DESIGN AND TESTING OF A NATURAL CONVECTION SOLAR FISH DRYER

by

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ABSTRACT

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A natural convection solar fish dryer consisting of a flat-plate solar collector, drying chamber, and an auxiliary heater was designed, constructed and tested in the Philippines. The dryer is capable of drying 5 kg of fish in 10 hours.

Water was first heated in a flat-plate solar collector then through thermosyphon effect, heat and mass was moved to the heat exchanger where heat was transferred to the air. Heated air was allowed to flow through the drying chamber where trays of prepared samples of fish were laid. Pre-drying treatment of fish similar to those used in commercial practice, were used for individual drying experiments in order to permit a general evaluation of the system.

Seven drying experiments using different fish samples were conducted and the data generated was used to determine the efficiency of the system in terms of solar energy utilization. Results indicate that the system function efficiently at a minimal water temperature increase of 10°C, and the dryer operates at a system efficiency of 9 per cent which compares well with the findings of Yu Wai Man (1986) which found that natural convection solar dryers operate in the efficiency range between 7 to 14 per cent.

Résumé

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La Conception et L'essai D'un Sechon Solaire A Poissons A Convection Naturelle

Un séchoir à poissons à convection naturelle consistant en un collecteur solaire à plaques minces, une chambre de séchage, et un chauffage auxiliaire a été concu, construit et testé au Philippines. Le séchoir est capable de sécher 5 kg de poissons en 10 heures

Tout d'alord l'eau a été chauffeé dans un collecteur solaire fuis par l'effet thermosiphon, la chaleur et la masse ont été deplacees vers l'echangeur de chaleur ou la chaleur a été transferé dans l'air. Par la suete l'air chaud a été admis dans la chambre de séchage ou des plateaux d'echantillons de poissons ont été placés. Un traitement de pré-séchage du poisson, similaire à ce que se fait dans la pratique commerciale, a été utilisé pour quelques experiences de séchage individuel dans le but de feure une évaluation générale du systéme.

Sept experiences de séchage utilisant differents éechantillons de poissons a été conduites et les données générées ont été utilisees pour déterminer l'efficacite du systeme en termes d'utilisation de l'energie solaire les resultats indequent que le systeme fonctionne efficacment à une augmentation minimale de 10°C de la temperature de l'eau et le séchoir opére à une efficacité de 9%, ce qui est comparable aux conclusions de Yu Wai Man (1986) qui indique que les séchoir solaires à convection naturelle opérent a une efficacité se situant entre 7 et 14%.

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List of Symbols and Abbreviations

Symbol	Description	Units
Moisture Content		
MC_{WB}	moisture content, wet basis	%
MC_{DB}	moisture content, dry basis	%
m_1	initial mass	kg
m_2	final mass	kg
Drying Stages		
e	evaporation rate	kg/sec
h_m	surface mass transfer coefficient	m/sec
A	surface area	m^2
ω_s	surface humidity	kg H_2O/m^3
ω_a	ambient air humidity	kg H_2O/m^3
d	diffusion rate	kg/sec
D	mass diffusivity	m^2/sec
t	thickness of flesh	m
C_s	moisture concentration, surface	kg H_2O/m^3
C_i	moisture concentration, inside	kg H_2O/m^3
Psychometry		
P_s	saturation vapour pressure	kPa
R	constant	dimensionless
T	dry bulb temperature	°K
A-G	constants	dimensionless
ω	absolute humidity	kg H_2O/kg air
P_w	water vapour pressure	kPa
P_a	atmospheric pressure	kPa
θ	relative humidity	%
v	specific volume	m^3/kg
h_a	enthalpy of air	kJ/kg
h_w	enthalpy of water vapour	kJ/kg
h	enthalpy of moist air	kJ/kg
t	temperature	°C

Insolation

I_{DN}	direct normal insolation	W/m^2
A,B,C	constants	dimensionless
β	altitude angle	(°)
α	azimuth angle	(°)
L	latitude	(°)
δ	declination	(°)
H	hour angle	(°)
β_c	corrected altitude angle	(°)
Σ	tilt angle	(°)

Natural Circulation Systems

m	flow rate	kg/sec
U_l	coefficient of heat transfer	W/m^2-°C
F'	collector efficiency factor	dimensionless
A_c	area of collector	m^2
C_p	specific heat	kJ/kg-°C
S	solar insolation	W/m^2
T_i	inlet temperature	°C
T_o	outlet temperature	°C

Heat Transfer

Q	amount of heat	kJ
m	mass	kg
C_p	specific heat	kJ/kg-°C
T_i	inlet temperature	°C
T_o	outlet temperature	°C
U	coefficient of heat transfer	W/m^2-°C
A	area of surface	m^2
LMTD	log mean temperature difference	°C

Adiabatic Efficiency

λ_a	adiabatic efficiency	%
ω_o	absolute humidity, outlet	kg H_{2O}/kg air
ω_i	absolute humidity, inlet	kg H_{2O}/kg air
ω_s	absolute humidity, saturation	kg H_{2O}/kg air

Dryer Efficiency

λ_d	dryer efficiency	%
m	mass of water removed	kg
L	latent heat of vaporization	kJ/kg
I	insolation level	kW/m^2
A_c	area of the collector	m^2

1. INTRODUCTION

1.1 Background

In the Philippines, dried fish is an important and affordable source of protein; properly dried fish can contain up to 80% of its weight in protein (Lupin, 1986). Although 46% of the total fish catch is dried (FAO 1981), this is done mainly in small-scale "backyard" enterprise by labour-intensive traditional methods that lack adequate quality control (Abduhasan, 1986). Open-air drying by direct sunlight is subject to interruptions, particularly during the monsoon season which may last seven months. Under such conditions, spoilage is inevitable. Losses have been estimated at 30%, yet there seems to be no viable alternative to sun-drying in the many remote coastal communities; electricity is unavailable and road links to marketing areas are too poor to ensure that unchilled fish may arrive unspoiled. Alternatives are needed.

One such alternative is the low-cost mechanical dryer to be described in this thesis. It can be constructed from locally available materials and powered by sunlight and locally-abundant biomass fuel sources such as rice hulls and coconut husks. The advantages that the dryer offers are: 1) faster drying due to the possibility of continuous batch operation, 2) protection of produce from insects and insect larvae, and 3) better dried fish quality due to control of the drying environment.

The adoption of such a dryer by local enterprises should provide economic benefits, and, assuming the sustainable productivity of nearby waters, ensure a better nutritional base for the population.

1.2 Statement of the problem

Traditional methods of open-air drying of fish result in high losses particularly during the long rainy season. High relative humidity and cloudy periods slow drying and increase bacterial and fungal activity which result in spoilage. The rapid development of blowfly eggs into larvae is also promoted under such conditions, particularly given that the fish is not adequately covered, and the larvae may more easily gorge themselves when the flesh stays soft and moist for long periods (Roberts, 1986a).

The social, geographic and economic reality of those communities that rely on fish, limit the possible improvements in fish preservation to those achievable by technologies that are affordable and based on locally-available materials and power sources.

1.3 Objectives

The primary objective of this study is to develop and test a natural convection solar fish drying system. To accomplish this objective, steps were taken to perform the following:

1. Review fish drying practices.
2. Examine the characteristics of cured fish.
3. Assess the potential of indirect solar drying to improve the fish drying process over traditional methods.

1.4 Scope

This study applies to fish species from the Philippines which are cured by salting or plain drying. Most of the analysis will center on the efficient utilization of the solar energy available for drying. The analysis of final product is limited to moisture content determination. Although water activity, salt content and fat content are important parameters in the broader picture, they are beyond the scope of this study.

2. REVIEW OF LITERATURE

2.1 Importance of Fish Drying

Drying is the most widely used method of food preservation and is an integral part of food processing. Proper drying results in a concentrated food source which is easy to handle and distribute due to weight and volume reduction. Almost every food product is dried at least once during its preparation for human or animal consumption. Dry food product is less susceptible to spoilage caused by the growth of bacteria, molds, and insect larvae. The activity of many microorganisms and insects is inhibited in an environment wherein the equilibrium relative humidity is below 70%. Likewise, the risk of unfavourable oxidative and enzymatic reaction is reduced.

Many favourable qualities and nutritional values of food products may be enhanced by drying. Palatability is improved and likewise, digestibility and metabolic conversion are increased. Loss of water in dried fish make the product a more concentrated source of nutrients. Proteins, fats, and carbohydrates are present in larger amounts per unit weight in dried fish than in fresh catch. Drying also changes colour, flavour, and the appearance of a food item.

2.2 Traditional Drying Practices

2.2.1 Sun-Drying

Sun-drying is based on the reduction of moisture content of the fish due to effects of solar insolation, wind, ambient temperature and relative humidity of the air (Bassey et al, 1986). The fish may be laid in racks, mats, straw or raised platforms and exposed to the sun. A wide variety of such drying systems exist and have been used extensively because they are relatively inexpensive.

In tropical countries, small fish or split large fish are commonly spread in the sun to allow moisture to evaporate from the flesh surface. In colder climates, fish are hung up to dry in the wind. Although the latter process is slower than sun drying, the lower ambient temperature slows spoilage. The fish are turned from time to time to hasten the process by exposing more of the surface of the fish to air. Drying time varies depending on the process and the weather. Three to ten days are generally required to prepare a typical sun-dried product. The moisture content of the final product may be varied depending on the desired storage and eating qualities of the product. Fish are usually dried after salting or may be dried unsalted.

Studies made by Poulter (1989) revealed that insect infestation by fly larvae pose a serious problem in traditional sun-drying. It results in flesh loss of up to 25% and the product sells at about half the price of unspoiled fish.

Beck and During (1985), describing their findings on the Fisheries Pilot Project in Tombo, Sierra Leone, adequately portray traditional sun-drying. The fish are scattered to dry on a bare floor or mat during the day and stored in a covered place at night. The sun-dried fish usually contain sand particles and grit picked up while drying on a dirty or sandy surface.

Studies conducted by Dicko (1986) describe traditional sun-drying practices in Mali. The fish undergoes several pre-drying treatments with dipping in "gardonan" water, a solution manufactured by Shell Chemicals Inc., as the final phase. The fish is then spread out on a bed of dry straw, with its open side exposed to the sun for drying. During the rainy season, the fish is spread out on the roofs of sheds that are specially built to protect it against humidity from the ground. Drying time extends from 2 to 3 days in the dry season to 7 days in the rainy season. The main disadvantage noted in these practices are the enormous losses due to attack by voracious fly larvae during drying, as well as due to soiling of dried fish by dust and sand.

2.2.2 Solar Drying

Solar fish drying can be categorized into two types: direct solar drying, where the material receives solar energy directly; and indirect solar drying, where heat energy from the sun is imparted to the material through a working fluid, such as air.

2.2.2.1 Direct Solar Drying

Direct dryers usually consists of an enclosure having a transparent cover. Generally, the inside of the dryer is painted black to allow more absorption of solar energy. The base and side walls are usually insulated to reduce conduction losses to ambient air. The transparent cover can either be single or double glazing made of glass, plastic or a combination of both. Air circulation within the dryer is provided by air vents located on the side walls of the dryer. Increased efficiency is usually attained by covering the dryer with glass and by controlling the air circulation within the dryer (Khan, 1964).

Lawand (1966) developed a solar dryer for agricultural crops which can reduce drying time and produce cleaner products with longer storage life, better flavor retention, and more attractive appearance as compared to the products which were sun-dried directly. The box type solar dryer is shown in Figure 1.

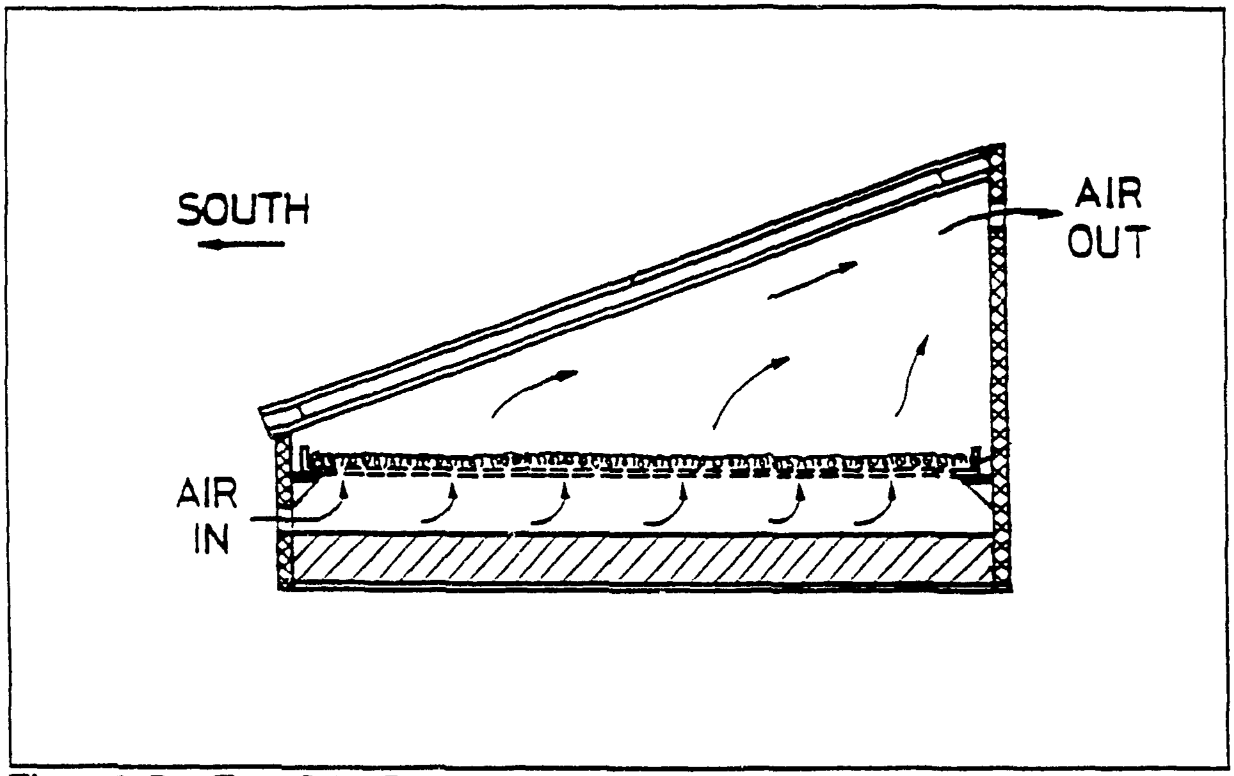


Figure 1. Box Type Solar Dryer

Project Sta. Barbara of the Bureau of Energy Development and the Philippine Women's University Barangay Technology Center (PWU-BATEK) and the University of the Philippines Institute of Small Scale Industries (UP-ISSI, 1980a) collaborated in the design, fabrication and standardization of a solar dryer called Soldry. The dryer is a rectangular hot box for drying agricultural and marine products on a small scale. The collector is made of wooden frames with galvanized iron sheet painted black at its base. The top and sides are covered with transparent poly-acetate which allows solar radiation to penetrate inside and prevent rain and insects from contaminating the drying materials. Products dried on the Soldry have improved quality, maximum retention of flavour and nutrients, low microbial load, freedom from insect infestation, no dust or dirt contamination, and hence, longer shelf-lives compared to conventionally sun-dried products. The use of Soldry is reported to reduce the drying time by 30-50%, space requirement by 30%, and cost in terms of labor and ingredients.

Another example of this type of dryer, which is in use in the Philippines, is the chair-type polyethylene dryer. It is a direct dryer constructed out of wood and polyethylene sheets in the form of a chair. Air movement within the dryer is accomplished through natural draft where heated air rises up over the cold layer of air. Moisture evaporated from the fish is carried out of the dryer through a chimney which also increases the draft. A small percentage of moisture condenses on the polyethylene cover resulting in an increase in the temperature inside the dryer.

Doe (1985) compared sun-drying with direct solar drying and found that the latter operates at a higher temperature which was attributed to the recovery of latent heat as a result of condensation of moisture from the air. Further, he found that relative humidity inside the dryer was high which permitted drying at higher temperatures without scorching or cooking the fish. The occurrence of case hardening, which retards the rate of water evaporation from the fish is minimized resulting in a reduction in drying time.

However encouraging these results are, the system still suffers considerable disadvantages since it is subject to unpredictable level of solar insolation. A reduction in solar insolation levels during drying could slow down the process and allow a significantly high growth of spoilage bacteria prior to completion of drying, and therefore to low quality product.

2.2.2.2 Indirect Solar Drying

In an indirect type of solar dryer, air is usually heated in a solar collector and drawn into the drying chamber by means of a fan or using natural draft, where heated air flows upward bringing moisture out of the drying chamber.

Both sun-drying and direct dryers involve the exposure of the product to ambient air in order to remove moisture. Indirect dryers, on the other hand, heat up the air prior to contact with the product. Solar energy is usually absorbed by metal plates which are painted black or by a black porous bed (Lalude and Buchberg, 1971). The air is heated as it passes in contact with the plates (Whillier, 1964). For the porous bed, air is heated by passing through the hot porous material heated by exposure to solar radiation. Heated air is then drawn into an enclosure where it passes through stacked trays of the product.

Kwendakwema (1983) designed and tested an indirect forced air solar food dryer consisting of a flat-plate solar collector, drying cabinet and a brick heat storage unit shown in Figure 2. Drying experiments were conducted using cabbage, okra, beef, pumpkin leaves and roselle. The results of the experiments showed that the moisture content of the dried foods were in agreement with known acceptable range of moisture content of less than 15%. The dryer was shown to be capable of drying foods in less than 18 hours to a final moisture content of 13% or less.

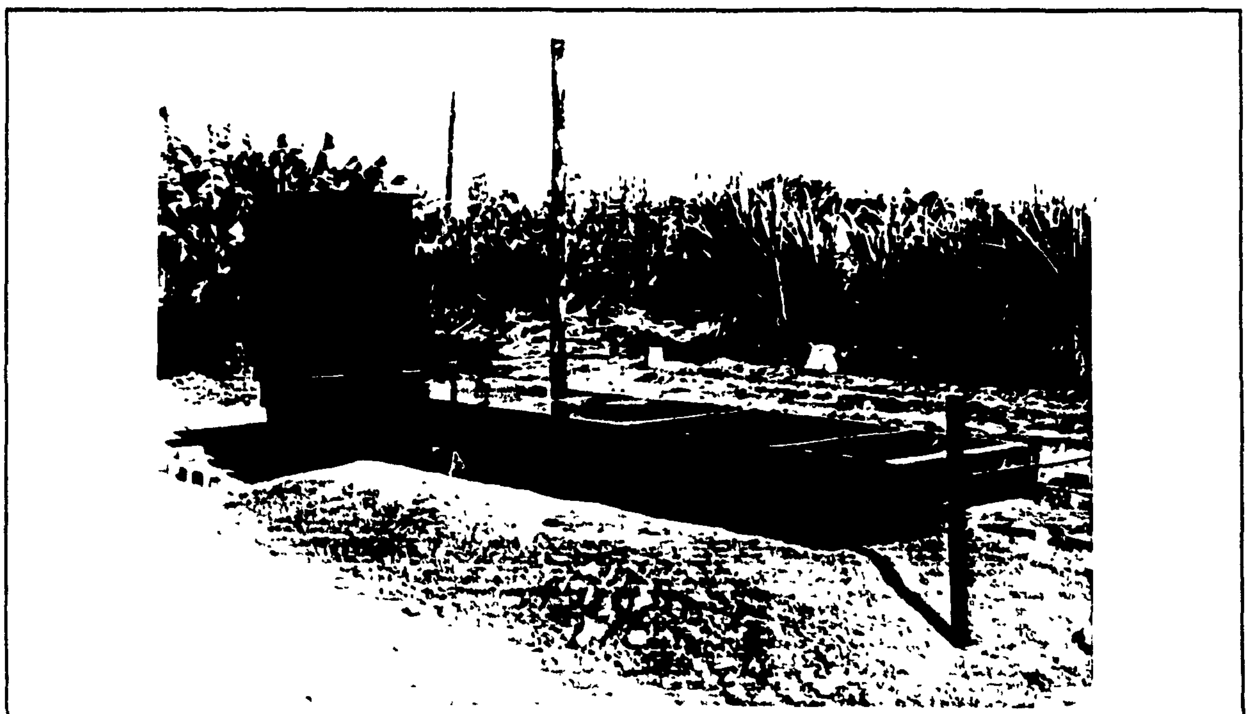


Figure 2. Forced Air Solar Food Dryer

Another example of this type is a dryer developed at the International Rice Research Institute (IRRI) which uses natural ventilation for moving process air inside the drying chamber. The dryer consists of a solar air heater and a drying chamber holding trays of drying material. Air enters through the bottom of the solar collector, passes between the absorbers and glazing material, and is drawn inside the drying chamber through an opening at its base. The heated air moves up, passing through the drying materials and exits through the chimney. A wind-powered rotary vane is used to increase the air flow rate inside the drying chamber. Drying time is reduced significantly compared to sun-drying. Tests conducted on fruits, vegetables and grains showed that the system offers optimum protection for the drying material from rain, dust, animals and insects. The main disadvantage of this dryer is its low capacity because of the limited number of trays that can be stacked inside the drying chamber. Overloading the dryer leads to a reduction in air flow rate which causes uneven drying of the material.

2.2.3 Agro-Waste Fish Drying

Agro-waste fish dryers are considered essential to the improvement of traditional fish drying techniques. They can produce well-dried, dust-free products and can be used effectively during the rainy season when flies are abundant and traditional sun drying is not possible (Tchiengue and Kaptouom, 1986). Unlike solar drying, agro-waste drying is not dependent on the availability of solar energy. Hence, drying is possible even at night or during the rainy season. Earlier designs of agro-waste dryers were based on indirect heating methods. Agro-waste materials are burned in a furnace and heat is transferred to air using a heat exchanger and the air is then passed over the fish to be dried. Some recent models are directly heated by utilizing charcoal as a smokeless fuel, thus making more efficient use of heat energy. Examples of agro-waste dryer designs are described below.

2.2.3.1 Low Cost Fish Dryer (LCF Dryer)

Constructed from hollow blocks (base), fibre board and wood (drying chamber), and G.I. sheet (furnace, roof, and chimney), the LCF dryer is an indirect vertical convection dryer fuelled by coconut husk, rice hull or firewood (Villadsen and Flores, 1982). Drying in this design is effected by hot air travelling horizontally inside the drying chamber over fish laid on the top of wood framed, polyethylene mesh trays. Tests conducted showed 15 to 18 drying hours for splitted roundscad (Decapterus sp.).This long drying time is a result of low air flows and inconsistent air temperatures inside the dryer. Low ambient air velocities have frustrated all attempts to improve the low air flow and temperature.

2.2.3.2 Steel Dryer

Constructed entirely of steel (Figure 3), this dryer was designed more for mobility of operations. The main structure of the dryer is made from galvanized steel plates with all its parts bolted together. The steel furnace is box-shaped with a central rectangular chimney which passes through the center of the drying chamber. Coconut husk, charcoal, or firewood can be used as fuel but rice hull proves unsuitable because of its low heating value.

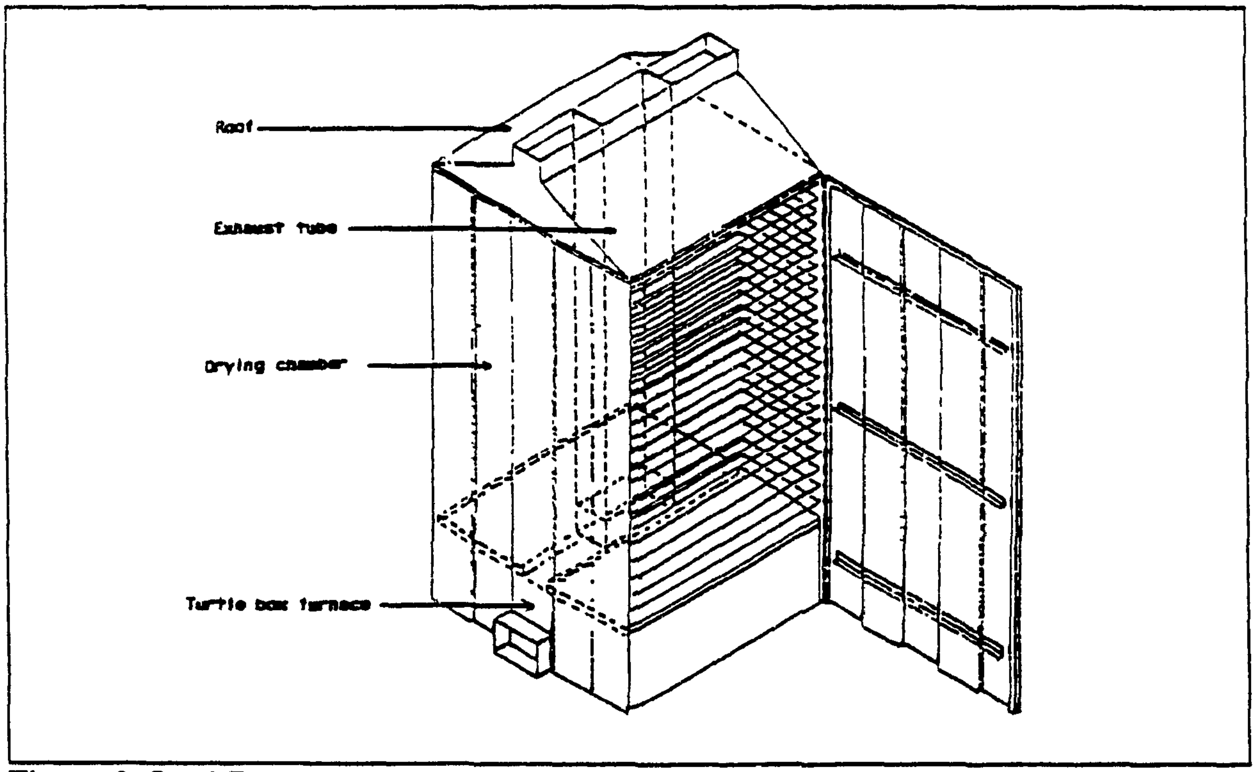


Figure 3. Steel Dryer

Drying is effected by putting the product on narrow steel wire trays which are positioned on either side of the chimney. Studies of the drying characteristic of fish dried showed cooking in the bottom 30% of trays, the central portion with wet fish and the upper 30% of trays with well dried fish. Low air velocity and excessive heat radiation from the central chimney were identified as the causes of the disappointing performance of the dryer.

Roberts (1986b) conducted performance tests on three recent designs using two species of fish commonly dried in the Philippines. These are threadfin bream (Nemipterid sp.) locally known as "Bisugo", and roundscad (Decapterus sp.) locally known as "Galunggong". The fish undergo similar pre-drying treatments and four physical parameters were monitored throughout the drying process: temperature, air velocity, relative humidity, and weight change of fish being dried. The results obtained from the tests indicate safe and extended storage capabilities of the products dried over a 9 to 12 hour period in the three dryers. However encouraging the results are, these designs are not often used in actual fish drying operations in the Philippines due to their high acquisition and maintenance costs.

N'Jai (1986) investigated solar drying methods in Gambia and found a similar aversion to use of mechanical dryers. He found that processors who rely on sun-drying do not really appreciate the method since, even with a well dried and cleaner product, the price usually remains the same as those dried by traditional methods. He suggested that processors should be made aware of how solar mechanical drying can reduce losses and thus increase the weight of the final product produced from a given input of fish.

The experience of the Fisheries Pilot Project in Tombo (Beck and During, 1985) highlights the necessity of mechanical drying in improving the quality of fish products and the productivity of the existing fish processing chain.

2.2.4 Solar Agro-Waste Drying

An indirect type of solar dryer can be augmented with an auxiliary heat source for continued drying during night time and during the rainy season when solar insolation is not enough to complete drying. One such modification is the Solar Agro-Waste Dryer, shown in Figure 4, which uses agricultural waste material to supply auxiliary heat to the drying chamber. An agro-waste burner serves as a heat source during rainy days and at night. This design sometimes include an air-to-air heat exchanger to prevent contact of smoke from the fuel with the material being dried. Some designs use charcoal as smokeless fuel and consume about 0.5 kg of charcoal per hour to maintain drying chamber temperature between 40°C to 50°C. Drying temperature monitored during operation of the agro-waste burner ranges from

30°C to 70°C, depending on the heating value of the waste material being burned (Roberts, 1986b).

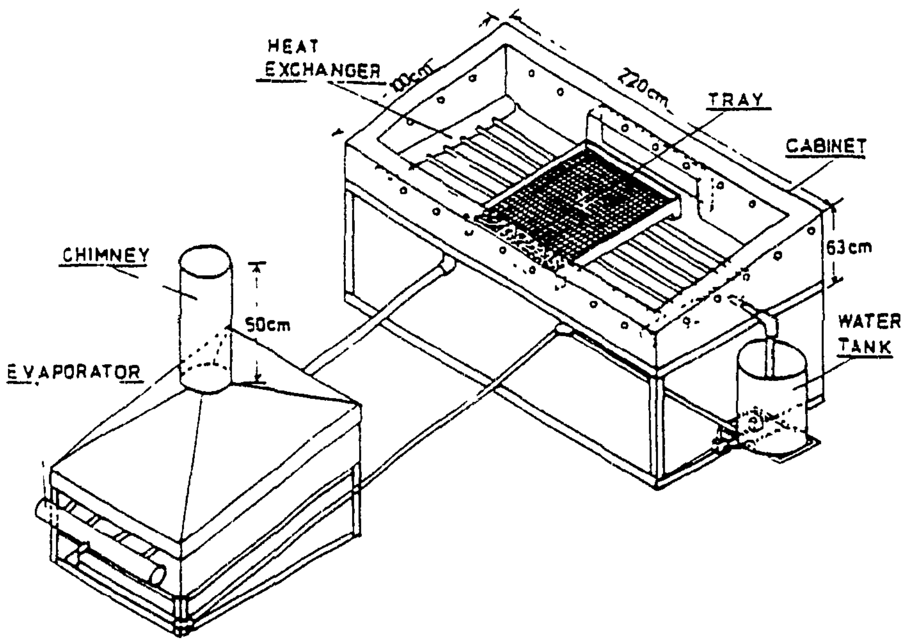


Figure 4. Solar Agro-Waste Dryer

2.3 Factors That Influence the Quality of the Dried Product

Several major factors affect the quality of the dried product. These are raw material quality, pre-drying treatment, drying rate, and drying temperature.

2.3.1 Raw Material Quality

Any dried product can only be as good as the material from which it was derived. Fish destined for drying should be fresh, or if frozen, at its optimum quality for processing. Stale or spoiled fish can not be improved by any form of processing, and that includes salting and/or drying. It must be sorted thoroughly by size and species in order to achieve uniformity of drying and consistency in the quality of the dried product.

2.3.2 Pre-drying Treatment

Several pre-drying treatments are accorded the fish prior to drying. The treatments vary according to the kind of dried product desired. These pre-drying treatments are cleaning, salting, and smoking.

2.3.2.1 Cleaning

Cleaning of fresh fish is the first and most important step in fish processing. Blood, gills, kidney and entrails are susceptible to rapid spoilage and are usually removed immediately. Eviscerating and washing in saltwater or fresh water is done to remove microorganisms and enzymes present in the digestive tract of the fish.

Splitting, slitting, or filleting of fish usually follows. This reduces the thickness of fish for subsequent processing and satisfies some market requirements. Small fish in the order of 15-20 pieces per kilogram are usually slitted and dried and/or smoked, while larger ones are split, cut in thin slabs and dried or smoked. Filleting is usually done on very large species and upon request by customers such as hotels and restaurants. Most of those filleted are usually smoked after cleaning.

2.3.2.2 Salting

One of the oldest techniques of preserving fish is salting. A traditional processing method used worldwide, salting is a simple method of fish preservation with salt and sometimes water as the only ingredients. More often it is used in combination with smoking and drying.

The most important effect of salt is the removal of water from the flesh of the fish to a point where microbial and enzymatic activities are retarded. With the difference in concentration between the salt solution inside and outside the flesh of the fish, water is withdrawn due to osmotic pressure. As water is drawn out of the flesh of the fish, salt penetrates the tissues. This process of salt/water movement continues until the strength of the salt solution inside and outside the fish reaches equilibrium.

The salting process plays other roles which are vital to the overall quality of the product. Salt extracts water making the flesh firm and easy to handle. It also confers a piquant flavour and improves the appearance by leaching out blood and yielding a glossy surface. A 70% to 80% saturated brine yields a glossy and attractive product while a 100% saturated brine results in a dull surface with powdery salt crystals. Low brine concentration (50%) makes the tissue swell slightly and gain 2% to 3% in weight (FAO, 1982). The length of salting is influenced by freshness, size of fish, method of preparation, brine strength, and temperature. Stirring the solution during brining ensures uniform salt concentration.

The amount of salt present in the flesh of the fish influences the removal of water for any subsequent process such as drying or smoke drying. The higher the concentration of the salt in the flesh the greater the amount of water leached out, hence, the less to be removed in the drying process. However, Roberts (1986a) found that the presence of salt in the flesh actually slows down the drying process since salt acts to retain water in the flesh of the fish as it equilibrates. Furthermore, he found that salt enhances moisture absorption from air, particularly at high ambient relative humidity.

Two forms of salting fish are commonly practised. They are wet salting and dry salting. Wet salting is the most common method of pre-treatment in the commercial production of dried fish in the Philippines. There are two usual methods of wet salting fish: brining and pickle curing. The choice of method to be used depend largely on whether the product will be further processed by drying or smoking, or preserved by salting alone.

Fish is usually brined prior to drying or smoking, and brining is used when light to heavy salt content is desired in the final product. The brine concentration normally used is between 80 and 100%, with 270 to 360 grams of salt per litre of the solution. The length of time a particular species is soaked in the solution determines the final salt content (Mendoza, 1986).

When fish is soaked in brine, salt removes water from the flesh and results in the dilution of the brine. Thus a saturated brine will gradually reduce in concentration unless salt is added and the solution is stirred. It is a usual practice in commercial processing to leave sufficient undissolved salt in the bottom of the container to maintain the strength of the brine.

Pickle curing of fish starts as a dry salting method where prepared fish is alternately layered with dry salt in a water tight container using a fish to salt ratio of 0.3 to 1.0. A pickle will quickly start to form with the salt dissolving in water extracted from the flesh of the fish by osmosis. The pickle is retained inside the water tight container and will eventually cover all of the fish. However, to reduce problems of oxidation, the fish is usually covered with liquid. The pickling process is hastened by adding saturated brine and keeping the fish immersed by putting a wooden cover and weights on top of the stack. Pickle curing is suitable for oily fish, i.e. fish with an oil content above 2%. Since fish is immersed in a pickle, the oxidation of fat is minimized.

Similar to pickle curing, dry salting involves placing the prepared fish and salt in alternate layers. The difference however, is that the liquid pickle that forms is allowed to drain. A cover with weights is placed on top of the stack to press the fish resulting in faster salt penetration and subsequent water removal. The fish is usually restacked everyday so that the fish previously on top of the stack ends up at the bottom with more salt added to the stack when necessary. This method is commonly used for lean fish since it is exposed to the atmosphere during salt treatment.

2.3.2.3 Smoking

Fish smoking is a method of fish preservation effected by a combination of salting, cooking, drying, and the deposition of naturally produced chemicals from the incomplete combustion of wood. Smoking can either be cold or hot depending on the temperature of the smoke house. Cold smoking temperature usually does not exceed 45°C while hot smoking can go up to 93°C, bringing the internal flesh temperature to 30°C and 60°C respectively.

Smoking of fish is done by exposing fish cooked in brine to smoke produced by the incomplete combustion and destructive distillation of wood. A complex mixture of alipathic and aromatic compounds in addition to water, carbon dioxide, and traces of hydrogen is partly responsible for the preservation and flavour of smoked fish. Smoke constituents are usually concentrated at the surface. However, studies done by Burgess et al (1967) found that smoke continues to diffuse from the surface to the flesh of the fish during storage, giving the flesh its distinct flavour.

The drying of the fish starts simultaneously with smoke deposition since evaporation occurs when flesh temperature is increased during smoking. The amount of moisture evaporated from the flesh of the fish depends upon the temperature used in the smokehouse and the length of smoking. The degree of salting, smoking and drying which characterize smoked fish all influence in various degree the quality and storage life of the product.

2.3.3 Drying Rate

The rate of drying influences the quality of the final product in two ways: a fast rate of drying can cause shrinkage, while very slow drying rate results in loss of rehydration capacity. As moisture migrates from the food tissues and evaporates from the surface, it is accompanied by a pronounced volume reduction. Material damage such as cracking and crushing of the tissues accompany such shrinkage. Furthermore, unequal shrinkage in various parts of a piece of material often warps and distorts the appearance of the dried product. This situation usually occurs in fast-drying materials with very high moisture content, but can be prevented by slow drying of highly shrinkable materials and materials having high moisture content.

The loss of the ability to rehydrate is physically manifested in terms of shrinkage and distortion of cells and capillaries where moisture migration occurs. However, much of the loss is chemical or physico-chemical in nature at the colloidal level. This is one of the unfavourable characteristics of a food product which has undergone very slow dehydration.

2.3.4 Drying Temperature

The composition of fish varies considerably in its fresh state and its composition changes with varying processing parameters. These processing parameters can influence the nutritional qualities of the product, foremost of which is protein quality and vitamin content. Drying does not have any direct adverse effect on protein content of fish. However, drying parameters may enhance oxidation and rancidity, and thereby cause a reduction in protein quality. These adverse effects are usually dependent on drying temperature and drying time. To reduce such adverse effects, drying should be conducted at 70°C or lower, in which range damage to protein quality is negligible (Opstvedt, 1989).

In terms of vitamin degradation, studies conducted by Burt (1989) showed that the vitamins present in fish are destroyed to varying extents as a result of high drying temperatures. The degree of loss of vitamins in fish is also dependent on whether the vitamins are fat soluble or water soluble. In both cases, losses of vitamins are less than 10%.

Another important effect of extreme drying temperature is case hardening which is the formation of a hard and relatively impermeable surface skin on a drying food product which retards moisture migration from within the tissues. It results in the amount of moisture removed from the surface being greater than the rate of diffusion of moisture from the tissue to the surface. This condition may be prevented by controlling the relative humidity and temperature of the drying air (Van Arsdel et al, 1973).

2.4 Characteristics of the Dried Product

In fish drying processes, two parameters are usually used as a measure of quality and storability of the product. They are moisture content and water activity.

2.4.1 Moisture Content

Moisture content is a measure of the amount of water present in the flesh of the fish in relation to its weight. The standard method for determining moisture content is described in Desrosier (1963). A weighed sample of fish is placed in a porcelain dish and dried in a drying oven at 105°C for 20 to 24 hours. After this time, the sample is cooled immediately in a desiccator for 20 minutes. The dried sample is then accurately weighed and moisture removed in the oven is calculated to serve as the basis for computing moisture content of the sample. The most common expression for moisture content is moisture content wet basis which is:

$$MC_{WB} = \frac{(m_w - m_d)}{m_w} \qquad (1)$$

where:

m_w = weight of fish before drying

m_d = weight of fish after drying

Alternatively, the dry basis moisture content can be given by:

$$MC_{DB} = \frac{(m_w - m_d)}{m_d} \tag{2}$$

These two are related by the formulae:

$$MC_{WB} = \frac{MC_{DB}}{1 + MC_{DB}} \tag{3}$$

$$MC_{DB} = \frac{MC_{WB}}{1 - MC_{WB}} \tag{4}$$

The final water content of the product is an important factor in determining the shelf-life or storability of the product as well as its quality. When the moisture content falls below 25% (wet basis), bacterial action stops and when it is further reduced below 15%, mould will cease to grow. If salt is added, a moisture content of 35 to 45% is often dry enough to inhibit the growth of molds and bacteria, depending on the amount of salt present (Doe, 1986).

Based on research conducted at the Department of Fish Processing Technology, University of the Philippines in the Visayas (1986), the moisture content of commercial samples of dried fish range from 40-45% moisture content (wet basis). At this level of moisture content, the product is considered dry enough to inhibit the growth of microorganisms that cause spoilage.

2.4.2 Water Activity

Water activity is a measure of the free or loosely bound water within a foodstuff. It is determined by placing a sample of the material in a closed container and measuring the relative humidity using some form of hygrometer. The relative humidity obtained, expressed as a decimal, is used as a measure of water activity. Another method of determining water activity is by calculating water activity from measurements of salt, moisture and fat content of the fish (Doe, 1986). This method has the advantage that the water activity can be calculated from the moisture content alone if the salt and fat contents of the fresh or brined fish are known or measured. Water activity can thus can be monitored as the fish dries.

2.4.3 Sorption Isotherms

Sorption isotherms or equilibrium moisture content diagrams are a way of showing the relationship between moisture content and water activity. There are two methods of measuring the sorption behaviour so that sorption isotherms can be plotted. The first method is to allow samples of the fish to equilibrate to different relative humidities in the air space inside closed containers above different saturated salt solutions at different temperatures. The second method is to dry samples to different moisture contents and then measure the water activity of the sample in a water activity meter, which uses a hair hygrometer to measure the relative humidity of the air space surrounding the fish sample kept in a closed container. Knowledge of the sorption behaviour of the fish is of great benefit in determining the amount of drying needed to produce a well dried product with a given shelf-life (Doe, 1986). Figure 5 shows a typical sorption isotherm of a hygroscopic material such as fish.

2.5 Factors That Influence Drying Rate

Drying is a combined heat and mass transfer operation. It involves the transfer of heat in process air to the fish and the transfer of water in the fish to process air. Water may be transported in the fish as bulk liquid or as vapour. In the liquid state, transport may occur due to concentration gradients that develop as water evaporates from the surface, thereby decreasing its concentration. Another important way in which internal water transport occurs is by capillary action. For liquids such as water which wet the walls of capillaries typically present in fish, there exists a pressure difference in a capillary and a connected bulk liquid. As water content of the fish decreases, transport in the capillaries and pores occurs primarily in the vapour phase. The two primary factors influencing the rate of drying are the type of material and the psychometric properties of drying air.

2.5.1 Type of Material

Materials to be dried may be divided into two categories: hygroscopic and non-

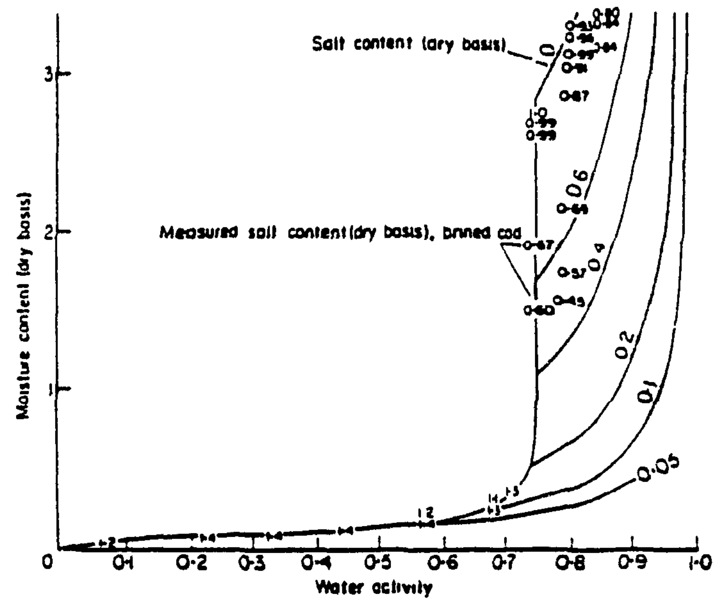


Figure 5. Typical Sorption Isotherm of a Hygroscopic Material

hygroscopic. A non-hygroscopic material is one in which the partial pressure of water in the material is equal to the vapor pressure of water. In hygroscopic materials, the partial pressure of water becomes lower than the vapor pressure of water at a critical level of moisture content. Most dried foods, including fish, are hygroscopic materials.

The process of drying involves the movement of water through a solid and its evaporation from a surface. Initially, the moisture content is uniform throughout the material. As water leaves the surface, its moisture content drops to some value which is close to being in equilibrium with surrounding air. Drying of a hygroscopic material is usually characterized by a period of constant rate drying followed by a longer period of falling rate drying as shown in Figure 6.

In a porous open solid like a sponge, there is very little resistance to diffusion, hence, evaporation is the governing process. Such solids dry at a 'constant rate'. The constant rate

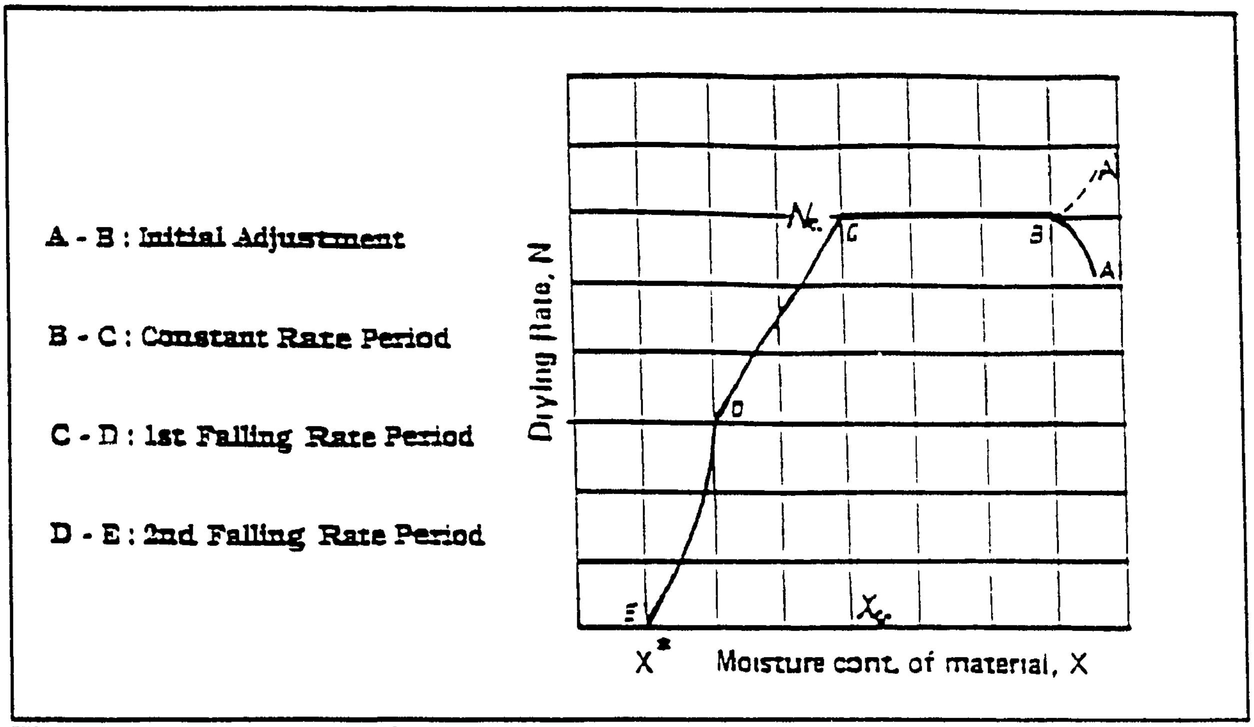


Figure 6. Drying Periods for a Hygroscopic Material

period continues as long as the supply of water to the surface suffices to maintain saturation of the surface. This will maintain a constant surface temperature and a water pressure equal to the vapour pressure of water at the corresponding wet bulb temperature. Thereby maintaining a vapour pressure gradient between the material surface and the lower vapour pressure of air resulting in moisture movement by evaporation.

Outside the fish, the evaporation rate e, can be found from the expression:

$$e = h_m * A * (\omega_s - \omega_a) \qquad (5)$$

where:

e = evaporation rate, kg/sec

h_m = surface mass transfer coefficient, m/s

A = surface area, m^2

ω_s = surface humidity, kg H_2O/m^3

ω_a = ambient air humidity, kg H_2O/m^3

The surface mass transfer coefficient depends on wind speed and aerodynamic shape. Thus the rate of evaporation from the surface can be increased by:

- increasing air speed;
- increasing surface area; and,
- decreasing humidity of the air inside the dryer.

Alternatively, a solid in which water is tightly bound will dry under diffusion governing condition, which is characterized by a spontaneous process of mass transfer to effect equalization of moisture concentrations within the material. Such drying is termed 'falling rate' drying since the rate of drying decreases as water diffuses out of the solid. During this drying period, it is assumed that transport to the surface occurs by transport in the gas phase, and that transport from the surface to the bulk of the air occurs through the gas film in the air. Drying in the falling rate period is an unsteady state process not only with respect to the moisture gradients but also with respect to the material temperature. The temperature at the beginning of the falling rate period is equal to the wet bulb temperature and rises throughout the falling rate period toward the dry bulb temperature of air.

Within the fish, the diffusion rate of water to the surface is given by:

$$d = \left[\frac{2DA}{b}\right] * [C_i - C_s] \qquad (6)$$

where:

d = rate of diffusion, kg/sec
D = mass diffusivity, m^2/sec
A = surface area, m^2
b = thickness of fish, m
C_i and C_s = moisture concentrations, kg H_2O/m^3

The rate of diffusion can be increased by:

- increasing mass diffusivity;
- increasing surface area; and,
- decreasing the thickness of the fish.

Apart from cutting the fish into thinner pieces, the only practical way to increase the rate of diffusion is to increase the drying temperature. This obviously has limitations due to the fish cooking at temperatures around 50°C, depending on the moisture content.

While the surface humidity remains constant, the drying rate is also constant. When surface humidity starts to fall due to the fish drying out, the drying rate starts to decrease. This fact explains the different behaviour of brined and unbrined fish. Salted fish exhibit a very short constant rate drying period and take longer to dry than unsalted fish (Doe, 1986).

2.5.2 Psychometric Properties of Drying Air

Psychometric properties of air or any air-water vapour mixture used in the drying process can be accurately calculated if any two independent psychometric properties of the mixture are known in addition to the atmospheric pressure. With three psychometric properties available, any or all of the following properties may be obtained: relative humidity (θ), enthalpy (h), humidity ratio (ω), specific volume (v), and vapour pressure (P_v). These psychometric properties can be calculated numerically using information available in the ASHRAE Handbook of Fundamentals (ASHRAE 1972).

The water vapour saturation pressure is frequently calculated in psychometric analyses. This calculation must be accurate since vapour pressure is used in calculating other psychometric properties. Four formulas are given by ASHRAE (1972), although no tolerance values are given. In food drying applications, the 0°C to 120°C temperature range is usually of interest. In this range, the following formula is most useful:

$$\ln\left(\frac{P_s}{R}\right) = \left[\frac{(A + BT + CT^2 + DT^3 + ET^4)}{(FT - GT^2)}\right] \quad (7)$$

where:

P_s = saturation vapour pressure, kPa

T = dry bulb temperature, °K

R = 22,105,649.25	D = 0.12558×10^{-3}
A = -27,405.526	E = -0.48502×10^{-7}
B = 97.5413	F = 4.34903
C = -0.146244	G = 0.39381×10^{-2}

By using the perfect gas relationships and the definitions of relative humidity and degree of saturation, the following relationships can be developed to find absolute humidity, water vapour pressure, relative humidity, and specific volume.

$$\omega = \left[\frac{(0.62198 * P_w)}{(P_a - P_w)}\right] \tag{8}$$

$$P_w = \left[\frac{(P_a * \omega)}{(0.62198 + \omega)}\right] \tag{9}$$

$$\theta = \left[\frac{P_w}{P_s}\right] \tag{10}$$

$$v = \frac{(R_a * T)}{P_a} * [1 + (1.607 * \omega)] \tag{11}$$

where:

ω = humidity ratio, kg H_2O/kg dry air
P_a = atmospheric pressure, kPa
P_s = saturation vapour pressure, kPa
P_w = vapour pressure, kPa
θ = relative humidity, %
v = specific volume, m^3/kg
R_a = gas constant, J/m-°K
T = temperature, °K

The enthalpy of moist air is derived from the sum of the enthalpies of dry air and enthalpy of the saturated water vapour. The enthalpy of dry air can be approximated closely as the product of the specific heat (C_p) of air and its temperature. Taking the value of C_p for air as 1.005 kJ/kg-°K at 300°K gives:

$$h_a = 1.005 * t \quad (12)$$

Considering water vapour to act as an ideal gas with a specific heat of 1.88 kJ/kg-°K, its enthalpy can be approximated by:

$$h_w = 2501 + 1.84 * t \quad (13)$$

Combining both equations to obtain the enthalpy of moist air will give:

$$h = 1.005\ t + \omega\ (2501 + 1.84\ t) \quad (14)$$

where:

ω = humidity ratio, kg H_2O/kg dry air
t = temperature, °C
h_a = enthalpy of air, kJ/kg
h_w = enthalpy of water vapour, kJ/kg
h = enthalpy of moist air, kJ/kg

Certain temperature limits are stated for the saturation formula as well as for that of the enthalpy of moist air. However, within the 0°C to 12°C temperature range, the relationships presented predict the actual conditions accurately.

The capacity of the air to remove moisture from fish depends on the temperature and relative humidity of the air. The study of the inter-relationship of temperature and relative humidity of the air is called psychometry and was thoroughly discussed above.

The temperature of the air measured by a thermometer bulb is the dry bulb temperature. If the thermometer bulb is surrounded by a wet cloth, heat is removed by the water evaporating from the cloth and the temperature falls. This lower temperature is called the wet bulb temperature. The difference between the two temperatures is used to find the relative humidity of the air on the psychometric chart. An increase in air temperature, or reduction in relative humidity, causes water to evaporate from a wet surface more rapidly and therefore produces a greater fall in temperature. This characteristic of process air can be observed from a psychometric diagram. Note that the wet bulb lines meet the dry bulb line on the saturation line, hence, dry bulb temperature equals wet bulb. Along this line the air is fully saturated and useless for drying. Lines of constant wet bulb temperature are close to adiabatic or constant heat lines. In actual practice, this means that air passing over the fish in the dryer will gain moisture and decrease in temperature along a line of constant wet bulb temperature. If the air leaving the top of the dryer is saturated, then the dryer is operated at its maximum capacity.

2.5.3 Air Flow Rate

The psychometric properties of drying air are not the only parameters affecting the drying process. At a certain level of temperature and relative humidity, the actual amount of drying air circulated inside the drying chamber also influences the rate at which water is removed from the drying material. As air enters the drying chamber at very low relative humidity, it gradually absorbs water from the material being dried. Before the air reaches its saturation point, it has to be exhausted from the drying chamber for incoming air to flow inside the chamber and continue the drying process. The rate at which drying air is moved through the chamber should ensure that a sufficient volume of fresh air is maintained to prevent saturation of process air. Thus, higher flow rates will ensure high water removal rate.

2.6 Solar Energy and Thermal Processes

2.6.1 Available Solar Energy

The sun is a huge nuclear power plant of the fusion variety which generates power in the form of radiant energy at a rate of 3.8×10^{23} kW (Goswami, 1986). This vast amount of energy is radiated all around the sun and a very small fraction, amounting to 1.8×10^{14} kW, is intercepted by the earth as it moves around the sun. The amount of solar radiation falling on a surface normal to the rays of the sun at mean earth-sun distance, the "solar constant", has been measured extensively and recent measurements have established the best value at 1.377 kW/m^2.

Since the sun's orbit is elliptical, the sun to earth distance varies slightly with time of year. Furthermore, the earth's axis is tilted at an angle of 23.45° to the plane of its elliptic path around the sun causing seasonal variation in the availability of solar radiation.

The solar energy that reaches the surface of the earth is made up of two parts: the energy in the direct beam, and diffuse energy from the sky. These can be approximated using the methods as described by Howell et al (1982) which predicts radiant energy for a specific latitude, time of day and the day of the year.

2.6.1.1 Methods of measurement

The solar intensity received at ground level can be measured in many ways. The most common unit of measure is the total radiant flux of sunlight falling on a horizontal absorbing surface. This quantity is commonly referred to as insolation. The units most often used for insolation are:

$$1 \text{ langley} = 1 \text{ cal/cm}^2\text{-hr} = 3.687 \text{ BTU/ft}^2\text{-hr} = 11.63 \text{ W/m}^2$$

The most common instrument for measuring insolation received at ground level is a device known as a pyranometer. A second instrument used for monitoring solar intensity is the normal incidence pyrheliometer, used for measuring solar intensities normal to the sun. Both instruments use thermocouples and the basic concept used is that a black surface will absorb most of the incident radiation and will reach an equilibrium temperature higher than ambient temperature. These temperature rises can be related to the rate of solar heat gain.

2.6.1.2 Insolation Data

Solar insolation data are available in several forms. They usually include information on whether the data are instantaneous measurements or averaged values over some period of time; the time and period of measurement; whether the measurement are of beam, diffuse or total radiation; the receiving-surface orientation; and if the values were averaged, the period over which they are averaged. In addition to solar insolation data, there are other meteorological measurement related to solar energy which, in the absence of radiation data, can be used to estimate insolation.

Another alternative is the estimation of radiation for a particular location by the use of data from other locations of similar latitude, topography and climate. For this type of estimation, the use of the Daily Means of Total Radiation (Beam + Diffuse) Map published by Lof et al (1966) and redrawn by de Jong (1973) (as cited in Parker, 1990), and the Table of Solar Heat Gain Factors (ASHRAE, 1972) for different latitudes is useful.

2.6.1.3 Radiation on a Horizontal Surface

The data in the ASHRAE Guide and Data Book, Fundamentals provide an accurate quantification of the magnitude of solar insolation and provide the necessary information for making this determination. The solar insolation on any horizontal surface can be approximated by the equation:

$$I = (C + Sin\beta)\, A\, e^{-\frac{B}{Sin\beta}} \tag{15}$$

where:

β = altitude

A, B, C = constants defined in Table 1

For a specific latitude, the sun's position can be determined by calculating its altitude and azimuth. The sun's altitude angle β from the horizon is given by:

$$Sin\beta = [Cos(L) * Cos(\delta) * Cos(H)] + [Sin(L) * Sin(\delta)] \tag{16}$$

The azimuth angle α, is given by:

$$Sin\ \alpha = \frac{Cos(\delta) * Sin(H)}{Cos(\beta)} \tag{17}$$

where:

β = altitude

δ = declination

H = hour angle

The declination varies between -23.45° and +23.45° in one year and this factor can be estimated by the formula:

$$\delta = 23.45 \, Sin \left[\frac{360 * (284 + N)}{365} \right] \tag{18}$$

where:

δ = declination

N = day number with January 1st as 1

Table 1. Solar Insolation Constants

Month	A, W/m²	B	C
Jan 21	1230	0.142	0.058
Feb 21	1214	0.144	0.060
Mar 21	1185	0.156	0.071
Apr 21	1135	0.180	0.097
May 21	1103	0.196	0.121
Jun 21	1088	0.205	0.134
Jul 21	1085	0.207	0.136
Aug 21	1107	0.201	0.122
Sep 21	1151	0.177	0.092
Oct 21	1192	0.160	0.073
Nov 21	1220	0.149	0.063
Dec 21	1233	0.142	0.057

2.6.1.4 Radiation on a Tilted Surface

Solar radiation falling on a surface of any orientation and tilted at an angle from the horizontal is obtained by multiplying the direct normal radiation I_{DN}, by the cosine of the angle of incidence, ϕ. The angle of incidence of the rays with the surface is a function of the surface orientation and the sun's position. For a tilted surface, the angle of incidence is given by:

$$Cos\phi = [Cos(\beta_c) * Cos(\alpha_c) * Sin(\Sigma)] + [Sin(\beta_c) * Cos(\Sigma)] \tag{19}$$

where:

β_c = corrected altitude angle

α_c = corrected azimuth angle

Σ = tilt angle of the surface

2.6.2 Solar Energy Collection System

2.6.2.1 Types of Collectors

A solar collector is a device designed to absorb incident solar radiation and to transfer the energy to a fluid passing in contact with it. Solar collectors may be classified according to their collecting characteristics, the way they are mounted, and the type of transfer fluid they employ.

Based on their collecting characteristics, solar collectors can be classified as non-concentrating or "flatplate" collectors, and concentrating or "focusing" collectors. A non-concentrating or flatplate collector is one in which the absorbing surface for solar radiation is essentially flat with no means of concentrating the incoming solar radiation. A concentrating collector is one which usually contains reflectors or employs other optical means to concentrate the energy falling on the aperture onto a surface area smaller than the aperture.

A typical flat-plate solar collector consists of a black solar energy absorbing surface with means of transferring the absorbed energy to a fluid; envelopes or glazing material transparent to solar radiation placed over the solar absorber surface to reduce convection and radiation heat losses to the atmosphere; and, back insulation to reduce conduction losses to ambient air. Flat-plate collectors are almost always mounted in a stationary position with an orientation optimized for the particular location and for the time of year in which the solar device is intended to operate.

Detailed study of the performance of flat-plate collectors was first undertaken by Hottel and Woertz (1942). The study was based on energy balance measurements on an array of collectors at an experimental solar heated building. Their analyses were basically collector performance calculations based on mean plate temperature, where they developed a correlation for thermal losses in flat-plate collectors.

Tabor (1958) modified the Hottel and Woertz thermal loss calculations by use of new correlations for convective heat transfer between parallel planes and using values of emittance of glass lower than those used by Hottel and Woertz. The modifications permitted estimation of loss coefficients for collectors where the original method did not give satisfactory results.

New collector designs appeared on the commercial market in the mid 70's prompting the development of standard tests to produce data required in process design. In response to this need, the National Bureau of Standards devised a test procedure which was later modified by ASHRAE (1977). Experiments to verify these standard procedures were undertaken by Hill et al (1979).

The basic method of measuring flat-plate collector performance is to expose the operating collector to solar radiation and measure fluid temperature and flow rate. External environment conditions such as radiation on the collector, ambient temperature, and wind speed were also recorded. Thus, two types of information are available: data on the output of the collector as well as on environmental conditions producing such output performance. These data permit the setting of characteristics of a collector by parameters that indicate how the collector absorbs solar energy and how it loses heat energy to its environment.

2.6.2.2 Heat transfer fluid

The transfer fluid is the medium which passes through or in contact with the solar collector and carries the thermal energy away from the collector to the storage or load. A collector may use either a liquid or a gas as the transfer fluid. The most common liquid is water or water-glycol solution. For thermosyphon systems, heat transfer fluids can be used in a single phase mode (liquid throughout) or in a two phase mode (some liquid, some vapour). Liquids used in single phase mode are water or propylene glycol; and in a two phase mode, some freons can be used (Mertol et al, 1981).

2.6.2.3 Natural circulation systems

Natural circulation of the working fluid in collector systems occurs when the heat transfer fluid warms up enough to establish a density difference between the lower collector inlet and the elevated inlet to the load. The density difference is a function of the temperature difference hence, the flow rate is thus a function of the useful gain of the collector which produces that temperature difference. Under these circumstances, these systems are self-adjusting, with increasing gain leading to increased flow rates through the system. It has been observed by Close (1962) and by Cooper (1973) (as cited by Duffie and Beckman, 1974) that under wide ranges of conditions, the increase in temperature of water through the collectors in natural circulation systems is 10°C.

Studies conducted by Fanney and Klein (1985) show that reduced flow rates in the collector significantly improve thermal performance of solar domestic hot water heating systems. Their findings have direct implications in the application of thermosyphon systems and in reducing initial system cost through the use of smaller piping and pumps in active systems. The work of Hollands et al (1985) supports this finding. In tests conducted at the University of Waterloo, they found a 15% increase in thermal energy and a substantial reduction in construction cost when the flow was reduced sixfold.

Close (1962) worked out an analysis of circulation rates in natural circulation systems and compared computed and experimental inlet and outlet temperatures. His results confirm the suggestion that temperature increases of about 10°C are representative of these systems if they are well designed and without serious flow restrictions. Gupta and Garg (1968) showed inlet and outlet temperature for two collectors that suggest nearly constant temperature rise across the collectors in a thermosyphon system.

Based on their findings, two alternative methods of modelling the performance of natural circulation systems can be used. The first is by an analysis of the temperature, density distribution and the resulting flow rates based on pressure drop calculations. The second is to assume a constant fluid temperature increase through the collector of 10°C (or any appropriate value) and calculate the flow rate that will produce this temperature difference at the estimated collector gain. By equating the total useful energy gain (Duffie and Beckman, 1980) of the collector given by:

$$Q_u = A_c F_r \, [S - U_l \, (T_0 - T_i)] \tag{20}$$

with the heat balance:

$$Q_s = mC_p \, (T_0 - T_i) \tag{21}$$

the value of the flow rate (m), can be solved if the collector efficiency is assumed to be independent of the flow rate. The resulting mass flow rate expression is given by:

$$\dot{m} = \frac{U_l F' A_c}{[C_p \ln (1 - U_l \, F' \, (T_0 - T_i))] \, / \, [S - U_l \, (T_0 - T_i)]} \tag{22}$$

where:

U_1 = heat transfer coefficient, W/m^2-°C
F' = collector efficiency factor, for copper
1 mm thick, F' = 0.97
A_c = area of collector, m^2
C_p = specific heat, kJ/kg-°C
S = solar insolation per unit area, W/m^2
T_i = inlet temperature of collector, °C
T_o = outlet temperature of collector, °C

Collector operation with a temperature difference of the order of 10°C implies for practical systems that water circulates through the system several times a day. Tabor (1969) suggested that resistance to the flow be increased and the increase in temperature made higher such that the fluid in the system makes one pass through the collector in a day. He calculated that the daily efficiency of a "one pass" high temperature difference system will be about the same as that of a system using several passes a day with lower temperature difference, if better stratification is obtained in the storage. These findings were verified by a few studies involving theoretical and experimental comparison of systems.

Chauhan and Kadambi (1968) tested a compact water heater under natural circulation and under forced circulation using a propeller. Use of the propeller produced no significant enhancement in the system thermal performance, showing that natural circulation alone is an adequate mode of fluid movement.

Fanney and Liu (1979) also found that the system efficiencies of active heaters are 5% to 45% lower than the thermosyphon. The conclusion was substantiated by a side-by-side test of a thermosyphon and five active systems employing a pump for fluid movement. Furthermore, if parasitic energy consumption were included, the effective system efficiencies of the active heaters were calculated to be 30% to 90% lower than that of the thermosyphon.

3. MATERIALS AND METHODS

The research study was conducted at the School of Technology and Environmental Resources, Miag-ao Campus of the University of the Philippines in the Visayas. The School is located at latitude 12°North and longitude 125°West. The area is characterized by a very pronounced dry season which normally falls between the months November and May with temperatures ranging from 28°C to 38°C. The area is in the middle of the typhoon belt and experiences an average of 27 typhoons annually creating very unpredictable weather conditions in the latter part of the dry season (May), as well as in the latter part of the wet season (October). The solar drying equipment was designed while working at Macdonald Campus and constructed in Iloilo City. Construction and testing of the equipment was done between December 1990 and August 1991.

3.1 Design and Construction

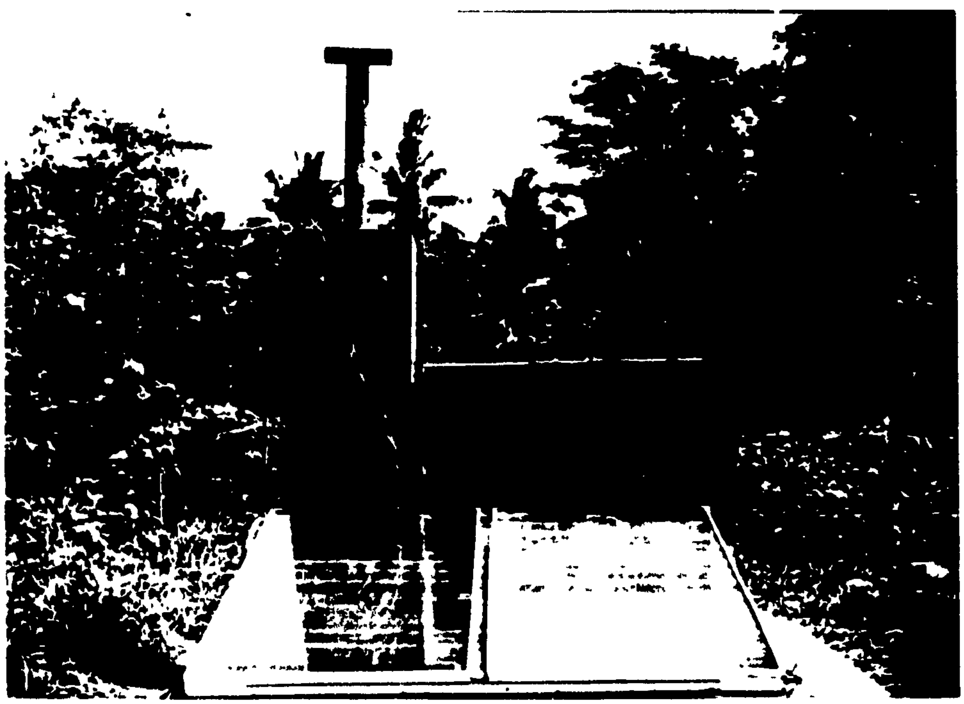
The solar drying system was designed to test the application of solar energy principles to fish dehydration. It consists of the following major components: a pair of solar panels, a heat exchanger, dryer cabinet with chimney and an electric auxiliary heater. The pilot model tested can be upgraded into a larger system for the commercial drying of fish and other fishery products. Figures 7a, 7b, and 8 show the major components of the solar dryer.

3.1.1 Drying Chamber

The drying chamber was designed for fish drying. To determine the operating characteristics of the drying chamber, certain assumptions were required. The drying chamber was designed to handle a maximum of five kilograms of wet fish at 75% moisture content. The final designed moisture content of the fish was 45% after allowing it to dry for 8 hours. Based on the design conditions stated above, the estimated mass of water to be removed from the flesh of the fish was 1.5 kilograms (Appendix A).

Studies conducted by Milla (1982) found that the optimum drying temperature for fish was 50°C. Short term exposure of fish to temperatures 60°C or higher may not be detrimental to product quality, depending on the stage of drying at which the temperature exceeds the optimum temperature. This fact is very important since the energy source is the radiant heat of the sun which shifts from low insolation during cloudy periods to very high insolation

7a. Perspective View



7b. Back View

Figure 7a and 7b. Views of the Solar Dryer

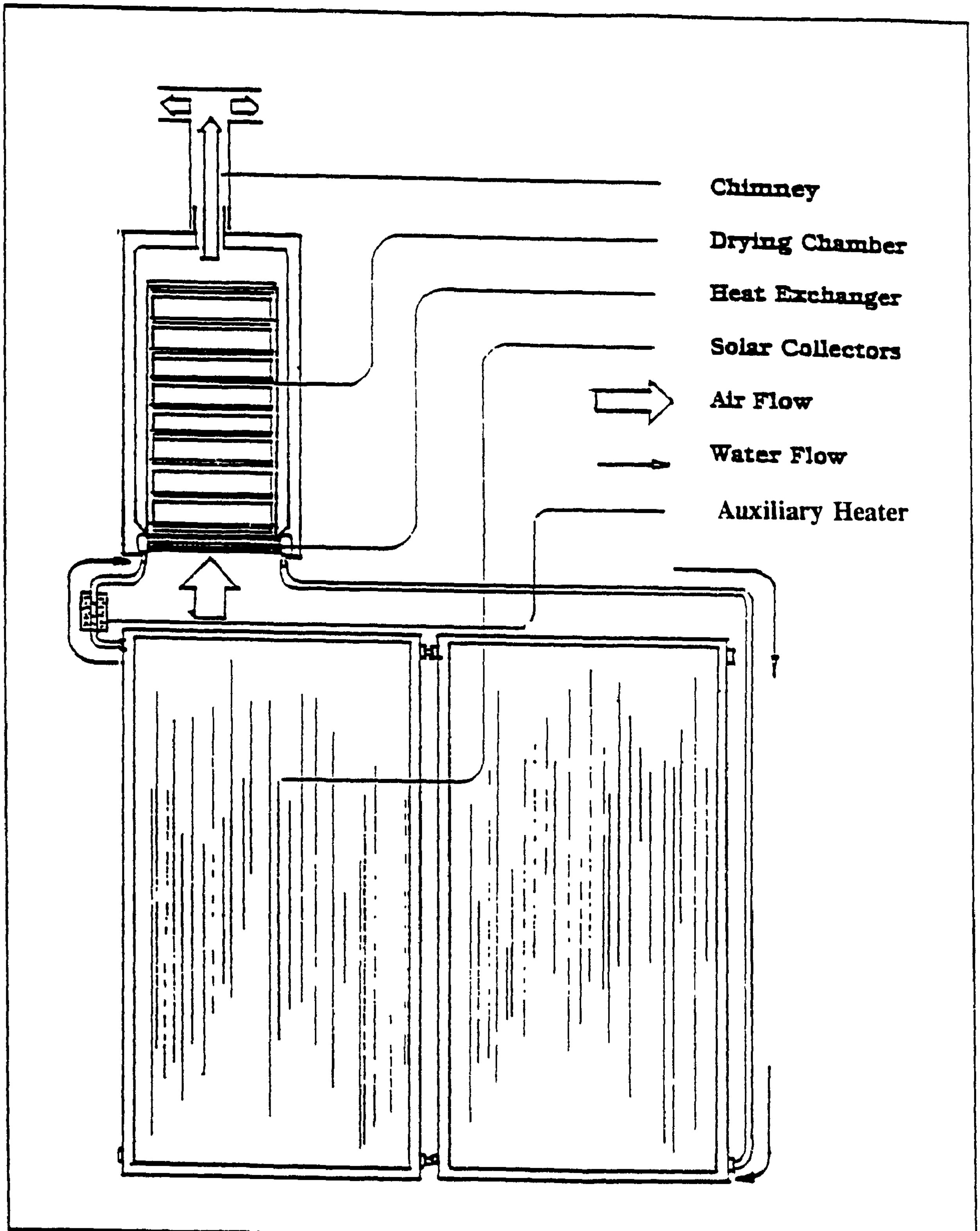


Figure 8. Components of the Solar Dryer

levels during clear periods. The collector panel used in the drying experiment was therefore designed for a maximum temperature increase of 20°C to prevent the operating temperature of the drying chamber from rising above 50°C.

Water in the fish has to gain a considerable amount of heat to change from a liquid to gaseous phase. Esmay and Dixon (1986) give the latent heat of vaporization in the normal liquid range of water for temperatures ranging from 0° to 100°C, which can be obtained by:

$$C_v = 2503 - 2.47 * t \qquad (23)$$

At the designed operating temperature of 50°C, the latent heat of vaporization of water is 2383 kJ/kg. The theoretical amount of heat needed to reduce the moisture content of fish from 75% to 45% will be 0.1240 kW for 8 hours operation (Appendix A). The heat input to the drying chamber comes from the heat added by the heat exchanger through conduction with air, and the enthalpy of air entering the heat exchanger. Outgoing air exhausted through the chimney rejects excess heat through the mass of water vaporized by the introduction of heat into the chamber. Conduction heat losses through the walls were assumed negligible since these losses were minimal compared to the heat lost in moisture removal.

Air fed into the chamber passes through a heat exchanger which raises the temperature from 28°C and 70% relative humidity to 50°C. Air is exhausted from the chamber at 35°C with a considerable increase in relative humidity. At the operating temperature of 50°C air carries 16.7 grams of water per kilogram of dry air; while at 35°C, air carries 25.0 grams of water per kilogram of dry air. This gives a net change in absolute humidity of 8.3 grams of water per kilogram of dry air. At the inlet of the heat exchanger, air enters at an ambient temperature of 28°C and has a specific volume (v) of 0.876 m^3/kg. Using these values, the theoretical volume of air needed to remove 1.5 kilograms of water from the drying chamber is given by:

The volume of air required to move moisture from the fish and out of the drying chamber was computed and it is 158 m^3. This amount of air has to be moved through the

$$V = \left[\frac{m}{(\omega_0 - \omega_1)}\right] * v \qquad (24)$$

drying chamber to remove moisture from the fish within 8 hours. The estimated flow rate of air through the heat exchanger will be 0.00549 m^3/sec. For a heat exchanger with a free air space of 0.0625 m^2, the estimated air velocity at the inlet of the drying chamber will be 0.08784 m/sec (Appendix A).

The drying chamber shown in Figure 9 consists of a converted 10 cubic feet refrigerator case. It was made of 26 gauge steel plate outside and an enamel coated inner shell made from the same material. Sandwiched between the inner and outer shell was a two inch fibreglass insulation. The top portion of the chamber was also insulated with fibreglass and contains the chimney assembly. An exhaust fan was installed in the chimney inlet to enhance draft inside the drying chamber when taking wet and dry bulb temperature readings. The bottom of the drying chamber was fully opened for air to enter with minimal air resistance. Joints between the chimney, the heat exchanger, and the drying chamber were silicone sealed to ensure lower ambient air infiltration in the drying chamber.

3.1.2 Solar Collector

To supply the heat requirement of the drying chamber, two sources of heat were utilized: a solar collector as the primary source and an electric heater as an auxiliary source. Since it was the primary source of heat, the size of the solar collector was designed to handle the total heat requirement of the drying process.

During the period of the experiment, the availability of solar energy was expected to be unstable, varying with respect to the sun's altitude and the cloud cover of the location. Daily estimate of insolation levels at latitude 12°North for August 21 are presented in Appendix B. The information required for estimating the solar insolation values in Appendix B were derived from the ASHRAE Guide and Data Book, Fundamentals. Parameter values from the book correspond to noontime values for the 21st of every month. These were used for purposes of estimation since monthly variations in the parameter values were not very significant, especially when used on daily estimates of insolation.

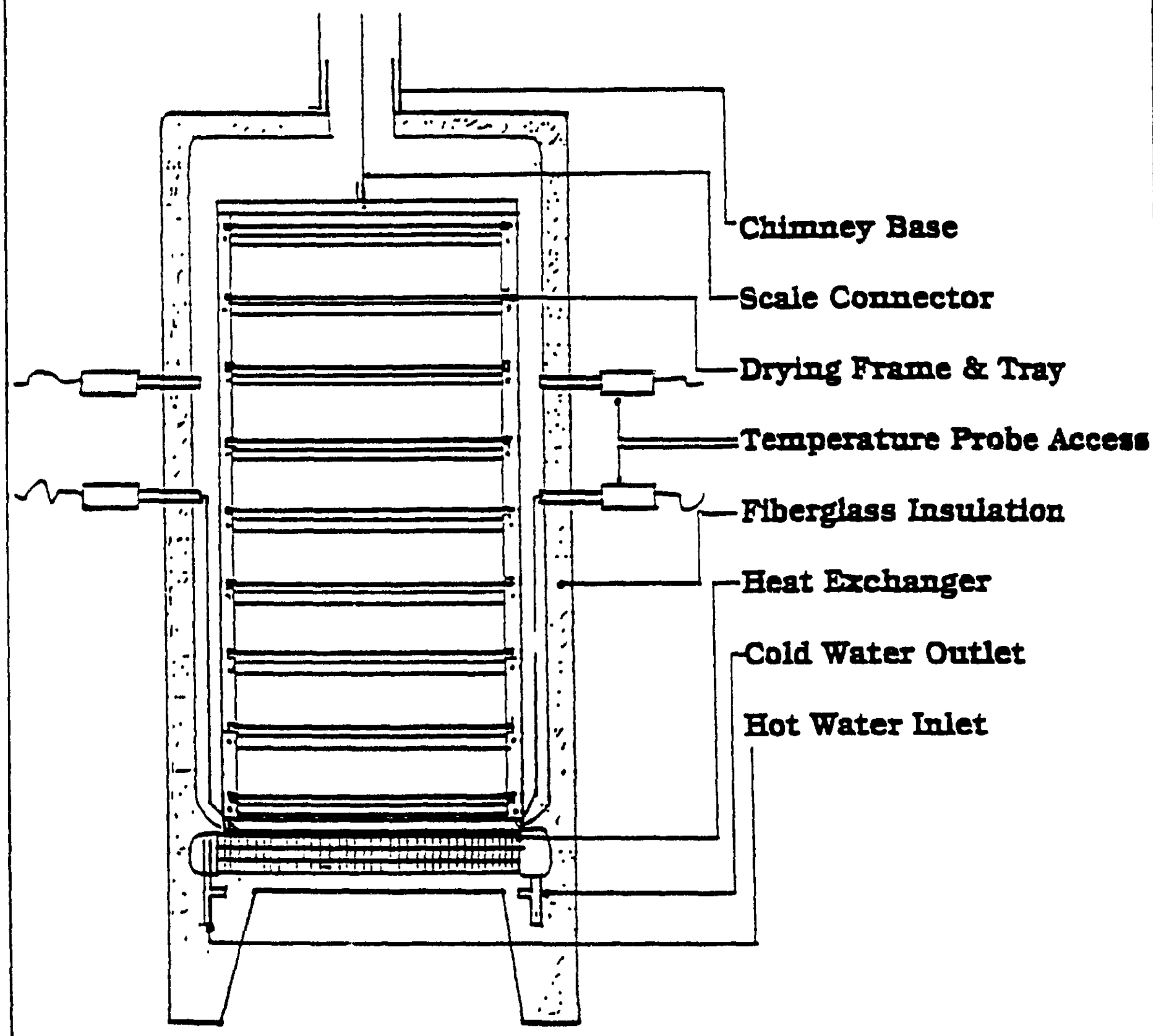


Figure 9. Details of the Drying Chamber

From the estimate of insolation levels for the month of August in Appendix B, the variability of solar insolation during the day was apparent, with a peak noontime insolation of 1015 W/m^2 and a low insolation level of 525 W/m^2 in the early morning hours. In a study of natural convection dryers, Yu Wai Man (1986), found an efficiency range of 7-14%. An efficiency of 10% will be used as the basis for calculating the estimated heat gain in the collector. The efficiency value accounts for the variability of solar energy between the early hours of the morning to sunset in the late afternoon. Using the direct insolation value on a tilted surface for the 21st of August the estimated useful energy available at the collector is 0.0875 kW/m^2. The amount of energy required to evaporate 1.5 kilograms of water is 0.1240 kW. Based on this, the area of the solar collector was computed to be 1.417 m^2 (Appendix A). The designed area was therefore 4.0 m^2 to ensure operability when insolation levels would be lower than the peak daily predicted value.

The system utilizes a Solahart Model 300J water heating solar collector shown in Figure 10. The panel has a special black chrome coating to ensure solar energy collection even at low solar insolation levels. The absorber material used for the solar panel was a pair of 0.6 mm low carbon steel sheets electrically welded forming 36 diamond shaped multi-flow fluid channels per panel. A single glazing made from glass with low iron content covers the absorber material. Tempered glass with low iron content was used so that fast heating was attained. A selective coating of Chromonyx BC091 was used for the absorber surface and a 8 cm fibreglass insulation isolates the absorber surface from a 0.7 mm thick aluminum casing material.

The solar panel has an overall size of 2075 mm X 1942 mm giving a nominal area of 4 square meters. It is tilted 15° from the horizontal and facing South to adjust for altitude at latitude 12°North to optimize solar radiation absorption. The collector unit is mounted in a steel base with fibreboard backing. The two collector panels were connected in parallel having a slight tilt on the discharge end to enhance the thermosyphon effect and prevent heat traps within the panel.

3.1.3 Heat Exchanger

At the rate of heat flow between the working fluid and process air, the effective area of the radiating surface of the heat exchanger was estimated to be 4.87 m^2 (Appendix A). The

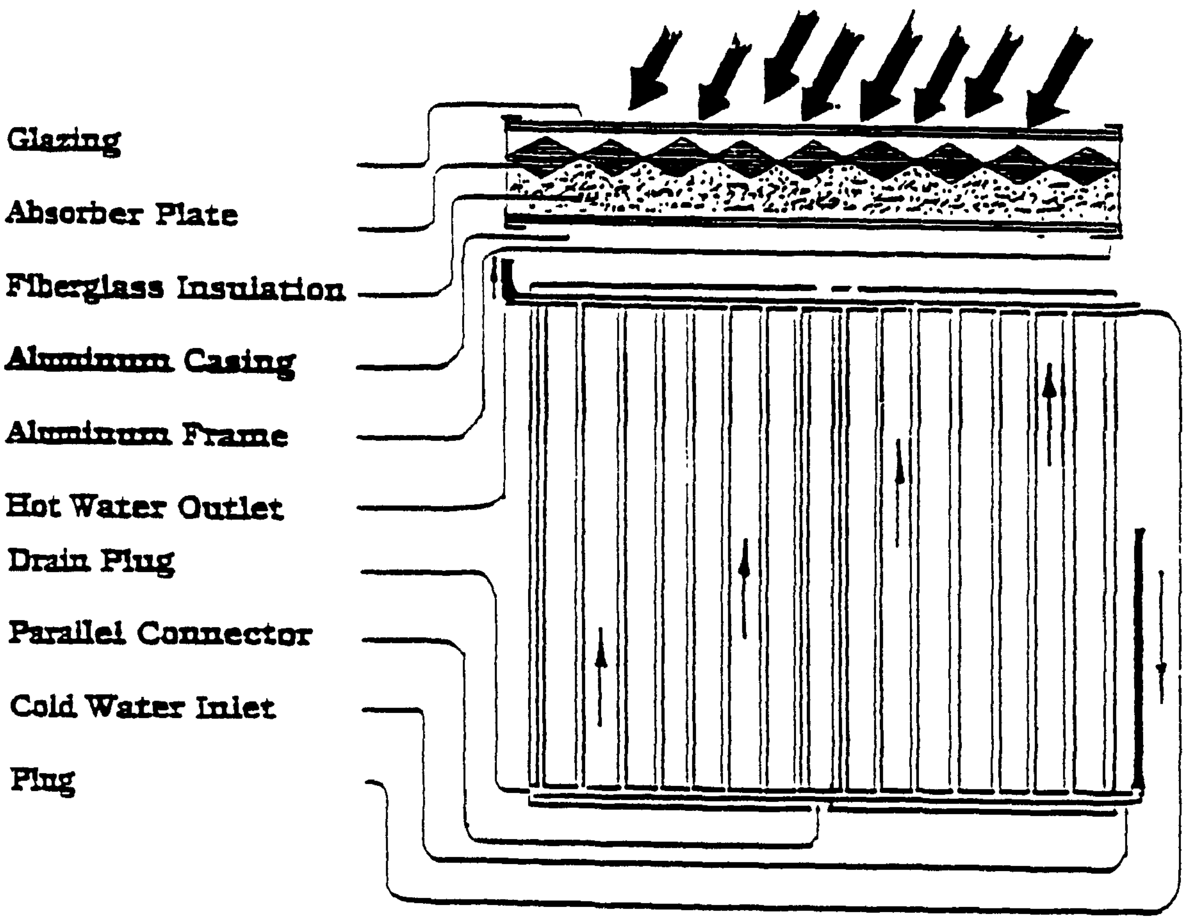


Figure 10. Details of the Solar Collector

heat exchanger used in the dryer was made from a converted automotive radiator (Figure 11). It consists of three layers of parallel copper tubes with aluminum fins welded on its side to increase heat transfer capacity. It is capable of holding 10 litres of water and can withstand high pressures associated with a closed loop configuration in solar hot water heating. It can also handle temperatures well beyond the required range for drying. The use of an automotive radiator ensure easy servicing of the unit whenever the heat exchanger fails to transfer enough heat from the working fluid to process air.

The inlet and outlet ports of the heat exchanger were so designed to ensure thermosyphon effect and avoid heat traps in the hot water loop of the system. Stratification requires the non-mixing of the fluid in the heat exchanger. This will ensure higher mass movement of the fluid resulting in higher heat recovery, and consequently, a higher efficiency of the system. The inlet port was elevated 5 cm higher than the discharge to ensure stratification. The discharge port was situated at the lowest portion of the heat exchanger case to ensure substantial difference in temperature between the inlet and discharge ports. Change in water temperature was monitored periodically to give an estimate of the amount of heat removed from the fluid.

3.1.4 Auxiliary Heater

During times when solar energy is not adequate to operate the dryer at a satisfactory rate, an auxiliary heater attached to the heat exchanger was used as a secondary source of energy. An electric heater was used for this purpose since there was a need to monitor the actual amount of energy infused by the secondary energy source and only electrical source of energy can be accurately and easily monitored. It also served to stabilize operating temperature in the drying chamber by adding heat when chamber temperature falls below a thermostatically designated level. The auxiliary heater shown in Figure 12 consist of an insulated 15 cm diameter pipe, 20 cm long, closed on both ends and containing a 1.0 kW immersion heater. A thermostatic switch was attached to the discharge end of the pipe for controlling the discharge temperature of the auxiliary heater. It switches on the immersion heater whenever the temperature of water entering the heat exchanger falls below 57°C. In that way the drying chamber temperature was maintained at the optimum drying temperature of approximately 50°C.

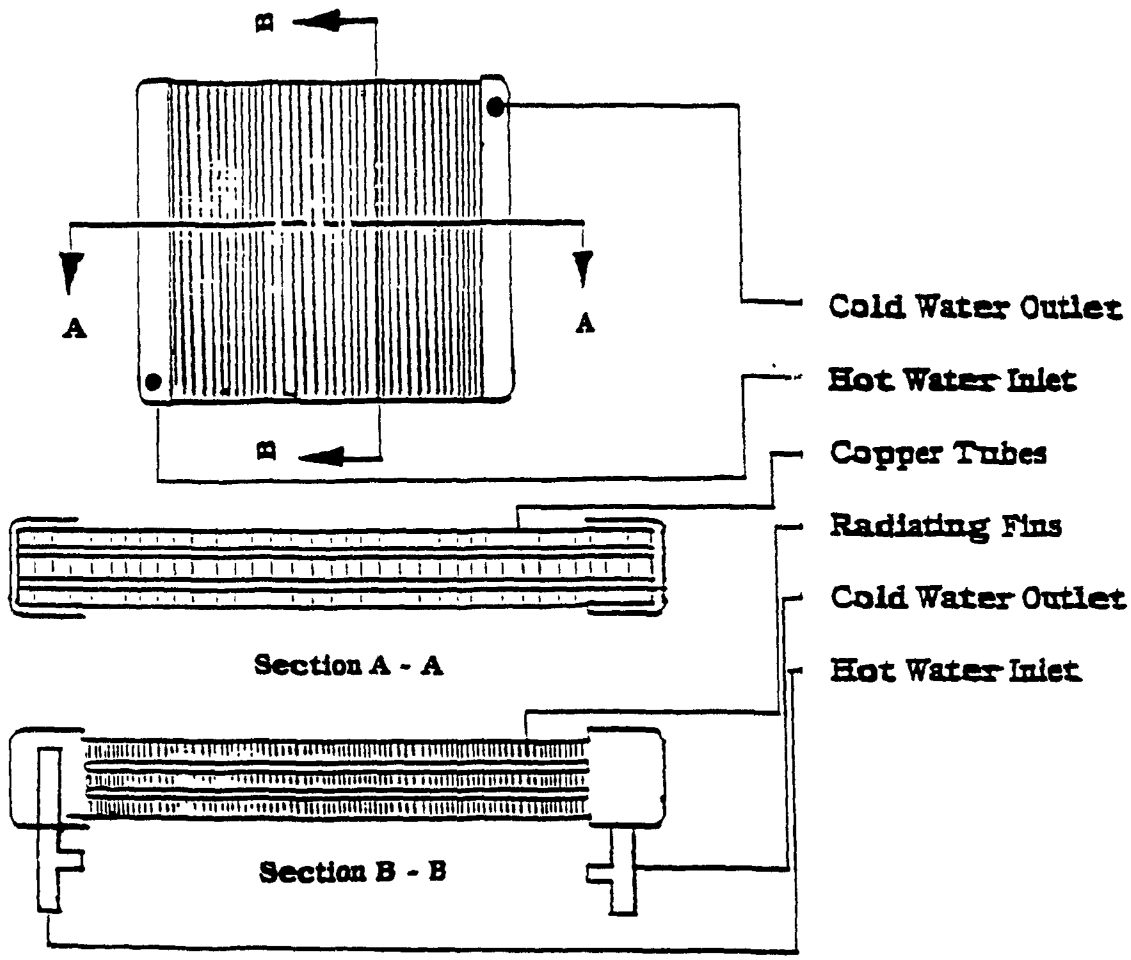


Figure 11. Details of the Heat Exchanger

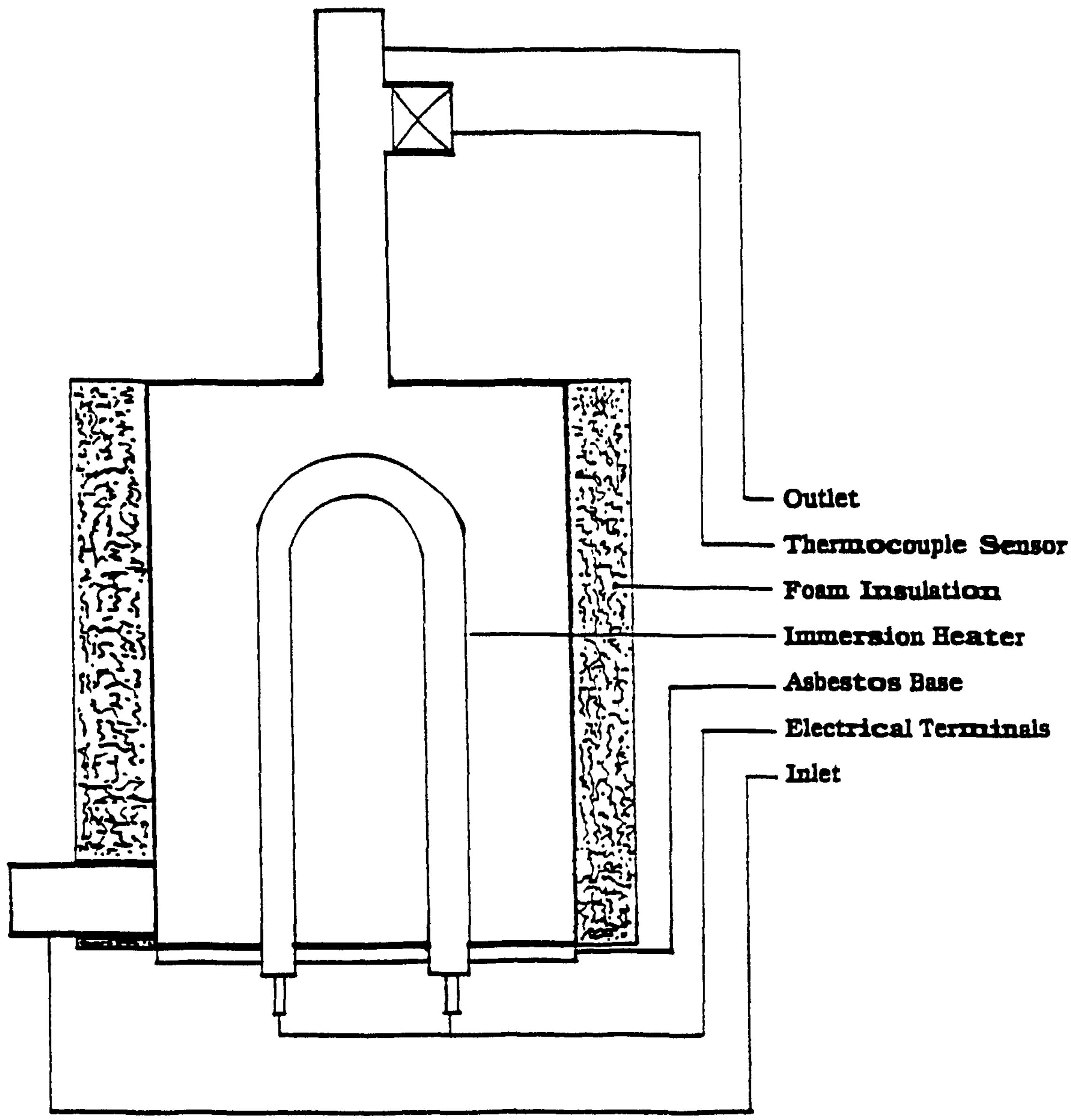


Figure 12. Details of the Auxilliary Heater

3.2 Measurements

During the experiment, several parameters were measured every hour until the fish was dried to a moisture content of around 45% wet basis. Temperature, relative humidity, air flow rate and product mass were continuously monitored during the drying process.

3.2.1 Temperature

Using a 12-channel recorder, temperature at several points along the closed hot water loop and within the drying chamber was monitored. Figure 13 shows the temperature monitoring diagram for the dryer.

At the closed hot water loop, inlet and outlet temperatures of the solar panel was monitored using channels 1 and 2. Channels 3 and 4 monitor the discharge temperatures of the auxiliary heater and the heat exchanger respectively. The temperature difference between solar panel discharge and auxiliary heater inlet, as well as auxiliary heater discharge to heat exchanger inlet were not considered since the hot water manifolds were too short and fully insulated so that whatever temperature drops they may have had were negligible compared to the high temperature drop in the heat exchanger.

Channels 5 and 6 of the thermometer monitor ambient air inlet temperature and hot air discharge temperature of the heat exchanger respectively. Two thermometers were allotted to monitoring flesh temperature of the fish during drying. Channel 7 thermocouple probe is imbedded in the flesh of the fish at the lowest level of the drying trays while another piercing probe attached to channel 8 monitors flesh temperature at the uppermost drying tray.

The temperature of air discharged from the drying chamber was monitored using two thermal probes placed at the base of the chimney. Channel 9 monitored the dry bulb temperature of exhaust air while a probe connected to channel 10 indicated the wet bulb temperature.

3.2.2 Relative Humidity

A handheld capacitive type relative humidity meter (digital) was used in monitoring relative humidity at three points in the dryer cabinet. Point 1 measures ambient relative humidity at the inlet of the heat exchanger. Point 2 measures relative humidity of heated air

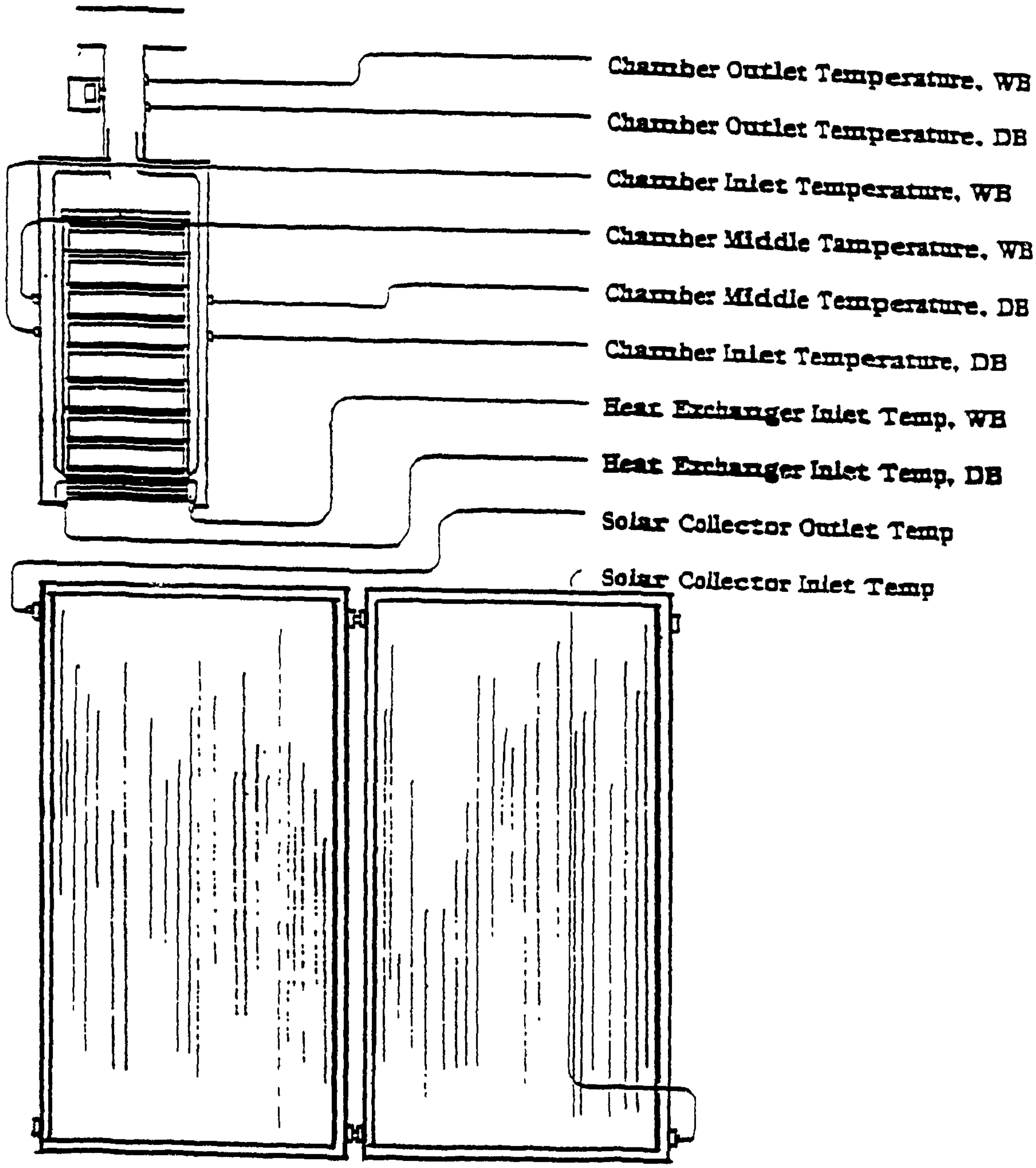


Figure 13. Temperature Monitoring Diagram

after the heat exchanger, just before it is introduced into the drying chamber. Point 3 measures the relative humidity of warm, humid air flowing through the chimney. Relative humidity of air at point 3 is crosschecked using two thermal probes giving both wet and dry bulb temperatures. A small ventilation fan was used to increase air velocity to around 5 meters per second which was necessary for an accurate prediction of the exhaust air relative humidity. The temperatures were plotted in a psychometric chart to estimate relative humidity. Ambient relative humidity was crosschecked using a mercury bulb thermometer with a water soaked wick to obtain wet bulb temperature.

3.2.3 Air Velocity

Air velocity inside the drying chamber was monitored using a handheld direct reading air velocity meter placed at the chimney of the dryer cabinet. Calculations for the air flow rate through the dryer were based on readings taken at the chimney. Since the system runs air straight through without any recirculation, natural draft was used for moving air inside the drying chamber. A small ventilation fan was installed at the base of the chimney to increase air velocity when taking wet and dry bulb temperature of air leaving the drying chamber. This fan is normally shut off during the drying process and is used only every hour when both temperatures need to be recorded for checking the relative humidity .

3.2.4 Weight Monitoring

The weight of fish loaded in trays inside the drying chamber was continuously monitored using a spring balance attached to an aluminum frame holding together all the drying trays as shown in Figure 14. The weight of the drying material reduces as water evaporates from the flesh of the fish and is carried out of the drying chamber by air. This weight reduction registers in the dial of the spring balance and is recorded every hour. Incremental reductions in the weight of the product are used to estimate moisture content of the fish using the formulas discussed in Section 2.4.1. Initial and final moisture content of the fish serve to verify moisture content calculated based on incremental weights recorded while drying.

3.3 Preparation of Fish Samples

The fish used in testing the solar drying system were fish fillets, split fish and scaled whole fish which undergo the usual pre-drying treatment commonly performed in commercial

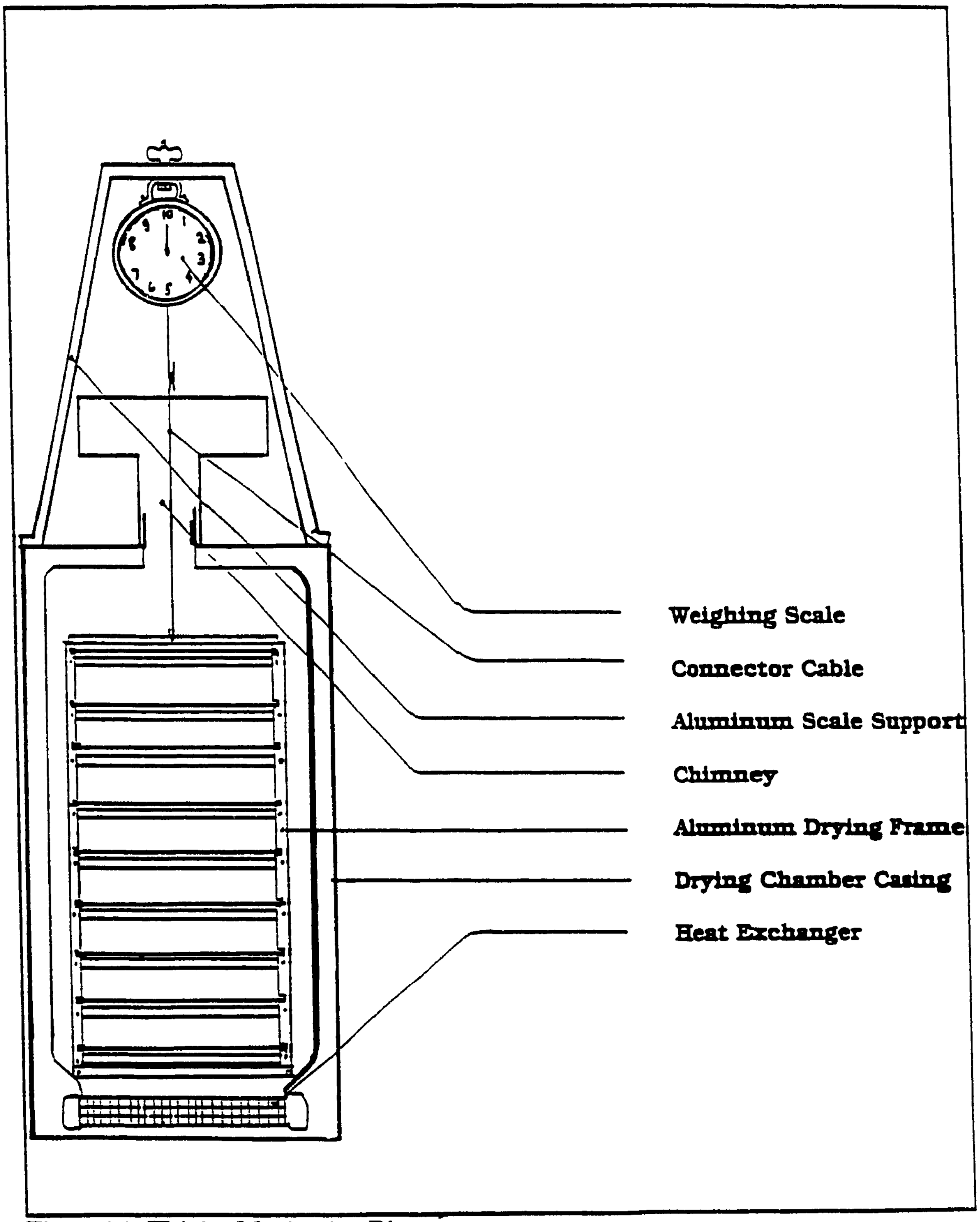


Figure 14. Weight Monitoring Diagram

fish drying (Milla, 1982). Fish used in the drying experiment were selected as to size and the amount of fat they contain. The larger fish used in the experiment usually weighs between 4 to 6 kilograms per piece while the smaller ones were 5-15 pieces per kilogram. Fatty fish were avoided since they were harder to dry and required longer drying times. Several runs were performed using filleted fish, split fish, and scaled whole fish. Preparation of the fish before drying consists of the following:

3.3.1 Cleaning

The first stage in the preparation of the samples is cleaning. It entails the removal of blood, gills, kidney and entrails which are susceptible to rapid spoilage. This was achieved by splitting the fish and pulling out the entrails and other organs that could hasten spoilage. For smaller fish, the samples were washed with water to remove dirt.

3.3.2 Cutting

Cutting of the fish for drying depends on the size of the fish and the desired thickness for drying. For those weighing 4 to 6 kilograms apiece, the fish is split and filleted or cut across getting elliptical shaped flesh. For smaller fish in the order of 5 to 15 pieces per kilogram, they were butterfly split, and fish smaller than 15 pieces per kilogram were washed and made ready for the next stage.

3.3.3 Brining

The cleaned and cut fish were then soaked in brine solution at strengths of about 80 to 100% for 15 to 20 minutes. The brine solution was prepared by dissolving 350 grams of salt for every litre of water. For the 5 kilogram sample of fish, 4 litres of water was used and 1.4 kilograms of salt was dissolved. A higher quantity of salt was used per litre of brine solution since the salt used was ordinary table salt which contains some impurities that lowers actual salt concentration of the brine solution.

Fish soaked in the brine solution were turned every 5 minutes until it has reached a residence time of 15 to 20 minutes. Turning and stirring of soaked fish allows homogeneity and mixes pockets of diluted brine forming around and between the fish. Soaking time of 20 minutes was used for fish which were cut in thick slabs to account for the thickness of the material in which salt has to penetrate. Shorter time (15 minutes) was used for split fish and scaled whole fish since salt easily penetrates the flesh of the fish.

3.3.4 Washing

After 15 to 20 minute duration of soaking in brine, the samples were washed with water to remove excess salt lodged around the flesh. This excess salt forms a white powder on top of the flesh as the fish dries and renders an undesirable appearance as well as hasten rehydration when the fish were removed from the drying chamber and made contact with ambient air.

Prior to loading the 5 kilogram samples of fish into the dryer, excess water was removed by allowing the fish to drip by putting it on top of a screen where free water could drip off the flesh of the fish. Additional moisture removal was effected by putting the fish on top of a piece of cheesecloth to facilitate diffusion of excess water from the fish to the cheesecloth. After these preparations, fish usually emerged with a moisture content of 72% after turning once in the cloth and were then placed into the drying trays ready for loading into the drying chamber (Figure 15). A sample was taken from the lot to determine the initial moisture content of the sample.

3.4 Starting the Dryer

The drying operation was started by opening the cover of the solar panels allowing solar radiation into the absorber plates of the panel. Temperature at the different points of the hot water loop were monitored to check for overheating and verify the thermosyphon effect. Other drying parameters such as initial chamber temperature, relative humidity, air velocity and product weight were recorded. Every hour-on-the-hour, these parameters were recorded and the drying was stopped when the estimated moisture content of fish samples fell below 45%. The above procedure was repeated for other samples of fish dried in the solar dryer.

15a. Loaded Drying Tray

15b. Aluminum Drying Frame

Figure 15. Drying Tray and Aluminum Frame

4. RESULTS AND DISCUSSIONS

Seven sets of drying experiments were carried out in August 1991 (Appendix C). For each drying experiment, a different species of fish was used. In six of the experiments, the only heat source for drying was solar energy. In drying experiment number seven, the auxiliary heater was used to supply the complete energy requirements of the dryer. The following is an analysis and discussion of the performance of the components of the solar dryer as well as of the overall performance of the system.

4.1 Solar Collector Performance

4.1.1 Available Solar Energy

An analog solar radiation meter was used to record the incident radiation falling upon the surface of the collector. Determination of the amount of solar energy available at the collector was accomplished by keeping a record of the solar radiation incident upon the solar collector. The correlation between observed and values predicted by the formula described in Section 2.6.1.4, Approximation of Solar Insolation on a Tilted Surface, presented in Appendix B was 0.495. Figure 16 shows a graph of the recorded solar radiation received by the collector over the predicted insolation level for the drying experiment conducted on August 21. A low level correlation exists between the predicted and recorded values as shown in the graph. This situation is due to the unpredictable weather conditions during the month where the cloud cover swings from low to high levels erratically, causing fluctuations in the recorded radiation level.

Comparison with readings on other drying experiments showed a similar low correlation between the predicted August 21 value and the actual recorded readings. Figure 17 shows a comparison of the August 21 prediction and values taken over several drying experiments for the same period of the day. Greater variability of the recorded insolation was apparent between 11:00 AM to 1:00 PM where predicted insolation values were relatively high. In anticipation of this, the solar collector had been constructed to accommodate lower than expected available solar energy. A nominal area of 4 m^2 was used instead of the designed 2 m^2. This arrangement served to provide added tolerance for the possibility of extreme weather conditions. However, during the first drying experiment, water temperature rose above the boiling point resulting in a reduction of the thermosyphon effect.

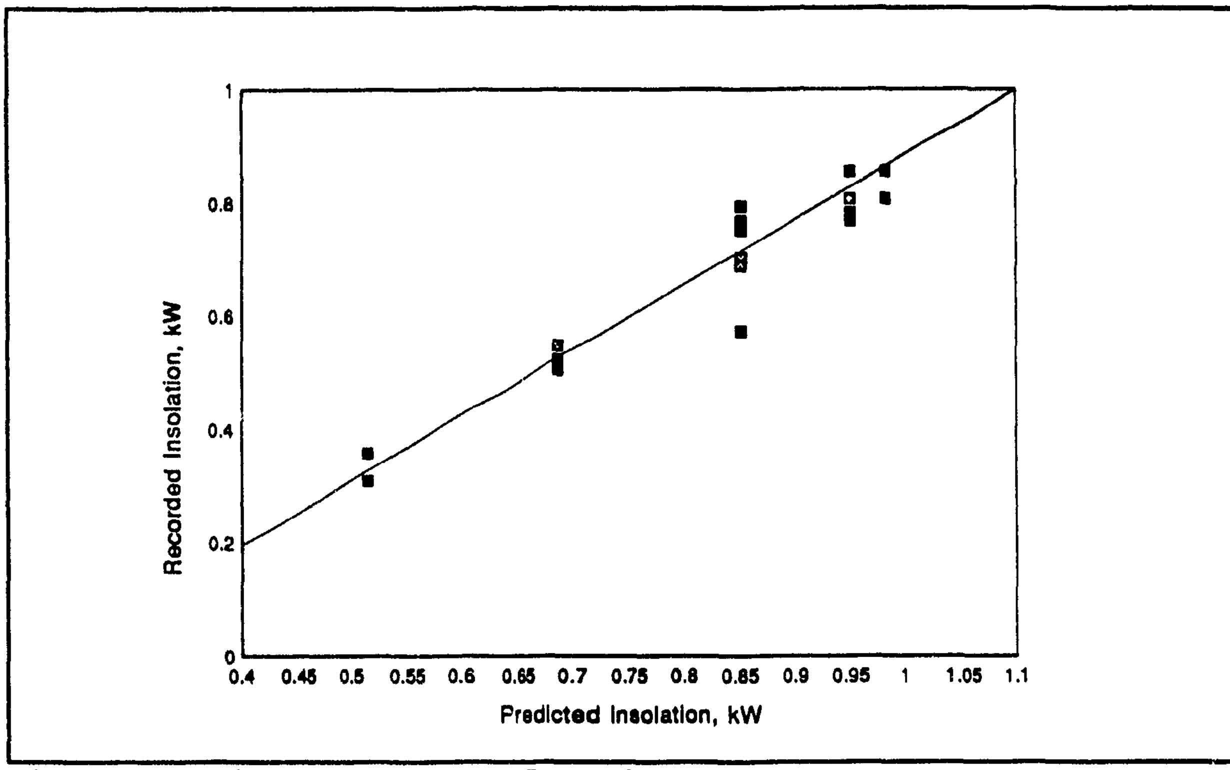


Figure 16. Predicted and Recorded Insolation

The first solar collector was therefore by-passed and only 2 m^2 were utilized for the five succeeding experiments.

The mean radiation recorded for August 21 was 460 W/m^2. Predicted radiation for the same day was 809 W/m^2, almost double the recorded level. Mean values of the recorded radiation however, compared well with the monthly averages of total daily radiation on a horizontal surface and also with the monthly average daily global radiation on a horizontal surface as found by Lof et al.,(1966) and de Jong (1973). The mean value recorded for Quezon City, Philippines for the month of August is 364 W/m^2, while from the map drawn by de Jong (1973) the value for the same period is 400 W/m^2.

4.1.2 Temperature Increase in the Collector

The performance of a solar collector connected in a closed loop configuration can be related to its ability to raise the temperature of the working fluid over the ambient fluid temperature. The collector attained an average increase in working fluid temperature of

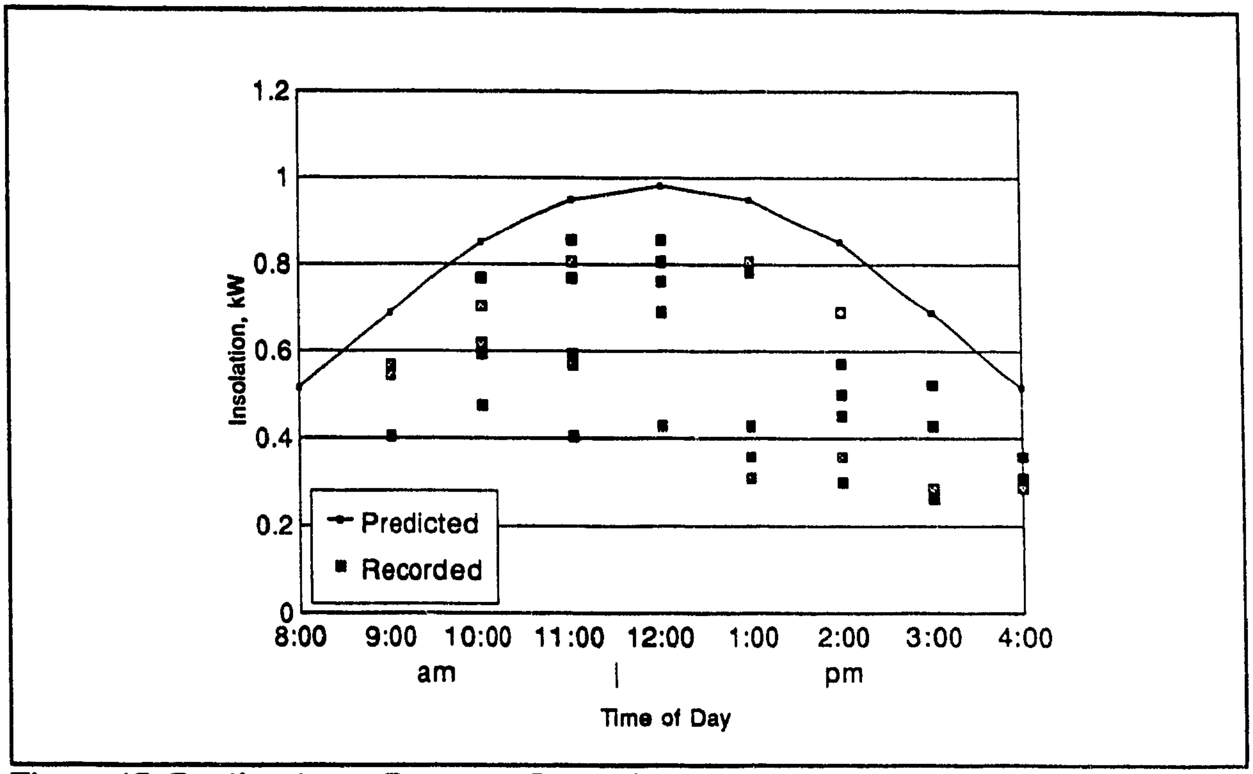


Figure 17. Predicted and Recorded Insolation Over Time

11 95°C over six experiments using different loads and at varying insolation levels. This confirms the observations made by Lof and Close (1967) and by Cooper (1973), as cited in Duffie and Beckman (1980), that under a wide range of conditions, the temperature increase in a natural circulation system is about 10°C. Figure 18 shows the increase in temperature in the collector with respect to the insolation levels prevailing during the drying experiments. It can be noted that the increase in fluid temperature follows the same pattern as the insolation level received by the collector.

4.1.3 Flow Rate of Working Fluid

The flow rate of water in the hot water loop of the dryer was calculated by equating the useful gain of the collector and the total heat absorbed by water in the hot water loop of the system as described in Section 2.6.2.3, Natural Circulation Systems. Figure 19 shows the relationship between the collector flow rate and the recorded insolation. The figure shows the significant effect of insolation level on the mass flow rate of the collector fluid. The increase in temperature and the flow rate in the solar collector are shown in Table B.2 of Appendix B.

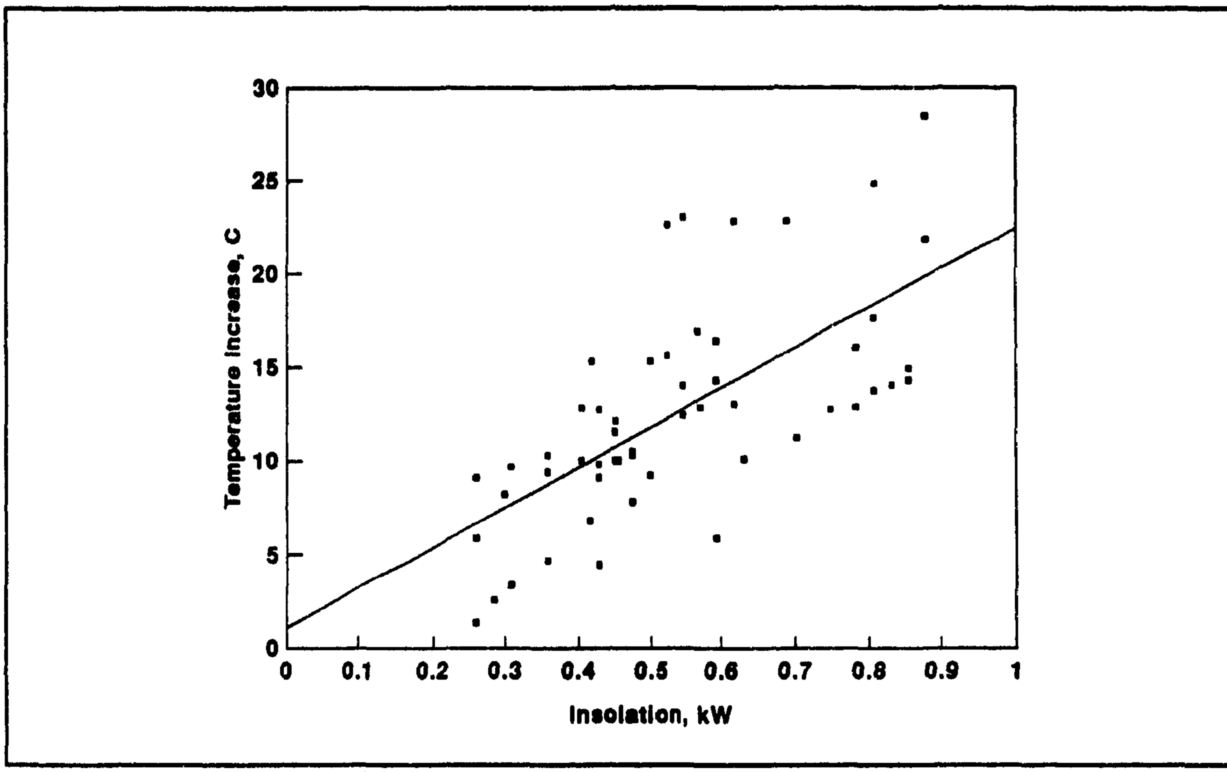


Figure 18. Temperature Increase in Collector

It can be observed that the estimated mass flow rate of the collector fluid is decreasing with higher temperature increase in the solar collector. This confirms the findings of Hollands et al.(1985) and Close (1962) that a 10°C increase in temperature and a low flow rate are representative of thermosyphon systems, and optimum performance can be attained at such levels of temperature and flow rates. The estimated flow rate of water through the solar collector is the basis for determining the heat input into the heat exchanger.

4.1.4 Energy Output of the Solar Collector

Heat output of the solar collector which goes into the heat exchanger can be approximated using the heat transfer formula:

$$Q = m * C_p * (T_0 - T_i) \qquad (25)$$

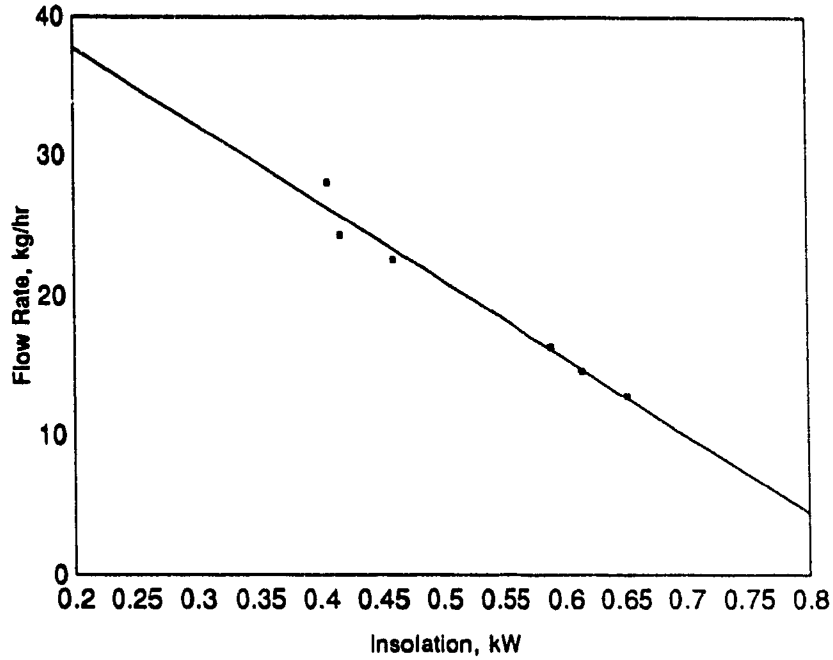


Figure 19. Flow Rate of Working Fluid

where:

Q = energy output of the collector

m = mass flow rate of working fluid

C_p = specific heat of water

T_i = inlet temperature of working fluid

T_o = outlet temperature of working fluid

From Table B.2 of Appendix B, the mean collector output from the six solar drying experiments was 0.264 kW, which is more than twice the energy required for removing the estimated 1.5 kilogram of water in the fish samples. This value shows that there was an underestimation of the amount of heat available from the solar collector.

4.2 Heat Exchanger Performance

4.2.1 Fluid Temperatures

Figure 20 shows the temperature increase of air in the heat exchanger with respect to the temperature drop of the collector fluid. This indicates that a high level of correlation between the collector fluid temperature and air temperature exists. Air enters at ambient temperature and is heated at the heat exchanger prior to its introduction to the drying chamber. A mean air temperature increase of 20°C was attained in the six solar drying experiments, and the outlet air temperatures was correlated with the mean insolation level as shown in Figure 21.

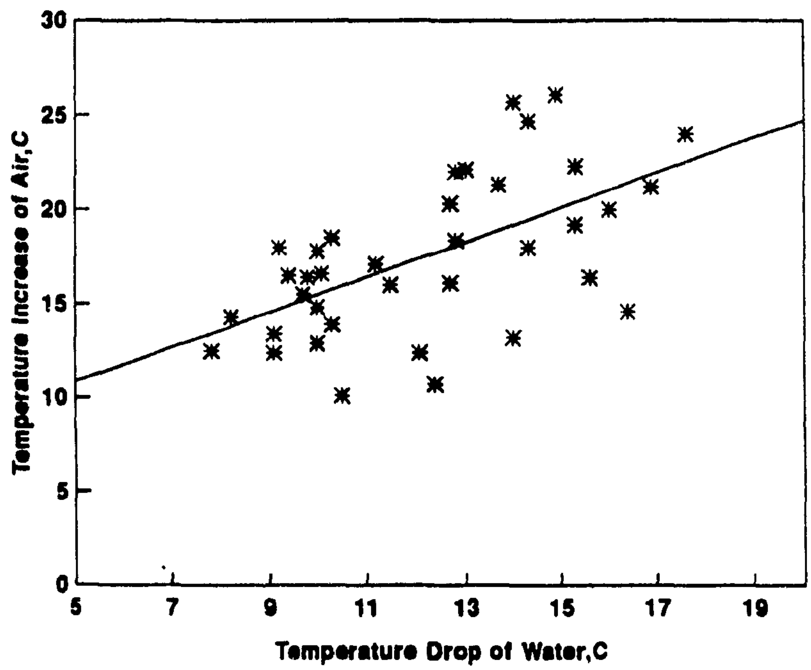


Figure 20. Fluid Temperatures in the Heat Exchanger

4.2.2 Overall Heat Transfer Coefficient

The overall coefficient of heat transfer of the heat exchanger was calculated by using the value of the heat output from the solar collector, which was absorbed by air as input into the heat transfer formula:

$$Q = U * A * (LMTD) \tag{26}$$

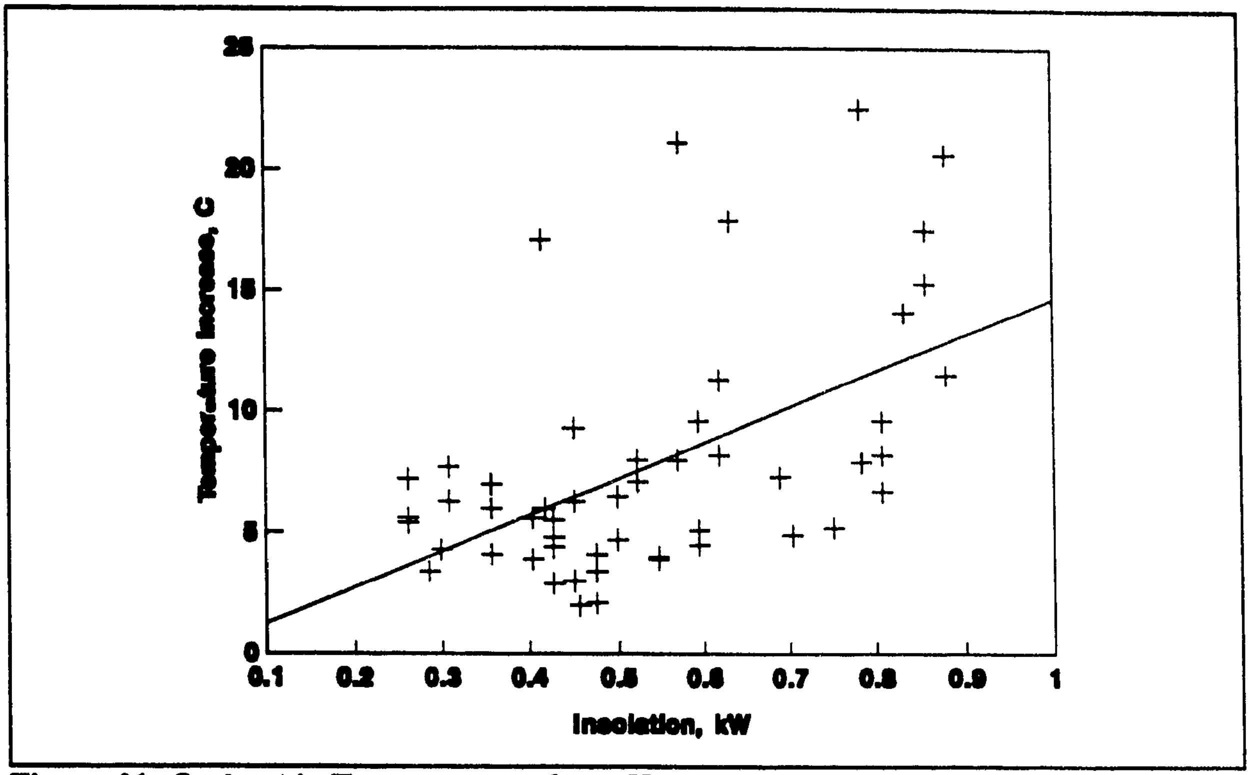


Figure 21. Outlet Air Temperature of the Heat Exchanger

where:

Q = amount of heat transferred
U = overall coefficient of heat transfer
A = effective area of the surface
LMTD = log mean temperature difference

The log mean temperature difference (LMTD) in the heat exchanger which is used in calculating the overall heat transfer coefficient was calculated using the formula:

$$LMTD = \frac{[\Delta T_i - \Delta T_0]}{\ln\left(\frac{\Delta T_i}{\Delta T_0}\right)} \qquad (27)$$

where:

ΔT_i = difference in the inlet temperature of the hot and cold fluid

ΔT_o = difference in the outlet temperatures of the hot and cold fluid

Table B.3 of Appendix B provides a summary of the performance characteristics of the heat exchanger, including the overall heat transfer coefficient for each individual drying experiment.

4.2.3 Energy Output of the Heat Exchanger

The heat transferred to the air passing through the heat exchanger and into the drying chamber was calculated using Equation 25. The estimated mean energy output of the heat exchanger was 0.109 kW as compared to the heat input of 0.264 kW. Both input and output heat values have a standard deviation of 0.04 and this suggests very minimal variability.

4.2.4 Heat Transfer Efficiency

The heat transfer efficiency of the heat exchanger was calculated to determine the amount of heat that can be transferred to air for a given heat input from the solar collector. The heat transfer efficiency was calculated as the ratio of the heat output of the exchanger used to warm the air entering the drying chamber to the input from the solar collector. Table B.3 presents a summary of the heat transfer efficiency calculation for the heat exchanger. A mean value of 44% was observed for the six solar drying experiments. Analysis of the heat transfer efficiency showed that a significant amount of heat was lost in the heat exchanger. Since the flow of drying air which gains heat from water in the heat exchanger was accomplished through buoyancy of heated air and natural convection, the mass of air moved through the heat exchanger was not sufficient to absorb all the heat, forcing excess heat to flow out of the heat exchanger and into ambient air.

The mean air flow rates for six solar drying experiments showed that collector fluid flow rate has no significant effect on the flow rate of air through the heat exchanger. Air flow was significantly affected by ambient air movement which serves to increase the draft in the chimney.

4.3 Drying Chamber Performance

4.3.1 Inlet and Outlet Air Temperature

The mean inlet and outlet air temperatures in the drying chamber taken during the six drying experiments are shown in Figure 22. It can be observed that the mean inlet temperature of the drying chamber was maintained at around 50°C which is the optimum drying temperature for fish as suggested by Milla (1982). The mean inlet temperature for the first drying experiment went up to 65°C when a very high level of solar insolation was experienced during the day. Mean outlet temperature of the drying chamber was almost stable, varying from 36°C to 47°C. The relative humidity for each drying experiment was included to gauge the relative drying capacity of air flowing through the chamber. A mean outlet relative humidity of 50% having a standard deviation of 5.6% was observed in the six solar drying experiments.

4.3.2 Adiabatic Efficiency

The adiabatic efficiency of the drying chamber can be defined as the ratio of the change in absolute humidity between the chamber inlet and outlet to the difference between absolute humidity at saturation and the chamber inlet, at the wet bulb temperature of the

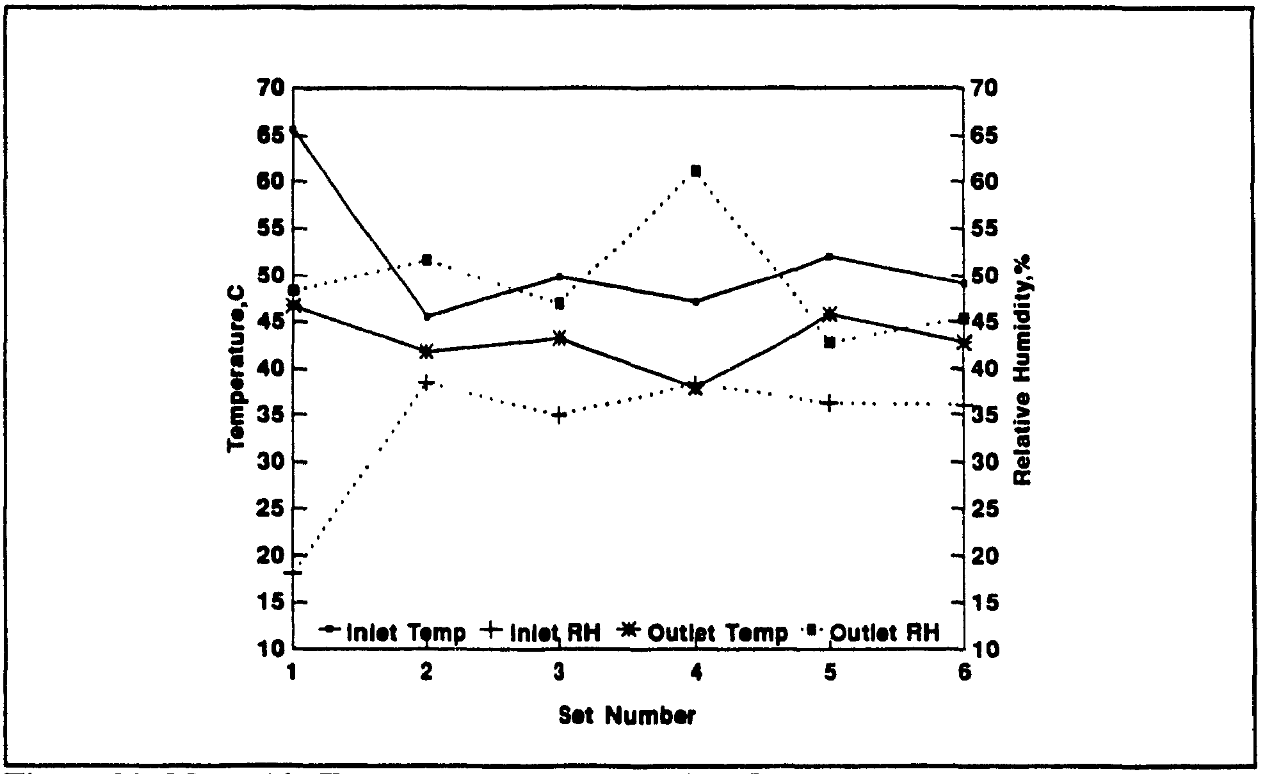


Figure 22. Mean Air Temperatures at the Drying Chamber

chamber (Yaou et al., 1986). Adiabatic efficiency can be calculated using the following formula:

$$\lambda_a = \frac{(\omega_0 - \omega_i)}{(\omega_s - \omega_i)} \qquad (28)$$

where:

λ_a = adiabatic efficiency

ω_0 = absolute humidity at outlet

ω_i = absolute humidity at inlet

ω_s = absolute humidity at saturation

Given the mean temperatures at the inlet and outlet of the drying chamber, the absolute humidity of drying air was calculated using a computer package designed by Albright (1990) based on the psychometric analysis described in Section 2.5.2, Psychometric Properties of Drying Air. Table B.4 of Appendix B shows the adiabatic efficiency of the drying chamber for the seven drying experiments. The mean value was 38.87%. Because actual drying is not adiabatic, the efficiency value of 38.87% is low and shows that the dryer has not reached full load capacity and that air exhausted out of the chimney has a high water absorbing capacity. This is confirmed by the fact that the mean relative humidity of air at the outlet was only 50%.

Closer examination of the drying chamber adiabatic efficiency shows that the efficiency attained was a function of the absolute humidity of ambient air and the degree of saturation of air exhausted from the chamber. Much higher efficiency values could have been attained if the dryer was loaded with a larger mass of fish samples.

4.3.3 Drying Rate

Figure 23 shows the drying rate of the different fish samples which undergo varied pre-drying treatments. It can be observed from the figure that a straight line generally describes the average drying rate in the solar dryer. This line will prove useful in approximating the drying time for most kinds of fish dried in this solar dryer. It was assumed that at moisture contents between 72% and 45% drying takes place in the constant rate period and a straight line describes the range of moisture contents over time. Table B.5 of Appendix B shows the correlation factors for drying rate with other drying parameters. From the table, it can be observed that the water removal rate for the six solar drying experiments has a mean value of 0.1449 kg/hr.

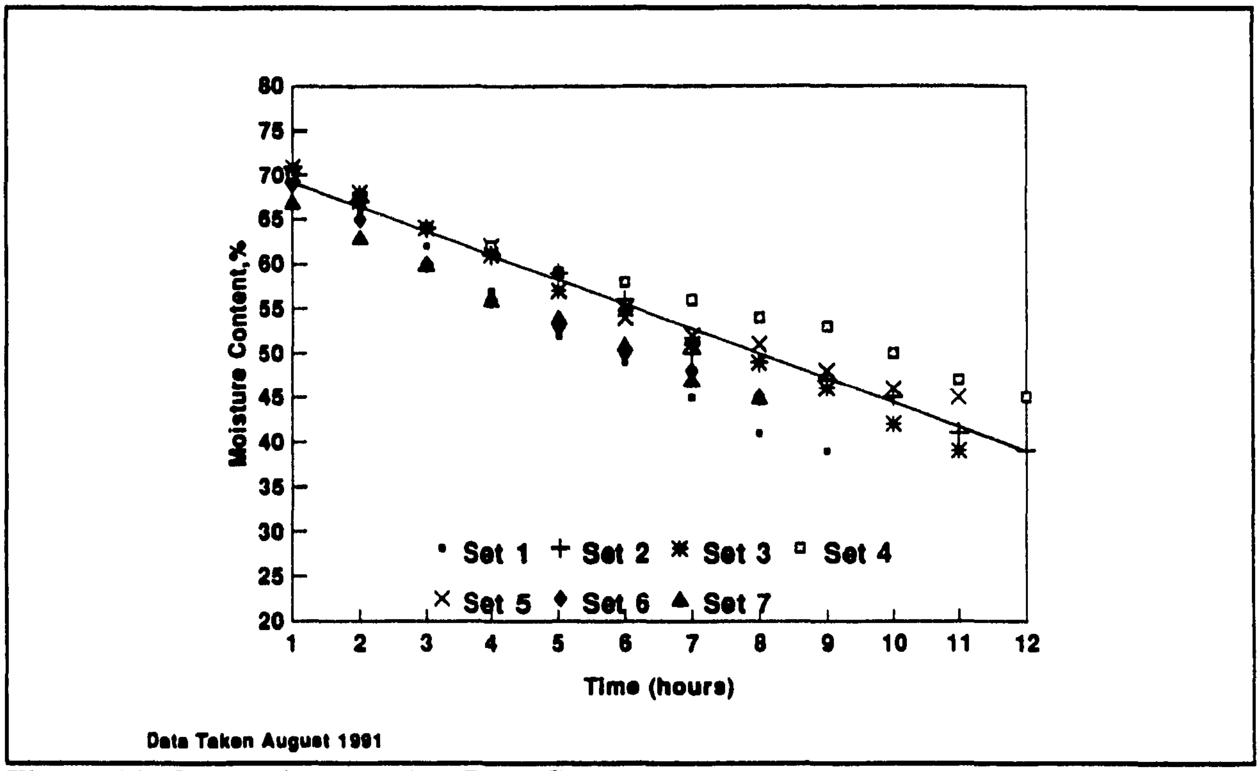


Figure 23. Generalized Drying Rate Curve

Figure 24 shows a graph of moisture removal from the fish with respect to total time required for drying. There is an almost constant rate of reduction in moisture content as can be seen from the trend line of moisture content over time. Drying of fish samples was accomplished at a mean drying time of 10 hours for the 6 drying experiments conducted. This means that 5 kilograms of fish can be processed in the dryer in one day with the support of the auxiliary heater. The drying chamber performance for all the solar drying experiments is shown in Figures C.1 to C.6 in Appendix C. Table 3 shows the moisture content of the seven fish samples.

4.4 Auxiliary Heater Performance

In drying experiment number seven conducted on 29 August 1991, the auxiliary

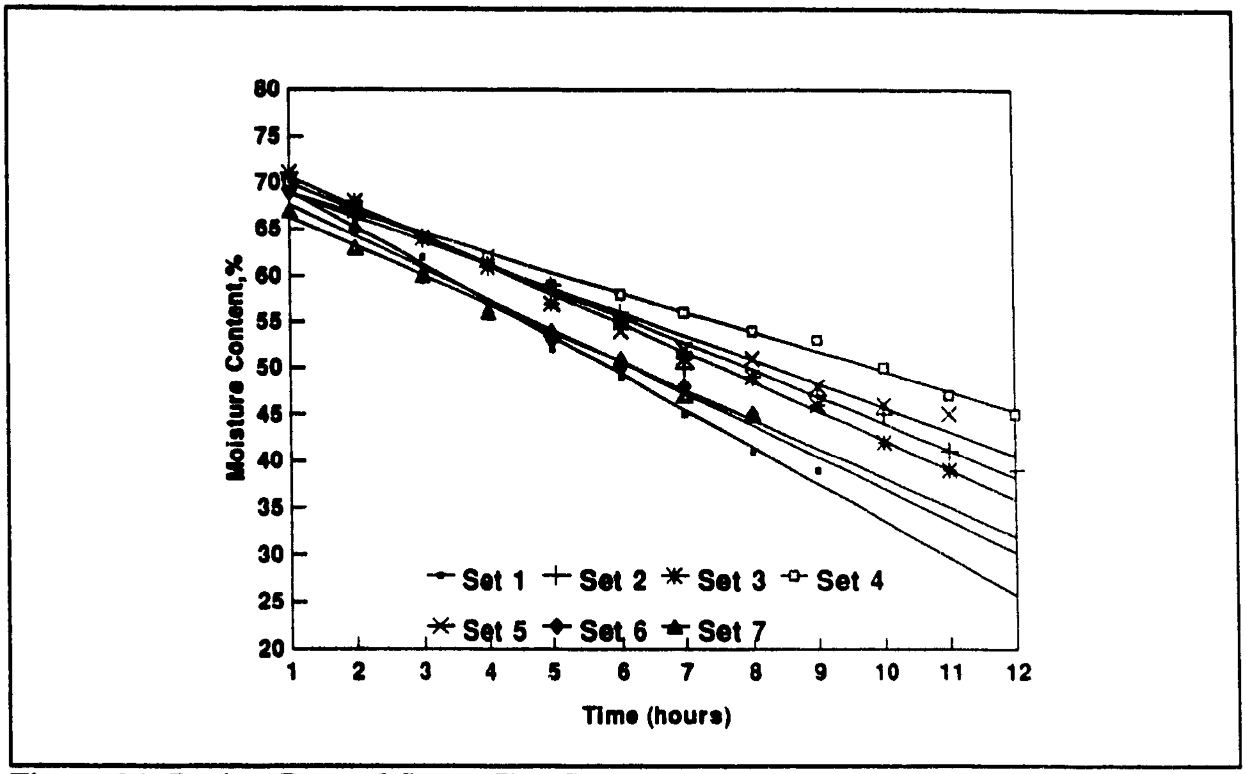


Figure 24. Drying Rate of Seven Fish Samples

heater was used to supply all energy requirements of the dryer. This experiment was conducted to check whether the 1 kilowatt heater element is sufficient to supply the energy requirement of the dryer when no solar radiation is available. It was also on this date that solar insolation was too low to supply the energy needed to dry the fish samples as can be seen in the very low ambient temperature readings of only 25.50°C as compared to 30°C and above for other drying experiments. Heat loss in the system was prevented by covering the solar collector with 10 cm of Urethane foam. With the solar collector fully covered and insulated, it was assumed that a negligible amount of heat was lost during the drying experiment. A distinct dryer performance was observed when the heater was used as will be shown in the following performance analysis of the auxiliary heater.

4.4.1 Fluid Temperatures

Figure 25 shows the drop in temperature of water in the heat exchanger as well as the increase in ambient temperature of air entering the drying chamber. It can be noted that a far greater drop in fluid temperature at the heat exchanger was noted using the auxiliary heater.

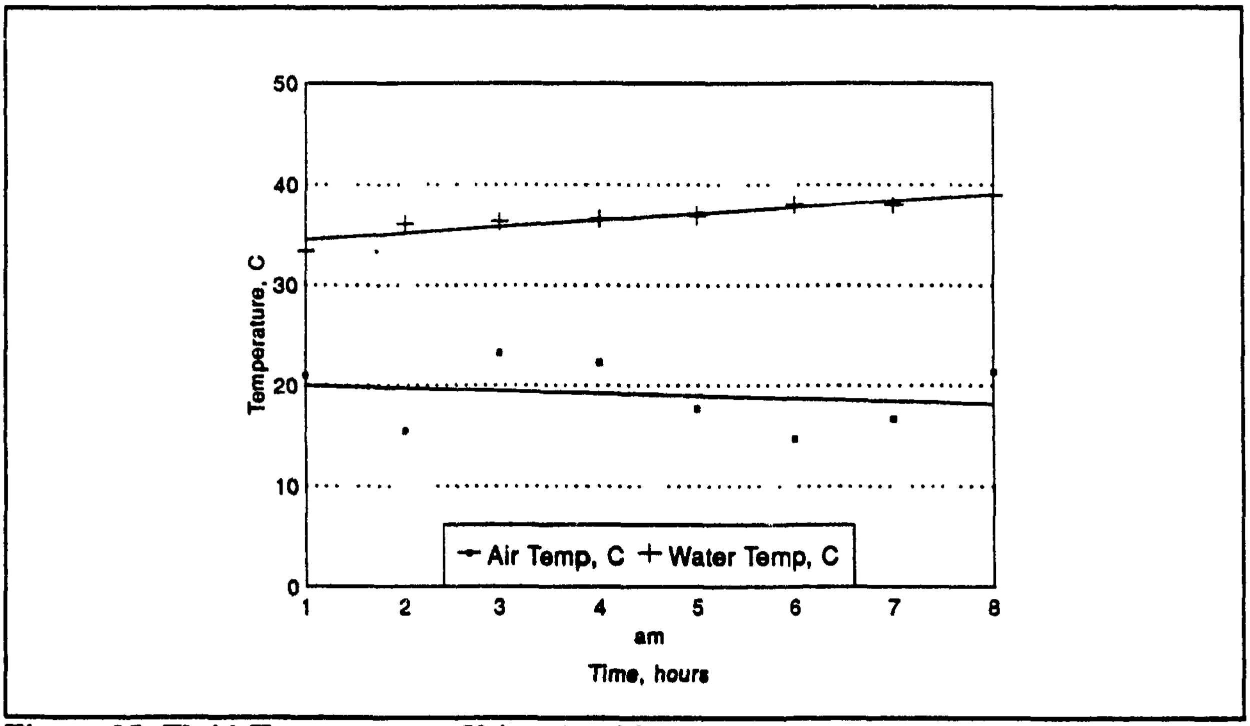


Figure 25. Fluid Temperatures Using Auxiliary Heat

A mean temperature drop of 36.83°C was observed at the heat exchanger using the auxiliary heat source, while for the six drying experiments using solar energy, the mean temperature drop was only 12.16°C. A far greater stability of the temperature difference was found in the use of the auxiliary heat source having a standard deviation of only 1.62°C compared to 5.73°C with the solar drying experiments. Statistical analysis conducted on the data set from the six drying experiments and experiment number 7 showed a significant difference in temperature reduction in the heat exchanger. This means that a greater amount of heat was transferred to drying air entering the drying chamber.

Increase in air temperature in the heat exchanger is also shown in Figure 25. It can be observed that the mean increase in the temperature of air is 19.06°C as compared to the mean value of 18.97°C for the six solar drying experiments. Variability of temperature increase in the solar drying experiments is higher with a standard deviation of 5.38°C compared to 3.0°C for the drying experiment using the auxiliary heat source. Using the t-test to assess the differences in air temperature increase, it was found that there was no significant difference in air temperature increase between the experiment using solar energy and the one using the auxiliary heat source.

4.4.2 Log Mean Temperature Difference

The log mean temperature difference for the drying experiment using the auxiliary heater is shown in Figure 26. A mean value of 29.23°C ±0.8828 was observed as compared to the six drying experiments having a mean of 22.81°C ±6.14. Statistical analysis showed a significant difference in the log mean temperature difference between the solar drying experiments and experiment 7 using the auxiliary heat source. These findings show that the auxiliary heater can provide a sufficient and stable amount of heat to the drying chamber.

4.4.3 Drying Rate

Figure 27 shows the moisture reduction over time for drying experiment number 7. Moisture reduction in this set has a mean of 0.15 kg H_2O/hr which compares well with the findings in the solar drying experiments which has a mean of 0.145 kg H_2O/hr. The rate of

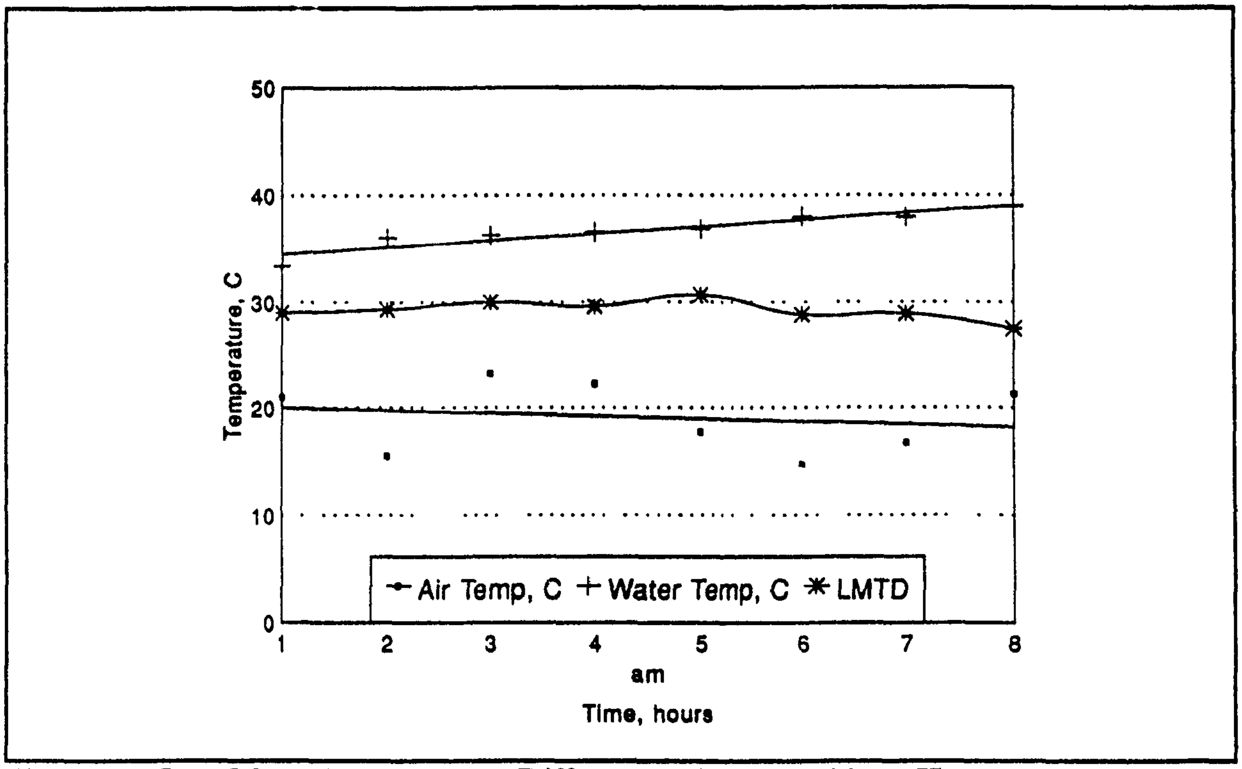


Figure 26. Log Mean Temperature Difference Using Auxiliary Heat

moisture reduction has a standard deviation of 0.04 which shows the rate as more or less constant and proves that at 72% to 45% moisture content, drying of fish occurs in the constant rate period.

4.4.4 Drying Efficiency

Drying efficiency using the auxiliary heat source was calculated using the same method as those for the six other drying experiments. Table B.6 in Appendix B shows efficiency values for all the drying experiments. It can be observed that the 1.0 kilowatt heater has the lowest drying efficiency (5%). The drying chamber has a mean adiabatic efficiency of 37.27% which compares well with the 38.87% mean of the solar drying experiments.

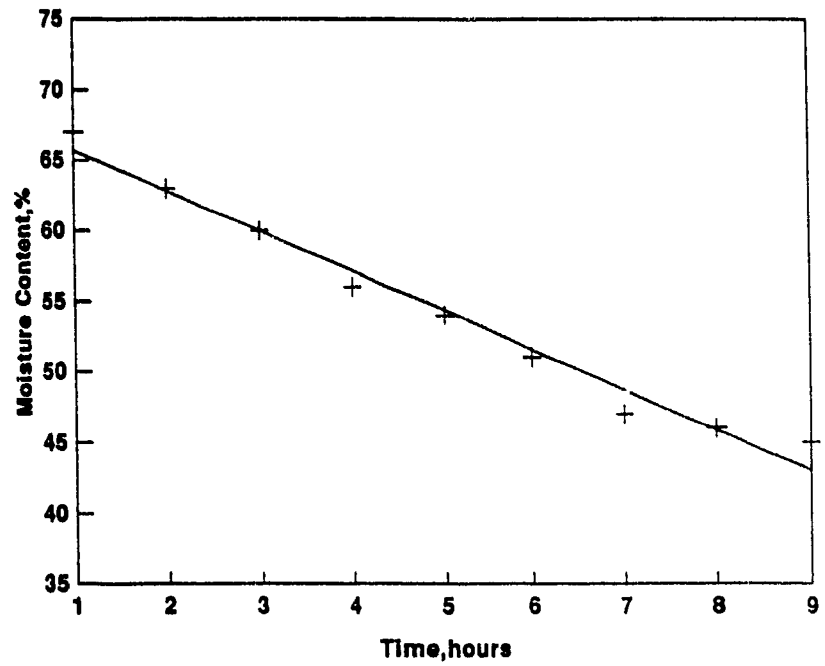


Figure 27. Moisture Removal Using Auxiliary Heat

The drying chamber uses natural convection for air movement and this permits self-regulation of chamber temperature and air flow rate. The auxiliary heater was activated throughout the drying experiment so the system was receiving 1000 watts during the entire drying experiment. The low drying efficiency value shows that too much energy was exhausted from the drying chamber and was therefore not used in the drying process.

These findings imply that when the auxiliary heat source is used, only a minimal amount of heat is required to operate the dryer. This means that when using agro-waste material (coconut husk, bagasse or rice hull) which has a heating value of around 13.96 mJ/kg, less than 4 kg/hr is needed to operate the dryer at an optimum drying rate.

4.5 System Performance

4.5.1 Efficiency

The overall efficiency of the drying system can be defined as the fraction of incident solar power that is used in vaporizing water to reduce the moisture content of the fish. Dryer efficiency was calculated using the following equation:

$$\lambda_d = \frac{(m * L)}{(I * A_c)} \tag{29}$$

where:

λ_d = dryer efficiency

m = mass of water removed

L = latent heat of vaporization

I = insolation level at collector

A_c = area of the collector

Table B.6 of Appendix B shows the efficiency of the different components of the solar fish dryer as well as the overall system efficiency. Me ·fficiency values for the heat exchanger include values for drying experiment 7 using · auxiliary heater, while for collector efficiency, drying experiment number 7 was not included. The mean system efficiency value over the six drying experiments was 9.33% and compares well with designs tested by Yu Wai Man (1986) which found that solar dryers of the natural convection type are operating in the efficiency range of 7-14%, compared to 11-18% for the forced convection system designs.

Figure 28 shows a graph of the system efficiency in relation to the temperature increase in the solar collector. It can be observed that system efficiency drops off at mean collector temperature increases above 10°C. The system efficiency reaches its peak value at mean collector temperature increase of between 9.61°C and 10.81°C which confirms earlier findings of Lof and Close (1967), Cooper (1973), Gupta and Garg (1968), Hollands et al., (1985), and Fanney and Klein (1985) that a 10°C temperature increase in the collector is sufficient to give optimum efficiency for the thermosyphon system.

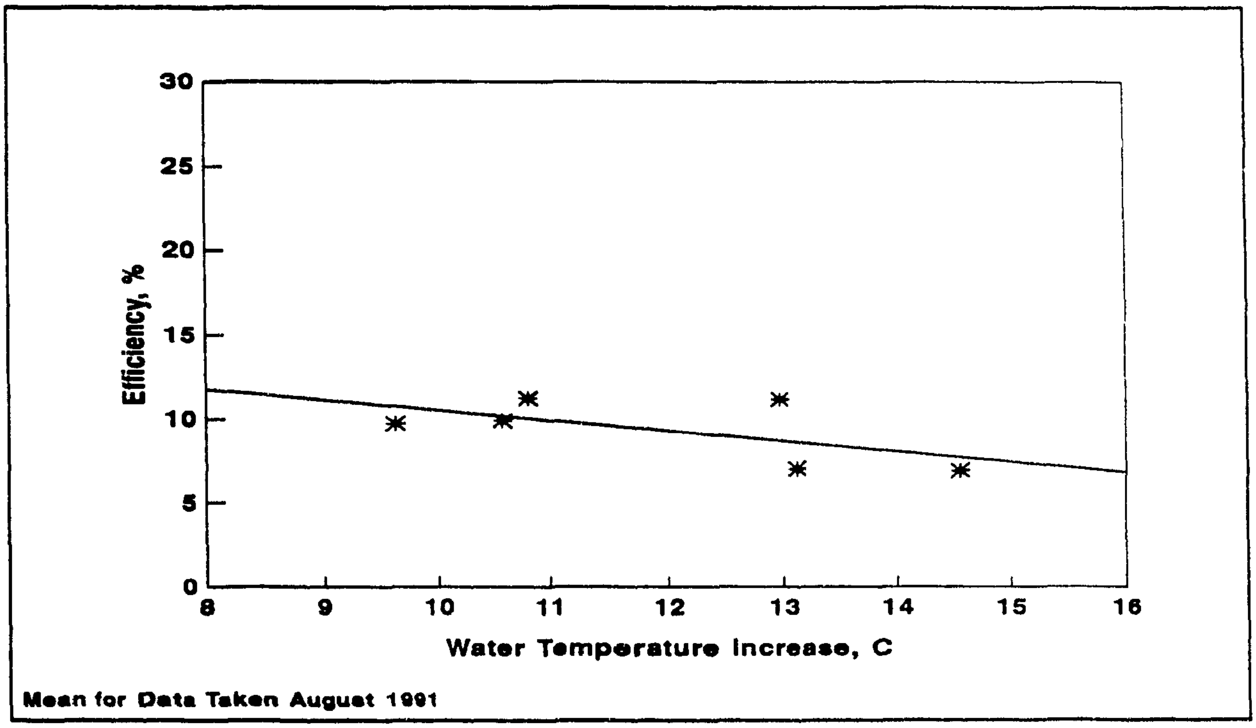


Figure 28. Drying Efficiency and Temperature Increase

4.5.2 Characteristics of Fish Samples

For each drying experiment, a different kind of fish sample was used. Table 2 shows the different samples and the forms in which each was processed in the dryer. The different form in which the samples were dried are typical of those which are used in commercial drying of fish. Pre-drying treatments accorded the samples were also similar to the treatments employed in commercial fish drying.

Table 3 shows the results of the drying experiments conducted. The six samples were loaded with a mean moisture content of 71.5% and after a mean drying time of 10.33 hours, the samples emerged with a mean moisture content of 42.17% (wet basis). This means that 5 kilograms of fish can be processed in the solar dryer in one day with minimal support from the auxiliary heater. Solar dryer performance for a typicai drying experiment is shown in Figure 29. Filleted Threadfin Bream (Nemipterid sp.) cut into strips a quarter of an inch thick was used as drying material. The moisture content of the fish samples was reduced from 72% to 40% in 10 hours with a mean insolation level of 524 W/m^2. Figures 30, 31 and 32 shows samples of fish dried in the natural convection solar fish dryer.

Table 2. Fish Samples Used in Drying Experiments.

Set	Species	Form/Treatment	Size,kg	MC_i,%
1	Indian Sardine	Unscaled/Salted	5.75	71.50
2	Mackerel	Split/Salted	5.00	72.00
3	Threadfin Bream	Filleted/Salted	4.60	72.50
4	Crevalle	Whole/Salted	5.95	72.00
5	Indian Sardine	Unscaled/Salted	5.00	71.00
6	Swordfish	Filleted/Salted	5.00	70.00
7	Roundscad	Whole/Salted	4.40	70.00

Table 3. Moisture Content and Drying Time

Set No.	Fish Sample	Initial MC,%	Final MC,%	Time,hr
1	Indian Sardine	71.50	39.00	9
2	Mackerel	72.00	39.00	12
3	Threadfin Bream	72.50	39.00	11
4	Crevalle	72.00	47.00	12
5	Indian Sardine	71.00	44.00	10
6	Swordfish	70.00	45.00	8
7	Roundscad	70.00	45.00	8

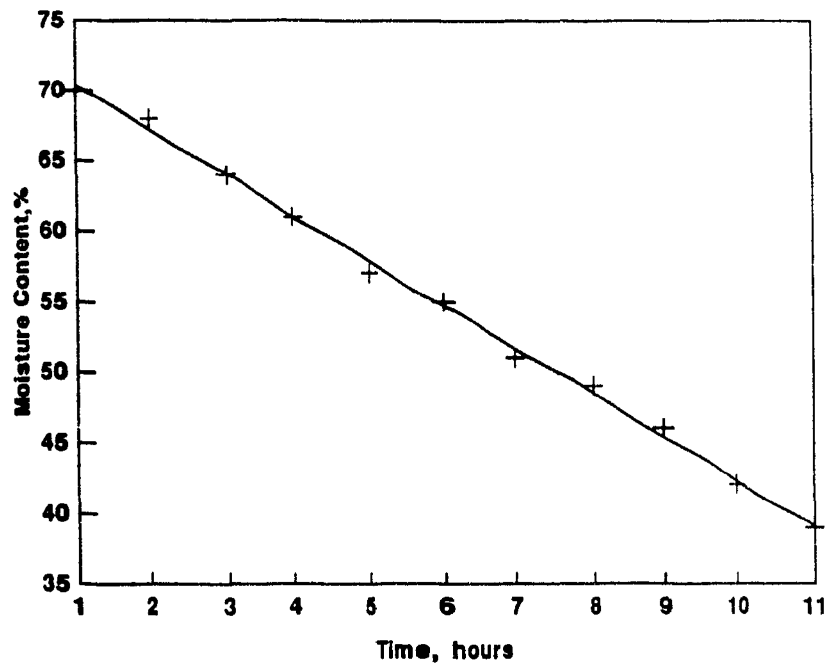


Figure 29. Typical Drying Rate for the Solar Dryer

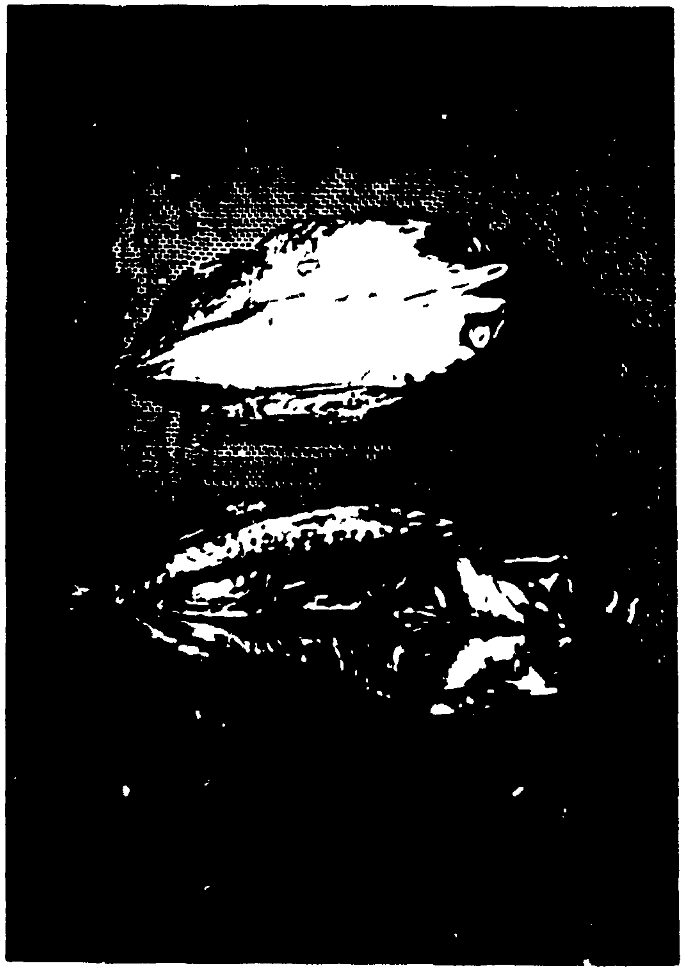


Figure 30. Dried Fish Sample: Butterfly Split Crevalle

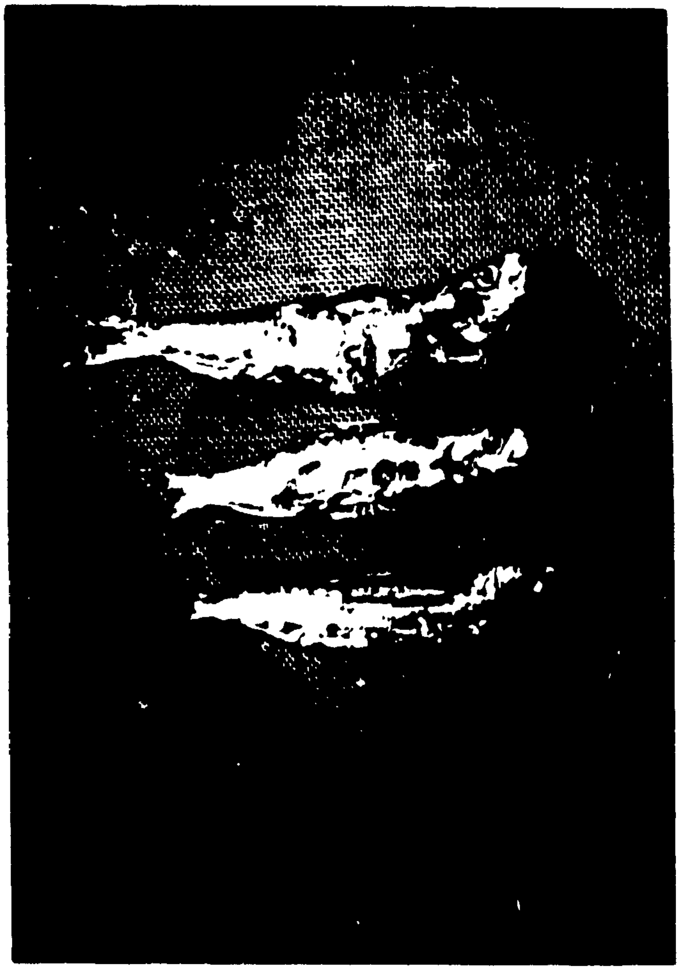


Figure 31. Dried Fish Sample: Unscaled Whole Indian Sardine

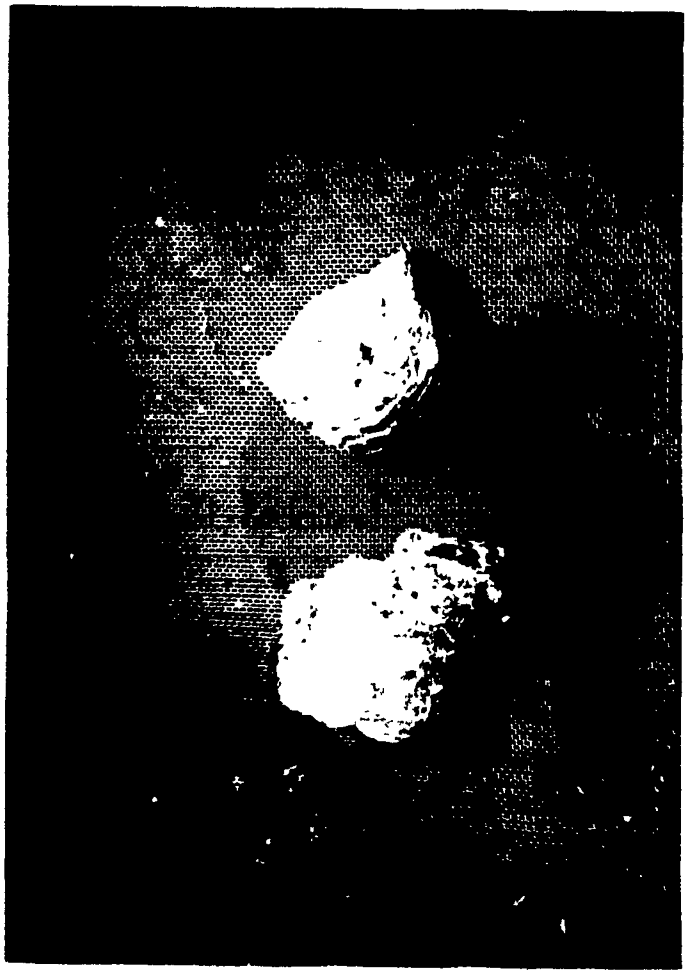


Figure 32. Dried Fish Sample: Filleted Swordfish

5. SUMMARY AND CONCLUSIONS

This study was planned to investigate the possibility of using solar thermal energy concepts in improving fish drying systems. A natural convection solar dryer was designed and a prototype was built. Different types of fish with different pre-drying treatments were dried to test the capability of the machine to reduce its moisture content from 72% to 45% in 8 hours. Six drying experiments were conducted to determine whether the dryer was successful in meeting the objectives. The results obtained in the study were used to develop a feasible system of reducing fish spoilage by utilizing solar energy in processing. The following summarizes the findings of this study:

1. A natural convection solar drying system can function efficiently at low insolation levels when the system is properly designed with minimal heat loss to the environment. Heat loss can be prevented by proper insulation of hot water pipes at the outlet of the solar collector.

2. The efficiency of a thermosyphon system is found to be optimum at a collector temperature increase of 10°C. This means that even at minimal insolation levels, fish drying is still possible, unlike in direct sun-drying where higher solar insolation is a necessity.

3. Natural convection in a cabinet dryer supplied with heat from a heat exchanger is sufficient to maintain an ideal drying temperature and air movement to remove moisture from the fish. The system proved to be self-regulating since a high relative humidity was maintained inside the drying chamber which prevented cooking the fish during surges of heat at high insolation levels. This was attained since excess thermal energy is exhausted as can be observed from several low humidity, high temperature chamber outlet readings.

4. Moisture reduction from 72% to 45%, which is common in fish drying, is in a constant rate period, and self-regulation of temperature and air movement inside the drying chamber proved beneficial in maintaining a constant rate of water movement from the flesh of the fish.

5. For a drying system that uses water as a heat transfer medium, a dryer efficiency of 9% is high and compares well with natural convection air dryers which have efficiencies in the range of 7 to 14%.

These findings indicate that the use of thermosyphon and natural convection systems is favourable to small or large scale drying operations. The system requires no moving parts and auxiliary power is only required for use during night time or rainy days. For operation in remote locations where access to electricity is not possible, an ordinary water tube heater made of metal pipes and heated by burning biomass fuel will satisfactorily replace the 1.0 kW auxiliary heater used in this study.

Since a natural convection system is self-regulating (i.e. temperature and air flow control), damage to the product can be prevented and the system requires no personnel to operate, thereby reducing the cost of the drying operation.

6. RECOMMENDATIONS

Several difficulties were encountered in the course of this study and require further detailed investigation.

1. Steam generation in the collector occurred several times and resulted in the loss of thermosyphon effect. Although higher temperatures are usually desirable in collector systems, the loss of thermosyphon effect, however, reduces or altogether stops heat movement to the heat exchanger. It is therefore recommended that thermosyphon systems be operated in a closed loop configuration, otherwise steam may be produced.

2. In the use of natural convection for heat transfer and air movement, it is highly recommended that a straight-through vertical movement of air be maintained. This arrangement will serve to enhance the self-regulating characteristic of the system.

3. Further studies on heat exchanger designs to suit low temperature applications are required. For large-scale use of solar heated water systems, low temperature, high transfer efficiency heat exchangers can improve the overall thermal efficiency of the system.

4. Solar heated water systems have a variety of other applications. It is highly recommended that these applications be analyzed with the purpose of integrating them into a single solar energy source.

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APPENDIX

8. APPENDICES

Appendix A. Design Calculations for Dryer Components

A.1 Amount of Water Removal

$m = W * (mc_1 - mc_2)$

$= 5 \text{ kg} * (0.75 - 0.45)$

$= 1.5 \text{ kg}$

A.2 Energy Requirement

$Q = m * Q_l$

$= 1.5 \text{ kg} * 2383 \text{ kJ/kg}$

$= 3{,}574.5 \text{ kJ} / 8 \text{ hr} * 3600 \text{ sec}$

$= 0.1240 \text{ kW}$

A.3 Volume of Air for Drying

$V = [m / (\omega_o - \omega_i)] * C_v$

$= [1.5 / (0.0250 - 0.0167) \text{kg} * 0.876 \text{ m}^3/\text{kg}$

$= 158 \text{ m}^3$

A.4 Required Air Flow at Heat Exchanger

$Q = V / t$

$= 158 \text{ m}^3 / 8 \text{ hr} * 3600 \text{ sec}$

$= 0.00549 \text{ m}^3/\text{sec}$

A.5 Air Velocity at Heat Exchanger

$v = Q / A$

$= 0.00549 \text{ m}^3/\text{sec} / 0.0625 \text{ m}^2$

$= 0.08784 \text{ m/sec}$

A.6 Available Solar Energy

$E = Id * \text{Eff.} * t$

$= 875 \text{ W/m}^2 * 0.10$

$= 87.5 \text{ W/m}^2$

$= 0.0875 \text{ kW/m}^2$

A.7 Estimated Area of Solar Collector

$$A = Q / E$$

$$= 0.1240 \text{ kW}/0.0875 \text{ kW/m}^2$$

$$= 1.417 \text{ m}^2$$

A.8 Estimated Surface Area of Heat Exchanger

$$Q = U * A * (T_f - T_a)$$

$$A = 0.124\text{kW} / [0.385\text{kW/m}^2\text{-°C} * 0.003\text{m} * (50\text{-}28)\text{°C}]$$

$$= 4.87 \text{ m}^2$$

Appendix B. Performance Calculations for Dryer Components

B.1. Estimate of Noontime Radiation for August 21

Latitude:

$$L = 12°$$

Hour Angle:

$$H = 15 * (T-12)$$

$$H = 15 * (12-12)$$

$$= 0°$$

Declination:

$$\delta = 23.45\ Sin\left[\frac{360 * (284 + N)}{365}\right] \qquad (18)$$

$$= 23.45 * \text{Sin}\ [(360/365) * (284+233)]$$

$$= 11.75°$$

Altitude:

$$Sin\beta = [Cos(L) * Cos(\delta) * Cos(H)] + [Sin(L) * Sin(\delta)] \qquad (16)$$

$$= \text{Cos}\ 12 * \text{Cos}\ 11.75 * \text{Cos}\ 0 + \text{Sin}\ 12 * \text{Sin}\ 11.75$$

$$\beta = 89.75°$$

Direct Normal Insolation:

$$I = (C + Sin\beta)\ A\ e^{-\frac{B}{Sin\beta}} \qquad (15)$$

$$= (0.122 + \text{Sin}\ 89.75) * 1107 * e^{-0.201/\text{Sin}\ 89.75}$$

$$= 1015\ W/m^2$$

Tilt:

$$\Sigma = 15°$$

Azimuth:

$$Sin\ \alpha = \frac{Cos(\delta) * Sin(H)}{Cos(\beta)} \qquad (17)$$

$= \text{Cos } 11.75 * \text{Sin } 0/\text{Cos } 89.75$

$\alpha = 0°$

Angle of Incidence:

$$Cos\phi = [Cos(\beta_c) * Cos(\alpha_c) * Sin(\Sigma)] + [Sin(\beta_c) * Cos(\Sigma)] \qquad (19)$$

$= \text{Cos } 89.75 * \text{Cos } 0 * \text{Sin } 15 + \text{Sin } 89.75 * \text{Cos } 15$

$\phi = 14.75°$

Radiation on a Tilted Surface:

$I_T = \text{Cos } \phi * I_{DN}$

$I_T = \text{Cos } 14.76 * 1015$

$= 981 \text{ W/m}^2$ or 0.981 kW

Table B.1 Summary of Predicted and Recorded Insolation for August 21

Time	Predicted Values, kW	Recorded Value, kW
9:00	0.688	0.569
10:00	0.851	0.618
11:00	0.950	0.569
12:00	0.982	0.689
1:00	0.950	0.308
2:00	0.851	0.357
3:00	0.688	0.285
4:00	0.515	0.285

B.2 Calculation for Collector Mass Flow Rate

Drying Experiment Set 1:

$U = 0.065\ kW/m^2$

$F' = 0.97$

$C_p = 4.17\ kJ/Kg\text{-}°C$

$S = 0.615\ kW/m^2$

$T = 12.97°C$

$A_c = 2\ m^2$

$$\dot{m} = \frac{U_l F' A_c}{[C_p \ln(1 - U_l F' (T_0 - T_i))] / [S - U_l (T_0 - T_i)]} \quad (22)$$

$$= \frac{[0.065 * 0.97]}{[4.17 * \ln(1-0.97*12.97)]/[0.615-(0.065*12.97)}$$

$= 0.00405$ kg/sec or 14.58 kg/hr

Table B.2 Summary of Increase in Temperature and Flow Rate in the Solar Collector

Set No.	Insolation, kW/m^2	Temperature Increase, °C	Flow Rate, kg/hr	Energy Output, kW
1	0.715	12.97	14.58	0.219
2	0.407	10.81	28.12	0.352
3	0.652	14.57	12.80	0.216
4	0.590	13.12	16.29	0.248
5	0.417	9.61	24.31	0.271
6	0.460	10.59	22.56	0.277

B.3 Calculation for Collector Energy Output

Drying Experiment Set 1:

$m = 14.58$ kg/hr

$C_p = 4.17\ kJ/kg\text{-}°C$

$\Delta T = 12.97°C$

$$Q_s = mC_p\,(T_0 - T_i) \tag{21}$$

$= 14.58 * 4.17 * 12.97$

$= 0.219$ kW

B.4 Calculation for Heat Exchanger Characteristics

Drying Experiment Set 1:

$T_i = 83.44 - 32.23$

$= 51.21°C$

$T_o = 70.48 - 65.63$

$= 4.85°C$

$$LMTD = \frac{[\Delta T_i - \Delta T_0]}{\ln\left(\frac{\Delta T_i}{\Delta T_0}\right)} \tag{27}$$

$$= \frac{(51.21 - 4.85)}{\ln(51.21/4.85)}$$

$= 19.67°C$

$Q_{out} = V * A * v * C_p * (T_o - T_i)$

$= 0.64 * 0.008107 * 1.09 * 1.005 * 33.40$

$= 0.189$ kW

$Eff = Q_{out} / Q_{in}$

$= 0.189/0.219$

$= 0.87$ or 87%

Table B.3 Summary of Heat Exchanger Characteristics

Set No.	Log Mean Temp. Diff.,°C	Energy Output,kW	Heat Trans. Coeff,W/m^2	Heat Trans. Effect,%
1	19.67	0.189	4.47	87%
2	17.22	0.084	2.27	24%
3	28.37	0.113	1.85	52%
4	21.81	0.099	2.11	40%
5	16.39	0.083	2.36	31%
6	33.37	0.086	1.20	31%
7	29.33	0 111	1.72	11%

B.5 Calculation for Adiabatic Efficiency

For Drying Experiment Set 1:

$W_o = 0.0285$

$W_i = 0.0204$

$W_s = 0.0341$

$$\lambda_a = \frac{(\omega_o - \omega_i)}{(\omega_s - \omega_i)} \tag{28}$$

= (0.0285-0.0204)/(0.0341-0.0204)

= 0.5776 or 57.76%

Table B.4 Summary of Adiabatic Efficiency of the Drying Chamber

Set No.	ω, inlet	ω, outlet	ω, saturation	Efficiency, %
1	0.0204	0.0285	0.0341	57.76
2	0.0196	0.0211	0.0264	22.62
3	0.0214	0.0242	0.0294	35.56
4	0.0212	0.0253	0.0284	56.69
5	0.0207	0.0229	0.0289	26.89
6	0.0187	0.0215	0.0270	33.70
7	0.0183	0.0207	0.0247	37.27

Table B.5 Summary of Correlation Factors for Drying Rate

Set No.	Rate, kg/hr	Insolation, kW/m^2	ΔT_t, °C	ΔT_{HE}, °C	ΔT_{DC}, °C	ΔT_{LMTD}, °C
1	0.2111	0.615	12.97	33.40	18.94	19.67
2	0.1375	0.407	10.81	14.22	3.69	17.22
3	0.1364	0.652	14.57	18.54	6.60	28.37
4	0.1250	0.590	13.12	16.72	9.27	21.81
5	0.1227	0.417	9.61	18.60	5.11	16.39
6	0.1375	0.460	10.59	18.71	6.30	33.37
Corr.	------	0.6481	0.2958	0.9370	0.8985	-0.1167

B.6 Calculation for Drying Efficiency

For Drying Experiment Set 1:

$m = 0.2111$ kg/hr

$L = 2344$ kJ/kg

$I_T = 0.615$ kW/m^2

$A_c = 2$ m^2

$$\lambda_d = \frac{(m * L)}{(I * A_c)} \qquad (29)$$

= (0.2111 * 2344) / (0.615 * 2)

= 0.1117 or 11.70%

Table B.6 Summary of System Efficiencies

Set No.	Collector, %	Heat Exchange, %	Dry Chamber, %	System, %
1	8.60	87	57.76	11.17
2	43.26	24	22.62	11.23
3	16.57	52	35.56	6.92
4	20.98	40	56.69	7.03
5	32.45	31	26.89	9.74
6	30.08	31	33.70	9.90
7	-----	11	37.27	5.00
Mean	25.32	39	38.64	9.33

Appendix C. Dryer Performance Using Solar Energy
Appendix C.1 Drying Experiment Number 1

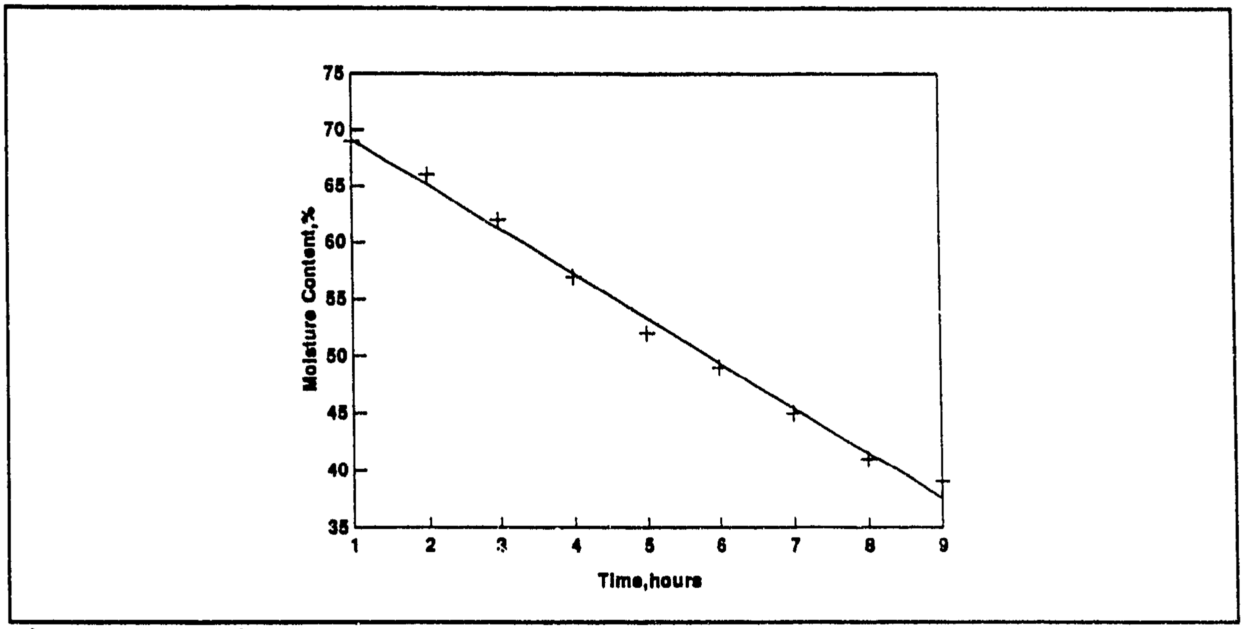


Figure C.1a Drying Rate

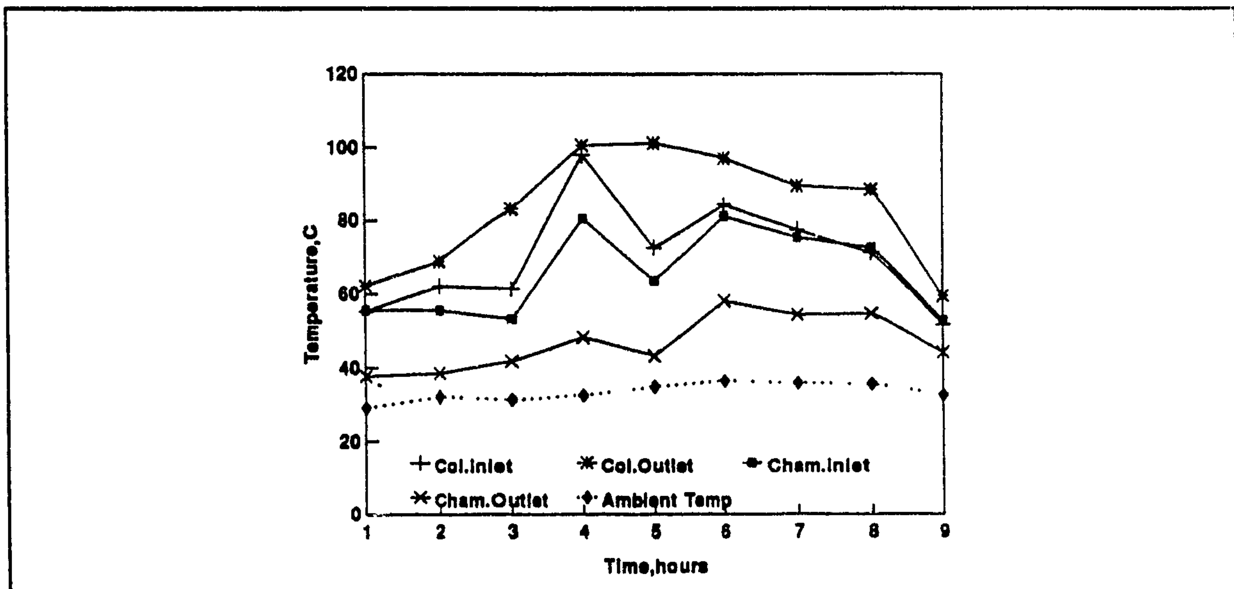


Figure C.1b Temperature Profile

Appendix C.2 Drying Experiment Number 2

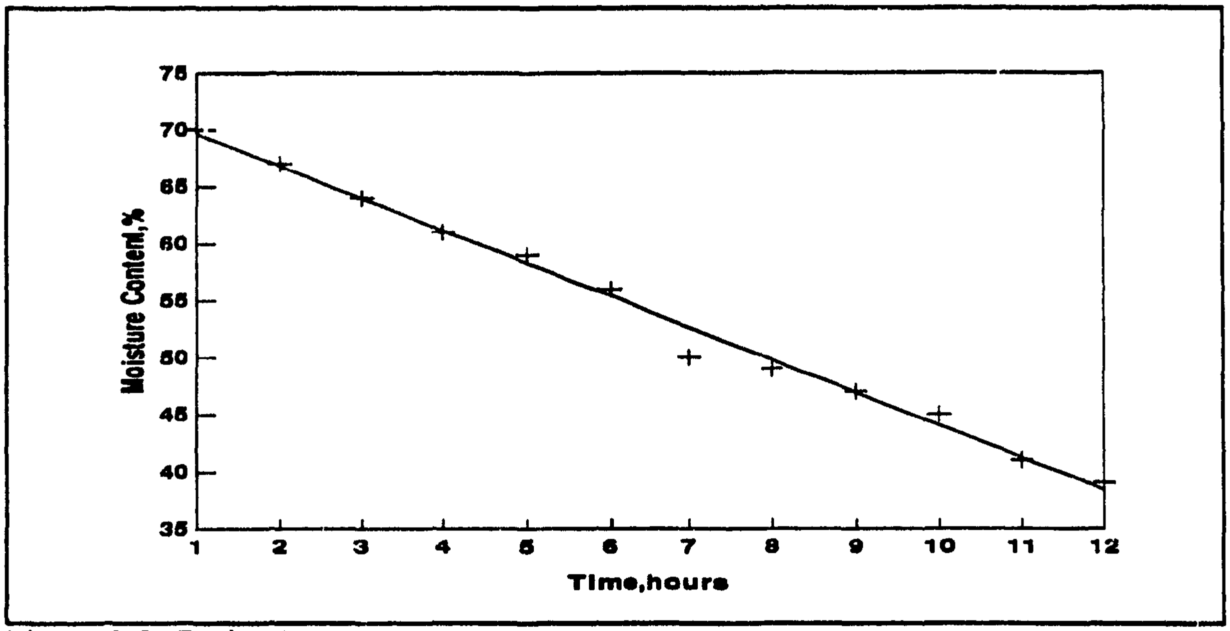


Figure C.2a Drying Rate

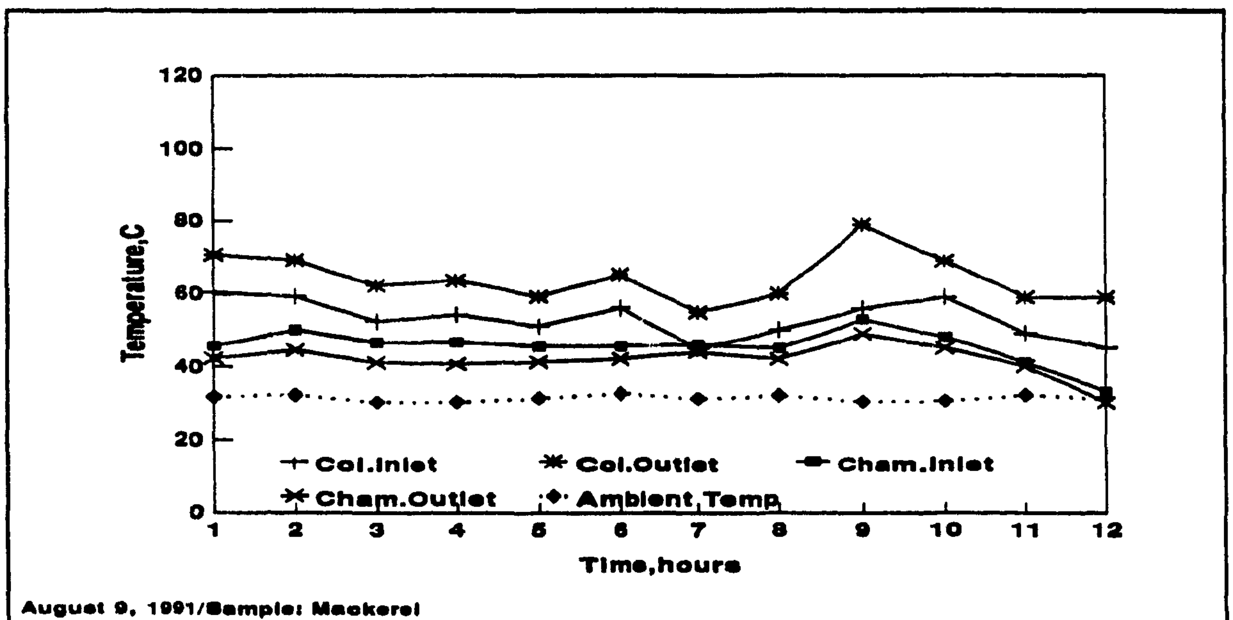


Figure C.2b Temperature Profile

Appendix C.3 Drying Experiment Number 3

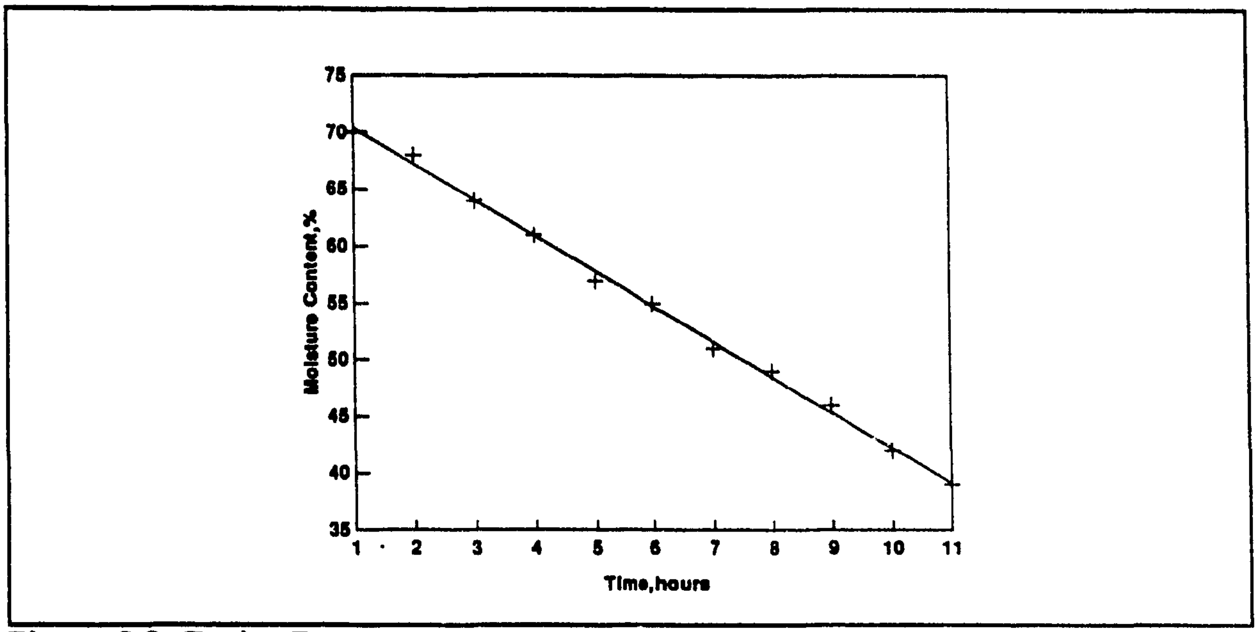


Figure C.3a Drying Rate

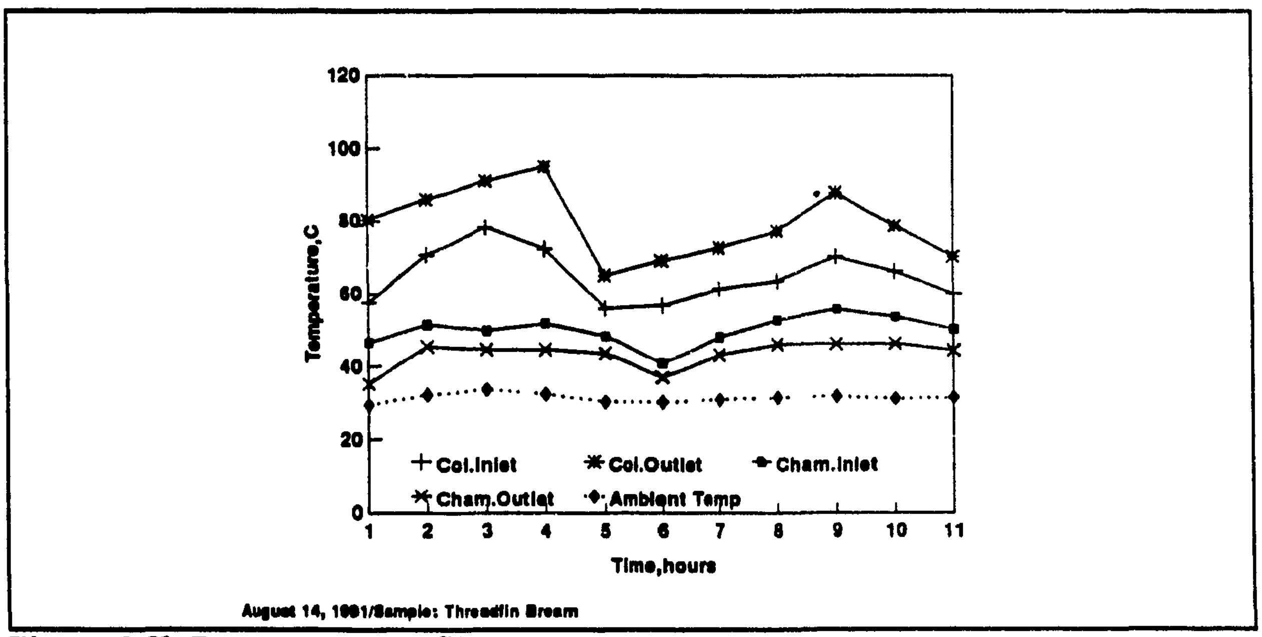


Figure C.3b Temperature Profile

Appendix C.4 Drying Experiment Number 4

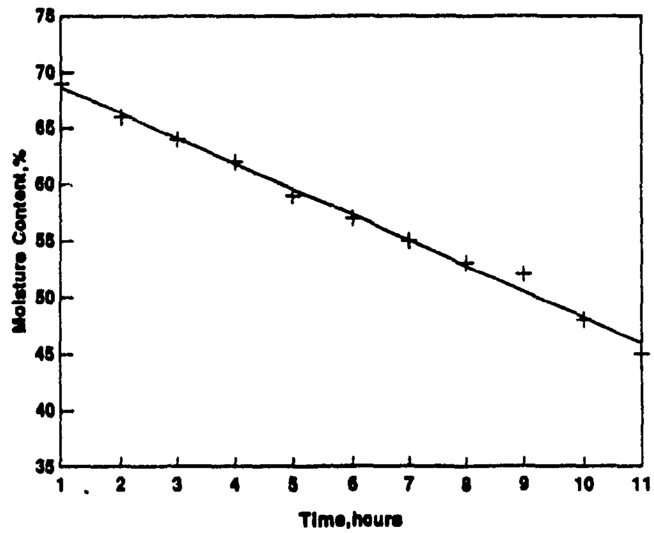
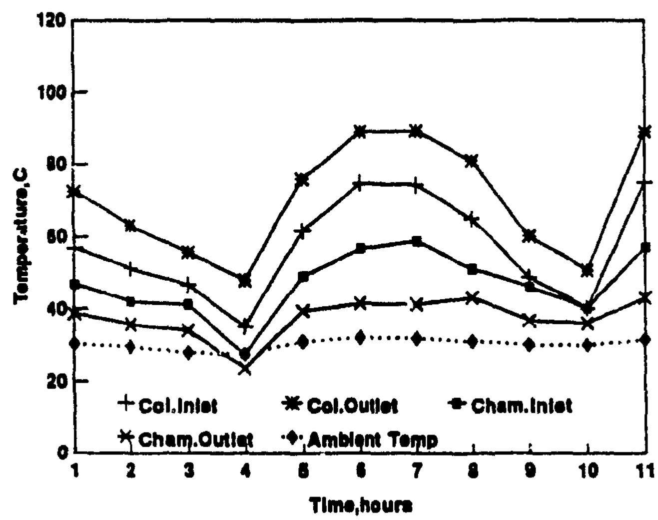


Figure C.4a Drying Rate



August 16, 1991/Sample: Crevalle

Figure C.4b Temperature Profile

Appendix C.5 Drying Experiment Number 5

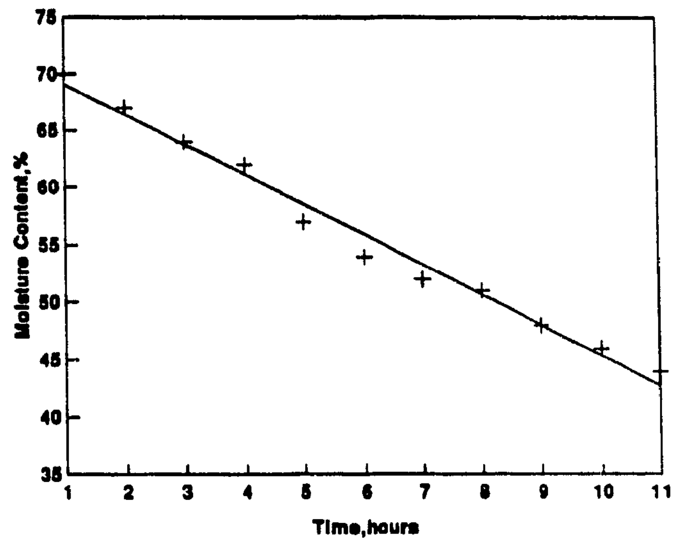


Figure C.5a Drying Rate

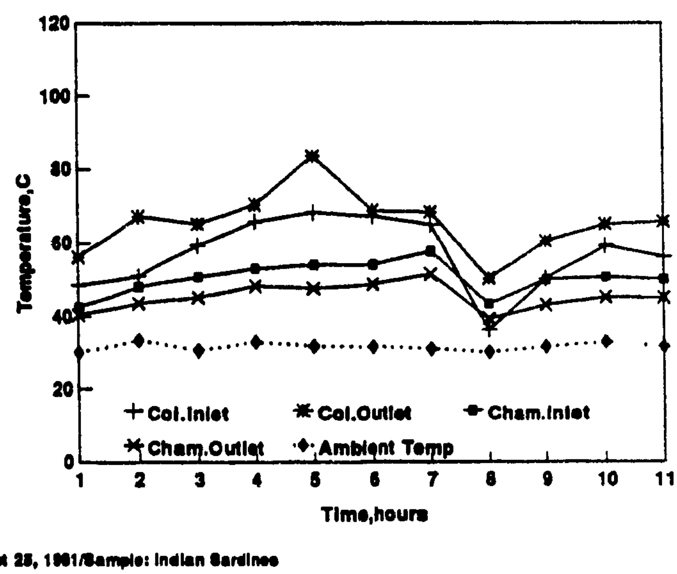


Figure C.5b Temperature Profile

Appendix C.6 Drying Experiment Number 6

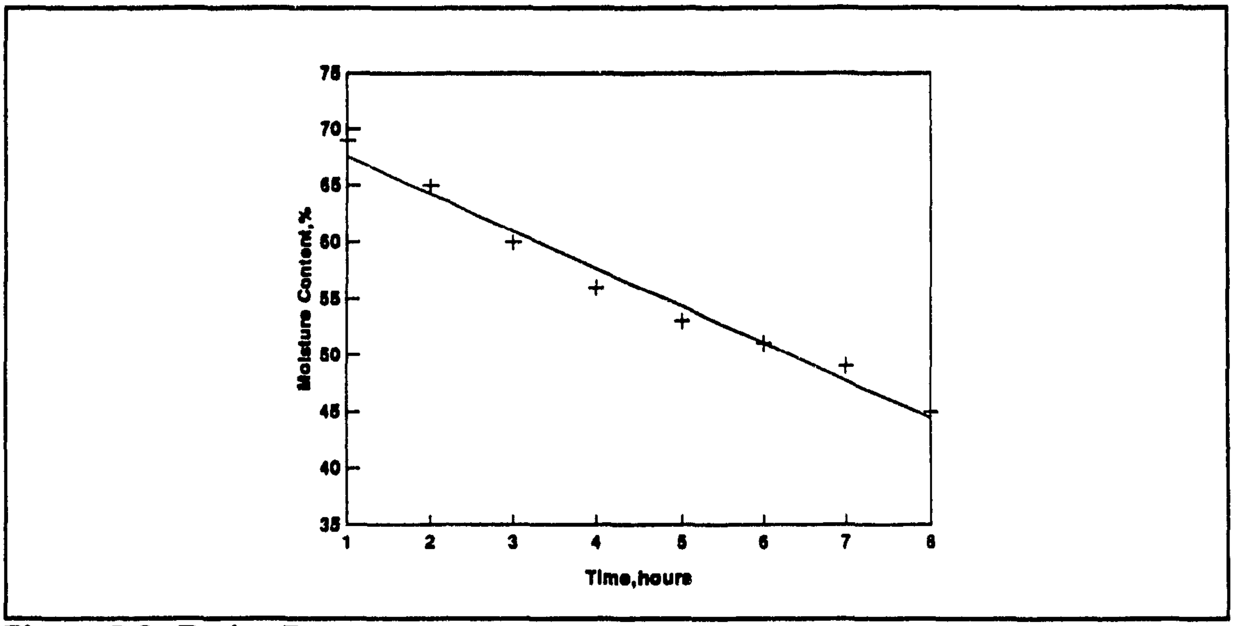


Figure C.6a Drying Rate

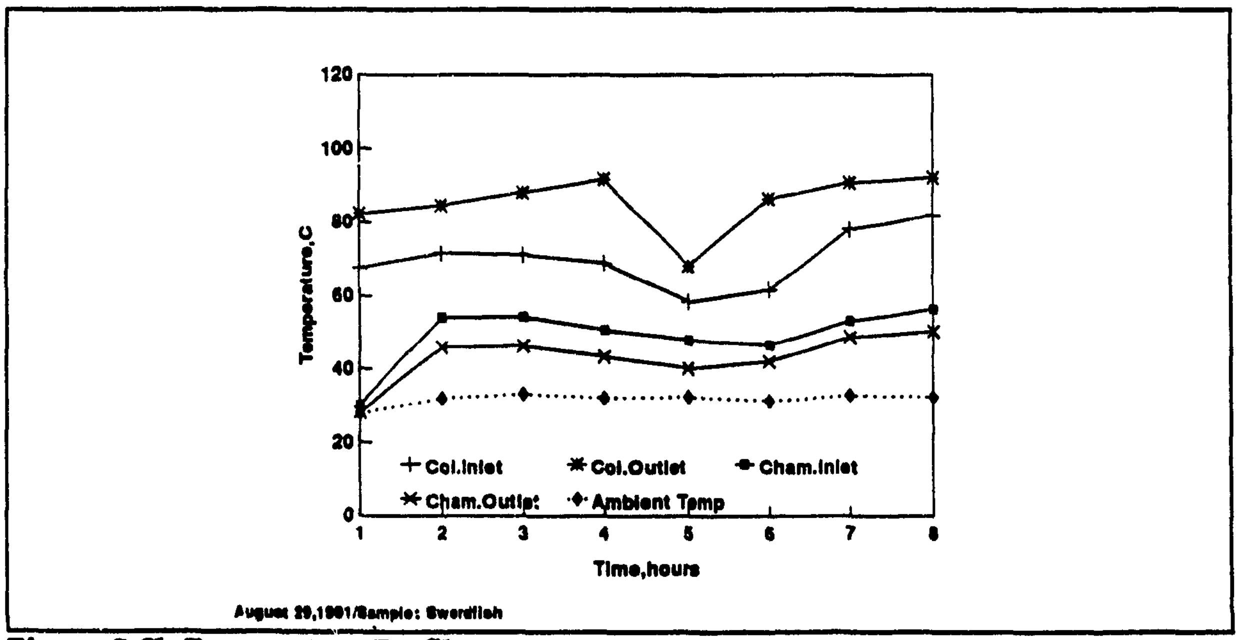


Figure C.6b Temperature Profile

Appendix D. Dryer Performance Using Auxiliary Heat

Appendix D.1 Drying Experiment Number 7

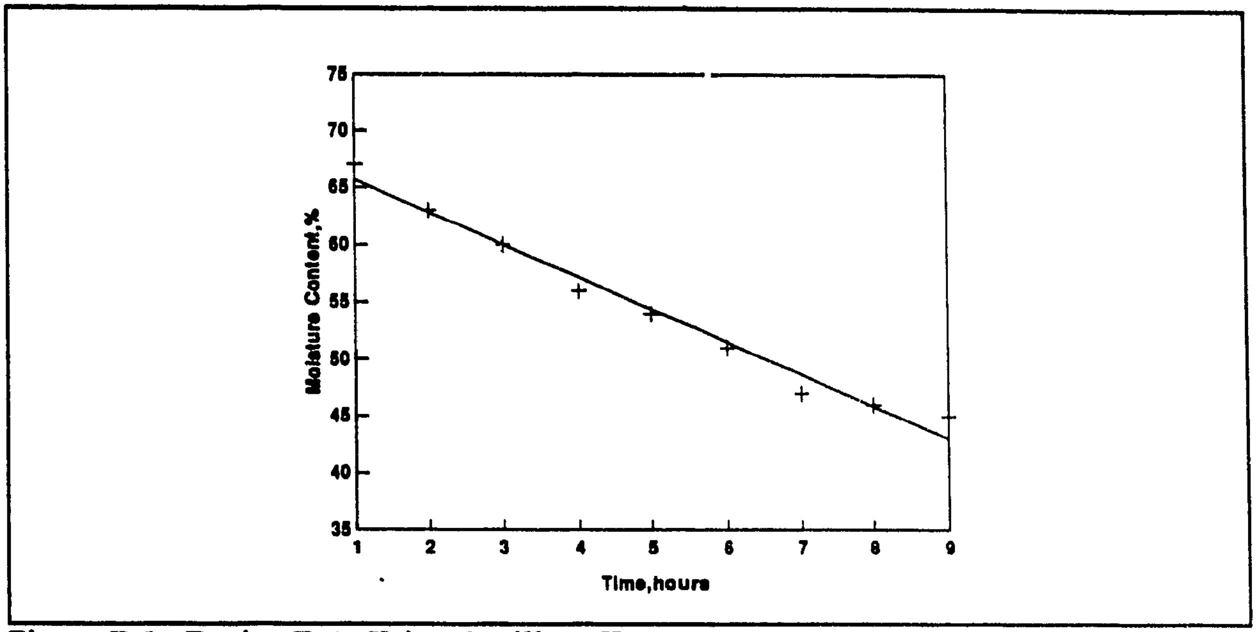


Figure D.1a Drying Rate Using Auxiliary Heat

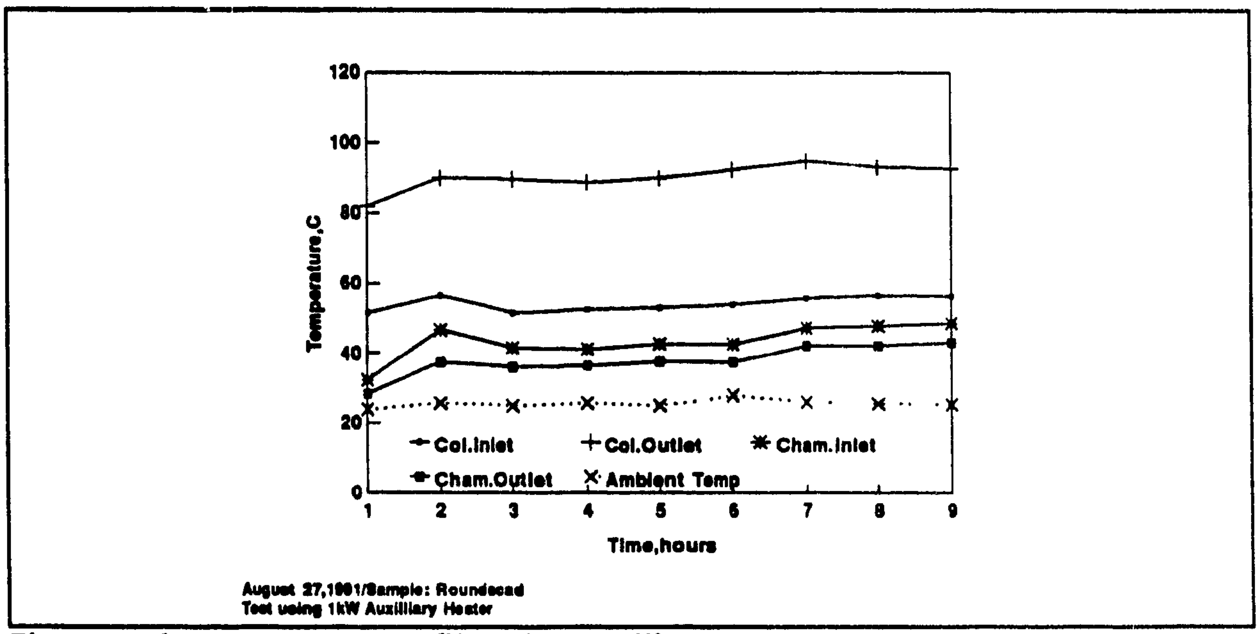


Figure D.1b Temperature Profile Using Auxiliary Heat