrometric chart where the vertical line representing the ambient temperature (dry bulb temperature) and the curve representing the relative humidity intersect. This is the air condition at the inlet of the solar collector.
2. *Point 2* is obtained by extending this line horizontally to the vertical line representing the outlet air temperature of the solar collector.
3. *Point 3* is obtained by drawing a line from point 2 parallel to the adiabatic cooling line up to the percentage saturation line corresponding to the equilibrium humidity or the design value of the air humidity at the bin outlet.

2.2.2 Calculation

Type in the following input parameters in the section reading ***"User inputs"*** (as before):

1. Desired collector outlet temperature, (Degrees centigrade)

The following parameters are read off from the psychrometric chart:

2. Bed outlet relative humidity in percentage, e.g. 60%
3. Bed outlet relative humidity (kg/kg)
4. Bed outlet temperature (Degrees centigrade)

Click on the ***"Calculate"*** button.

The answer for the airflow rate (kg/s) and the heater power (W) is displayed in the section reading "Outputs".

A message reading *"Do you wish to proceed with calculation of the bin size?"* appears on the screen. Click appropriately.

2.3 DETERMINATION OF THE BIN SIZE

Type in the following input parameters in the section ***"User Inputs"***.

1. Desired air velocity in the drying bin (m/s). *A recommended range is given as ($1 m/s \leq V \leq 2m/s$).*
2. Desired area fraction in decimal, e.g. 0.15. *Recommended range is any value above 15%.*
3. Length of the type of fish to be dried (m)
4. Height of the type of fish to be dried (m)
5. Thickness of the type of the fish to dried (m)
6. Average mass of a single sample of the type of fish to be dried (kg)

Click on the ***"Calculate"*** button.

The following outputs are obtained in the section reading ***"Outputs"***:

1. Length and the Width of the drying bin (m)
2. Bin height (m)
3. Tray length (m)
4. Tray width (m)
5. Tray thickness (m)
6. Number of fish along the length of the bin
7. Number of fish along the width of the bin
8. Number of fish along the height of the bin
9. Gap between the fish along the length of the bin (m)
10. Gap between the fish along the width of the bin (m)

A message reading *"Do you wish to proceed with calculation of the pressure drop through the bin"* appears. Click appropriately.

2.4 DETERMINATION OF THE PRESSURE DROP THROUGH THE BIN

The calculated bin height automatically appears on the screen. If desirable, this value may be rounded off.

Type in the following input parameters in the section reading ***"User inputs"***:

1. Bin height (m)
2. Specific air resistance of fish (m^{-1})
3. Air density (kg/m^3)
4. Air velocity through the drying bin (m/s). *This parameter has already been specified and may be left out.*
5. Blower / Motor combined efficiency in decimal, e.g. "0.4", or ". 4".

Click on the ***"Calculate"*** button.

The following output parameters are displayed in the section reading ***"outputs"***:

1. Electrical fan power required (W)
2. Pressure drop through the bin (N/m^2)

A message reading "Do you wish with the design of the solar collector?" appears on the screen. Click appropriately.

2.5 DESIGN OF THE SOLAR COLLECTOR

From the drop down on the screen, click on the month in which drying is to take place. Then type in the following input parameters:

1. Day number of the month in which drying is to take place. *A list of the average days for each month is displayed on the screen as a guide for this selection.*
2. Latitude of the place where the dryer will be situated. (North positive, South negative).
3. Average available insolation (Joules)
4. Surface azimuth angle (180° if collector is facing North, 0° if collector is facing south). *An easy and quick way of checking this is by trying both values and choosing the greater result of the average insolation.*

Click on the ***"Calculate"*** button.

The following outputs are displayed on the screen:

1. Average insolation per hour / day. (Watts)
2. Declination angle. (Degrees)
3. Slope (or inclination angle) of the solar collector. (Degrees)

A message that reads *"Do you wish to continue with the calculation of the collector efficiency?"* appears on the screen. Click Appropriately.

2.6 DETERMINATION OF THE COLLECTOR EFFICIENCY

SISOFID-1 automatically recognises the first three parameters, which have already been either specified or calculated. Similarly, the value for the average insolation is also recognised in the background. These parameters therefore need not be typed in.

The parameters to be typed in are:

1. Transmissivity – Absorptivity product of the solar collector cover *(Selected from standard tables).*
2. Heat transfer coefficient between the absorber plate and the flowing air. *SISOFID automatically interpolates and applies correction factors for airflow and recalculates the specified heat transfer coefficient only for the range investigated by Whillier, ($11.4 W/m^2K \leq h \leq 90.9\ W/m^2K$). Above and below this range, the limiting correction factors are applied. It is therefore advised to work within this range.*

Click on the ***"Calculate"*** button.

The following output parameters are displayed in the section reading "Outputs":

1. Collector efficiency in decimal
2. Corrected collector efficiency for airflow in decimal
3. Collector area (m^2)
4. Corrected collector area for airflow (m^2).

A message that reads *"Do you wish to proceed with the calculation of the collector dimensions?"* appears on the screen. Click accordingly.

2.7 DETERMINATION OF THE COLLECTOR DIMENSIONS

This is somewhat an iterative approach since it requires the specification of the collector length and width, after which the heat transfer coefficient is recalculated.

Using the noted value of the calculated corrected collector area, choose values for the collector length and width that multiply to give the obtained collector area. The calculator in *"Accessories"* of the standard *"Programmes"* menu for Windows can be used for this purpose.

Type in the following input parameters:

1. Chosen collector length (m)
2. Chosen collector width (m)
3. Chosen collector depth (m)
4. Volumetric airflow rate (m^3/s). *This value is automatically recognised by SISOFID and does not need to be specified.*
5. Friction factor of the absorber plate. *This value is chosen from the Moody diagram.*

Click on the ***"Calculate"*** button.

The following calculated parameters are displayed on the screen:

1. Air velocity in the collector (m/s). *Keep changing the specified collector length and width until this value falls within the recommended range $2.5 m/s \leq V \leq 5 m/s$.*
2. Reynolds number
3. Nusselt number
4. Actual recalculated heat transfer coefficient (W/m^2K)

5. Corrected heat transfer coefficient (W/m^2K): *Compare this value to the specified design value. If it agrees within 0.1% error, then proceed with the calculation. If not, choose another set of dimensions or another value for the friction factor. Hint: In order to increase the heat transfer coefficient, choose lower values for the collector width and depth, along with a high value for the friction factor, and the opposite for decreasing it.*

A message that reads *"Do you wish to continue by optimising the collector dimensions?"* appears on the screen. Click appropriately.

2.8 DETERMINATION OF NEW COLLECTOR LENGTH AND WIDTH

This step aims at optimising the collector perimeter in order to cut down on manufacturing cost.

The obtained collector length, width and perimeter are displayed on the screen. At this point, one may round off these values if desirable. Then type in the following input parameters:

1. Collector length (m). *(Optional)*
2. Collector width (m). *(Optional)*
3. Number of desired passes. *This causes the air to flow in a serpentine manner within the collector.*
   The number of passes = Number of times the air changes direction + 1

Click on the ***"Calculate"*** button.

The following output parameters are displayed on the screen:

1. New collector length (m)
2. New collector Width (m)
3. New collector perimeter (m)

A message that reads *"Do you wish to continue with the calculation of the pressure drop through the collector?"* appears on the screen. Click appropriately.

2.9 DETERMINATION OF THE PRESSURE DROP THROUGH THE COLLECTOR

Most of the user inputs for this purpose have already been calculated and need not be specified since *SISOFID-1* automatically recognises them.

Type in the following input parameter:

1. Combined blower / motor efficiency in decimal

Click on the ***"Calculate"*** button.

The following output parameters are displayed on the screen:

1. Total length of the air path (m)
2. Pressure drop through the collector (N/m^2)
3. Blower power (W)

A message that reads *"Do you wish to calculate the drying time"* appears on the screen. Click appropriately.

2.10 DETERMINATION OF THE DRYING TIME

All the parameters required for this purpose have been calculated and *SISOFID-1* automatically displays them on the screen. A safety factor of 20% is given to the required air flow rate. However, any value may be adjusted accordingly by re-typing it in the appropriate text box.

Click on the ***"Calculate"*** button.

The value for the final moisture content appears in the section reading ***"Output"***.

2.11 SAVING THE CALCULATED DATA

In order to save the calculated data, first of all click on the buttons labelled ***"Clear Dbase"*** and ***"Delete DB"***. This clears the in-built database in *SISOFID-1* and a message reading *"Table emptied"* appears on the screen. Click "OK".

Then click on the ***"Save"*** button. A message reading *"Posted"* appears on the screen. This means that all the data has been transferred to the database and may be printed. Click "OK".

At this stage, you have completed the design of your solar dryer!

2.12 PRINTING THE SAVED DATA

In order to print the saved data, click on the ***"Start"*** button and go to "Borland Delphi 2.0". Open the folder "Borland Delphi 2.0" (not the programme Delphi). Follow the procedure outlined below.

1. Double click on the icon ***"Report smith 3.0"***.
2. Open a new file and select ***"Column report"***. Click "OK".
3. This leads to the screen entitled ***"Report Query - Tables"***
4. Select ***"Tables"*** and click on the button ***"Add Tables"***
5. This leads to the screen entitled ***"Select table to be added"***
6. In order to view the values of moisture content levels at any time, select "SISOFID 1 and double click ***"moisture.db"***.
7. In order to view all the input and output parameters of the dryer design, OPEN the file "SISOFID 1" and click on the icon ***"Rep"***. Specify the "run number" and click OK.
8. For (6) "Report query" appears again, this time click on the button ***"Done"***.
9. For (6), all the values appear on the screen and for (7), all the input and output parameters are displayed on the screen.
10. These pages can then be printed in the usual way by selecting *"Print"* from the *"File"* menu on the tool bar.

3 MODELLING WITH SISOFID-2

A detailed procedure for the modelling procedures for *SISOFID-2*, which carries out the cost analysis of the designed dryer, is given in this part. This requires some of the outputs obtained by *SISOFID-1*. Any currency can be used for the costing during a particular run.

3.1 DRYER COSTING

In order to determine the cost of the dryer, type the following inputs in the box labelled ***"Inputs"*** on the screen:

1. Collector length (m)
2. Collector width (m)
3. Collector depth (m)
4. Bin length (m)
5. Bin width (m)

6. Bin height (m)
7. Number of trays
8. Tray width (m)
9. Tray thickness (m)
10. Standard length of the collector frame material (m)
11. Cost of the standard length
12. Standard area of the absorber plate material (m^2)
13. Cost of the standard area
14. Standard area of the back and side plate (m^2)
15. Cost of the standard area
16. Standard area of the collector insulation (m^2)
17. Cost of the standard area
18. Standard area of the collector cover (m^2)
19. Cost of the standard area
20. Standard length of the bin frame material (m)
21. Cost of the standard length
22. Standard area of the bin covering sheet (m^2)
23. Cost of the standard area
24. Standard area of the bin insulation (m^2)
25. Cost of the standard area
26. Standard length of the tray frame material (m)
27. Cost of the standard length
28. Standard area of the mesh (m^2)
29. Cost of the standard area

Click on the ***"Calculate"*** button.

The following outputs are then displayed on the screen labelled ***"Outputs"***:

1. Cost of the Collector
   - (i) Cost of the collector frame
   - (ii) Cost of the back and side plates
   - (iii) Cost of the collector insulation
   - (iv) Cost of the collector cover
2. Cost of the drying bin
   - (i) Cost of the bin frame
   - (ii) Cost of the bin covering sheet
   - (iii) Cost of the bin insulation
3. Cost of the tray
   - (i) Cost of the tray frame
   - (ii) Cost of the mesh
4. Total cost of the dryer

A message reading *"Do you wish to continue with the costing?"* appears on the screen. Click ***"Yes"*** or ***"No"*** accordingly.

3.2 CAPITAL INVESTMENT

Type in the following input parameters:

1. Total dryer cost *(Automatically displayed on the screen)*
2. Cost of the air duct
3. Cost of the blower
4. Cost of labour
5. Cost of electricity

6. Miscellaneous cost
7. Operational period (Days)
8. Total pressure drop through the system (N/m^2) *(Obtained by adding the pressure drop through the bin and the collector)*
9. Total system fan power *(Obtained by adding the fan power required for the bin and the collector)*
10. Operating time / day (Hours)
11. Interest rate in decimal, e.g. 0.55
12. Time period (Years) *(Life of the dryer)*
13. Daily evaporated moisture in decimal, e.g. 0.22 (Obtained from the print out from SISOFID-1)

Click on the ***"Calculate"*** button.

The following outputs are displayed on the screen:

1. Capital investment cost
2. Daily pumping cost
3. Salvage fund factor
4. Salvage value
5. Daily salvage value
6. Capital recovery factor
7. Daily cost
8. Daily cost / Daily evaporated moisture

At this stage, you have completed the costing of the dryer and can exit the programme.

3.3 PRINTING THE SAVED DATA

In order to print the saved data, click on the ***"Start"*** button and go to "Borland Delphi 2.0". Open the folder "Borland Delphi 2.0" (not the programme Delphi). Follow the procedure outlined below.

11. Double click on the icon ***"Report smith 3.0"***.
12. In order to view all the input and output parameters used in the cost analysis, open the file "SISOFID 2" and click on the icon ***"Rep 2"***.
13. All the input and output parameters are displayed on the screen.
14. These pages can then be printed in the usual way by selecting *"Print"* from the *"File"* menu on the tool bar.

APPENDIX 7: DELPHI CODE

SISOFID - 1

```
unit pass;

interface

uses
  Windows, Messages, SysUtils, Classes, Graphics, Controls, Forms, Dialogs,
  ExtCtrls, StdCtrls, Mask;

type
  TForm11 = class(TForm)

MaskEdit1: TMaskEdit;
    Label1: TLabel;
    Panel1: TPanel;
    Image3: TImage;
    Label2: TLabel;
    Label3: TLabel;
    Label4: TLabel;
    Label5: TLabel;
    Label6: TLabel;
    Label7: TLabel;
    Label8: TLabel;
    Label9: TLabel;
    Label10: TLabel;
    Label11: TLabel;
    Label12: TLabel;

 procedure MaskEdit1KeyPress(Sender: TObject; var Key: Char);
    procedure MaskEdit1Change(Sender: TObject);
  private
    { Private declarations }
  public
    { Public declarations }
  end;

var
  Form11: TForm11;

implementation

uses water;

{$R *.DFM}

procedure TForm11.MaskEdit1KeyPress(Sender: TObject; var Key: Char);
begin
IF KEY=#13 THEN
BEGIN
IF MASKEDIT1.TEXT='SISOFID' THEN
BEGIN
FORM1.SHOW;
FORM11.HIDE;
END
ELSE
SHOWMESSAGE('Invalid Password');

END;
end;

procedure TForm11.MaskEdit1Change(Sender: TObject);
begin

end;

end.


unit water;

interface

uses
  Windows, Messages, SysUtils, Classes, Graphics, Controls, Forms, Dialogs,
  StdCtrls, Buttons, DB, DBTables;

type
  TForm1 = class(TForm)
    GroupBox1: TGroupBox;

Label1: TLabel;
    Label2: TLabel;
    Label3: TLabel;
    Label4: TLabel;
    Label5: TLabel;
    Label6: TLabel;
    Label7: TLabel;
    Label8: TLabel;
    Label9: TLabel;
    Label10: TLabel;
    Edit10: TEdit;
    Edit9: TEdit;
    Edit8: TEdit;
    Edit7: TEdit;
    Edit6: TEdit;
    Edit5: TEdit;
    Edit4: TEdit;
    Edit3: TEdit;
    Edit2: TEdit;
    Edit1: TEdit;

 GroupBox2: TGroupBox;
```

```
Label11: TLabel;
  Edit11: TEdit;
  Button1: TButton;
  SpeedButton1: TSpeedButton;
  Table1: TTable;
  DataSource1: TDataSource;
  Table1TypdrMat: TStringField;
  Table1InitMC: TFloatField;
  Table1FinMC: TFloatField;
  Table1DrTmp: TFloatField;
  Table1AmbTmp: TFloatField;
  Table1AmbMC: TFloatField;
  Table1AmbRH: TFloatField;
  Table1BachCap: TFloatField;
  Table1DrTime: TFloatField;
  Table1Mw: TFloatField;
  Table1CoutTmp: TFloatField;
  Table1BoutRH: TFloatField;
  Table1BoutMC: TFloatField;
  Table1BoutTmp: TFloatField;
  Table1AirFlRt: TFloatField;
  Table1HtrPr: TFloatField;
  Table1BAirSpd: TFloatField;
  Table1ArFrac: TFloatField;
  Table1FL: TFloatField;
  Table1FH: TFloatField;
  Table1Fthk: TFloatField;
  Table1FAveWt: TFloatField;
  Table1BLW: TFloatField;
  Table1BH: TFloatField;
  Table1TL: TFloatField;
  Table1TW: TFloatField;
  Table1Tthk: TFloatField;
  Table1NFBL: TFloatField;
  Table1NFBW: TFloatField;
  Table1NFBH: TFloatField;
  Table1GBL: TFloatField;
  Table1GBW: TFloatField;
  Table1DMonth: TFloatField;
  Table1LatAng: TFloatField;
  Table1AveRadJ: TFloatField;
  Table1AzAng: TFloatField;
  Table1AveInsW: TFloatField;
  Table1DecAng: TFloatField;
  Table1OptAng: TFloatField;
  Table1Ih67: TFloatField;
  Table1Ih78: TFloatField;
  Table1Ih89: TFloatField;
  Table1Ih910: TFloatField;
  Table1Ih1011: TFloatField;
  Table1Ih1112: TFloatField;
  Table1Rb67: TFloatField;
  Table1Rb78: TFloatField;
  Table1Rb89: TFloatField;
  Table1Rb910: TFloatField;
  Table1Rb1011: TFloatField;
  Table1Rb1112: TFloatField;
  Table1Kt67: TFloatField;
  Table1Kt78: TFloatField;
  Table1Kt89: TFloatField;
  Table1Kt910: TFloatField;
  Table1Kt1011: TFloatField;
  Table1Kt1112: TFloatField;
  Table1Idlh67: TFloatField;
  Table1Idlh78: TFloatField;
  Table1Idlh89: TFloatField;
  Table1Idlh910: TFloatField;
  Table1Idlh1011: TFloatField;
  Table1Idlh1112: TFloatField;
  Table1Ic67: TFloatField;
  Table1Ic78: TFloatField;
  Table1Ic89: TFloatField;
  Table1Ic910: TFloatField;
  Table1Ic1011: TFloatField;
  Table1Ic1112: TFloatField;
  Table1TAProd: TFloatField;
  Table1H: TFloatField;
  Table1CEff: TFloatField;
  Table1CAr: TFloatField;
  Table1CorCAr: TFloatField;
  Table1CorCEffA: TFloatField;
  Table1Lc: TFloatField;
  Table1Wc: TFloatField;
  Table1Dc: TFloatField;
  Table1VolFlo: TFloatField;
  Table1F: TFloatField;
  Table1CAirFlo: TFloatField;
  Table1Re: TFloatField;
  Table1Nu: TFloatField;
  Table1HAct: TFloatField;
  Table1CorCEffh: TFloatField;
  Table1W: TFloatField;
  Table1AirDen: TFloatField;
  Table1BMEff: TFloatField;
  Table1Bdp: TFloatField;
  Table1BFanPr: TFloatField;
  Table1Lc1: TFloatField;
  Table1Wc1: TFloatField;
  Table1NPases: TFloatField;
  Table1PMeter: TFloatField;
  Table1NLc: TFloatField;
  Table1NWc: TFloatField;
  Table1NPMeter: TFloatField;
  Table1DHyd: TFloatField;
  Table1TAirL: TFloatField;
  Table1Cdp: TFloatField;
  Table1CFanPr: TFloatField;
  Table1BatCap: TFloatField;
  Table1MasFlo: TFloatField;
  Table1Int: TFloatField;
  Table1LstMC: TFloatField;
  Table1CAirVel: TFloatField;
  Table1CorEffh: TFloatField;
  Table1DrSeason: TStringField;
  Table1CoutTemp: TFloatField;
  Table1Run: TFloatField;
  Label12: TLabel;
  Edit12: TEdit;

procedure Button1Click(Sender: TObject);
  procedure SpeedButton1Click(Sender: TObject);
  procedure Button4Click(Sender: TObject);

 private
  { Private declarations }
 public
  { Public declarations }
 end;

var
 Form1: TForm1;

implementation

uses air, binsize, Solar, Unit10;

{$R *.DFM}

procedure TForm1.Button1Click(Sender: TObject);
var Xi,Xf,Mdot,Ms,Mw : double;
begin
{Calculation of Xi,Xf}
Xi:= strtofloat(Edit2.text)/(100 -strtofloat(Edit2.text));
Xf:= strtofloat(Edit3.text)/(100 -strtofloat(Edit3.text));
{Calculation of Drying rate}
Mdot := strtofloat(Edit8.text) /strtofloat(Edit9.text);
{Calculation of Amount of water with reference to solid}
Ms :=  Mdot / (1+Xi);
{Calculation of drying rate}
Mw := Ms*(Xi - Xf);
Edit11.text := floattostr(Mw);
if messagedlg('Do you wish to proceed with calculation of #13 air flow rate and heater power?',mtinformation,[mbyes,mbno],0)=mryes then

begin
Form10.edit1.text:=Edit8.text;
Form10.edit2.text:=Edit5.text;
Form10.edit8.text:=Edit2.text;
Form10.edit9.text:=Edit3.text;
Form2.show;
Form1.hide;
end;

end;

procedure TForm1.SpeedButton1Click(Sender: TObject);
begin
form2.show;
form1.hide
end;

procedure TForm1.Button4Click(Sender: TObject);
var
```

```
run1 : integer;
begin
{Inputs}
run1:=strtoint(inputbox('Run Number','Enter the Run Number',''));
Table1.edit;
table1.edit;
table1.findkey([run1]);

Edit1.text:=table1TypDrMat.value;
Edit2.text:=table1InitMC.asstring;
Edit3.text:=table1FinMC.asstring;
Edit4.text:=table1DrTmp.asstring;
Edit5.text:=table1AmbTmp.asstring;
Edit6.text:=table1AmbMC.asstring;
Edit7.text:=table1AmbRH.asstring;
Edit8.text:=table1BachCap.asstring;
Edit9.text:=table1DrTime.asstring;
Edit10.text:=table1drSeason.value;

{Outputs}
Edit1.text:=table1MW.asstring;
end;
end.

unit air;

interface

uses
  Windows, Messages, SysUtils, Classes, Graphics, Controls, Forms, Dialogs,
  StdCtrls, Buttons, DB, DBTables;

type
  TForm2 = class(TForm)
    Button1: TButton;
    GroupBox1: TGroupBox;

  Label4: TLabel;
    Label5: TLabel;
Label6: TLabel;
Label7: TLabel;
Edit4: TEdit;
Edit5: TEdit;
Edit6: TEdit;
Edit7: TEdit;

  GroupBox2: TGroupBox;

  Label8: TLabel;
    Label9: TLabel;
    Edit8: TEdit;
    Edit9: TEdit;
    SpeedButton1: TSpeedButton;
    SpeedButton2: TSpeedButton;
    Table1: TTable;
    DataSource1: TDataSource;
    Table1TypdrMat: TStringField;
    Table1InitMC: TFloatField;
    Table1FinMC: TFloatField;
    Table1DrTmp: TFloatField;
    Table1AmbTmp: TFloatField;
    Table1AmbMC: TFloatField;
    Table1AmbRH: TFloatField;
    Table1BachCap: TFloatField;
    Table1DrTime: TFloatField;
    Table1Mw: TFloatField;
    Table1CoutTmp: TFloatField;
    Table1BoutRH: TFloatField;
    Table1BoutMC: TFloatField;
    Table1BoutTmp: TFloatField;
    Table1AirFlRt: TFloatField;
    Table1HtrPr: TFloatField;
    Table1BAirSpd: TFloatField;
    Table1ArFrac: TFloatField;
    Table1FL: TFloatField;
    Table1FH: TFloatField;
    Table1Fthk: TFloatField;
    Table1FAveWt: TFloatField;
Table1BLW: TFloatField;
Table1BH: TFloatField;
Table1TL: TFloatField;
Table1TW: TFloatField;
Table1Tthk: TFloatField;
Table1NFBL: TFloatField;
Table1NFBW: TFloatField;
Table1NFBH: TFloatField;
Table1GBL: TFloatField;
Table1GBW: TFloatField;
Table1DMonth: TFloatField;
Table1LatAng: TFloatField;
Table1AveRadJ: TFloatField;
Table1AzAng: TFloatField;
Table1AveInsW: TFloatField;
Table1DecAng: TFloatField;
Table1OptAng: TFloatField;
Table1Ih67: TFloatField;
Table1Ih78: TFloatField;
Table1Ih89: TFloatField;
Table1Ih910: TFloatField;
Table1Ih1011: TFloatField;
Table1Ih1112: TFloatField;
Table1Rb67: TFloatField;
Table1Rb78: TFloatField;
Table1Rb89: TFloatField;
Table1Rb910: TFloatField;
Table1Rb1011: TFloatField;
Table1Rb1112: TFloatField;
Table1Kt67: TFloatField;
Table1Kt78: TFloatField;
Table1Kt89: TFloatField;
Table1Kt910: TFloatField;
Table1Kt1011: TFloatField;
Table1Kt1112: TFloatField;
Table1IdIh67: TFloatField;
Table1IdIh78: TFloatField;
Table1IdIh89: TFloatField;
Table1IdIh910: TFloatField;
Table1IdIh1011: TFloatField;
Table1IdIh1112: TFloatField;
Table1Ic67: TFloatField;
Table1Ic78: TFloatField;
Table1Ic89: TFloatField;
Table1Ic910: TFloatField;
Table1Ic1011: TFloatField;
Table1Ic1112: TFloatField;
Table1TAProd: TFloatField;
Table1H: TFloatField;
Table1CEff: TFloatField;
Table1CAr: TFloatField;
Table1CorCAr: TFloatField;
Table1CorCEffA: TFloatField;
Table1Lc: TFloatField;
Table1Wc: TFloatField;
Table1Dc: TFloatField;
Table1VolFlo: TFloatField;
Table1F: TFloatField;
Table1CAirFlo: TFloatField;
Table1Re: TFloatField;
Table1Nu: TFloatField;
Table1HAct: TFloatField;
Table1CorCEffh: TFloatField;
Table1W: TFloatField;
Table1AirDen: TFloatField;
Table1BMEff: TFloatField;
Table1Bdp: TFloatField;
Table1BFanPr: TFloatField;
Table1Lc1: TFloatField;
Table1Wc1: TFloatField;
Table1NPases: TFloatField;
Table1PMeter: TFloatField;
Table1NLc: TFloatField;
Table1NWc: TFloatField;
Table1NPMeter: TFloatField;
Table1DHyd: TFloatField;
Table1TAirL: TFloatField;
Table1Cdp: TFloatField;
Table1CFanPr: TFloatField;
Table1BatCap: TFloatField;
Table1MasFlo: TFloatField;
Table1Int: TFloatField;
Table1LstMC: TFloatField;
Table1DrSeason: TStringField;
Table1CAirVel: TFloatField;
Table1CorEffh: TFloatField;
Table1CoutTemp: TFloatField;

procedure Button1Click(Sender: TObject);
    procedure SpeedButton1Click(Sender: TObject);
    procedure SpeedButton2Click(Sender: TObject);
    procedure Button3Click(Sender: TObject);
  private
    { Private declarations }
  public
    { Public declarations }
  end;

var
  Form2: TForm2;

implementation

uses water, binsize, Unit9, Unit10,

{$R *.DFM}

procedure TForm2.Button1Click(Sender: TObject);
var hi,h2,hf,Mdot1,Q:double;
begin
{Calculation of Initial Air Enthalpy, hi}
hi:= (1.007*strtofloat(form1.Edit5.text)-0.026)+strtofloat(form1.Edit6.text)*(2501+1.84*strtofloat(form1.Edit5.text));
```

```
{Enthalpy of air at Collector Outlet, h2}
h2:= (1.007*strtofloat(Edit4.text)-0.026)+strtofloat(form1.Edit6.text)*(2501+1.84*strtofloat(Edit4.text));
{Enthalpy of Air at bed outlet}
hf:= (1.007*strtofloat(Edit7.text)-0.026)+strtofloat(Edit6.text)*(2501+1.84*strtofloat(Edit7.text));

{Air flow rate}
mdot1 := strtofloat(form1.Edit11.text)/(Strtofloat(Edit6.text)-strtofloat(form1.Edit6.text))/3600;
Edit8.text:=floattostr(mdot1);

{Heater power}
Q := (hf-hi)*(mdot1);
Edit9.text:=floattostr(Q);

if messageDLG('Do you wish to proceed to Bin Size Calculation?',MTinformation,[MByès, MBNo],0)=MRyes then
begin
Form10.edit3.text:=Edit4.text;
Form10.edit11.text:=Edit7.text;
Form9.edit3.text:=floattostr(mdot1);
Form10.edit4.text:=floattostr(mdot1*1.2);
Form3.show;
Form2.hide;
end;
end;

procedure TForm2.SpeedButton1Click(Sender: TObject);
begin
form3.show;
form2.hide;
end;

procedure TForm2.SpeedButton2Click(Sender: TObject);
begin
Form1.show;
Form2.hide;
end;

procedure TForm2.Button3Click(Sender: TObject);
begin
{Inputs}
Table1.edit;
Edit4.text:=table1CoutTmp.asstring;
Edit5.text:=table1BoutRH.asstring;
Edit6.text:=table1BoutMC.asstring;
Edit7.text:=table1BoutTmp.asstring;

{Outputs}
Edit8.text:=table1AirFlRt.asstring;
Edit9.text:=table1HtrPr.asstring;

end;

end.
```

unit binsize;

```
interface

uses
  Windows, Messages, SysUtils, Classes, Graphics, Controls, Forms, Dialogs,
  StdCtrls, Buttons, DB, DBTables;

type
  Tform3 = class(TForm)
    Button1: TButton;
    SpeedButton1: TSpeedButton;
    SpeedButton2: TSpeedButton;

Label16: TLabel;
    Button3: TButton;
    DataSource1: TDataSource;
    Table1: TTable;
    Table1TypdrMat: TStringField;
    Table1InitMC: TFloatField;
    Table1FinMC: TFloatField;
    Table1DrTmp: TFloatField;
    Table1AmbTmp: TFloatField;
    Table1AmbMC: TFloatField;
    Table1AmbRH: TFloatField;
    Table1BachCap: TFloatField;
    Table1DrTime: TFloatField;
    Table1Mw: TFloatField;
    Table1CoutTmp: TFloatField;
    Table1BoutRH: TFloatField;
    Table1BoutMC: TFloatField;
    Table1BoutTmp: TFloatField;
Table1AirFlRt: TFloatField;
Table1HtrPr: TFloatField;
Table1BAirSpd: TFloatField;
Table1ArFrac: TFloatField;
Table1FL: TFloatField;
Table1FH: TFloatField;
Table1Fthk: TFloatField;
Table1FAveWt: TFloatField;
Table1BLW: TFloatField;
Table1BH: TFloatField;
Table1TL: TFloatField;
Table1TW: TFloatField;
Table1Tthk: TFloatField;
Table1NFBL: TFloatField;
Table1NFBW: TFloatField;
Table1NFBH: TFloatField;
Table1GBL: TFloatField;
Table1GBW: TFloatField;
Table1DMonth: TFloatField;
Table1LatAng: TFloatField;
Table1AveRadJ: TFloatField;
Table1AzAng: TFloatField;
Table1AveInsW: TFloatField;
Table1DecAng: TFloatField;
Table1OptAng: TFloatField;
Table1Ih67: TFloatField;
Table1Ih78: TFloatField;
Table1Ih89: TFloatField;
Table1Ih910: TFloatField;
Table1Ih1011: TFloatField;
Table1Ih1112: TFloatField;
Table1Rb67: TFloatField;
Table1Rb78: TFloatField;
Table1Rb89: TFloatField;
Table1Rb910: TFloatField;
Table1Rb1011: TFloatField;
Table1Rb1112: TFloatField;
Table1Kt67: TFloatField;
Table1Kt78: TFloatField;
Table1Kt89: TFloatField;
Table1Kt910: TFloatField;
Table1Kt1011: TFloatField;
Table1Kt1112: TFloatField;
Table1IdIh67: TFloatField;
Table1IdIh78: TFloatField;
Table1IdIh89: TFloatField;
Table1IdIh910: TFloatField;
Table1IdIh1011: TFloatField;
Table1IdIh1112: TFloatField;
Table1Ic67: TFloatField;
Table1Ic78: TFloatField;
Table1Ic89: TFloatField;
Table1Ic910: TFloatField;
Table1Ic1011: TFloatField;
```

```
Table1lc1112: TFloatField;
Table1TAProd: TFloatField;
Table1H: TFloatField;
Table1CEff: TFloatField;
Table1CAr: TFloatField;
Table1CorCAr: TFloatField;
Table1CorCEffA: TFloatField;
Table1Lc: TFloatField;
Table1Wc: TFloatField;
Table1Dc: TFloatField;
Table1VolFlo: TFloatField;
Table1F: TFloatField;
Table1CAirFlo: TFloatField;
Table1Re: TFloatField;
Table1Nu: TFloatField;
Table1HAct: TFloatField;
Table1CorCEffh: TFloatField;
Table1W: TFloatField;
Table1AirDen: TFloatField;
Table1BMEff: TFloatField;
Table1Bdp: TFloatField;
Table1BFanPr: TFloatField;
Table1Lc1: TFloatField;
Table1Wc1: TFloatField;
Table1NPases: TFloatField;
Table1PMeter: TFloatField;
Table1NLc: TFloatField;
Table1NWc: TFloatField;
Table1NPMeter: TFloatField;
Table1DHyd: TFloatField;
Table1TAirL: TFloatField;
Table1Cdp: TFloatField;
Table1CFanPr: TFloatField;
Table1BatCap: TFloatField;
Table1MasFlo: TFloatField;
Table1Int: TFloatField;
Table1LstMC: TFloatField;
Table1DrSeason: TStringField;
Table1CAirVel: TFloatField;
Table1CorEffh: TFloatField;
Table1CoutTemp: TFloatField
;

GroupBox1: TGroupBox;

Label2: TLabel;
  Label3: TLabel;
  Label4: TLabel;
  Label5: TLabel;
  Label6: TLabel;
  Label7: TLabel;
  Label13: TLabel;
  Edit4: TEdit;
  Edit7: TEdit;
Edit6: TEdit;
Edit5: TEdit;
Edit3: TEdit;
Edit2: TEdit;
Outputs: TGroupBox;
Label8: TLabel;
Label9: TLabel;
Label10: TLabel;
Label11: TLabel;
Label12: TLabel;
Label1: TLabel;
Label14: TLabel;
Label15: TLabel;
Edit14: TEdit;
Edit13: TEdit;
Edit1: TEdit;
Edit12: TEdit;
Edit11: TEdit;
Edit10: TEdit;
Edit9: TEdit;
Edit8: TEdit;
Edit15: TEdit;
Edit16: TEdit;
Label18: TLabel;
Label17: TLabel;

procedure Button1Click(Sender: TObject);
  procedure SpeedButton1Click(Sender: TObject);
  procedure SpeedButton2Click(Sender: TObject);
  procedure Button3Click(Sender: TObject);
 private
  { Private declarations }
 public
  { Public declarations }
 end;

var
 form3: Tform3;

implementation

uses air, water, Solar, pressuredrop;

{$R *.DFM}

procedure Tform3.Button1Click(Sender: TObject);
var Av,Av1,AT,Am,LT,WT,Lm,Wm,NA,NL,NW,Lv,Wv,FL,GL,GW,Tth,TL,TW,NT,LW,TN,Nc,Wfc,Tv,H:double;
begin
{Required Void Area}
showmessage('Airflow rate:='+form2.edit8.text);
Av1:= (strtofloat(form2.Edit8.text)/(1.2));
showmessage('Av1:='+floattostr(Av1));
Av:=Av1/strtofloat(Edit2.text);
{Required total area}
AT:= Av/strtofloat(Edit3.text);
{Required material Area}
Am:= (AT-Av);
{Bin Length = Bin Width}
LT:=sqrt(AT);
WT:=AT/LT;
{Answer for Bin length & Width}
Edit8.text:=floattostr(LT);
{Material Length = Material Width}
Lm:= sqrt(Am);
Wm:= Am/Lm;
{Number of fish per unit area}
NA:= Am/strtofloat(Edit6.text)*strtofloat(Edit7.text); {Fish height*Fish thickness=Area of one fish}
{Number of fish per length}
NL:= Lm/strtofloat(Edit6.text); {Edit6.text = Fish height}
{Answer}
Edit1.text:=floattostr(NL);
{Number of fish across Width}
NW:= Wm/strtofloat(Edit7.text); {Edit7.text = Fish thickness}
{Answer}
Edit13.text:=floattostr(NW);
{Available void length}
Lv:=(LT-Lm);
{Available void width}
Wv:= (WT-Wm);
{Gap between fish along the length}
GL:= Lv/(NL+1);
{Answer}
Edit15.text:=floattostr(GL);
```

```
{Gap between fish along the width}
GW:= Wv/(NW+1);

{Answer}
Edit16.text:=floattostr(GW);
{Tray thickness}
Tth:= GW + strtofloat(Edit7.text); {Edit7.text = fish thickness}
{Answer for tray thickness}
Edit12.text:=floattostr(Tth);
{Tray length}
TL:=LT;
{Answer for tray length}
Edit10.text:=floattostr(TL);
{Tray width}
TW:=strtofloat(Edit5.text);
{Answer for tray width}
Edit11.text:=floattostr(TW);
{Number of fish per tray}
NT:= NL;
{Number of trays}
TN:= NW;
{Number of fish per cross section of bin}
Nc:= NL*NW;
{Weight of fish per cross section}
Wfc:= strtofloat(Edit4.text)*Nc; {WF = Average weight of each fish}
{Number of trays placed vertically}
Tv:= strtofloat(form1.Edit8.text)/Wfc; {Edit13.text = Batch capacity}
{Answer}
Edit14.text:=floattostr(Tv);
{Bin height}
H:= Tv*Tw;
{Answer for Bin height}
Edit9.text:= floattostr(H);

if messageDLG('Do you wish to proceed with Calculation of the pressure drop through thè bin?',MTinformation,[MByes, MBNo],0)=MRyes then
begin
form7.Edit1.text:= floattostr(H);
Form7.show;
Form3.hide;
end;
end;

procedure Tform3.SpeedButton1Click(Sender: TObject);
begin
form7.show;
form3.hide;
end;

procedure Tform3.SpeedButton2Click(Sender: TObject);
begin
Form2.show;
Form3.hide;
end;

procedure Tform3.Button3Click(Sender: TObject);
begin

{Inputs}
Table1.edit;
Edit2.text:=table1BAirSpd.asstring;
Edit3.text:=table1ArFrac.asstring;
Edit5.text:=table1FL.asstring;
Edit6.text:=table1FH.asstring;
Edit7.text:=table1Fthk.asstring;
Edit4.text:=table1FAveWt.asstring;
{Outputs}
Edit8.text:=table1BLW.asstring;
Edit9.text:=table1BH.asstring;
Edit10.text:=table1TL.asstring;
Edit11.text:=table1TW.asstring;
Edit12.text:=table1Tthk.asstring;
Edit1.text:=table1NFBL.asstring;
Edit13.text:=table1NFBW.asstring;
Edit14.text:=table1NFBH.asstring;
Edit15.text:=table1GBL.asstring;
Edit16.text:=table1GBW.asstring;


end;

end.
```

unit pressuredrop;

```
interface

uses
  Windows, Messages, SysUtils, Classes, Graphics, Controls, Forms, Dialogs,
  StdCtrls, Buttons, DB, DBTables;
```

```
type
 TForm7 = class(TForm)
  Label5: TLabel;
  Button1: TButton;
  SpeedButton2: TSpeedButton;
  SpeedButton1: TSpeedButton;
  DataSource1: TDataSource;

 Table1: TTable;
  Table1TypdrMat: TStringField;
  Table1InitMC: TFloatField;
  Table1FinMC: TFloatField;
  Table1DrTmp: TFloatField;
  Table1AmbTmp: TFloatField;
  Table1AmbMC: TFloatField;
  Table1AmbRH: TFloatField;
  Table1BachCap: TFloatField;
  Table1DrTime: TFloatField;
  Table1Mw: TFloatField;
  Table1CoutTmp: TFloatField;
  Table1BoutRH: TFloatField;
  Table1BoutMC: TFloatField;
  Table1BoutTmp: TFloatField;
  Table1AirFlRt: TFloatField;
  Table1HtrPr: TFloatField;
  Table1BAirSpd: TFloatField;
  Table1ArFrac: TFloatField;
  Table1FL: TFloatField;
  Table1FH: TFloatField;
  Table1Fthk: TFloatField;
  Table1FAveWt: TFloatField;
  Table1BLW: TFloatField;
  Table1BH: TFloatField;
  Table1TL: TFloatField;
  Table1TW: TFloatField;
  Table1Tthk: TFloatField;
  Table1NFBL: TFloatField;
  Table1NFBW: TFloatField;
  Table1NFBH: TFloatField;
  Table1GBL: TFloatField;
  Table1GBW: TFloatField;
  Table1DMonth: TFloatField;
  Table1LatAng: TFloatField;
  Table1AveRadJ: TFloatField;
  Table1AzAng: TFloatField;
  Table1AveInsW: TFloatField;
  Table1DecAng: TFloatField;
  Table1OptAng: TFloatField;
  Table1Ih67: TFloatField;
  Table1Ih78: TFloatField;
  Table1Ih89: TFloatField;
  Table1Ih910: TFloatField;
  Table1Ih1011: TFloatField;
  Table1Ih1112: TFloatField;
  Table1Rb67: TFloatField;
  Table1Rb78: TFloatField;
  Table1Rb89: TFloatField;
  Table1Rb910: TFloatField;
  Table1Rb1011: TFloatField;
  Table1Rb1112: TFloatField;
  Table1Kt67: TFloatField;
  Table1Kt78: TFloatField;
  Table1Kt89: TFloatField;
  Table1Kt910: TFloatField;
  Table1Kt1011: TFloatField;
  Table1Kt1112: TFloatField;
  Table1Idlh67: TFloatField;
  Table1Idlh78: TFloatField;
  Table1Idlh89: TFloatField;
  Table1Idlh910: TFloatField;
  Table1Idlh1011: TFloatField;
  Table1Idlh1112: TFloatField;
  Table1Ic67: TFloatField;
  Table1Ic78: TFloatField;
  Table1Ic89: TFloatField;
  Table1Ic910: TFloatField;
  Table1Ic1011: TFloatField;
  Table1Ic1112: TFloatField;
  Table1TAProd: TFloatField;
  Table1H: TFloatField;
  Table1CEff: TFloatField;
  Table1CAr: TFloatField;
  Table1CorCAr: TFloatField;
  Table1CorCEffA: TFloatField;
  Table1Lc: TFloatField;
  Table1Wc: TFloatField;
  Table1Dc: TFloatField;
  Table1VolFlo: TFloatField;
  Table1F: TFloatField;
  Table1CAirFlo: TFloatField;
  Table1Re: TFloatField;
  Table1Nu: TFloatField;
  Table1HAct: TFloatField;
  Table1CorCEffh: TFloatField;
  Table1W: TFloatField;
  Table1AirDen: TFloatField;
  Table1BMEff: TFloatField;
  Table1Bdp: TFloatField;
  Table1BFanPr: TFloatField;
  Table1Lc1: TFloatField;
  Table1Wc1: TFloatField;
  Table1NPases: TFloatField;
  Table1PMeter: TFloatField;
  Table1NLc: TFloatField;
  Table1NWc: TFloatField;
  Table1NPMeter: TFloatField;
  Table1DHyd: TFloatField;
  Table1TAirL: TFloatField;
  Table1Cdp: TFloatField;
  Table1CFanPr: TFloatField;
  Table1BatCap: TFloatField;
  Table1MasFlo: TFloatField;
  Table1Int: TFloatField;
  Table1LstMC: TFloatField;
  Table1DrSeason: TStringField;
  Table1CAirVel: TFloatField;
  Table1CorEffh: TFloatField;
  Table1CoutTemp: TFloatField;

GroupBox1: TGroupBox;

Label1: TLabel;
  Label2: TLabel;
  Label3: TLabel;
  Edit5: TEdit;
  Label4: TLabel;
  Label6: TLabel;
  Edit6: TEdit;
  Edit4: TEdit;
  Edit3: TEdit;
  Edit2: TEdit;
  Edit1: TEdit;
  GroupBox2: TGroupBox;
  Label7: TLabel;
  Label8: TLabel;
  Edit8: TEdit;
  Edit7: TEdit;

 procedure Button1Click(Sender: TObject);

  procedure SpeedButton2Click(Sender: TObject);
  procedure SpeedButton1Click(Sender: TObject);
  procedure Button3Click(Sender: TObject);
 private
  { Private declarations }
 public
  { Public declarations }
 end;

var
 Form7: TForm7;

implementation

uses binsize, air, Solar;

{$R *.DFM}

procedure TForm7.Button1Click(Sender: TObject);
var DeltaPB,PB:Double;
begin
{1.Pressure drop through the bin}
DeltaPB:= strtofloat(Edit1.text)*strtofloat(Edit2.text)*strtofloat(Edit3.text)*sqr(strtofloat(Form3.Edit2.text));
{Display answer}
Edit7.text:= floattostr(DeltaPB);
{2.Electrical Power consumption}
PB:= strtofloat(Form2.Edit8.text)*DeltaPB/1.2/strtofloat(Edit6.text);
{Display answer}
Edit8.text:=floattostr(PB);

if messageDLG('Do you wish to proceed with the design of the solar collector?',MTinformation,[MByes, MBNo],0)=MRyes then
begin
Form4.show;
Form7.hide;
end;

begin
form7.hide;
form4.show;
```

```
end;
end;

procedure TForm7.SpeedButton2Click(Sender: TObject);
begin
form3.show;
Form7.hide;
end;
procedure TForm7.SpeedButton1Click(Sender: TObject);
begin
Form4.show;
Form7.hide;
end;

procedure TForm7.Button3Click(Sender: TObject);
begin
{Inputs}
Table1.edit;
Edit1.text:=table1BH.asstring;
Edit2.text:=table1w.asstring;
Edit3.text:=table1AirDen.asstring;
Edit4.text:=table1BAirSpd.asstring;
Edit6.text:=table1BMEff.asstring;
{Outputs}
Edit7.text:=table1Bdp.asstring;
Edit8.text:=table1BFanPr.asstring;

end;

end.
```

unit Solar;

```
interface

uses
  Windows, Messages, SysUtils, Classes, Graphics, Controls, Forms, Dialogs,
  StdCtrls, Buttons, DB, DBTables;

type
  TForm4 = class(TForm)
    GroupBox1: TGroupBox;
    ComboBox1: TComboBox;
    Label1: TLabel;
    Edit1: TEdit;
    Edit2: TEdit;
    Edit3: TEdit;
    Label2: TLabel;
    Label3: TLabel;
    Label4: TLabel;
    GroupBox2: TGroupBox;
    Label5: TLabel;
    Label6: TLabel;
    Label7: TLabel;
    Label8: TLabel;
    Label9: TLabel;
    Label10: TLabel;
    Label11: TLabel;
    Label12: TLabel;
    Label13: TLabel;
    Label14: TLabel;
    Label15: TLabel;
    Label16: TLabel;
    Button1: TButton;
    Label17: TLabel;
    Edit4: TEdit;
    SpeedButton1: TSpeedButton;
    SpeedButton2: TSpeedButton;
    Edit8: TEdit;
    Edit9: TEdit;
    Label21: TLabel;
    Label22: TLabel;
    Label23: TLabel;
    Label24: TLabel;
    Label25: TLabel;
    Label26: TLabel;
    Label27: TLabel;
    Label28: TLabel;
    Label29: TLabel;
    Label30: TLabel;
    Label31: TLabel;
    Label32: TLabel;
    Label33: TLabel;
    Label34: TLabel;
    Label35: TLabel;
    Label36: TLabel;
    Label37: TLabel;
    Label38: TLabel;
    Label39: TLabel;
    Label40: TLabel;
    Label41: TLabel;
    Label42: TLabel;
    Label43: TLabel;
    Label44: TLabel;
    Edit10: TEdit;
    Edit11: TEdit;
    Edit12: TEdit;
    Edit13: TEdit;
    Edit14: TEdit;
    Edit15: TEdit;
    Edit16: TEdit;
    Edit17: TEdit;
    Edit18: TEdit;
    Edit19: TEdit;
    Edit20: TEdit;
    Edit21: TEdit;
    Edit22: TEdit;
    Edit23: TEdit;
    Edit24: TEdit;
    Edit25: TEdit;
    Edit26: TEdit;
    Edit27: TEdit;
    Edit28: TEdit;
    Edit29: TEdit;
    Edit30: TEdit;
    Edit31: TEdit;
    Edit32: TEdit;
    Edit33: TEdit;
    Label45: TLabel;
    Label46: TLabel;
    Label47: TLabel;
    Label48: TLabel;
    Label49: TLabel;
    Label50: TLabel;
    Edit34: TEdit;
    Edit35: TEdit;
    Edit36: TEdit;
    Edit37: TEdit;
    Edit38: TEdit;
    Edit39: TEdit;

 Button3: TButton;

DataSource1: TDataSource;
    Table1: TTable;
    Table1TypdrMat: TStringField;
    Table1InitMC: TFloatField;
    Table1FinMC: TFloatField;
    Table1DrTmp: TFloatField;
    Table1AmbTmp: TFloatField;
    Table1AmbMC: TFloatField;
    Table1AmbRH: TFloatField;
    Table1BachCap: TFloatField;
    Table1DrTime: TFloatField;
    Table1Mw: TFloatField;
    Table1CoutTmp: TFloatField;
    Table1BoutRH: TFloatField;
    Table1BoutMC: TFloatField;
    Table1BoutTmp: TFloatField;
    Table1AirFlRt: TFloatField;
    Table1HtrPr: TFloatField;
    Table1BAirSpd: TFloatField;
    Table1ArFrac: TFloatField;
    Table1FL: TFloatField;
    Table1FH: TFloatField;
    Table1Fthk: TFloatField;
Table1FAveWt: TFloatField;
Table1BLW: TFloatField;
Table1BH: TFloatField;
Table1TL: TFloatField;
Table1TW: TFloatField;
Table1Tthk: TFloatField;
Table1NFBL: TFloatField;
Table1NFBW: TFloatField;
Table1NFBH: TFloatField;
Table1GBL: TFloatField;
Table1GBW: TFloatField;
Table1DMonth: TFloatField;
Table1LatAng: TFloatField;
Table1AveRadJ: TFloatField;
Table1AzAng: TFloatField;
Table1AveInsW: TFloatField;
Table1DecAng: TFloatField;
Table1OptAng: TFloatField;
Table1Ih67: TFloatField;
Table1Ih78: TFloatField;
Table1Ih89: TFloatField;
Table1Ih910: TFloatField;
Table1Ih1011: TFloatField;
Table1Ih1112: TFloatField;
Table1Rb67: TFloatField;
Table1Rb78: TFloatField;
Table1Rb89: TFloatField;
Table1Rb910: TFloatField;
Table1Rb1011: TFloatField;
Table1Rb1112: TFloatField;
Table1Kt67: TFloatField;
Table1Kt78: TFloatField;
Table1Kt89: TFloatField;
Table1Kt910: TFloatField;
Table1Kt1011: TFloatField;
Table1Kt1112: TFloatField;
Table1IdIh67: TFloatField;
Table1IdIh78: TFloatField;
Table1IdIh89: TFloatField;
Table1IdIh910: TFloatField;
Table1IdIh1011: TFloatField;
Table1IdIh1112: TFloatField;
Table1Ic67: TFloatField;
Table1Ic78: TFloatField;
Table1Ic89: TFloatField;
Table1Ic910: TFloatField;
Table1Ic1011: TFloatField;
Table1Ic1112: TFloatField;
Table1TAProd: TFloatField;
Table1H: TFloatField;
Table1CEff: TFloatField;
Table1CAr: TFloatField;
Table1CorCAr: TFloatField;
Table1CorCEffA: TFloatField;
Table1Lc: TFloatField;
Table1Wc: TFloatField;
Table1Dc: TFloatField;
Table1VolFlo: TFloatField;
Table1F: TFloatField;
Table1CAirFlo: TFloatField;
Table1Re: TFloatField;
Table1Nu: TFloatField;
Table1HAct: TFloatField;
Table1CorCEffh: TFloatField;
Table1W: TFloatField;
Table1AirDen: TFloatField;
Table1BMEff: TFloatField;
Table1Bdp: TFloatField;
Table1BFanPr: TFloatField;
```

```
Table1Lc1: TFloatField;          Table1NWc: TFloatField;          Table1CFanPr: TFloatField;     Table1DrSeason: TStringField;
Table1Wc1: TFloatField;          Table1NPMeter: TFloatField;      Table1BatCap: TFloatField;     Table1CAirVel: TFloatField;
Table1NPases: TFloatField;       Table1DHyd: TFloatField;         Table1MasFlo: TFloatField;     Table1CorEffh: TFloatField;
Table1PMeter: TFloatField;       Table1TAirL: TFloatField;        Table1Int: TFloatField;        Table1CoutTemp: TFloatField;
Table1NLc: TFloatField;          Table1Cdp: TFloatField;          Table1LstMC: TFloatField;

GroupBox3: TGroupBox;

Label18: TLabel;                 Label20: TLabel;                 Edit6: TEdit;
Label19: TLabel;                 Edit7: TEdit;                    Edit5: TEdit;

procedure TForm4.Button1Click(Sender: TObject);

Var
n,Delta,Beta,Phi,Gama,CosThetah67,sum,CosThetah78,CosThetah89,CosThetah910,CosThetah1011,CosThetah1112,CosThetah1213,CosThetah1314, CosThetah1415,CosThetah1516,CosThetah1617,CosThetah1718,
Ih67,Ih78,Ih89,Ih910,Ih1011,Ih1112,Ih1213,Ih1314,Ih1415,Ih1516,Ih1617,Ih1718,
CosTheta67,CosTheta78,CosTheta89,CosTheta910,CosTheta1011,CosTheta1112,CosTheta1213,CosTheta1314,CosTheta1415,CosTheta1516,CosTheta1617,CosTheta1718,
Io67,Io78,Io89,Io910,Io1011,Io1112,Io1213,Io1314,Io1415,Io1516,Io1617,Io1718,
Kt67,Kt78,Kt89,Kt910,Kt1011,Kt1112,Kt1213,Kt1314,Kt1415,Kt1516,Kt1617,Kt1718,
i67,i78,i89,i910,i1011,i1112,i1213,i1314,i1415,i1516,i1617,i1718,
Rb67,Rb78,Rb89,Rb910,Rb1011,Rb1112,Rb1213,Rb1314,Rb1415,Rb1516,Rb1617,Rb1718,
Ic67,Ic78,Ic89,Ic910,Ic1011,Ic1112,Ic1213,Ic1314,Ic1415,Ic1516,Ic1617,Ic1718,Icave:double;

begin

if combobox1.text='January' then
n:=strtofloat(Edit1.text)
else if combobox1.text='February' then
n:=strtofloat(Edit1.text)+31
else if combobox1.text='March' then
n:=strtofloat(Edit1.text)+59
else if combobox1.text='April' then
n:=strtofloat(Edit1.text)+90
else if combobox1.text='May' then
n:=strtofloat(Edit1.text)+120
else if combobox1.text='June' then
n:=strtofloat(Edit1.text)+151
else if combobox1.text='July' then
n:=strtofloat(Edit1.text)+181
else if combobox1.text='August' then
n:=strtofloat(Edit1.text)+212
else if combobox1.text='September' then
n:=strtofloat(Edit1.text)+243
else if combobox1.text='October' then
n:=strtofloat(Edit1.text)+273
else if combobox1.text='November' then
n:=strtofloat(Edit1.text)+304
else if combobox1.text='December' then
n:=strtofloat(Edit1.text)+334;

{1.Declination Angle}
Delta:= 23.45*Sin(0.9863*(284+n)*(pi/180));
edit6.text:=floattostr(delta);

{2.Optimum Slope angle}
Beta:=  abs(strtofloat(Edit2.text)-(Delta));
edit7.text:=floattostr(beta);

{3.Angle of incidence on a Horizontal surface}
CosThetah67:=Sin(Delta*(pi/180))*Sin(strtofloat(Edit2.text)*(pi/180))+Cos(Delta*(pi/180))
*Cos(strtofloat(Edit2.text)*(pi/180))*Cos(-82.5*(pi/180));
CosThetah78:=Sin(Delta*(pi/180))*Sin(strtofloat(Edit2.text)*(pi/180))+Cos(Delta*(pi/180))
*Cos(strtofloat(Edit2.text)*(pi/180))*Cos(-67.5*(pi/180));
CosThetah89:=Sin(Delta*(pi/180))*Sin(strtofloat(Edit2.text)*(pi/180))+Cos(Delta*(pi/180))
*Cos(strtofloat(Edit2.text)*(pi/180))*Cos(-52.5*(pi/180));
CosThetah910:=Sin(Delta*(pi/180))*Sin(strtofloat(Edit2.text)*(pi/180))+Cos(Delta*(pi/180))
*Cos(strtofloat(Edit2.text)*(pi/180))*Cos(-37.5*(pi/180));
CosThetah1011:=Sin(Delta*(pi/180))*Sin(strtofloat(Edit2.text)*(pi/180))+Cos(Delta*(pi/180))
*Cos(strtofloat(Edit2.text)*(pi/180))*Cos(-22.5*(pi/180));
CosThetah1112:=Sin(Delta*(pi/180))*Sin(strtofloat(Edit2.text)*(pi/180))+Cos(Delta*(pi/180))
*Cos(strtofloat(Edit2.text)*(pi/180))*Cos(-7.5*(pi/180));

CosThetah1213:= CosThetah1112;
```

```
CosThetah1314:= CosThetah1011;
CosThetah1415:= CosThetah910;
CosThetah1516:= CosThetah89;
CosThetah1617:= CosThetah78;
CosThetah1718:= CosThetah67;

{4.Insolation on Horizontal Surface}
Ih67:=(strtofloat(Edit3.text)*CosThetah67)/(CosThetah67+CosThetah78+CosThetah89+CosThetah910+CosThetah1011+CosThetah1112+CosThetah
1213+CosThetah1314+CosThetah1415+CosThetah1516+CosThetah1617
+CosThetah1718);
Edit10.text:=floattostr(Ih67);
Ih78:=(strtofloat(Edit3.text)*CosThetah78)/(CosThetah67+CosThetah78+CosThetah89+CosThetah910+CosThetah1011+CosThetah1112+CosThetah
1213+CosThetah1314+CosThetah1415+CosThetah1516+CosThetah1617
+CosThetah1718);
Edit11.text:=floattostr(Ih78);
Ih89:=(strtofloat(Edit3.text)*CosThetah89)/(CosThetah67+CosThetah78+CosThetah89+CosThetah910+CosThetah1011+CosThetah1112+CosThetah
1213+CosThetah1314+CosThetah1415+CosThetah1516+CosThetah1617
+CosThetah1718);
Edit12.text:=floattostr(Ih89);
Ih910:=(strtofloat(Edit3.text)*CosThetah910)/(CosThetah67+CosThetah78+CosThetah89+CosThetah910+CosThetah1011+CosThetah1112+CosThe
tah1213+CosThetah1314+CosThetah1415+CosThetah1516+CosThetah1617
+CosThetah1718);
Edit13.text:=floattostr(Ih910);
Ih1011:=(strtofloat(Edit3.text)*CosThetah1011)/(CosThetah67+CosThetah78+CosThetah89+CosThetah910+CosThetah1011+CosThetah1112+CosT
hetah1213+CosThetah1314+CosThetah1415+CosThetah1516+CosThetah1617
+CosThetah1718);
Edit14.text:=floattostr(Ih1011);
Ih1112:=(strtofloat(Edit3.text)*CosThetah1112)/(CosThetah67+CosThetah78+CosThetah89+CosThetah910+CosThetah1011+CosThetah1112+CosT
hetah1213+CosThetah1314+CosThetah1415+CosThetah1516+CosThetah1617
+CosThetah1718);
Edit15.text:=floattostr(Ih1112);

Ih1213:= Ih1112;
Ih1314:= Ih1011;
Ih1415:= Ih910;
Ih1516:= Ih89;
Ih1617:= Ih78;
Ih1718:= Ih67;

{5.Hourly Extraterrestrial Radiation}
Io67:=18797599.3427*(1+(0.033*Cos(0.98630136986*n*(pi/180))))
   *((cos(strtofloat(edit2.text)*(pi/180))*Cos(delta*(pi/180)))*(sin(-75*(pi/180))-sin(-90*(pi/180)))
   +(0.26179938779*sin(strtofloat(Edit2.text)*(pi/180))*sin(delta*(pi/180))));
Io78:=18797599.3427*(1+(0.033*Cos(0.98630136986*n*(pi/180))))
   *((cos(strtofloat(edit2.text)*(pi/180))*Cos(delta*(pi/180)))*(sin(-60*(pi/180))-sin(-75*(pi/180)))
   +(0.26179938779*sin(strtofloat(Edit2.text)*(pi/180))*sin(delta*(pi/180))));
Io89:=18797599.3427*(1+(0.033*Cos(0.98630136986*n*(pi/180))))
   *((cos(strtofloat(edit2.text)*(pi/180))*Cos(delta*(pi/180)))*(sin(-45*(pi/180))-sin(-60*(pi/180)))
   +(0.26179938779*sin(strtofloat(Edit2.text)*(pi/180))*sin(delta*(pi/180))));
Io910:=18797599.3427*(1+(0.033*Cos(0.98630136986*n*(pi/180))))
   *((cos(strtofloat(edit2.text)*(pi/180))*Cos(delta*(pi/180)))*(sin(-30*(pi/180))-sin(-45*(pi/180)))
   +(0.26179938779*sin(strtofloat(Edit2.text)*(pi/180))*sin(delta*(pi/180))));
Io1011:=18797599.3427*(1+(0.033*Cos(0.98630136986*n*(pi/180))))
   *((cos(strtofloat(edit2.text)*(pi/180))*Cos(delta*(pi/180)))*(sin(-15*(pi/180))-sin(-30*(pi/180)))
   +(0.26179938779*sin(strtofloat(Edit2.text)*(pi/180))*sin(delta*(pi/180))));
Io1112:=18797599.3427*(1+(0.033*Cos(0.98630136986*n*(pi/180))))
   *((cos(strtofloat(edit2.text)*(pi/180))*Cos(delta*(pi/180)))*(sin(-0*(pi/180))-sin(-15*(pi/180)))
   +(0.26179938779*sin(strtofloat(Edit2.text)*(pi/180))*sin(delta*(pi/180))));

Io1213:=Io1112;
Io1314:=Io1011;
Io1415:=Io910;
Io1516:=Io89;
Io1617:=Io78;
Io1718:=Io67;

Edit8.text:=floattostr(Io67);

{6.Hourly Index}
Kt67:=Ih67/Io67;
Edit22.text:=floattostr(Kt67);
Kt78:=Ih78/Io78;
Edit23.text:=floattostr(Kt78);
```

```
Kt89:=Ih89/Io89;
Edit24.text:=floattostr(Kt89);
Kt910:=Ih910/Io910;
Edit25.text:=floattostr(Kt910);
Kt1011:=Ih1011/Io1011;
Edit26.text:=floattostr(Kt1011);
Kt1112:=Ih1112/Io1112;
Edit27.text:=floattostr(Kt1112);

Kt1213:=Kt1112;
Kt1314:=Kt1011;
Kt1415:=Kt910;
Kt1516:=Kt89;
Kt1617:=Kt78;
Kt1718:=Kt67;

{7.Diffuse Ratio = Id/Ih =i}
i67:=0.9511-(0.1604*Kt67)+(4.388*Kt67*Kt67)-(16.638*Kt67*Kt67*Kt67)+(12.336*Kt67*Kt67*Kt67*Kt67);
Edit34.text:=floattostr(i67);
i78:=0.9511-(0.1604*Kt78)+(4.388*Kt78*Kt78)-(16.638*Kt78*Kt78*Kt78)+(12.336*Kt78*Kt78*Kt78*Kt78);
Edit35.text:=floattostr(i78);
i89:=0.9511-(0.1604*Kt89)+(4.388*Kt89*Kt89)-(16.638*Kt89*Kt89*Kt89)+(12.336*Kt89*Kt89*Kt89*Kt89);
Edit36.text:=floattostr(i89);
i910:=0.9511-(0.1604*Kt910)+(4.388*Kt910*Kt910)-(16.638*Kt910*Kt910*Kt910)+(12.336*Kt910*Kt910*Kt910*Kt910);
Edit37.text:=floattostr(i910);
i1011:=0.9511-(0.1604*Kt1011)+(4.388*Kt1011*Kt1011)-(16.638*Kt1011*Kt1011*Kt1011)+(12.336*Kt1011*Kt1011*Kt1011*Kt1011);
Edit38.text:=floattostr(i1011);
i1112:=0.9511-(0.1604*Kt1112)+(4.388*Kt1112*Kt1112)-(16.638*Kt1112*Kt1112*Kt1112)+(12.336*Kt1112*Kt1112*Kt1112*Kt1112);
Edit39.text:=floattostr(i1112);
i1213:=i1112;
i1314:=i1011;
i1415:=i910;
i1516:=i89;
i1617:=i78;
i1718:=i67;

{8.Angle of Incidence upon Collector}
Gama:=strtofloat(Edit4.text);
CosTheta67:= Sin(Delta*(pi/180))*Sin(strtofloat(Edit2.text)*(pi/180))*Cos(Beta*(pi/180))
- Sin(Delta*(pi/180))*Cos(strtofloat(Edit2.text)*(pi/180))*Sin(Beta*(pi/180))*Cos(Gama*(pi/180))
+ Cos(Delta*(pi/180))*Cos(strtofloat(Edit2.text)*(pi/180))*Cos(Beta*(pi/180))*Cos(-82.5*(pi/180))
+ Cos(Delta*(pi/180))*Sin(strtofloat(Edit2.text)*(pi/180))*Sin(Beta*(pi/180))*Cos(Gama*(pi/180))
*Cos(-82.5*(pi/180))+ Cos(Delta*(pi/180))*Sin(Beta*(pi/180))*Sin(Gama*(pi/180))*Sin(-82.5*(pi/180));

CosTheta78:= Sin(Delta*(pi/180))*Sin(strtofloat(Edit2.text)*(pi/180))*Cos(Beta*(pi/180))
- Sin(Delta*(pi/180))*Cos(strtofloat(Edit2.text)*(pi/180))*Sin(Beta*(pi/180))*Cos(Gama*(pi/180))
+ Cos(Delta*(pi/180))*Cos(strtofloat(Edit2.text)*(pi/180))*Cos(Beta*(pi/180))*Cos(-67.5*(pi/180))
+ Cos(Delta*(pi/180))*Sin(strtofloat(Edit2.text)*(pi/180))*Sin(Beta*(pi/180))*Cos(Gama*(pi/180))
*Cos(-67.5*(pi/180))+ Cos(Delta*(pi/180))*Sin(Beta*(pi/180))*Sin(Gama*(pi/180))*Sin(-67.5*(pi/180));

CosTheta89:= Sin(Delta*(pi/180))*Sin(strtofloat(Edit2.text)*(pi/180))*Cos(Beta*(pi/180))
- Sin(Delta*(pi/180))*Cos(strtofloat(Edit2.text)*(pi/180))*Sin(Beta*(pi/180))*Cos(Gama*(pi/180))
+ Cos(Delta*(pi/180))*Cos(strtofloat(Edit2.text)*(pi/180))*Cos(Beta*(pi/180))*Cos(-52.5*(pi/180))
+ Cos(Delta*(pi/180))*Sin(strtofloat(Edit2.text)*(pi/180))*Sin(Beta*(pi/180))*Cos(Gama*(pi/180))
*Cos(-52.5*(pi/180))+ Cos(Delta*(pi/180))*Sin(Beta*(pi/180))*Sin(Gama*(pi/180))*Sin(-52.5*(pi/180));

CosTheta910:= Sin(Delta*(pi/180))*Sin(strtofloat(Edit2.text)*(pi/180))*Cos(Beta*(pi/180))
- Sin(Delta*(pi/180))*Cos(strtofloat(Edit2.text)*(pi/180))*Sin(Beta*(pi/180))*Cos(Gama*(pi/180))
+ Cos(Delta*(pi/180))*Cos(strtofloat(Edit2.text)*(pi/180))*Cos(Beta*(pi/180))*Cos(-37.5*(pi/180))
+ Cos(Delta*(pi/180))*Sin(strtofloat(Edit2.text)*(pi/180))*Sin(Beta*(pi/180))*Cos(Gama*(pi/180))
*Cos(-37.5*(pi/180))+ Cos(Delta*(pi/180))*Sin(Beta*(pi/180))*Sin(Gama)*Sin(-37.5*(pi/180));

CosTheta1011:= Sin(Delta*(pi/180))*Sin(strtofloat(Edit2.text)*(pi/180))*Cos(Beta*(pi/180))
- Sin(Delta*(pi/180))*Cos(strtofloat(Edit2.text)*(pi/180))*Sin(Beta*(pi/180))*Cos(Gama*(pi/180))
+ Cos(Delta*(pi/180))*Cos(strtofloat(Edit2.text)*(pi/180))*Cos(Beta*(pi/180))*Cos(-22.5*(pi/180))
+ Cos(Delta*(pi/180))*Sin(strtofloat(Edit2.text)*(pi/180))*Sin(Beta*(pi/180))*Cos(Gama*(pi/180))
*Cos(-22.5*(pi/180))+ Cos(Delta*(pi/180))*Sin(Beta*(pi/180))*Sin(Gama*(pi/180))*Sin(-22.5*(pi/180));

CosTheta1112:= Sin(Delta*(pi/180))*Sin(strtofloat(Edit2.text)*(pi/180))*Cos(Beta*(pi/180))
- Sin(Delta*(pi/180))*Cos(strtofloat(Edit2.text)*(pi/180))*Sin(Beta*(pi/180))*Cos(Gama*(pi/180))
+ Cos(Delta*(pi/180))*Cos(strtofloat(Edit2.text)*(pi/180))*Cos(Beta*(pi/180))*Cos(-7.5*(pi/180))
+ Cos(Delta*(pi/180))*Sin(strtofloat(Edit2.text)*(pi/180))*Sin(Beta*(pi/180))*Cos(Gama*(pi/180))
*Cos(-7.5*(pi/180))+ Cos(Delta*(pi/180))*Sin(Beta*(pi/180))*Sin(Gama*(pi/180))*Sin(-7.5*(pi/180));
```

```
CosTheta1213:=CosTheta1112;
CosTheta1314:=CosTheta1011;
CosTheta1415:=CosTheta910;
CosTheta1516:=CosTheta89;
CosTheta1617:=CosTheta78;
CosTheta1718:=CosTheta67;

{9.Geometric Factor,Rb}
Rb67:= (CosThetah67)/CosThetah67;
Edit16.text:=floattostr(Rb67);
Rb78:= (CosTheta78)/CosThetah78;
Edit17.text:=floattostr(Rb78);
Rb89:= (CosTheta89)/CosThetah89;
Edit18.text:=floattostr(Rb89);
Rb910:= (CosTheta910)/CosThetah910;
Edit19.text:=floattostr(Rb910);
Rb1011:= (CosTheta1011)/CosThetah1011;
Edit20.text:=floattostr(Rb1011);
Rb1112:= (CosTheta1112)/CosThetah1112;
Edit21.text:=floattostr(Rb1112);

Rb1213:=Rb1112 ;
Rb1314:=Rb1011 ;
Rb1415:=Rb910 ;
Rb1516:=Rb89 ;
Rb1617:=Rb78 ;
Rb1718:=Rb67 ;

{10.Insolation on Collector Surface}
Ic67:= Ih67*Rb67*(1-i67)+Ih67*i67*(0.5 + 0.5*Cos(Beta*(pi/180)))+ 0.2*Ih67*(0.5-0.5*Cos(Beta*(pi/180)));
Edit28.text:=floattostr(Ic67);
Ic78:= Ih78*Rb78*(1-i78)+Ih78*i78*(0.5 + 0.5*Cos(Beta*(pi/180)))+ 0.2*Ih78*(0.5-0.5*Cos(Beta*(pi/180)));
Edit29.text:=floattostr(Ic78);
Ic89:= Ih89*Rb89*(1-i89)+Ih89*i89*(0.5 + 0.5*Cos(Beta*(pi/180)))+ 0.2*Ih89*(0.5-0.5*Cos(Beta*(pi/180)));
Edit30.text:=floattostr(Ic89);
Ic910:= Ih910*Rb910*(1-i910)+Ih910*i910*(0.5 + 0.5*Cos(Beta*(pi/180)))+ 0.2*Ih910
*(0.5-0.5*Cos(Beta*(pi/180)));
Edit31.text:=floattostr(Ic910);
Ic1011:= Ih1011*Rb1011*(1-i1011)+Ih1011*i1011*(0.5 + 0.5*Cos(Beta*(pi/180)))+ 0.2*Ih1011
*(0.5-0.5*Cos(Beta*(pi/180)));
Edit32.text:=floattostr(Ic1011);
Ic1112:= Ih1112*Rb1112*(1-i1112)+Ih1112*i1112*(0.5 + 0.5*Cos(Beta*(pi/180)))+ 0.2*Ih1112
*(0.5-0.5*Cos(Beta*(pi/180)));
Edit33.text:=floattostr(Ic1112);

edit9.text:=floattostr(Ic67);

Ic1213:=Ic1112;
Ic1314:=Ic1011;
Ic1415:=Ic910;
Ic1516:=Ic89;
Ic1617:=Ic78;
Ic1718:=Ic67;

{11.Average Insolation}
Icave:=(Ic67+Ic78+ Ic89+ Ic910+ Ic1011+ Ic1112+ Ic1213+ Ic1314+ Ic1415+ Ic1516+ Ic1617+ Ic1718)/43200;
edit5.text:=floattostr(Icave);
if messageDLG('Do you wish to proceed with the calculation of the collector efficiency?',MTinformation,[MByes, MBNo],0)=MRyes then
begin
Form9.edit8.text:=floattostr(Beta);
Form10.edit5.text:=floattostr(Icave);
Form5.show;
Form4.hide;
end;
end;

procedure TForm4.SpeedButton1Click(Sender: TObject);
begin
form5.show;
form4.hide;
end;

procedure TForm4.SpeedButton2Click(Sender: TObject);
begin
Form7.show;
```

```
Form4.hide;
end;

procedure TForm4.Button3Click(Sender: TObject);
begin

{Inputs}
Table1.edit;
Edit1.text:=table1DMonth.asstring;
Edit2.text:=table1LatAng.asstring;
Edit3.text:=table1AveRadJ.asstring;
Edit4.text:=table1AzAng.asstring;
{Outputs}
Edit5.text:=table1AveInsW.asstring;
Edit6.text:=table1DecAng.asstring;
Edit7.text:=table1OptAng.asstring;

Edit10.text:=table1Ih67.asstring;
Edit11.text:=table1Ih78.asstring;
Edit12.text:=table1Ih89.asstring;
Edit13.text:=table1Ih910.asstring;
Edit14.text:=table1Ih1011.asstring;
Edit15.text:=table1Ih1112.asstring;

Edit16.text:=table1Rb67.asstring;
Edit17.text:=table1Rb78.asstring;
Edit18.text:=table1Rb89.asstring;
Edit19.text:=table1Rb910.asstring;
Edit20.text:=table1Rb1011.asstring;
Edit21.text:=table1Rb1112.asstring;

Edit22.text:=table1Kt67.asstring;
Edit23.text:=table1Kt78.asstring;
Edit24.text:=table1Kt89.asstring;
Edit25.text:=table1Kt910.asstring;
Edit26.text:=table1Kt1011.asstring;
Edit27.text:=table1Kt1112.asstring;

Edit34.text:=table1IdIh67.asstring;
Edit35.text:=table1IdIh78.asstring;
Edit36.text:=table1IdIh89.asstring;
Edit37.text:=table1IdIh910.asstring;
Edit38.text:=table1IdIh1011.asstring
;
Edit39.text:=table1IdIh1112.asstring
;

Edit28.text:=table1Ic67.asstring;
Edit29.text:=table1Ic78.asstring;
Edit30.text:=table1Ic89.asstring;
Edit31.text:=table1Ic910.asstring;
Edit32.text:=table1Ic1011.asstring;
Edit33.text:=table1Ic1112.asstring;

end;

end.
```

unit CollArea;

```
interface

uses
  Windows, Messages, SysUtils, Classes, Graphics, Controls, Forms, Dialogs,
  StdCtrls, Buttons, DB, DBTables;

type
  TForm5 = class(TForm)
    Calculate: TButton;
    SpeedButton1: TSpeedButton;
    SpeedButton2: TSpeedButton;
    DataSource1: TDataSource;
    Table1: TTable;

Table1TypdrMat: TStringField;
    Table1InitMC: TFloatField;
    Table1FinMC: TFloatField;
    Table1DrTmp: TFloatField;
    Table1AmbTmp: TFloatField;
    Table1AmbMC: TFloatField;
    Table1AmbRH: TFloatField;
    Table1BachCap: TFloatField;
    Table1DrTime: TFloatField;
    Table1Mw: TFloatField;
    Table1CoutTmp: TFloatField;
    Table1BoutRH: TFloatField;
    Table1BoutMC: TFloatField;
    Table1BoutTmp: TFloatField;
    Table1AirFlRt: TFloatField;
    Table1HtrPr: TFloatField;
    Table1BAirSpd: TFloatField;
    Table1ArFrac: TFloatField;
    Table1FL: TFloatField;
    Table1FH: TFloatField;
    Table1Fthk: TFloatField;
    Table1FAveWt: TFloatField;
    Table1BLW: TFloatField;
    Table1BH: TFloatField;
    Table1TL: TFloatField;
    Table1TW: TFloatField;
    Table1Tthk: TFloatField;
    Table1NFBL: TFloatField;
Table1NFBW: TFloatField;
Table1NFBH: TFloatField;
Table1GBL: TFloatField;
Table1GBW: TFloatField;
Table1DMonth: TFloatField;
Table1LatAng: TFloatField;
Table1AveRadJ: TFloatField;
Table1AzAng: TFloatField;
Table1AveInsW: TFloatField;
Table1DecAng: TFloatField;
Table1OptAng: TFloatField;
Table1Ih67: TFloatField;
Table1Ih78: TFloatField;
Table1Ih89: TFloatField;
Table1Ih910: TFloatField;
Table1Ih1011: TFloatField;
Table1Ih1112: TFloatField;
Table1Rb67: TFloatField;
Table1Rb78: TFloatField;
Table1Rb89: TFloatField;
Table1Rb910: TFloatField;
Table1Rb1011: TFloatField;
Table1Rb1112: TFloatField;
Table1Kt67: TFloatField;
Table1Kt78: TFloatField;
Table1Kt89: TFloatField;
Table1Kt910: TFloatField;
Table1Kt1011: TFloatField;
Table1Kt1112: TFloatField;
Table1IdIh67: TFloatField;
Table1IdIh78: TFloatField;
Table1IdIh89: TFloatField;
Table1IdIh910: TFloatField;
Table1IdIh1011: TFloatField;
Table1IdIh1112: TFloatField;
Table1Ic67: TFloatField;
Table1Ic78: TFloatField;
Table1Ic89: TFloatField;
Table1Ic910: TFloatField;
Table1Ic1011: TFloatField;
Table1Ic1112: TFloatField;
Table1TAProd: TFloatField;
Table1H: TFloatField;
Table1CEff: TFloatField;
Table1CAr: TFloatField;
Table1CorCAr: TFloatField;
Table1CorCEffA: TFloatField;
Table1Lc: TFloatField;
Table1Wc: TFloatField;
Table1Dc: TFloatField;
Table1VolFlo: TFloatField;
Table1F: TFloatField;
Table1CAirFlo: TFloatField;
Table1Re: TFloatField;
Table1Nu: TFloatField;
Table1HAct: TFloatField;
Table1CorCEffh: TFloatField;
Table1W: TFloatField;
Table1AirDen: TFloatField;
Table1BMEff: TFloatField;
Table1Bdp: TFloatField;
Table1BFanPr: TFloatField;
Table1Lc1: TFloatField;
Table1Wc1: TFloatField;
Table1NPases: TFloatField;
Table1PMeter: TFloatField;
Table1NLc: TFloatField;
Table1NWc: TFloatField;
Table1NPMeter: TFloatField;
Table1DHyd: TFloatField;
Table1TAirL: TFloatField;
Table1Cdp: TFloatField;
Table1CFanPr: TFloatField;
Table1BatCap: TFloatField;
Table1MasFlo: TFloatField;
Table1Int: TFloatField;
Table1LstMC: TFloatField;
Table1CAirVel: TFloatField;
Table1CorEffh: TFloatField;
Table1CoutTemp: TFloatField;
Table1DrSeason: TStringField;

GroupBox1: TGroupBox;

Label1: TLabel;
    Label2: TLabel;
    Label3: TLabel;
    Label4: TLabel;
    Label5: TLabel;
Label10: TLabel;
Edit10: TEdit;
Edit5: TEdit;
Edit4: TEdit;
Edit3: TEdit;
Edit2: TEdit;
Edit1: TEdit;
Label6: TLabel;
Label7: TLabel;
Label8: TLabel;
Label9: TLabel;
Edit9: TEdit;
Edit8: TEdit;
Edit7: TEdit;
Edit6: TEdit;

procedure CalculateClick(Sender: TObject);
    procedure SpeedButton1Click(Sender: TObject);
    procedure SpeedButton2Click(Sender: TObject);
    procedure Button3Click(Sender: TObject);
  private
    { Private declarations }
  public
    { Public declarations }
  end;
```

```
var
  Form5: TForm5;

implementation

uses projDim, air, water, Solar, Unit10;
{$R *.DFM}

procedure TForm5.CalculateClick(Sender: TObject);
var Effwc,Ac,K1,h,K2,Acc,Ga:double;
begin

{Willier's Collector Efficiency}
Effwc:=0.93806896261*strtofloat(Edit4.text)/(1+(6.99/strtofloat(Edit10.text)));
{Ans}
Edit6.text:=floattostr(Effwc);

{Collector area}
edit1.text:= Form2.Edit8.text;
edit2.text:= Form1.Edit5.text;
edit3.text:= Form2.Edit4.text;
edit5.text:= Form4.Edit5.text;
Ac:=1005*strtofloat(Form2.Edit8.text)*(strtofloat(Form2.Edit4.text)-strtofloat(Form1.Edit5.text))/Effwc/strtofloat(Form4.Edit5.text);
{Ans}
Edit7.text:=floattostr(Ac);

{Mass flow rate per unit Collector Area}
Ga:=strtofloat(Form2.Edit8.text)/Ac;
{Correction factors for Air flow rate}
if (ga<0.00136)then
K1:=0.26 ;
if (ga>=0.00136) and (ga<=0.0068) then
K1:=(0.73-0.08639705882*(0.0068-Ga));
if (ga>0.0068) and (ga<=0.0136) then
K1:=(0.88-0.02205882352*(0.0136-Ga));
if (ga>0.0136) and (ga<=0.0408) then
K1:=(1-0.00441176470588*(0.0408-Ga));
if (ga>0.0408) and (ga<=0.068) then
K1:=(1.03-0.00110294117647*(0.068-Ga));
if (ga>0.068) and (ga<=0.136) then
K1:=(1.05-0.000294117647059*(0.136-Ga));
if (ga>0.136)then
K1:= 1.05;

{Correction factors for Heat transfer coefficient}
h:=strtofloat(Edit10.text);
if (h>=11.4) and (h<=22.7)then
K2:=(1-0.01769911504*(22.7-h));
if (h>22.7) and (h<=34.1)then
K2:=(1.09-0.00789473684211*(34.1-h));
if (h>34.1) and (h<=45.4)then
K2:=(1.14-0.00442477876106*(45.4-h));
if (h>45.4) and (h<=68.2)then
K2:=(1.2-0.00263157894737*(68.2-h));
if (h>68.2) and (h<=90.9)then
K2:=(1.23-0.00132158590308*(90.9-h));
{Corrected Collector Area}
Acc:=Ac/K1;
{Ans}
Edit8.text:=floattostr(Acc);
Edit9.text:=floattostr(Effwc*K1);
if messageDLG('Do you wish to proceed with calculation of the collector dimensions?',MTinformation,[MByes, MBNo],0)=MRyes then
begin
Form6.edit12.text:=(edit8.text);
Form10.edit7.text:=(edit8.text);
Form6.show;
Form5.hide;
end;
end;

procedure TForm5.SpeedButton1Click(Sender: TObject);
begin
Form6.show;
Form5.hide;
end;
```

```
procedure TForm5.SpeedButton2Click(Sender: TObject);
begin
Form4.show;
Form5.hide;
end;

procedure TForm5.Button3Click(Sender: TObject);
begin

{Inputs}
Table1.edit;
Edit1.text:=table1MasFLo.asstring;
Edit2.text:=table1AmbTmp.asstring;
Edit3.text:=table1CoutTmp.asstring;
Edit4.text:=table1TAProd.asstring;
Edit5.text:=table1AveInsW.asstring;
Edit10.text:=table1h.asstring;
{Outputs}
Edit6.text:=table1CEff.asstring;
Edit7.text:=table1CAr.asstring;
Edit8.text:=table1CorCAr.asstring;
Edit9.text:=table1CorCEffA.asstring
;

end;

end.
```

unit projDim;

```
interface

uses
  Windows, Messages, SysUtils, Classes, Graphics, Controls, Forms, Dialogs,
  StdCtrls, Buttons, DB, DBTables;

type
  TForm6 = class(TForm)
    Button1: TButton;
    SpeedButton1: TSpeedButton;
    SpeedButton2: TSpeedButton;
    DataSource1: TDataSource;
    Table1: TTable;

Table1TypdrMat: TStringField;
    Table1InitMC: TFloatField;
    Table1FinMC: TFloatField;
    Table1DrTmp: TFloatField;
    Table1AmbTmp: TFloatField;
    Table1AmbMC: TFloatField;
    Table1AmbRH: TFloatField;
    Table1BachCap: TFloatField;
    Table1DrTime: TFloatField;
    Table1Mw: TFloatField;
    Table1CoutTmp: TFloatField;
    Table1BoutRH: TFloatField;
    Table1BoutMC: TFloatField;
    Table1BoutTmp: TFloatField;
    Table1AirFlRt: TFloatField;
    Table1HtrPr: TFloatField;
    Table1BAirSpd: TFloatField;
    Table1ArFrac: TFloatField;
    Table1FL: TFloatField;
    Table1FH: TFloatField;
    Table1Fthk: TFloatField;
    Table1FAveWt: TFloatField;
    Table1BLW: TFloatField;
    Table1BH: TFloatField;
    Table1TL: TFloatField;
    Table1TW: TFloatField;
    Table1Tthk: TFloatField;
    Table1NFBL: TFloatField;
    Table1NFBW: TFloatField;
    Table1NFBH: TFloatField;
    Table1GBL: TFloatField;
    Table1GBW: TFloatField;
    Table1DMonth: TFloatField;
    Table1LatAng: TFloatField;
    Table1AveRadJ: TFloatField;
    Table1AzAng: TFloatField;
    Table1AveInsW: TFloatField;
    Table1DecAng: TFloatField;
    Table1OptAng: TFloatField;
    Table1Ih67: TFloatField;
    Table1Ih78: TFloatField;
    Table1Ih89: TFloatField;
    Table1Ih910: TFloatField;
    Table1Ih1011: TFloatField;
    Table1Ih1112: TFloatField;
    Table1Rb67: TFloatField;
    Table1Rb78: TFloatField;
    Table1Rb89: TFloatField;
    Table1Rb910: TFloatField;
    Table1Rb1011: TFloatField;
    Table1Rb1112: TFloatField;
    Table1Kt67: TFloatField;
    Table1Kt78: TFloatField;
    Table1Kt89: TFloatField;
    Table1Kt910: TFloatField;
    Table1Kt1011: TFloatField;
    Table1Kt1112: TFloatField;
    Table1IdIh67: TFloatField;
    Table1IdIh78: TFloatField;
    Table1IdIh89: TFloatField;
    Table1IdIh910: TFloatField;
    Table1IdIh1011: TFloatField;
    Table1IdIh1112: TFloatField;
    Table1Ic67: TFloatField;
    Table1Ic78: TFloatField;
    Table1Ic89: TFloatField;
    Table1Ic910: TFloatField;
    Table1Ic1011: TFloatField;
    Table1Ic1112: TFloatField;
    Table1TAProd: TFloatField;
    Table1H: TFloatField;
    Table1CEff: TFloatField;
    Table1CAr: TFloatField;
    Table1CorCAr: TFloatField;
    Table1CorCEffA: TFloatField;
    Table1Lc: TFloatField;
    Table1Wc: TFloatField;
    Table1Dc: TFloatField;
    Table1VolFlo: TFloatField;
    Table1F: TFloatField;
    Table1CAirFlo: TFloatField;
    Table1Re: TFloatField;
    Table1Nu: TFloatField;
    Table1HAct: TFloatField;
    Table1CorCEffh: TFloatField;
    Table1W: TFloatField;
    Table1AirDen: TFloatField;
    Table1BMEff: TFloatField;
    Table1Bdp: TFloatField;
    Table1BFanPr: TFloatField;
    Table1Lc1: TFloatField;
    Table1Wc1: TFloatField;
    Table1NPases: TFloatField;
    Table1PMeter: TFloatField;
    Table1NLc: TFloatField;
    Table1NWc: TFloatField;
    Table1NPMeter: TFloatField;
    Table1DHyd: TFloatField;
    Table1TAirL: TFloatField;
    Table1Cdp: TFloatField;
    Table1CFanPr: TFloatField;
    Table1BatCap: TFloatField;
    Table1MasFlo: TFloatField;
    Table1Int: TFloatField;
    Table1LstMC: TFloatField;
    Table1CAirVel: TFloatField;
    Table1CorEffh: TFloatField;
    Table1DrSeason: TStringField;
    Table1CoutTemp: TFloatField;

GroupBox1: TGroupBox;

Label1: TLabel;
    Label2: TLabel;
    Label3: TLabel;
    Label4: TLabel;
    Label5: TLabel;
    Edit5: TEdit;
    Edit4: TEdit;
    Edit3: TEdit;
    Edit2: TEdit;
    Edit1: TEdit;
    Label6: TLabel;
    Label11: TLabel;
    Label7: TLabel;
    Label8: TLabel;
    Label9: TLabel;
    Label10: TLabel;
    Label12: TLabel;
    Edit11: TEdit;
    Edit10: TEdit;
    Edit9: TEdit;
    Edit8: TEdit;
    Edit7: TEdit;
    Edit6: TEdit;
    Edit12: TEdit;
    Label13: TLabel;
    Label14: TLabel;

procedure Button1Click(Sender: TObject);
    procedure SpeedButton2Click(Sender: TObject);
    procedure SpeedButton1Click(Sender: TObject);
    procedure Button3Click(Sender: TObject);
  private
    { Private declarations }
  public
    { Public declarations }
  end;

var
  Form6: TForm6;
implementation

uses air, Unit9, Unit8, CollArea, Unit10;

{$R *.DFM}
```

```
procedure TForm6.Button1Click(Sender: TObject);
Var Dhyd,Vc,Re,Nu,hact,Pm,K2:double;
begin

{1.Hydraulic diameter}
Dhyd:=2*strtofloat(Edit2.text)*strtofloat(Edit3.text)/(strtofloat(Edit2.text)+strtofloat(Edit3.text));
{2.Air Velocity through Collector}
edit4.text:=Form2.Edit8.text;
Vc:=strtofloat(Form2.Edit8.text)/1.2/(strtofloat(Edit2.text)*Strtofloat(Edit3.text));
{Ans}
Edit6.text:=floattostr(Vc);

{3.Reynolds Number}
Re:=65217.3913043*Vc*Dhyd;
{Ans}
Edit7.text:=floattostr(Re);

{4.Nusselt Number}
Nu:=(strtofloat(Edit5.text)/8)*(Re-1000)*0.707/(1-2.47655257496*sqrt(strtofloat(Edit5.text)/8));
{Ans}
Edit8.text:=floattostr(Nu);

{Actual Heat Transfer Coefficient}
hact:=0.025*Nu/Dhyd;
{Ans}
Edit9.text:=floattostr(hact);

{Perimeter}
Pm:=(strtofloat(Edit1.text)*2)+(strtofloat(Edit2.text)*2);
{Ans}
Form8.Edit7.text:=floattostr(Pm);

{Correction factors for Heat transfer coefficient}
If (hact<11.4)then
K2:= 0.8 ;
if (hact>=11.4) and (hact<=22.7)then
K2:=(1-0.01769911504*(22.7-hact));
if (hact>22.7) and (hact<=34.1)then
K2:=(1.09-0.00789473684211*(34.1-hact));
if (hact>34.1) and (hact<=45.4)then
K2:=(1.14-0.00442477876106*(45.4-hact));
if (hact>45.4) and (hact<=68.2)then
K2:=(1.2-0.00263157894737*(68.2-hact));
if (hact>68.2) and (hact<=90.9)then
K2:=(1.23-0.00132158590308*(90.9-hact));
if (hact>90.9)then
K2:= 1.23;
Edit10.text:=floattostr(strtofloat(Form5.Edit9.text)*K2);

{if messageDLG('Do you wish to proceed to Bin Size Calculation?',MTinformation,[MByes, MBNo],0)=MRyes then
begin

Form7.show;
Form6.hide;
end;}
if messageDLG('Do you wish to proceed to optimization of the collector dimensions?',MTinformation,[MByes, MBNo],0)=MRyes then
begin
form10.edit6.text:=(edit10.text);
form9.Edit2.text:=floattostr(Dhyd);
form9.Edit1.text:=Edit5.text;
form8.Edit1.text:= Edit1.text;
form8.Edit2.text:= Edit2.text;
Form8.show;
Form6.hide;
end;
end;

procedure TForm6.SpeedButton2Click(Sender: TObject);
begin
Form8.show;
Form6.hide;
end;

procedure TForm6.SpeedButton1Click(Sender: TObject);
begin
```

```
Form5.show;
Form6.hide;
end;

procedure TForm6.Button3Click(Sender: TObject);
begin

{Inputs}
Table1.edit;
Edit1.text:=table1Lc.asstring;
Edit2.text:=table1Wc.asstring;
Edit3.text:=table1dc.asstring;
Edit4.text:=table1VolFlo.asstring;
Edit5.text:=table1f.asstring;
{Outputs}
Edit6.text:=table1CAirVel.asstring;
Edit7.text:=table1Re.asstring;
Edit8.text:=table1Nu.asstring;
Edit9.text:=table1hAct.asstring;
Edit10.text:=table1CorEffh.asstring;

end;

end.
```

unit Unit8;

```
interface

uses
  Windows, Messages, SysUtils, Classes, Graphics, Controls, Forms, Dialogs,
  StdCtrls, Buttons, DB, DBTables;

type
  TForm8 = class(TForm)
    Button1: TButton;
    SpeedButton1: TSpeedButton;
    SpeedButton2: TSpeedButton;
    DataSource1: TDataSource;
    Table1: TTable;

Table1TypdrMat: TStringField;
    Table1InitMC: TFloatField;
    Table1FinMC: TFloatField;
    Table1DrTmp: TFloatField;
    Table1AmbTmp: TFloatField;
    Table1AmbMC: TFloatField;
    Table1AmbRH: TFloatField;
    Table1BachCap: TFloatField;
    Table1DrTime: TFloatField;
    Table1Mw: TFloatField;
    Table1CoutTmp: TFloatField;
    Table1BoutRH: TFloatField;
    Table1BoutMC: TFloatField;
    Table1BoutTmp: TFloatField;
    Table1AirFlRt: TFloatField;
    Table1HtrPr: TFloatField;
    Table1BAirSpd: TFloatField;
    Table1ArFrac: TFloatField;
    Table1FL: TFloatField;
    Table1FH: TFloatField;
    Table1Fthk: TFloatField;
    Table1FAveWt: TFloatField;
    Table1BLW: TFloatField;
    Table1BH: TFloatField;
    Table1TL: TFloatField;
    Table1TW: TFloatField;
    Table1Tthk: TFloatField;
    Table1NFBL: TFloatField;
Table1NFBW: TFloatField;
Table1NFBH: TFloatField;
Table1GBL: TFloatField;
Table1GBW: TFloatField;
Table1DMonth: TFloatField;
Table1LatAng: TFloatField;
Table1AveRadJ: TFloatField;
Table1AzAng: TFloatField;
Table1AveInsW: TFloatField;
Table1DecAng: TFloatField;
Table1OptAng: TFloatField;
Table1Ih67: TFloatField;
Table1Ih78: TFloatField;
Table1Ih89: TFloatField;
Table1Ih910: TFloatField;
Table1Ih1011: TFloatField;
Table1Ih1112: TFloatField;
Table1Rb67: TFloatField;
Table1Rb78: TFloatField;
Table1Rb89: TFloatField;
Table1Rb910: TFloatField;
Table1Rb1011: TFloatField;
Table1Rb1112: TFloatField;
Table1Kt67: TFloatField;
Table1Kt78: TFloatField;
Table1Kt89: TFloatField;
Table1Kt910: TFloatField;
Table1Kt1011: TFloatField;
Table1Kt1112: TFloatField;
Table1Idlh67: TFloatField;
Table1Idlh78: TFloatField;
Table1Idlh89: TFloatField;
Table1Idlh910: TFloatField;
Table1Idlh1011: TFloatField;
Table1Idlh1112: TFloatField;
Table1Ic67: TFloatField;
Table1Ic78: TFloatField;
Table1Ic89: TFloatField;
Table1Ic910: TFloatField;
Table1Ic1011: TFloatField;
Table1Ic1112: TFloatField;
Table1TAProd: TFloatField;
Table1H: TFloatField;
Table1CEff: TFloatField;
Table1CAr: TFloatField;
Table1CorCAr: TFloatField;
Table1CorCEffA: TFloatField;
Table1Lc: TFloatField;
Table1Wc: TFloatField;
Table1Dc: TFloatField;
Table1VolFlo: TFloatField;
Table1F: TFloatField;
Table1CAirFlo: TFloatField;
Table1Re: TFloatField;
Table1Nu: TFloatField;
Table1HAct: TFloatField;
Table1CorCEffh: TFloatField;
Table1W: TFloatField;
Table1AirDen: TFloatField;
Table1BMEff: TFloatField;
Table1Bdp: TFloatField;
Table1BFanPr: TFloatField;
Table1Lc1: TFloatField;
Table1Wc1: TFloatField;
Table1NPases: TFloatField;
Table1PMeter: TFloatField;
Table1NLc: TFloatField;
Table1NWc: TFloatField;
Table1NPMeter: TFloatField;
Table1DHyd: TFloatField;
Table1TAirL: TFloatField;
Table1Cdp: TFloatField;
Table1CFanPr: TFloatField;
Table1BatCap: TFloatField;
Table1MasFlo: TFloatField;
Table1Int: TFloatField;
Table1LstMC: TFloatField;
Table1DrSeason: TStringField;
Table1CAirVel: TFloatField;
Table1CorEffh: TFloatField;
Table1CoutTemp: TFloatField;


GroupBox1: TGroupBox;

    Label7: TLabel;
    Label3: TLabel;
    Label2: TLabel;
    Label1: TLabel;
Edit7: TEdit;
Edit3: TEdit;
Edit2: TEdit;
Edit1: TEdit;
GroupBox2: TGroupBox;
Label6: TLabel;
Label5: TLabel;
Label4: TLabel;
Edit6: TEdit;
Edit5: TEdit;
Edit4: TEdit;

 procedure Button1Click(Sender: TObject);
   procedure SpeedButton1Click(Sender: TObject);
   procedure SpeedButton2Click(Sender: TObject);
   procedure Button3Click(Sender: TObject);
 private
   { Private declarations }
 public
   { Public declarations }
 end;

var
  Form8: TForm8;
implementation
uses Unit9, projDim;
{$R *.DFM}
procedure TForm8.Button1Click(Sender: TObject);

Var Lnew,Wnew,Pmnew:double;
begin
```

```
{New Length}
Lnew:= strtofloat(Edit1.text)/strtofloat(Edit3.text);
{Ans}
Edit4.text:=floattostr(Lnew);
{New Width}
Wnew:=strtofloat(Edit2.text)*strtofloat(Edit3.text);
{Ans}
Edit5.text:=floattostr(Wnew);
{New Perimeter}
Pmnew:=(Lnew*2)+(Wnew*2);
{Ans}
Edit6.text:=floattostr(Pmnew);

if messageDLG('Do you wish to proceed with the calculation of the pressure drop through the collector?',MTinformation,[MByes, MBNo],0)=MRyes
then
begin

Form9.show;
Form8.hide;
end;
end;

procedure TForm8.SpeedButton1Click(Sender: TObject);
begin
Form6.show;
Form8.hide;
end;

procedure TForm8.SpeedButton2Click(Sender: TObject);
begin
Form9.show;
Form8.hide;
end;

procedure TForm8.Button3Click(Sender: TObject);
begin

{Inputs}
Table1.edit;
Edit1.text:=table1Lc1.asstring;
Edit2.text:=table1Wc1.asstring;
Edit3.text:=table1NPases.asstring;
Edit7.text:=table1PMeter.asstring;
{Outputs}
Edit4.text:=table1NLc.asstring;
Edit5.text:=table1NWc.asstring;
Edit6.text:=table1NPMeter.asstring;

end;

end.
```

unit Unit9;

```
interface

uses
 Windows, Messages, SysUtils, Classes, Graphics, Controls, Forms, Dialogs,
 StdCtrls,unit10, Buttons, DB, DBTables;

type
 TForm9 = class(TForm)
  Button1: TButton;
  SpeedButton1: TSpeedButton;
  SpeedButton2: TSpeedButton;
  DataSource1: TDataSource;
  Table1: TTable;
  Table1TypdrMat: TStringField;
  Table1InitMC: TFloatField;
  Table1FinMC: TFloatField;
  Table1DrTmp: TFloatField;
  Table1AmbTmp: TFloatField;
  Table1AmbMC: TFloatField;
  Table1AmbRH: TFloatField;
  Table1BachCap: TFloatField;
  Table1DrTime: TFloatField;
  Table1Mw: TFloatField;
  Table1CoutTmp: TFloatField;
  Table1BoutRH: TFloatField;
  Table1BoutMC: TFloatField;
  Table1BoutTmp: TFloatField;
  Table1AirFlRt: TFloatField;
  Table1HtrPr: TFloatField;
  Table1BAirSpd: TFloatField;
  Table1ArFrac: TFloatField;
  Table1FL: TFloatField;
  Table1FH: TFloatField;
  Table1Fthk: TFloatField;
  Table1FAveWt: TFloatField;
  Table1BLW: TFloatField;
  Table1BH: TFloatField;
  Table1TL: TFloatField;
  Table1TW: TFloatField;
  Table1Tthk: TFloatField;
  Table1NFBL: TFloatField;
  Table1NFBW: TFloatField;
  Table1NFBH: TFloatField;
  Table1GBL: TFloatField;
  Table1GBW: TFloatField;
  Table1DMonth: TFloatField;
  Table1LatAng: TFloatField;
  Table1AveRadJ: TFloatField;
  Table1AzAng: TFloatField;
  Table1AveInsW: TFloatField;
  Table1DecAng: TFloatField;
  Table1OptAng: TFloatField;
  Table1Ih67: TFloatField;
  Table1Ih78: TFloatField;
  Table1Ih89: TFloatField;
  Table1Ih910: TFloatField;
  Table1Ih1011: TFloatField;
  Table1Ih1112: TFloatField;
  Table1Rb67: TFloatField;
  Table1Rb78: TFloatField;
  Table1Rb89: TFloatField;
  Table1Rb910: TFloatField;
  Table1Rb1011: TFloatField;
  Table1Rb1112: TFloatField;
  Table1Kt67: TFloatField;
  Table1Kt78: TFloatField;
  Table1Kt89: TFloatField;
  Table1Kt910: TFloatField;
  Table1Kt1011: TFloatField;
  Table1Kt1112: TFloatField;
  Table1Idlh67: TFloatField;
  Table1Idlh78: TFloatField;
  Table1Idlh89: TFloatField;
  Table1Idlh910: TFloatField;
  Table1Idlh1011: TFloatField;
  Table1Idlh1112: TFloatField;
  Table1Ic67: TFloatField;
  Table1Ic78: TFloatField;
  Table1Ic89: TFloatField;
  Table1Ic910: TFloatField;
  Table1Ic1011: TFloatField;
  Table1Ic1112: TFloatField;
  Table1TAProd: TFloatField;
  Table1H: TFloatField;
  Table1CEff: TFloatField;
  Table1CAr: TFloatField;
  Table1CorCAr: TFloatField;
  Table1CorCEffA: TFloatField;
  Table1Lc: TFloatField;
  Table1Wc: TFloatField;
  Table1Dc: TFloatField;
  Table1VolFlo: TFloatField;
  Table1F: TFloatField;
  Table1CAirFlo: TFloatField;
  Table1Re: TFloatField;
  Table1Nu: TFloatField;
  Table1HAct: TFloatField;
  Table1CorCEffh: TFloatField;
  Table1W: TFloatField;
  Table1AirDen: TFloatField;
  Table1BMEff: TFloatField;
  Table1Bdp: TFloatField;
  Table1BFanPr: TFloatField;
  Table1Lc1: TFloatField;
  Table1Wc1: TFloatField;
  Table1NPases: TFloatField;
  Table1PMeter: TFloatField;
  Table1NLc: TFloatField;
  Table1NWc: TFloatField;
  Table1NPMeter: TFloatField;
  Table1DHyd: TFloatField;
  Table1TAirL: TFloatField;
  Table1Cdp: TFloatField;
```

```
    Table1CFanPr: TFloatField;          Table1LstMC: TFloatField;          Table1CoutTemp: TFloatField;
    Table1BatCap: TFloatField;          Table1DrSeason: TStringField;
    Table1MasFlo: TFloatField;          Table1CAirVel: TFloatField;
    Table1Int: TFloatField;             Table1CorEffh: TFloatField;
   GroupBox1: TGroupBox;

   Label9: TLabel;                      Edit9: TEdit;        Label10: TLabel;          Label12: TLabel;
    Label8: TLabel;                     Edit8: TEdit;        Label7: TLabel;           Label13: TLabel;
    Label4: TLabel;                     Edit4: TEdit;        Label6: TLabel;           edit5: TEdit;
    Label3: TLabel;                     Edit3: TEdit;        Label5: TLabel;           edit6: TEdit;
    Label2: TLabel;                     Edit2: TEdit;        GroupBox2: TGroupBox;     edit7: TEdit;
    Label1: TLabel;                     Edit1: TEdit;        Label11: TLabel;

procedure Button1Click(Sender: TObject);
  procedure SpeedButton1Click(Sender: TObject);
  procedure Button3Click(Sender: TObject);
  procedure SpeedButton2Click(Sender: TObject);
 private
  { Private declarations }
 public
  { Public declarations }
 end;

var
 Form9: TForm9;

implementation

uses projDim, Unit8;

{$R *.DFM}

procedure TForm9.Button1Click(Sender: TObject);

Var Gd,Rhyd,DeltaPc,PBc,LTa:double;
begin

{1.Mass flow rate of air per unit duct area}
Gd:=strtofloat(Edit3.text)/strtofloat(form6.edit2.text)/strtofloat(form6.edit3.text);
{2.Hydraulic Radius}
Rhyd:=strtofloat(Edit2.text)/2;
{3.Total length of air path}
LTa:= strtofloat(form8.Edit3.text)*strtofloat(form8.Edit4.text)+(strtofloat(form8.Edit2.text)*(strtofloat(form8.Edit3.text)-1));
{Ans}
Edit5.text:=floattostr(LTa);
{4.Pressure drop}
DeltaPc:= 0.5*strtofloat(Edit1.text)*LTa*sqr(Gd)/Rhyd/1.2 +(1.2*9.81*strtofloat(form8.edit4.text)*sin(strtofloat(Edit8.text)));
{Ans}
Edit6.text:=floattostr(DeltaPc);
{5.Electrical power of blower}
PBc:=strtofloat(Edit3.text)*DeltaPc/strtofloat(Edit9.text);
{Ans}
Edit7.text:=floattostr(PBc);
if messageDLG('Do you wish to proceed calculation of the Drying Time?',MTinformation,[MByes, MBNo],0)=MRyes then
begin
Form10.show;
Form9.hide;
end;
end;

procedure TForm9.SpeedButton1Click(Sender: TObject);
begin
Form8.show;
Form9.hide;

end;

procedure TForm9.Button3Click(Sender: TObject);
begin
Table1.edit;
Edit2.text:=table1DHyd.asstring;
Edit9.text:=table1BMEff.asstring;
Edit5.text:=table1TAirL.asstring;
Edit6.text:=table1Cdp.asstring;
Edit7.text:=table1CFanPr.asstring;

end;

procedure TForm9.SpeedButton2Click(Sender: TObject);
begin
form10.show;
form9.hide;
end;

end.
```

unit Unit10;

```
interface

uses
  Windows, Messages, SysUtils, Classes, Graphics, Controls, Forms, Dialogs,
  StdCtrls, Buttons, DB, DBTables;

type
  TForm10 = class(TForm)
    Button1: TButton;
    SpeedButton1: TSpeedButton;
    Table1: TTable;
    DataSource1: TDataSource;
    Table1Mt: TFloatField;
    Table1S: TFloatField;
    Button2: TButton;
    Button3: TButton;
    Table2: TTable;

    DataSource2: TDataSource;
        Table2TypdrMat: TStringField;
        Table2InitMC: TFloatField;
        Table2FinMC: TFloatField;
        Table2DrTmp: TFloatField;
        Table2AmbTmp: TFloatField;
        Table2AmbMC: TFloatField;
        Table2AmbRH: TFloatField;
        Table2BachCap: TFloatField;
        Table2DrTime: TFloatField;
        Table2Mw: TFloatField;
        Table2CoutTmp: TFloatField;
        Table2BoutRH: TFloatField;
        Table2BoutMC: TFloatField;
        Table2BoutTmp: TFloatField;
        Table2AirFlRt: TFloatField;
        Table2HtrPr: TFloatField;
        Table2BAirSpd: TFloatField;
        Table2ArFrac: TFloatField;
        Table2FL: TFloatField;
        Table2FH: TFloatField;
        Table2Fthk: TFloatField;
        Table2FAveWt: TFloatField;
        Table2BLW: TFloatField;
        Table2BH: TFloatField;
        Table2TL: TFloatField;
        Table2TW: TFloatField;
        Table2Tthk: TFloatField;
        Table2NFBL: TFloatField;
        Table2NFBW: TFloatField;
        Table2NFBH: TFloatField;
        Table2GBL: TFloatField;
        Table2GBW: TFloatField;
        Table2DMonth: TFloatField;
        Table2LatAng: TFloatField;
        Table2AveRadJ: TFloatField;
        Table2AzAng: TFloatField;
        Table2AveInsW: TFloatField;
        Table2DecAng: TFloatField;
        Table2OptAng: TFloatField;
        Table2Ih67: TFloatField;
        Table2Ih78: TFloatField;
        Table2Ih89: TFloatField;
        Table2Ih910: TFloatField;
        Table2Ih1011: TFloatField;
        Table2Ih1112: TFloatField;
        Table2Rb67: TFloatField;
        Table2Rb78: TFloatField;
        Table2Rb89: TFloatField;
        Table2Rb910: TFloatField;
        Table2Rb1011: TFloatField;
        Table2Rb1112: TFloatField;
        Table2Kt67: TFloatField;
        Table2Kt78: TFloatField;
        Table2Kt89: TFloatField;
        Table2Kt910: TFloatField;
        Table2Kt1011: TFloatField;
        Table2Kt1112: TFloatField;
        Table2IdIh67: TFloatField;
        Table2IdIh78: TFloatField;
        Table2IdIh89: TFloatField;
        Table2IdIh910: TFloatField;
        Table2IdIh1011: TFloatField;
        Table2IdIh1112: TFloatField;
        Table2Ic67: TFloatField;
        Table2Ic78: TFloatField;
        Table2Ic89: TFloatField;
        Table2Ic910: TFloatField;
        Table2Ic1011: TFloatField;
        Table2Ic1112: TFloatField;
        Table2TAProd: TFloatField;
        Table2H: TFloatField;
        Table2CEff: TFloatField;
        Table2CAr: TFloatField;
        Table2CorCAr: TFloatField;
        Table2CorCEffA: TFloatField;
        Table2Lc: TFloatField;
        Table2Wc: TFloatField;
        Table2Dc: TFloatField;
        Table2VolFlo: TFloatField;
        Table2F: TFloatField;
        Table2CAirFlo: TFloatField;
        Table2Re: TFloatField;
        Table2Nu: TFloatField;
        Table2HAct: TFloatField;
        Table2CorCEffh: TFloatField;
        Table2W: TFloatField;
        Table2AirDen: TFloatField;
        Table2BMEff: TFloatField;
        Table2Bdp: TFloatField;
        Table2BFanPr: TFloatField;
        Table2Lc1: TFloatField;
        Table2Wc1: TFloatField;
        Table2NPases: TFloatField;
        Table2PMeter: TFloatField;
        Table2NLc: TFloatField;
        Table2NWc: TFloatField;
        Table2NPMeter: TFloatField;
        Table2DHyd: TFloatField;
        Table2TAirL: TFloatField;
        Table2Cdp: TFloatField;
        Table2CFanPr: TFloatField;
        Table2BatCap: TFloatField;
        Table2MasFlo: TFloatField;
        Table2Int: TFloatField;
        Table2LstMC: TFloatField;
        Table2DrSeason: TStringField;
        Table2CAirVel: TFloatField;
        Table2CorEffh: TFloatField;
        Table2CoutTemp: TFloatField;
        Table2Run: TFloatField;

    Button5: TButton;
      Button6: TButton;
      GroupBox1: TGroupBox;
    Label3: TLabel;
      Label9: TLabel;
      Label8: TLabel;
      Label7: TLabel;
      Label6: TLabel;
    Label5: TLabel;
    Label11: TLabel;
    Label4: TLabel;
    Label2: TLabel;
    Label1: TLabel;
    Edit1: TEdit;
    Edit2: TEdit;
    Edit3: TEdit;
    Edit11: TEdit;
    Edit4: TEdit;
    Edit5: TEdit;
    Edit6: TEdit;
    Edit7: TEdit;
    Edit8: TEdit;
    Edit9: TEdit;

    GroupBox2: TGroupBox;
      Edit10: TEdit;
      Label10: TLabel;
      procedure SpeedButton1Click(Sender: TObject);
      procedure Button1Click(Sender: TObject);
      procedure Button2Click(Sender: TObject);
      procedure Button3Click(Sender: TObject);
      procedure Button4Click(Sender: TObject);
      procedure Button5Click(Sender: TObject);
      procedure Button6Click(Sender: TObject);
    private
      { Private declarations }
    public
      { Public declarations }
    end;

  var
  Form10: TForm10;
  n,Delta,Beta,Phi,Gama,CosThetah67,sum,CosThetah78,CosThetah89,CosThetah910,CosThetah1011,CosThetah1112,CosThetah1213,CosThetah1314,
  CosThetah1415,CosThetah1516,CosThetah1617,CosThetah1718,
  Ih67,Ih78,Ih89,Ih910,Ih1011,Ih1112,Ih1213,Ih1314,Ih1415,Ih1516,Ih1617,Ih1718,
  CosTheta67,CosTheta78,CosTheta89,CosTheta910,CosTheta1011,CosTheta1112,CosTheta1213,CosTheta1314,CosTheta1415,CosTheta1516,CosTheta1617,CosTheta1718,
  Io67,Io78,Io89,Io910,Io1011,Io1112,Io1213,Io1314,Io1415,Io1516,Io1617,Io1718,
  Kt67,Kt78,Kt89,Kt910,Kt1011,Kt1112,Kt1213,Kt1314,Kt1415,Kt1516,Kt1617,Kt1718,
  i67,i78,i89,i910,i1011,i1112,i1213,i1314,i1415,i1516,i1617,i1718,
  Rb67,Rb78,Rb89,Rb910,Rb1011,Rb1112,Rb1213,Rb1314,Rb1415,Rb1516,Rb1617,Rb1718,
  Ic67,Ic78,Ic89,Ic910,Ic1011,Ic1112,Ic1213,Ic1314,Ic1415,Ic1516,Ic1617,Ic1718,Icave:double;
  sq: integer;
  implementation

  uses Unit9, Solar, water, air, binsize, CollArea, projDim, pressuredrop,
    Unit8;

  {$R *.DFM}
```

```
procedure TForm10.SpeedButton1Click(Sender: TObject);
begin
Form9.show;
Form10.hide;
end;

procedure TForm10.Button1Click(Sender: TObject);
var TcTa67,TcTa78,TcTa89,TcTa910,TcTa1011,TcTa1112,TcTa1213,TcTa1314,TcTa1415,TcTa1516,TcTa1617,TcTa1718,
WoWa67,WoWa78,WoWa89,WoWa910,WoWa1011,WoWa1112,WoWa1213,WoWa1314,WoWa1415,WoWa1516,WoWa1617,WoWa1718,
dM67,dM78,dM89,dM910,dM1011,dM1112,dM1213,dM1314,dM1415,dM1516,dM1617,dM1718,
Mt:double;
begin

{1.Energy balance for solar Collector
Energy into collector = Energy into air from collector}
TcTa67:=strtofloat(edit6.text)*(strtofloat(form4.edit28.text)/3600)*(strtofloat(Edit7.text)/(strtofloat(Edit4.text)*1206));
showmessage('IC67 is '+form4.edit28.text);
showmessage('TcTa67 is '+floattostr(TcTa67));
TcTa78:=strtofloat(edit6.text)*(strtofloat(form4.edit29.text)/3600)*(strtofloat(Edit7.text)/(strtofloat(Edit4.text)
*1206));
TcTa89:=strtofloat(edit6.text)*(strtofloat(form4.edit30.text)/3600)*(strtofloat(Edit7.text)/(strtofloat(Edit4.text)
*1206));
TcTa910:=strtofloat(edit6.text)*(strtofloat(form4.edit31.text)/3600)*(strtofloat(Edit7.text)/(strtofloat(Edit4.text)
*1206));
TcTa1011:=strtofloat(edit6.text)*(strtofloat(form4.edit32.text)/3600)*(strtofloat(Edit7.text)/(strtofloat(Edit4.text)
*1206));
TcTa1112:=strtofloat(edit6.text)*(strtofloat(form4.edit33.text)/3600)*(strtofloat(Edit7.text)/(strtofloat(Edit4.text)
*1206));

TcTa1213:=TcTa1112;
TcTa1314:=TcTa1011;
TcTa1415:=TcTa910;
TcTa1516:=TcTa89;
TcTa1617:=TcTa78;
TcTa1718:=TcTa67;

{2.Energy balance for fish bed
Energy in the air = energy used to evaporate water from the bed}
WoWa67:=1005*((TcTa67)-strtofloat(edit11.text)+strtofloat(edit2.text))/2300000;
WoWa78:=1005*((TcTa78)-strtofloat(edit11.text)+strtofloat(edit2.text))/2300000;
WoWa89:=1005*((TcTa89)-strtofloat(edit11.text)+strtofloat(edit2.text))/2300000;
WoWa910:=1005*((TcTa910)-strtofloat(edit11.text)+strtofloat(edit2.text))/2300000;
WoWa1011:=1005*((TcTa1011)-strtofloat(edit11.text)+strtofloat(edit2.text))/2300000;
WoWa1112:=1005*((TcTa1112)-strtofloat(edit11.text)+strtofloat(edit2.text))/2300000;

WoWa1213:=WoWa1112;
WoWa1314:=WoWa1011;
WoWa1415:=WoWa910;
WoWa1516:=WoWa89;
WoWa1617:=WoWa78;
WoWa1718:=WoWa67;

{3.Moisture balance}
dM67:=(strtofloat(edit4.text)*(WoWa67)*3600)/strtofloat(Edit1.text);
dM78:=(strtofloat(edit4.text)*(WoWa78)*3600)/strtofloat(Edit1.text);
dM89:=(strtofloat(edit4.text)*(WoWa89)*3600)/strtofloat(Edit1.text);
dM910:=(strtofloat(edit4.text)*(WoWa910)*3600)/strtofloat(Edit1.text);
dM1011:=(strtofloat(edit4.text)*(WoWa1011)*3600)/strtofloat(Edit1.text);
dM1112:=(strtofloat(edit4.text)*(WoWa1112)*3600)/strtofloat(Edit1.text);

dM1213:=dM1112;
dM1314:=dM1011;
dM1415:=dM910;
dM1516:=dM89;
dM1617:=dM78;
dM1718:=dM67;

{4.Moisture content - Finite Difference Approach}
sq:=0;
t:=(strtofloat(Edit8.text)/100);
table1.edit;
table1.insert;
table1mt.value:=mt;
table1s.value:=sq;
sq:=sq+1;
table1.post;
Mt:=(strtofloat(Edit8.text)/100)-dM67;
table1.edit;
table1.insert;
table1mt.value:=mt;
table1s.value:=sq;
sq:=sq+1;
table1.post;
```

```
while ((Mt)>=(strtofloat(edit9.text)/100)) do
begin
Mt:=Mt-dM78;
table1.edit;
table1.insert;
table1mt.value:=mt;
table1s.value:=sq;
sq:=sq+1;
table1.post;

if (Mt)>=(strtofloat(edit9.text)/100) then
begin
Mt:=Mt-dM89;
table1.edit;
table1.insert;
table1mt.value:=mt;
table1s.value:=sq;
sq:=sq+1;
table1.post;
end;

if (Mt)>=(strtofloat(edit9.text)/100) then
begin
Mt:=Mt-dM910;
table1.edit;
table1.insert;
table1mt.value:=mt;
table1s.value:=sq;
sq:=sq+1;
table1.post;
end;

if (Mt)>=(strtofloat(edit9.text)/100) then
begin
Mt:=Mt-dM1011;
table1.edit;
table1.insert;
table1mt.value:=mt;
table1s.value:=sq;
sq:=sq+1;
table1.post;
end;

if (Mt)>=(strtofloat(edit9.text)/100) then
begin
Mt:=Mt-dM1112;
table1.edit;
table1.insert;
table1mt.value:=mt;
table1s.value:=sq;
sq:=sq+1;
table1.post;
end;

if (Mt)>=(strtofloat(edit9.text)/100) then
begin
Mt:=Mt-dM1213;
table1.edit;
table1.insert;
table1mt.value:=mt;
table1s.value:=sq;
sq:=sq+1;
table1.post;
end;

if (Mt)>=(strtofloat(edit9.text)/100) then
showmessage('The value of Mt is '+floattostr(Mt));
end;
Edit10.text:=floattostr(Mt);

end;

procedure TForm10.Button2Click(Sender: TObject);
```

```
begin
Mt:=Mt-dM1314;
table1.edit;
table1.insert;
table1mt.value:=mt;
table1s.value:=sq;
sq:=sq+1;
table1.post;
end;

if (Mt)>=(strtofloat(edit9.text)/100) then
begin
Mt:=Mt-dM1415;
table1.edit;
table1.insert;
table1mt.value:=mt;
table1s.value:=sq;
sq:=sq+1;
table1.post;
end;

if (Mt)>=(strtofloat(edit9.text)/100) then
begin
Mt:=Mt-dM1516;
table1.edit;
table1.insert;
table1mt.value:=mt;
table1s.value:=sq;
sq:=sq+1;
table1.post;
end;

if (Mt)>=(strtofloat(edit9.text)/100) then
begin
Mt:=Mt-dM1617;
table1.edit;
table1.insert;
table1mt.value:=mt;
table1s.value:=sq;
sq:=sq+1;
table1.post;
end;

if (Mt)>=(strtofloat(edit9.text)/100) then
begin
Mt:=Mt-dM1718;
table1.edit;
table1.insert;
table1mt.value:=mt;
table1s.value:=sq;
sq:=sq+1;
table1.post;
end;

if (Mt)>=(strtofloat(edit9.text)/100) then
begin
Mt:=Mt-dM67;
table1.edit;
table1.insert;
table1mt.value:=mt;
table1s.value:=sq;
sq:=sq+1;
table1.post;
end;
```

```
begin
table1.edit;
table1.active:=false;
table1.emptytable;
table1.active:=true;
end;

procedure TForm10.Button3Click(Sender: TObject);
begin
table2.edit;
table2.insert;

table2typdrmat.value:=form1.edit1.text;
table2InitMC.value:=strtofloat(form1.edit2.text);
table2FinMC.value:=strtofloat(form1.edit3.text);
table2Drtmp.value:=strtofloat(form1.edit4.text);
table2Ambtmp.value:=strtofloat(form1.edit5.text);
table2AmbMC.value:=strtofloat(form1.edit6.text);
table2AmbRH.value:=strtofloat(form1.edit7.text);
table2BachCap.value:=strtofloat(form1.edit8.text);
table2DrTime.value:=strtofloat(form1.edit9.text);
table2drSeason.value:=form1.edit10.text;
table2run.value:=strtoint(form1.edit12.text);
{Outputs}
table2Mw.value:=strtofloat(form1.edit11.text);
 {Inputs}
table2CoutTmp.value:=strtofloat(form2.edit4.text);
table2BoutRH.value:=strtofloat(form2.edit5.text);table1.edit
;
table2BoutMC.value:=strtofloat(form2.edit6.text);
table2BoutTmp.value:=strtofloat(form2.edit7.text);
{Outputs}
table2AirFlRt.value:=strtofloat(form2.edit8.text);
table2HtrPr.value:=strtofloat(form2.edit9.text);
{Inputs}
table2BAirSpd.value:=strtofloat(form3.edit2.text);
table2ArFrac.value:=strtofloat(form3.edit3.text);
table2FL.value:=strtofloat(form3.edit5.text);
table2FH.value:=strtofloat(form3.edit6.text);
table2Fthk.value:=strtofloat(form3.edit7.text);
table2FAveWt.value:=strtofloat(form3.edit4.text);
{Outputs}
table2BLW.value:=strtofloat(form3.edit8.text);
table2BH.value:=strtofloat(form3.edit9.text);
table2TL.value:=strtofloat(form3.edit10.text);
table2TW.value:=strtofloat(form3.edit11.text);
table2Tthk.value:=strtofloat(form3.edit12.text);
table2NFBL.value:=strtofloat(form3.edit1.text);
table2NFBW.value:=strtofloat(form3.edit13.text);
table2NFBH.value:=strtofloat(form3.edit14.text);
table2GBL.value:=strtofloat(form3.edit15.text);
table2GBW.value:=strtofloat(form3.edit16.text);
{Inputs}
table2.edit;
table2DMonth.value:=strtofloat(form4.edit1.text);
table2LatAng.value:=strtofloat(form4.edit2.text);
table2AveRadJ.value:=strtofloat(form4.edit3.text);
table2AzAng.value:=strtofloat(form4.edit4.text);
table2AveInsW.value:=strtofloat(form4.edit5.text);
table2DecAng.value:=strtofloat(form4.edit6.text);
table2OptAng.value:=strtofloat(form4.edit7.text);
{Outputs}
table2Ih67.value:=strtofloat(Form4.edit10.text);
table2Ih78.value:=strtofloat(Form4.edit11.text);
table2Ih89.value:=strtofloat(Form4.edit12.text);
table2Ih910.value:=strtofloat(Form4.edit13.text);
table2Ih1011.value:=strtofloat(Form4.edit14.text);
table2Ih1112.value:=strtofloat(Form4.edit15.text);

table2Rb67.value:=strtofloat(Form4.edit16.text);
table2Rb78.value:=strtofloat(Form4.edit17.text);
table2Rb89.value:=strtofloat(Form4.edit18.text);
table2Rb910.value:=strtofloat(Form4.edit19.text);
table2Rb1011.value:=strtofloat(Form4.edit20.text);
table2Rb1112.value:=strtofloat(Form4.edit21.text);

table2Kt67.value:=strtofloat(Form4.edit22.text);
table2Kt78.value:=strtofloat(Form4.edit23.text);
table2Kt89.value:=strtofloat(Form4.edit24.text);
table2Kt910.value:=strtofloat(Form4.edit25.text);
table2Kt1011.value:=strtofloat(Form4.edit26.text);
table2Kt1112.value:=strtofloat(Form4.edit27.text);

table2IdIh67.value:=strtofloat(Form4.edit34.text);
table2IdIh78.value:=strtofloat(Form4.edit35.text);
table2IdIh89.value:=strtofloat(Form4.edit36.text);
table2IdIh910.value:=strtofloat(Form4.edit37.text);
table2IdIh1011.value:=strtofloat(Form4.edit38.text);
table2IdIh1112.value:=strtofloat(Form4.edit39.text);

table2Ic67.value:=strtofloat(Form4.edit28.text);
table2Ic78.value:=strtofloat(Form4.edit29.text);
table2Ic89.value:=strtofloat(Form4.edit30.text);
table2Ic910.value:=strtofloat(Form4.edit31.text);
table2Ic1011.value:=strtofloat(Form4.edit32.text);
table2Ic1112.value:=strtofloat(Form4.edit33.text);
{Inputs}
table2MasFlo.value:=strtofloat(Form5.edit1.text);
table2Ambtmp.value:=strtofloat(Form5.edit2.text);
table2CoutTemp.value:=strtofloat(Form5.edit3.text);
table2TAProd.value:=strtofloat(Form5.edit4.text);
table2AveInsW.value:=strtofloat(Form5.edit5.text);
table2h.value:=strtofloat(Form5.edit10.text);
{Outputs}
table2CEff.value:=strtofloat(Form5.edit6.text);
table2CAr.value:=strtofloat(Form5.edit7.text);
table2CorCAr.value:=strtofloat(Form5.edit8.text);
table2CorCEffA.value:=strtofloat(Form5.edit9.text);
{Inputs}
table2Lc.value:=strtofloat(Form6.edit1.text);
table2Wc.value:=strtofloat(Form6.edit2.text);
table2dc.value:=strtofloat(Form6.edit3.text);
table2VolFlo.value:=strtofloat(Form6.edit4.text);
table2f.value:=strtofloat(Form6.edit5.text);
{Outputs}
table2CAirVel.value:=strtofloat(Form6.edit6.text);
table2Re.value:=strtofloat(Form6.edit7.text);
table2Nu.value:=strtofloat(Form6.edit8.text);
table2hAct.value:=strtofloat(Form6.edit9.text);
table2CorCEffh.value:=strtofloat(Form6.edit10.text);
{Inputs}
table2.edit;
table2BH.value:=strtofloat(Form7.edit1.text);
table2w.value:=strtofloat(Form7.edit2.text);
table2Airden.value:=strtofloat(Form7.edit3.text);
table2BAirSpd.value:=strtofloat(Form7.edit4.text);
table2BMEff.value:=strtofloat(Form7.edit6.text);
{Outputs}
table2Bdp.value:=strtofloat(Form7.edit7.text);
table2BFanPr.value:=strtofloat(Form7.edit8.text);
{Inputs}
table2Lc1.value:=strtofloat(Form8.edit1.text);
table2Wc1.value:=strtofloat(Form8.edit2.text);
table2NPases.value:=strtofloat(Form8.edit3.text);
table2PMeter.value:=strtofloat(Form8.edit7.text);
{Outputs}
table2NLc.value:=strtofloat(Form8.edit4.text);
table2NWc.value:=strtofloat(Form8.edit5.text);
table2NPMeter.value:=strtofloat(Form8.edit6.text);
{Inputs}
table2DHyd.value:=strtofloat(Form9.edit2.text);
table2BMEff.value:=strtofloat(Form9.edit9.text);
{Outputs}
table2TAirL.value:=strtofloat(Form9.edit5.text);
table2Cdp.value:=strtofloat(Form9.edit6.text);
table2CFanPr.value:=strtofloat(Form9.edit7.text);
table2batcap.value:=strtofloat(edit1.text);
table2AmbTmp.value:=strtofloat(edit2.text);
table2CoutTmp.value:=strtofloat(edit3.text);
table2BoutTmp.value:=strtofloat(edit11.text);
table2MasFlo.value:=strtofloat(edit4.text);
table2Int.value:=strtofloat(edit5.text);
table2CEff.value:=strtofloat(edit6.text);
table2Car.value:=strtofloat(edit7.text);
table2InitMC.value:=strtofloat(edit8.text);
table2FinMC.value:=strtofloat(edit9.text);
table2LstMC.value:=strtofloat(edit10.text);
table2.post;
table2.edit;

showmessage('Posted');

end;
procedure TForm10.Button4Click(Sender: TObject);
begin
Table2.edit;

Edit1.text:=table2Batcap.asstring;
Edit2.text:=table2AmbTmp.asstring;
Edit3.text:=table2CoutTmp.asstring;
Edit11.text:=table2BoutTmp.asstring
;
Edit4.text:=table2MasFlo.asstring;
Edit5.text:=table2Int.asstring;
Edit6.text:=table2CEff.asstring;
Edit7.text:=table2CAr.asstring;
Edit8.text:=table2InitMC.asstring;
Edit9.text:=table2FinMC.asstring;
Edit10.text:=table2LstMC.asstring;

end;

procedure TForm10.Button5Click(Sender: TObject);
begin
table2.edit;
table2.active:=false;
table2.emptytable;
table2.active:=true;
showmessage('Table Emptied')
end;
procedure TForm10.Button6Click(Sender: TObject);
begin
Application.terminate;
end;

end
```

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unit Cost;

```
interface

uses
  Windows, Messages, SysUtils, Classes,
Graphics, Controls, Forms, Dialogs,
  StdCtrls, Buttons, DB, DBTables;

type
  TForm1 = class(TForm)
    GroupBox1: TGroupBox;
    Label19: TLabel;
    Label22: TLabel;
    Label25: TLabel;
    Edit19: TEdit;
    Edit22: TEdit;
    Edit25: TEdit;
    Label20: TLabel;
    Label23: TLabel;
    Label26: TLabel;
    Edit26: TEdit;
    Edit23: TEdit;
    Edit20: TEdit;
    Label21: TLabel;
    Label24: TLabel;
    Label27: TLabel;
    Edit27: TEdit;
    Edit24: TEdit;
    Edit21: TEdit;
    Label1: TLabel;
    Label3: TLabel;
    Label5: TLabel;
    Label7: TLabel;
    Label45: TLabel;
    Label9: TLabel;
    Label11: TLabel;
    Label13: TLabel;
    Label15: TLabel;
    Label17: TLabel;
    Edit1: TEdit;
    Edit3: TEdit;
    Edit5: TEdit;
    Edit7: TEdit;
    Edit42: TEdit;
    Edit9: TEdit;
    Edit11: TEdit;
    Edit13: TEdit;
    Edit15: TEdit;
    Edit17: TEdit;
    Label18: TLabel;
    Label16: TLabel;
    Label14: TLabel;
    Label12: TLabel;
    Label10: TLabel;
    Label46: TLabel;
    Label8: TLabel;
    Label6: TLabel;
    Label4: TLabel;
    Label2: TLabel;
    Edit2: TEdit;
    Edit4: TEdit;
    Edit6: TEdit;
    Edit8: TEdit;
    Edit43: TEdit;
    Edit10: TEdit;
    Edit12: TEdit;
    Edit14: TEdit;
    Edit16: TEdit;
    Edit18: TEdit;
    GroupBox2: TGroupBox;
    Edit28: TEdit;
    Edit29: TEdit;
    Edit30: TEdit;
    Edit31: TEdit;
    Edit32: TEdit;
    Edit33: TEdit;
    Edit34: TEdit;
    Edit35: TEdit;
    Edit36: TEdit;
    Edit37: TEdit;
    Edit38: TEdit;
    Edit39: TEdit;
    Edit40: TEdit;
    Edit41: TEdit;
    Label28: TLabel;
    Label29: TLabel;
    Label30: TLabel;
    Label31: TLabel;
    Label32: TLabel;
    Label33: TLabel;
    Label34: TLabel;
    Label35: TLabel;
    Label36: TLabel;
    Label37: TLabel;
    Label38: TLabel;
    Label39: TLabel;
    Label40: TLabel;
    Label41: TLabel;
    Button1: TButton;
    SpeedButton1: TSpeedButton;

procedure Button1Click(Sender: TObject);
    procedure SpeedButton1Click(Sender: TObject);
  private
    { Private declarations }
  public
    { Public declarations }
  end;

var
  Form1: TForm1;

implementation

uses Capinv;
{$R *.DFM}

procedure TForm1.Button1Click(Sender: TObject);
Var Lcf,Nscf,Ccf,Aap,Nspt,Cap,Aci,Nsci,Cci,Absp,Nbsp,Cbsp,Ci,Acc,Nscc,Ccc,
Lbf,Nslb,Cbf,Ash,Nss,Cs,Abi,Nsbi,Cbi,
Ltw,Amsh,Nsw,Nsmsh,Ctwr,Ctmsh:double;
begin


{SOLAR COLLECTOR}
{1. Frame}
{Length of Frame}
Lcf:=(4*(strtofloat(Edit19.text)+strtofloat(Edit20.text)
+strtofloat(Edit21.text)));
{No. of required Standard lengths}
Nscf:=(4*(strtofloat(Edit19.text)+strtofloat(Edit20.text)
+strtofloat(Edit21.text)))/strtofloat(Edit1.text);
{Cost of Frame}
Ccf:=Nscf*(Strtofloat(Edit2.text));
{Answer}
Edit28.text:=floattostr(Ccf);

{2. Absorber Plate}
{Required Area}
Aap:= (strtofloat(Edit19.text)*strtofloat(Edit20.text));
{No. of standard plates required}
Nspt:=(Aap/strtofloat(Edit3.text));
{Cost of Absorber plate}
Cap:=(Nspt*strtofloat(edit4.text));
{Answer}
Edit29.text:=floattostr(Cap);

{3. Insulation}
{Required Area}
Aci:= ((2*strtofloat(edit19.text)*strtofloat(edit21.text))
+(2*strtofloat(edit20.text)*strtofloat(edit21.text))
+(strtofloat(edit19.text)*strtofloat(Edit20.text)));
{No. of standard pieces required}
Nsci:=(Aci/strtofloat(edit7.text));
{Cost of Insulation}
Cci:=(Nsci*strtofloat(edit8.text));
{Answer}
Edit31.text:=floattostr(Cci);
{4. Collector back / Side plate}
{Area of Back/side plate}
Absp:=((2*strtofloat(edit19.text)*strtofloat(edit21.text))
+(2*strtofloat(edit20.text)*strtofloat(Edit21.text))
+(strtofloat(edit19.text)*strtofloat(edit20.text)));
{No. of plates required}
Nbsp:=(Absp/strtofloat(edit5.text));
{Cost of back/side plate}
Cbsp:=(Nbsp*strtofloat(edit6.text));
{answer}
Edit30.text:=floattostr(Cbsp);
```

```
{5. Collector Cover}
{Area of Cover}
Acc:=(strtofloat(Edit19.text)*strtofloat(Edit20.text));
{Number of standard covers needed}
Nscc:=(Acc/strtofloat(edit42.text));
{Cost of cover}
Ccc:=(Nscc*strtofloat(edit43.text));
{Answer}
Edit41.text:=floattostr(Ccc);

{Collector Cost}
Edit37.text:=floattostr(Ccf+Cap+Cci+Cbsp+Ccc);

{B. DRYING BIN}
{1.Bin Frame}
{Required length for bin frame}
Lbf:=(4*(strtofloat(edit22.text)+strtofloat(edit23.text)
+strtofloat(edit24.text)));
{No. of standard lengths required}
Nslb:=Lbf/strtofloat(edit9.text);
{Cost of Bin frame}
Cbf:=Nslb*strtofloat(edit10.text);
{Answer}
Edit32.text:=floattostr(Cbf);

{2.Covering sheet}
{Required area of sheet}
Ash:=(4*((strtofloat(edit23.text)*strtofloat(edit24.text))
+(strtofloat(Edit22.text)*strtofloat(edit24.text))
+(strtofloat(edit22.text)*strtofloat(edit23.text))));
{No. of standard sheets required}
Nss:=(Ash/strtofloat(edit11.text));
{Cost of sheet}
Cs:=(Nss*strtofloat(edit12.text));
{Answer}
Edit33.text:=floattostr(Cs);

{3.Bin Insulation}
{Area of insulation required}
Abi:=(2*((strtofloat(edit23.text)*strtofloat(Edit24.text))
+(strtofloat(edit22.text)*strtofloat(edit24.text))
+(strtofloat(edit22.text)*strtofloat(edit23.text))));
{No. of standard pieces required}
Nsbi:=(Abi/strtofloat(edit13.text));
{Cost of bin insulation}
Cbi:=(Nsbi*strtofloat(edit14.text));
{Answer}
Edit34.text:=floattostr(Cbi);
{Cost of bin}
Edit38.text:=floattostr(Cbf+Cs+Cbi);

{C.TRAYS}
{1.Length of tray frame material required (wire)}
Ltw:=(10*((strtofloat(edit25.text)+strtofloat(edit26.text)
+strtofloat(edit27.text))));

{2.Required area of wire mesh}
Amsh:=(2*((strtofloat(edit25.text)*strtofloat(edit26.text))
+(strtofloat(edit25.text)*strtofloat(edit27.text))
+(strtofloat(edit26.text)*strtofloat(edit27.text))));

{3.Number of standard lengths for frame material (wire)}
Nsw:=(Ltw/strtofloat(edit15.text));

{4. Number of standard wire mesh areas required}
Nsmsh:=(Amsh/strtofloat(edit17.text));

{5.Cost of frame material (wire)}
Ctwr:=(Nsw*strtofloat(edit16.text));
{Answer}
Edit35.text:=floattostr(Ctwr);

{6.Cost of wire mesh}
Ctmsh:=(Nsmsh*strtofloat(edit18.text));
{Answer}
Edit36.text:=floattostr(Ctmsh);

{Cost of tray}
Edit39.text:=floattostr(Ctwr+Ctmsh);

{Total Dryer cost}
Edit40.text:=floattostr(Ccf+Cap+Cci+Cbsp+Ccc+Cbf+Cs+Cbi+Ctwr+Ctmsh);

Form2.edit1.text:=(edit40.text);
end;

procedure TForm1.SpeedButton1Click(Sender: TObject);
begin
Form2.show;
Form1.hide;
end;

end.
```

unit Capinv;

```
interface

uses
 Windows, Messages, SysUtils, Classes, Graphics, Controls, Forms, Dialogs,
 StdCtrls, math, Buttons, DB, DBTables ;

type
 TForm2 = class(TForm)
  Table1: TTable;
  Table1ColL: TFloatField;
  Table1ColW: TFloatField;
  Table1ColD: TFloatField;
  Table1BinL: TFloatField;
  Table1BinW: TFloatField;
  Table1BinH: TFloatField;
  Table1TrL: TFloatField;
  Table1TrW: TFloatField;
  Table1Trth: TFloatField;
  Table1SLCf: TFloatField;
  Table1SACap: TFloatField;
  Table1SAbsp: TFloatField;
  Table1SACI: TFloatField;
  Table1SACCov: TFloatField;
  Table1SLBf: TFloatField;
  Table1SABCov: TFloatField;
  Table1SABI: TFloatField;
  Table1SLTr: TFloatField;
  Table1SAMsh: TFloatField;
  Table1CSLCf: TFloatField;
  Table1CSACap: TFloatField;
  Table1CSAbsp: TFloatField;
  Table1CSACI: TFloatField;
  Table1CSACCov: TFloatField;
  Table1CSLBf: TFloatField;
  Table1CSABCov: TFloatField;
  Table1CSABI: TFloatField;
  Table1CSLTr: TFloatField;
  Table1CSAMsh: TFloatField;
  Table1CCFrame: TFloatField;
  Table1CAbsPt: TFloatField;
```

```
    Table1CbsPt: TFloatField;
    Table1CCIns: TFloatField;
    Table1CColCov: TFloatField;
    Table1ColCost: TFloatField;
    Table1CBFrame: TFloatField;
    Table1CCovSht: TFloatField;
    Table1CBIns: TFloatField;
    Table1BinCost: TFloatField;
    Table1CTrFrame: TFloatField;
    Table1CMsh: TFloatField;
    Table1TrayCost: TFloatField;
    Table1TotlCost: TFloatField;
    Table1CAirDuct: TFloatField;
    Table1CBlower: TFloatField;
    Table1CLabour: TFloatField;
    Table1CE: TFloatField;
    Table1OpDays: TFloatField;
    Table1DrdP: TFloatField;
    Table1FlRate: TFloatField;
    Table1OpHrs: TFloatField;
    Table1IntRt: TFloatField;
    Table1DrLife: TFloatField;
    Table1EvM: TFloatField;
    Table1CI: TFloatField;
    Table1DPC: TFloatField;
    Table1SFF: TFloatField;
    Table1SV: TFloatField;
    Table1DSV: TFloatField;
    Table1CRF: TFloatField;
    Table1DC: TFloatField;
    Table1DCperDEM: TFloatField;
    DataSource1: TDataSource;
    GroupBox1: TGroupBox;
    Label1: TLabel;
    Label2: TLabel;
    Label3: TLabel;
    Label4: TLabel;
    Label5: TLabel;
    Edit5: TEdit;
    Edit4: TEdit;
    Edit3: TEdit;
    Edit2: TEdit;
    Edit1: TEdit;
    Label6: TLabel;
    Label7: TLabel;
    Label8: TLabel;
    Label9: TLabel;
    Label10: TLabel;
    Edit10: TEdit;
    Edit9: TEdit;
    Edit8: TEdit;
    Edit7: TEdit;
    Edit6: TEdit;
    Label11: TLabel;
    Label12: TLabel;
    Edit11: TEdit;
    Edit12: TEdit;
    GroupBox2: TGroupBox;
    Label20: TLabel;
    Edit20: TEdit;
    Label13: TLabel;
    Label14: TLabel;
    Label15: TLabel;
    Label16: TLabel;
    Label17: TLabel;
    Edit17: TEdit;
    Edit16: TEdit;
    Edit15: TEdit;
    Edit14: TEdit;
    Edit13: TEdit;
    Label18: TLabel;
    Label19: TLabel;
    Edit18: TEdit;
    Edit19: TEdit;
    SpeedButton1: TSpeedButton;
    Button2: TButton;
    Button1: TButton;
    Button3: TButton;
    Button4: TButton;
    Label21: TLabel;

  procedure Button1Click(Sender: TObject);
    procedure SpeedButton1Click(Sender: TObject);
    procedure Button2Click(Sender: TObject);
    procedure Button3Click(Sender: TObject);
    procedure Button4Click(Sender: TObject);
  private
    { Private declarations }
  public
    { Public declarations }
  end;

var
  Form2: TForm2;

implementation

uses Cost;

{$R *.DFM}

procedure TForm2.Button1Click(Sender: TObject);
var CI,DPC,CRF,SV,SFF,DSV,DC,DCDME : double;
begin
{Capital Investment(CI)}
CI:=(strtofloat(edit1.text)+strtofloat(edit2.text)+strtofloat(edit3.text)+strtofloat(edit4.text));
{Answer}
Edit20.text:=floattostr(CI);
{Daily Pumping Cost (DPC)}
DPC:= (strtofloat(edit8.text)*strtofloat(edit7.text)*strtofloat(Edit9.text)*strtofloat(Edit5.text))/1.2;
{Answer}
Edit13.text:=floattostr(DPC);
{Sulvage Fund Factor (SFF)}
SFF:=strtofloat(edit10.text)/((Power(strtofloat(edit10.text)+1,strtofloat(edit11.text)))-1);
{Answer}
Edit14.text:=floattostr(SFF);
{Sulvage Value}
SV:=(0.1*CI);
{Answer}
Edit15.text:=floattostr(SV);
{Capital Recovery Factor (CRF)}
CRF:=(Power(strtofloat(edit10.text)+1,(strtofloat(edit11.text)))*SFF);
{Answer}
Edit17.text:=floattostr(CRF);
{Daily Sulvage Value (DSV)}
DSV:=(SFF*SV)/(strtofloat(edit9.text));
{Answer}
Edit16.text:=floattostr(DSV);
{Daily Cost (DC)}
DC:=(DPC-DSV);
{Answer}
Edit18.text:=floattostr(DC);
{Daily Cost per Daily Moisture Evaporated (DCDME)}
DCDME:=DC/(strtofloat(edit12.text));
Edit19.text:=floattostr(DCDME);
end;

procedure TForm2.SpeedButton1Click(Sender: TObject);
begin
Form1.show;
Form2.hide;
end;
```

```
procedure TForm2.Button2Click(Sender: TObject);
begin
Table1.edit;
Table1.insert;

Table1ColL.value:=strtofloat(form1.edit19.text);
Table1ColW.value:=strtofloat(form1.edit20.text);
Table1ColD.value:=strtofloat(form1.edit21.text);

Table1BinL.value:=strtofloat(form1.edit22.text);
Table1BinW.value:=strtofloat(form1.edit23.text);
Table1BinH.value:=strtofloat(form1.edit24.text);

Table1TrL.value:=strtofloat(form1.edit25.text);
Table1TrW.value:=strtofloat(form1.edit26.text);
Table1Trth.value:=strtofloat(form1.edit27.text);

Table1SLCf.value:=strtofloat(form1.edit1.text);
Table1SACap.value:=strtofloat(form1.edit3.text);
Table1SAbsp.value:=strtofloat(form1.edit5.text);
Table1SACI.value:=strtofloat(form1.edit7.text);
Table1SACCov.value:=strtofloat(form1.edit42.text);
Table1SLBf.value:=strtofloat(form1.edit9.text);
Table1SABCov.value:=strtofloat(form1.edit11.text);
Table1SABI.value:=strtofloat(form1.edit13.text);
Table1SLTr.value:=strtofloat(form1.edit15.text);
Table1SAMsh.value:=strtofloat(form1.edit17.text);

Table1CSLCf.value:=strtofloat(form1.edit2.text);
Table1CSACap.value:=strtofloat(form1.edit4.text);
Table1CSAbsp.value:=strtofloat(form1.edit6.text);
Table1CSACI.value:=strtofloat(form1.edit8.text);
Table1CSACCov.value:=strtofloat(form1.edit43.text);
Table1CSLBf.value:=strtofloat(form1.edit10.text);
Table1CSABCov.value:=strtofloat(form1.edit12.text);
Table1CSABI.value:=strtofloat(form1.edit14.text);
Table1CSLTr.value:=strtofloat(form1.edit16.text);
Table1CSAMsh.value:=strtofloat(form1.edit18.text);

Table1CCFrame.value:=strtofloat(form1.edit28.text);
Table1CAbsPt.value:=strtofloat(form1.edit29.text);
Table1CBSPt.value:=strtofloat(form1.edit30.text);
Table1CCIns.value:=strtofloat(form1.edit31.text);
Table1CColCov.value:=strtofloat(form1.edit41.text);
Table1ColCost.value:=strtofloat(form1.edit37.text);

Table1CBFrame.value:=strtofloat(form1.edit32.text);
Table1CCovSht.value:=strtofloat(form1.edit33.text);
Table1CBIns.value:=strtofloat(form1.edit34.text);
Table1BinCost.value:=strtofloat(form1.edit38.text);

Table1CTrFrame.value:=strtofloat(form1.edit35.text);
Table1CMsh.value:=strtofloat(form1.edit36.text);
Table1TrayCost.value:=strtofloat(form1.edit39.text);

Table1TotlCost.value:=strtofloat(form1.edit40.text);

Table1CAirDuct.value:=strtofloat(form2.edit2.text);
Table1CBlower.value:=strtofloat(form2.edit3.text);
Table1CLabour.value:=strtofloat(form2.edit4.text);
Table1CE.value:=strtofloat(form2.edit5.text);

Table1OPDays.value:=strtofloat(form2.edit6.text);
Table1DrdP.value:=strtofloat(form2.edit7.text);
Table1FlRate.value:=strtofloat(form2.edit8.text);
Table1OPHrs.value:=strtofloat(form2.edit9.text);
Table1IntRt.value:=strtofloat(form2.edit10.text);
Table1DrLife.value:=strtofloat(form2.edit11.text);
Table1EvM.value:=strtofloat(form2.edit12.text);

Table1CI.value:=strtofloat(form2.edit20.text);
Table1DPC.value:=strtofloat(form2.edit13.text);
Table1SFF.value:=strtofloat(form2.edit14.text);
Table1SV.value:=strtofloat(form2.edit15.text);
Table1DSV.value:=strtofloat(form2.edit16.text);
Table1CRF.value:=strtofloat(form2.edit17.text);
Table1DC.value:=strtofloat(form2.edit18.text);
Table1DCperDEM.value:=strtofloat(form2.edit19.text);
Table1.post;
showmessage('Posted');

end;

procedure TForm2.Button3Click(Sender: TObject);
begin
Application.terminate;
end;

procedure TForm2.Button4Click(Sender: TObject);
begin
table1.active:=false;
table1.emptytable;
table1.active:=true;
Showmessage('Empty');
end;

end.
```

APPENDIX 8: SAMPLE SISOFID 1 OUTPUT

Determination of Evaporated Water

Type of Drying Material:	Fish		
Initial Moisture Content	85		
Final Moisture Content	15		
Drying Temperature (°C)	55	Amount of Evaporated Water (kg/hr)	
Ambient Temperature (°C)	18	5.14705882352941	
Ambient Moisture Content (kg/kg)	.0062		
Ambient Relative Humidity (%)	47		
Batch Capacity (kg)	300		
Drying Time (Hrs)	48		
Drying Season	October		

Determination of Air Flow rate and Heater Power

Collector outlet Temperature (°C)	55	Air Flow Rate (kg/s)	.108313527431174
Bed outlet Relative Humidity (%)	100	Heater Power (W)	4.35722661665676
Bed outlet Moisture Content (kg/kg)	.0194		
Bed outlet Temperature (°C)	24.5		

Determination of Bin Size

Bin Air Speed (m/s)	1.5	Bin Length / Width (m)	.548517009336118
Area Fraction	.2	Bin Height (m)	2.07852480000001
Fish Length (m)	.3	Tray Length (m)	.548517009336118
Fish Height (m)	.09	Tray Width (m)	.3
		Tray thickness (m)	.0388560958272263
Fish Thickness (m)	.035		
Average Weight of Fish (kg)	.566666666666667		

Number of Fish along Bin Length	5.45120586529087
Number of Fish along Bin Width	14.017386510748
Number of Fish along Bin Height	6.92841600000003
Gap along Bin Length (m)	.00897638095406343
Gap along Bin Width (m)	.00385609582722628

Design of Solar Collector

Day of Month	15	Average Insulation (W)	535.234971916861
Latitude Angle	-15	Declination Angle	-9.59910463850091
Average Radiation (J)	23000000	Optimum Inclination Angle	5.40089536149909
Azimuth Angle	180		
Ih67	492909.771148975	Rb67	1
Ih7	1199741.45925502	Rb78	.980918150828346
Ih910	2350906.12185533	Rb910	1.05710435569373
Ih1011	2716789.12698295	Rbl0ll	1.00317740673002
Ih1112	2906184.10699569	Rblll2	1.00432462068814

Kt67	.594576436227089	Id/ih67	.451469332829781
Kt78	.59483467840624	I/ih78	.450897082284715
Kt89	.594896957436789	Id/ih89	.450759093003137
Kt910	.594922911957268	Id/ih910	.45070158859254
Ktl011	.594935298318453	Id/ihl0ll	.450674145995973
Ktl112	.594940485064179	Id/ihlll2	.450662654585106

Ic67	492634.62900109
Ic78	1186502.51785732
Ic89	1827108.1299089
Ic910	2423339.50540287
Icl0ll	2720019.38099353
Icl112	2911471.23024049

Collector Efficiency

Transmissivity Absorbtivity product	.88
Heat Tranfer Coefficient (W/m^2)	22.7
Collector Efficiency	.555390146061645
Collector Area (m^2)	13.5500029806225
Corrected Collector Area (m^2)	13.5500029806225
Corrected Collector Efficiency for Air flow	.555349790711369l

Determination of Collector Dimensions

Collector Length (m)	14.1959172138	Re	11720.4674000795
Collector Width (m)	.9545	Nu	86.3153235538381
Collector Depth (m)	.05	Hact	22.709204428976
Volumetric Flow (m^3/s)	108313527431174		
Surface Roughness (f)	.07		
Corrected Collector Efficiency for 'h'	.555390146061645		

Determination of Pressure Drop through the Bin **and Required Bin Fan Power**

Specific air resistance (m^{-1})	2000	Bin Pressure Drop (N/m^2)	11224.0339200001
Air Density (kg/m^3)	1.2	Bin Fan Power (W)	3376.98529411765
Blower Motor efficiency	.3		

Determination of Collector Length and Width

Collector Length (m)	14,1959172138	New Collector Length (m)	3.54897930345
Collector Width (m)	.9545	New Collector Width (m)	3.818
Number of Passes	4	New Perimeter Meter (m)	14.7339586069
Perimeter Meter (m)	30.3008344276		

Determination of Pressure Drop through the Collector and Required Collector Fan Power

Hydraulic Diameter (m)	.0950223992035839
Total Airpath Length (m)	17.0594172138

Collector Pressure Drop (N/m^2)	21.6809315370968
Collector Fan Power (W)	7.82779390925581

Drying Curve

Batch Capacity (kg)	300
Mass Flow (kg/s)	.129976232917409
Average Intensity (W/m^2)	535.234971916861
Air Velocity in Collector (m/s)	1.89127863508249
Collector outlet Temperature (°C)	55
Final Moisture Content (%)	.143527977729751

MOISTURE CONTENT	DRYING HOURS
.85	0
.8499524644885	1
.843598492675161	2
.831422175496246	3
.813826822141858	4
.793535000529609	5
.771503108636639	6
.749471216743669	7
.72917939513142	8
.711584041777032	9
.699407724598117	10
.693053752784778	11
.693006217273278	12
.692958681761778	13
.686604709948439	14
.674428392769524	15
.656833039415136	16
.636541217802887	17
.614509325909917	18
.592477434016947	19
.572185612404698	20
.55459025905031	21
.542413941871395	22
.536059970058056	23
.536012434546556	24
.535964899035056	25
.529610927221717	26
.517434610042802	27
.499839256688414	28
.479547435076165	29
.457515543183195	30
.435483651290225	31
.415191829677976	32
.397596476323588	33
.385420159144673	34
.379066187331334	35
.3790186518f9834	36
.378971116308334	37
.372617144494995	38
.36044082731608	39
.342845473961692	40
.322553652349443	41
.500521760456473	42
.278489868563503	43
.258198046951254	44
.240602693596866	45
.228426376417951	46
.222072404604612	47
.222024869093112	48
.221977333581612	49
.215623361768273	50
.203447044589358	51
.18585169123497	52
.165559869622721	53
.143527977729751	54

APPENDIX 9: PRESENTATIONS AND PUBLICATIONS

1. Kanyanga S B, Ng'andu A N, and **Virdy S S** ; **"DESIGN OF A SOLAR FISH DRYER – A PARAMETRIC STUDY"**; Paper presented at the Engineering Institution of Zambia National Symposium on "Engineering: A Sub-Regional Perspective", held at Taj Pamodzi Hotel, Lusaka, 27th & 28th August, 1999; (To be published).

2. Kanyanga S B, Ng'andu A N, and **Virdy S S** ; **"A NUMERICAL APPROACH FOR DESIGNING A SOLAR FISH DRYER"**; Paper presented at the First National Conference on Engineering Research and Development, held at Hotel Intercontinental, Lusaka, 12 & 13 November 1999; Published in "The Zambian Engineer", Vol 34 no. 1, ISBN 9982-41-008-8, Publ. Engineering Institution of Zambia, Lusaka, November, 1999, pp 13 – 18.