EXPERIMENTAL PERFORMANCE EVALUATION OF LABORATORY AND FIELD SOLAR AND HYBRIDS CROP DRYERS

BY

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A THESIS SUBMITTED TO THE POSTGRADUATE SCHOOL BELLO UNIVERSITY, ZARIA IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE AWARD OF DEGREE OF MASTER OF SCIENCE IN AGRICULTURAL ENGINEERING

JULY 1991

DECLARATION

I hereby declare that this thesis is written by me (EKE AKACHUKWU BEN) and that it is a record of my own research work. It has not been presented beofre in any perivous application for a higher degree. All the sources of information which are not my own originals were duely acknowledged by means of references.

DEDICATION

I dedicate this project to the
Author of Wisdom.

CERTIFICATION

This thesis entitled EXPERIMENTAL PERFORMANCE EVALUATION OF LABORATORY AND FIELD SOLAR AND HYBRID CROP DRYERS by the author EKE AKACHUKWU BEN meets the regulations governing the award of the degree of Master of Science (Agricultural Engineering) of Ahmadu Bello University, and is approved for its contribution to knowledge and literary presentation.

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ACKNOWLEDGEMENT

My best regards goes first to God Almighty, who granted me good health, wisdom, strength and generally saw me through in this research work.

I am expressing my unreserved gratitude to Dr. E.A. Arinze, my major supervisor who kindly provided me with all the necessary materials for the good success of this project. He as well took time to critically inspect my laboratory and field construction/emperimental evaluation work. Dr. Arinze also patiently went through my manuscript.

I am indebted to Dr. C.N. Asota co-supervisor for this project, for his invaluable suggestions and guidance all through the project work. Besides he opened up his library and offered me the valuable testbooks.

The funding of this project was undertaken by the International Development Research Centre of Canada (IDRC), I remain grateful to them.

My special gratitude to Messres Adebija, Umoh, Ekah, Adamu, Baba Andrew and other workshop staff of the Department of Agricultural Engineering, who assisted me in construction of the dryers.

The co-operation of Dr. F.G. Braide, Dr. O.J. Mudiare, Dr. J.O. Olukosi, Prof. R,N. Kaul and the Institute for Agricultural Research is fully acknowledged. Special thanks to Victoria E. Chikezie for neatly typing this work.

I am ever grateful to my parents Mr. and Mrs. B.E. Eke for their moral support, understanding and home training to me. I am immensely indebted to my brothers and sisters, in particular brother Ibezim Eke and sister Ijeoma Eme for their encouragement. I must also thank my prayer band members for supporting me in prayers.

May God bless you all in Jesus name.

ABSTRACT

Five small scale and two medium scale crop dryers with and without rockbed heat store well as a hybrid crop dryer, suitable for crop drying in different locations in savanna of Norther Nigeria were designed, constructed and lab-tested in IAR/ABU, Zaria

The full capacity of the small scale dryers are 50kg of maize grain, 20kg of fresh tomatoes and 15kg of fresh okro The full capacity of the medium scale dryer fresh tomatoes and 30kg of fresh okro. The hybrid dryer is of capacity 600kg of unthreshed maize. The medium scale wood type, large scale metal type solar crop dryers were constructed the field, at Jere in Kaduna State, New-Wuse and Kwada in Niger State, The full capacity of the medium wood type dryer is 250kg of unthreshed fresh maize and 400kg of unthreshed fresh maize for each of the metal and mud type solar dryers. These dryers were built with the locally available and affordable materials.

Laboratory and field tests were conducted on these dryers from May 1990 to June 1991.

During the test 50 to 99% of savings in drying time were achieved with the natural convection solar dryers and the hybrid crop dryer when compared with the traditional open sun

drying method. Up to 60% crop drying parcentage cash flow gain over the traditional drying method was realised. Dryers cost analysis and their payback period showed that the designed dryers are within the farmers reach and that it is more economically profitable than the usual traditional open sun drying method.

The nutrient value of vegetables and. fruits dried with the direct mode solar dryers having rockbed heat storage proved to the best when compared to the traditional drying method and the indirect mode solar crop dryer method.

Data on the rate of crop drying are fully presented in Chapter five.

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LIST OF SYMBOLS

A = Surface area of heat transfer wall, m^2

A_m = material shape constant

Ac = collector area, m^2

C_p = specific heat of material, kJ/kg ^oC

D_m = dry matter, kg

E = collector useful energy gain, kJ

E_1 = nsible heat added to the material, kJ

E_2 = heat of evaporation, kJ

F = collector efficiency factor, (decical)

F_R = heat removal factor, (decimal)

Gr = grashof number

h_{c_1}, h_{c_2} = specific enthalpy at state 1 and state 2 respectively, kJ/kg - dry air

h_1, h_2 = convection heat transfer coefficients on each side of the wall respectively, $W/m^2\ ^oC$

h_{ps} = fan shaft power, w

Hr = humidity ratio

I = intensity of solar radiation per unit area of the absorbing surface, w/m^2

I_H = average monthly total horizontal solar radiation w/m^2

K = thermal conductivity of onject, w/m ^oC

k = drying constants

L = width of solar collector, m

Lv = heat of vaporization, kJ/kg

M = moisture content, wet basis after a period of time, %

M_a = mass flow rate of air, kg/s

M_b = bending moment, N/m

MC_{fd} = final moisture content of material, dry basis, %

MC_{id} = initial moisture content of material, dry basis, %

MC_{iw} = initial moisture content of material, wet basis, %

M_E = equilibrium moisture content, %

M_{max} = maximum bending stress, N/m^2

M_o = initial moisture content, %

M_R = moisture ratio

M_t = torsional moment, N-m

n = speed, rps

Nu = nusselt number, hl/k

P = barometric pressure - total pressure of moist air, N/m^2

p = pressure in atmosphere, kpa

P_{vs} = pressure of water vapour at saturation N/m^2

q_A = actual heat transfer, w

q_L = rate of energy losses, w

q_m = maximum possible heat transfer, w

Q_s = rate of energy storage, w

Qu = rate of useful heat gain, w

Ra = Rayheigh number

Rh = relative humidity, %

RH = equilibrium relative humiduty

T = torque, N-m

t = time, sec.

Ta = ambient temperature, ^oC

T_c and T_h = hot and cold fluid temperature on each side of the plane wall respectively, ^oC

T_{fe} = collector air outlet temperature, ^oC

T_m = mean temperature of fluid in collector, ^oC

T_p = temperature of hot surface of absorber plate, ^oC

T_1 = collector inlet temperature, ^oC

T_2 = temperature of air inside dryer, ^oC

T_{h1} = temperature of hot fluid flowing out of the heat exchanger, ^oC

Th_2 = temperature of hot fluid flowing in the heat exchanger, ^oC

U = overall heat transfer coefficient for the heat exchanger, $w/m^2\ ^oC$

U_L = total heat loss coefficient of collector, $w/m^2\ ^oC$

v = kinematic viscosity

V = volumetric flow rate of air, m^3/s

W_m = weight of material, kg

W_t = quantity of water removed, kg

x = thickness of the wall, m

α = thermal diffusivity

β = coefficient of thermal expansion

δ_n = direct tangential stress, N/m^2

δ_r = direct radial stress, N/m^2

ε_v = void space in grain

Σ = effectiveness of heat exchanger

ρ = density of material, kg/m^3

η = instantaneous solar collector efficiency, %

γ_{max} = maximum shear stress, N/m^2

$\tau\alpha_e$ = effective transmittance - absorptance product

ν = possion ratio

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CHAPTER ONE

1. INTRODUCTION

1.1 Statement of Problem

The importance of effective drying and preservation of crops as a means of improving the standard of living in the third world countries cannot be ever emphasized. The need to feed the teeming population in developing countries has forced farmers to increase their food production. Besides, the extending of high yielding varieties and granting of loans at subsidized rate to the farmers has resulted in boosting agricultural production. Consequently, Nigeria which is also a developing nation recorded in 1987, about 15 million tonnes of grains production as reported by Nasko (1987).

The positive result of emphasis on food production has set in another important problem of post harvest handling of crops. This is because the common crops, such as yam, cassava, maize, millet, sorghum, cowpeas, soya beans, groundnuts, rice, pepper, okra, tomatoes and onions, grown in the tropics and in Nigeria in particular generally mature for harvest during the rainy season when the weather conditions are not favourable for field or open sun drying of crops. The need for crop drying is more serious in the middle-belt and southern parts of Nigeria where ambient relative humidity is relatively high during the harvesting season Arinze et al. (1990).

Crops harvested in rains under high moisture content still experience some internal physiological activities due to enzymatic reactions. In order to eliminate or reduce the destruction of crops by micro-organisms which thrive under high moisture content of crops, the crops have to be dried artificially or stored in a cold environment (refrigerated storage). Drying of agricultural products is more convenient to handle, and less energy demanding than preservation by cold storage. Crops that are normally harvested during the heavy rains, mostly from June to September, need some means of heating the relatively humid air artificially to enhance drying of such crops. In sub-saharan northern parts of Nigeria, where there is high intensity of sunshine and low relative humidity in most part of the year, grain crops are normally left to dry naturally in the field before final harvest. Some early maturing crops in sub-saharan region need supplemental heating of the drying air for effective drying of the crops to safe storage conditions.

There are many approaches to crop drying, which include natural field-drying and open sun-drying, free and forced convection solar crop drying, and conventional artificial heated-air crop drying. The natural field crop drying is the system where by the agricultural products are left in the field to dry down to safe storage moisture content. This approach may lead to

considerable field losses, and it is limited to sub-saharan region of Nigeria with relatively favourable outdoor weather. Thus, only grains that mature for harvesting during the dry season can effectively dry in the field.

Open sun drying of agricultural products is the traditional system of crop drying generally in Nigeria. Over 90% of agricultural products are sun dried in Nigeria and in most other developing African countries Arinze et al. (1990). Traditionally the farmer spread their crops in the sun on mats, top of rocks, roofs, or road sides, and by hanging on trees to dry. Although sun drying requires little capital and man power, it is associated with many problems and short comings. A considerable percentage of food items deteriorate rapidly due to the slow rate of drying in this process. In addition, large quantity of the crops spread for drying in open sun are consumed or damaged by insects, rodents, birds and other animal pests. They are further spoilt by micro-organisms, especially moulds, and possibly rewetting by rains or dew. The undamaged ones are commonly contaminated by dirts, sands, plant and animal remains.

In the equatorial regions of the third world countries, there is rainfall almost all the months of the year and so the crops after harvest may dry very slowly if left outside. The farmers in these regions normally apply the

traditional artificial heated air crop drying system. In this case the crops are dried by hanging the ear maize or bunches of unthreshed grains, pepper, vegetables, slices of yam and cassava above the fire points in the kitchen. This method of drying is also associated with its own peculiar problems. Heat supply is only available during cooking hours. This prolongs the drying period of the crops, such that most of them spoil before they are dried to the required storage moisture content. Besides, kitchen crop drying can accommodate only a very small quantity of grains and other crops in a batch drying process.

The length of time an agricultural product can be preserved is a direct function of the moisture content of the crop in question. Normally, crops are preserved for a long time if the moisture content is low (below 12%, wet basis for most grains) due to proper drying. Renewable energy can be harnessed from the sun and biomaterials for artificial drying of crops. Generally the earth's heat energy comes directly or indirectly from the sun. Indirectly in the sense that the fossil fuels, which farmers mostly depend on for generating their needed heat energy, is the stored solar energy in plants through photosynthesis. Fossil fuels in the form of gas, liquid or solid fuels can be burnt to generate heat energy for drying crops. On the other hand solar energy can be tapped

directly from the sun by photothermal conversion. Photothermal conversion is the process by which solar energy is directly converted into thermal energy by intercepting the solar radiation and turning it into heat by the spectral selected Surface Dixon and Leslie, (1978). The heat energy so generated can be used in drying agricultural products.

The Agricultural Engineers among others, have developed various systems utilizing solar energy in drying agricultural products. The two basic systems are the forced and free convection heated-air solar dryers. These mechanized solar crop dryers are easier and cheaper to construct and maintain, than the conventional fossil fuel heated-air systems. They can also be located at any place the farmer finds convenient, especially the free convection type, which does not require a blower. On the other hand the use of the forced convection solar dryer normally operated by fan coupled to an electric motor or fuel engine is restricted only to places where there is electricity or provision for operating fuel engines.

Artificially heated-air crop drying system is another area of interest where research work is advancing. In this system air is artificially preheated by a fossil fuel burner or electric heater, and then forced to the crop drying section by a blower.

Most of the artificially heated-air crop dryers used in developed countries are too large, highly capital intensive and incompatible with the requirements of small scale farmers who constitute about 80% of all farm holdings Ijere (1986) in Nigeria. The forced convection solar dryers and the artificially heated-air dryers are restricted only to places where there is electricity and to the negligible number of large scale farmers who can afford the cost of fossil fuel engines. The performance of relatively cheaper free convection solar dryers is only limited by weather conditions. In the case of free convective solar dryers little or no attempt has been made in designing them to suit drying of perishable vegetables and fruits in Nigeria. Consequently these essential food items are only available in abundance during the harvest seasons. It can be rightly said that the effective drying of agricultural products at any season of the year has remained a problem yet unsolved in Nigeria.

In this project the drying problems of farmers in Nigeria are critically studied. The project is limited to the construction and experimental evaluation of natural convection solar crop dryers and hybrid crop dryers for forced convection systems.

1.2 Objectives of the Study

The main objectives of this study are:

(a) To construct and experimentally evaluate the performance of simple inexpensive free convection solar crop dryers suitable for on-farm use by the farmers.

(b) To conduct field tests on these dryers in selected locations in northern Nigeria.

(c) To construct and experimentally evaluate the performance of hybrid dryer using both solar energy and gas-fired heaters.

CHAPTER TWO

2. LITERATURE REVIEW

2.1 Introduction

The construction of crop dryers has persisted with the history of mankind. Food crop drying operation is not entirely a new system. As far back as 1715 B.C. there was a great exhibition of drying and storage technology by the Biblical Joseph Jacob, who designed and constructed crop dryers, storage bins and silos, that successfully dried and *stored* enough grains that fed the Egyptains and their neighbouring countries for a period of fourteen years, since then the awareness of drying and storage as a means of preserving food items has been created. Hence research work has continued on the improvement of existing dryers and development of new crop drying technology. Available literature on solar crop drying is discussed in this section.

2.2 Solar Dryers

Controlled solar gain drying tests were initiated in 1957 by Davis et al. (1959) who compared solar supplemented drying with natural air drying. However, Dixon and Lesile (1979) reported that the flat plate solar fluid heater was invented by H.B. Saussure during the

second half of the 17th century. Theywent on to say tht that K.W. Miller introduced one of the early over lapped glass plate air heated in 1945.

Arinze (1973) in Nigeria designed, constructre and tested a solar energy model dryers, which utilized wind cups and chimney effect to obtain air flow through the dryer. The test revealed that the specific energy consumption rate (watts per kilogramme) - water evaporated, fr for a 30 to 59mm thick layer of corn receiving solar radiation directly through a transparent plastic film was comparable to the figure obtained for a conventional high temperature heated air deep bed dryer. Obi (1984) reported that fibre glass as a cover material has the highest collector useful energy gain, and that the higher useful energy gain for the single fiber glass cover is mainly due to the higher heat removal factor or collector efficiency factor obtained by using this cover material. According to Mahendra et al. (1987) solar kilm for drying lumber under controlled conditions of temperature and relative humidity is one of the earliest example of solar drying.

The simplest type of solar dryer introduced for drying grains and fruits is the one in which the heating of the inlet ambient air and removal of moisture from the product takes place in the same unit Alver (1975). In Colombia a natural convection solar dryer was used for drying coffee as reported in Alver(1975).

A simple solar dryer designed with locally available materials such as bamboo, sticks, mud and ropes were developed by the Development Technology Centre, Banding, Indoneasia as was reported by Mahandra et al. (1987).

Light weight portable collapsible collector was built and tested for drying sorghum and wheat Converse et al. (1978).

Initial experiments using solar heated air with no storage and solar heated air with water heat storage were used to dry small model bins (145kg capacity) of peanuts Troeger and Butter (1977), various geometries, collector efficiency and pressure drop variations for different flow conditions were investigated by Kuzay et al. (1974).

NRCC (1978) reported that some work has been done on design and construction of rock bed solar dryer in which the flow distribution study indicated that a minimum pressure drop across the bed of approximately 40Pa was required to achieve a uniform flow distribution through the bed of a particular plenum 200 and 175 mm high. Work done on solar energy intensifier-thermal energy stroage (SEI-TES) system, for drying corn and other agricultural products was presented by Mylo et al. (1980). In their work a rock bed was used as the heat storage system.

Kranzle et al. (1980) showed that low-temperature drying appears well suited to solar thermal supplementation for drying most agricultural crops, which do not need high temperature in order to retain their viability after drying. They recommended that if polythene cover is used on the heat collector, it should be replaced after each drying season, due to UV deterioration.

Mahendra et al. (1987) stated that in general, a cabinet type dryer reduces the drying period by one half in comparison to open sun-drying, and that the shorter drying period improves the quality of agricultural products. Duffie and Beckman (1974) stated that development of efficient solar drying processes would permit increased production of dried food while reducing industrial dependance on fossil fuels. They went on to explain that technology is now available for designing flat-plate solar collectors and thermal storage systems that could be used to heat air for conventional continuous food drying process.

William (1978) reported that a continuous drying process might require storage of up to 75 percent of the daily solar energy as thermal energy to provide continuous supply of air at 50°C to 70°C for over night use. Badewes et al. (1979) in Nigeria designed a simple and cheap drying system for onions. Also in Nigeria Adeniyi (1976) investigated the principles of indirect solar heating. In his work fresh pepper was successfully dried to 7 percent moisture content, wet basis and okro to 8 percent moisture content.

A Mathematical model to describe the solar air heater operating by natural convection was developed by Grainger et al. (1981). They presented this in a form of three energy-balance equations for the cover, air and

absorber plate. Akani (1990) designed ani constructed direct and indirect mode mud-type free convection solar crop dryers. He found that wooden and soil black surfaces were as good as metal heat absorption.

2.3 General Configuration of Solar Dryers

A close investigation on different models of solar crop dryers has revealed that there are two major sections of the dryer, namely solar collector and drying sections.

A solar collector is normally made of a rectangular box with wooden, metal or mud framework, a blackened insulated bottom, a black-painted absorber plate or floor, a transparent glass or plastic cover fixed in such a way that air plenum is created between the transparent cover and the blankened absorber. Solar radiation at the earth's surface has wave lengths from 0.3 to 3.0 micrometre Ihekoronye and Nogoddy (1985). The solar radiation wave lengths are short-waves. Short-wave radiation is able to pass through clear transparent substances, but it is absorbed by matt black objects. After the short wave length has been absorbed, the black material emits heat radiation with wave lengths of more than 3.0 micrometre, that is long-waves. Long-wave radiation cannot readily pass through some clear materials such as glass. If matt black material lying on an insulated base covered with such a clear material (glass or plastic) is placed under the sun it can act as a

collector for solar radiation in the form of heat. In free convection solar dryer, air flow in the collector is as a result of air density variation, caused by the temperature difference. Thus, the hotter air rises thereby creating natural convection. The insulation minimizes heat losses to the surroundings. The above description is the simple principle of a solar collector.

A significant advantage of the use of a plate collector to produce energy is that it is responsive to both direct and diffuse solar energy components, thus it will provide useful heat energy even under cloudy sky conditions Ihekoronye and Ngoddy (1985). Duffie and Beckman (1974) reported that glass as a transparent cover on the collector is the best material, as compared to plastic materials. Basu and Chakraborty (1978) carried out an experiment to simulate natural convective heat transfer in inclined layers. They found that conduction and convection heat losses decreased as the air gap increased, up to a certain limit, beyond which further increase in air gap caused increase in heat losses. Kordylas (1990) pointed out that the dryers which include solar collectors with controlled ventilation are quite good for an effective solar crop crying. For high efficiency and sanitary reasons, the frame should be air tight, except for the vents which help to direct air through the dryer.

Dixon and Leslie (1978) stated that plastic materials such as polyethylene and fiber glass sheets, have been used in solar heaters, but they deteriorate with time and at high temperatures. Moreover ultraviolet radiation discolours them, although they are easier to handle than glass cover. They went on to state that generally, the area absorbing solar radiation should be the same as the area intercepting the solar radiation, and that the recommended gap between the black-plate and the glass cover is 40 to 80mm, because of the shading effect which affects the efficiency of the collector.

In the work done by Daniel (1964), he reported that solar collector should be tilted toward the equator, because they collect a greater fraction of the solar heat in that orientation. In the northern hemisphere, they are faced south and tilted at an angle with the horizontal equal to the latitude angle of the location. In the winter the flat plate collector should be tilted at the angle of latitude plus 15^{o} and in the summer at the angle of latitude minus 15^{o}. From Barbour et al. (1982) Nigeria lies within latitude 4^{o} and 14^{o} N.

A cross section of basic flat-plate solar collector is shown in figure 2.1.

2.4 Theoretical Analysis of a Flat-Plate Solar Collector.

2.4.1 Introduction

A typical flat plate collector as shown in Figure 2.1 comprises of a black energy absorbing surface, a transparent cover to reduce convection and radiation losses to the surroundings, an air space for flow of the air in contact with the heat absorbing surface, and back and edge insulations to reduce conduction loss to the surroundings. The performance of a solar collector is described by an energy balance that indicates the distribution of incident solar energy into useful energy and various losses.

2.4.2 The Basic Flat-Plate Energy Balance Equation and Collector Efficiency.

Duffie and Beckman (1974) gave the Basic Flat-plate Energy Balance as:

$$A_c\, I_t\, (\gamma\alpha) = Q_u + Q_L + Q_s \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad 2.1$$

where

A_c = collector area, m^2

I_t = total solar irradiation incident on the collector cover plate with transmittance equal to $\gamma\alpha_e$ W/m^2

$\gamma\alpha_e$ = transmittance - Absorptance product of the collector, dimensionless factor.

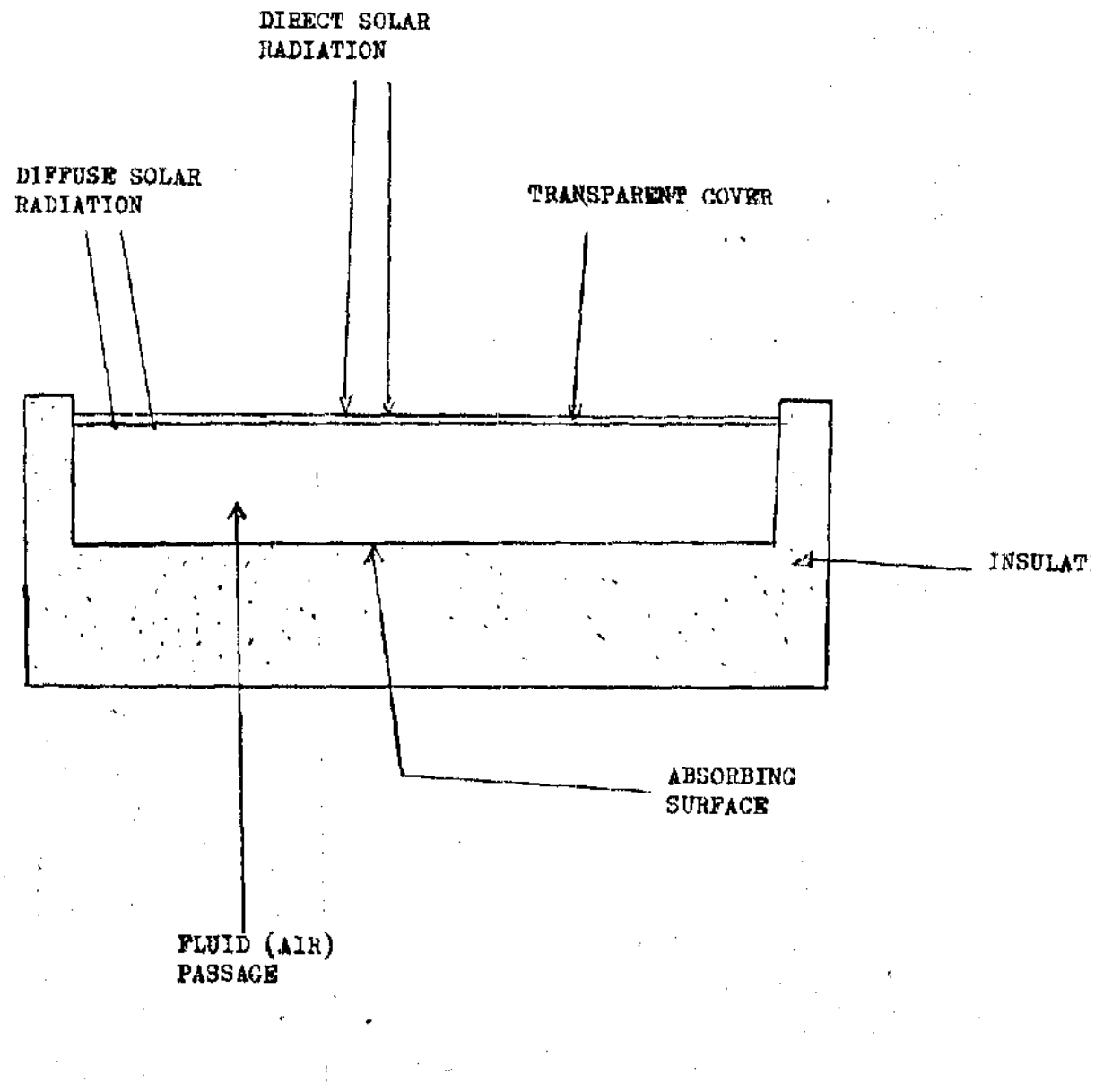


FIGURE 2.1: CROSS SECTION OF BASIC FLAT-PLATE SOLAR COLLECTOR

Q_u = rate of useful heat transfer to a working fluid in the solar heat exchanger, W

Q_L = rate of energy losses from the collector to the surroundings by the radiation, convection and by conduction through supports for the absorber plate, W

Q_s = rate of energy storage in the collector, W

The useful energy under steady state conditions is obtained from the three energy balance equations given by Duffie and Beckman (1974)

$$q_u = F\,((\tau\alpha)eI - U_L\,(T_f - T_a)) \quad \ldots\ldots\ldots 2.2$$

considering the fact that there may be some heat loss from the collector, equation 2.2 becomes

$$q_u = F_F\,((\tau\alpha)eI - U_L\,(T_{fi} - T_a)) \quad \ldots\ldots\ldots 2.3$$

By definition, instantaneous solar collector efficiency is:

$$\eta = q_u/I \quad \ldots\ldots\ldots 2.4$$

Hill and Streed (1976) gave an expression for the instantaneous efficiency in terms of both the useful energy and the air flow rate:

$$\eta = q_u/I = M\,\frac{C_p(T_{fe} - T_{fi})}{I} \quad \ldots\ldots\ldots 2.5$$

where

q_u = useful heat flow per unit area, W

I = solar irradiation, w/m^2

F = collector efficiency factor

$(\tau\alpha)e$ = effective absorptance-transmittance product

U_L = Total heat loss coefficient of collector, $W/m^2\ ^oC$

T_f = mean temperature of air in collector ^oC

T_{fi} = collector air inlet temperature, ^oC

T_{fe} = collector air outlet temperature, ^oC

M = mass flow rate of air per unit collector area, kg/s

C_p = specific heat of air at constant pressure, J/kg ^oC

F_R = collector heat removal factor, W/m^2 k

T_a = ambient temperature, ^oC

η = instantaneous solar collector efficiency %

2.4.3 Collector Efficiency

Collector efficiency is given by Mahendra et al. (1987) as:

$$\eta = F^1 \ (\tau\alpha)_e - U_L \frac{(T_f - T_a)}{I} \quad \ldots\ldots\ldots 2.6$$

where

η = instantaneous solar collector efficiency %

F^1 = collector efficiency factor

$\tau\alpha_e$ = effective transmittance - absorptance product for the solar collector

U_L = total heat loss coefficient of the solar collector, W/m^2 k

T_f = temperature of air leaving the collector, ^oC

T_a = ambient temperature, ^oC

I = intensity of solar radiation per unit area of the absorbing surface, W/m^2

The above Equation (2.6) is based on the performance of flat-plate collector operating under steady-state conditions and under the following assumptions:

1. The ends of the collector cover represents a small area and can be neglected.
2. End passages privide uniform flow of fluid over the collector plate surface.
3. There is one dimensional heat flow through the cover
4. There is a negligible temperature drop through the cover.
5. There is one dimensional heat flow through back and edge-insulation.
6. Glass cover material is thin with the thickness ranging from 3mm to 5mm.
7. The sky can be considered as a black body for long-wave-length radiation at an equivalent sky temperature.
8. Properties of the fluid and absorbing surface are independent of temperature.
9. The effect of dust and dirt on the collector are negligible.
10. Shading of the collector absorbing plate is negligible.

2.4.4 Solar Energy Availability

Irradiance is the amount of solar radiant energy falling on a unit surface area per unit time. The energy received from the sun on a unit area exposed normally to the sun's rays at the average sun-earth distance outside the earth's atmosphere is called solar constant Dixon and Leslie (1978). Thekaekara, and Drummond (1971) gave the value of solar constant as 1353 W/m^2. As the solar constant (radiation) passes through the atmosphere, it is partly scattered, reflected and absorbed by the atmospheric particles, so that only a portion reaches the earth surface. The portion that reaches the earth depends on the atmospheric condition of the particular location. The solar radiation reaching the earth consists of two components : direct or beam radiation and diffuse radiation. Beam radiations is the solar radiation received by a surface with negligible or no direction change and scattering in the atmosphere, while diffuse radiation is that solar radiation received from the sun after its direction has been changed by reflection and scattering by the atmosphere. Total radiation is the sum of beam and diffuse radiation. Most solar radiation measuring instruments (HAENI SOLAR 118 DELTA) measure the total radiation.

The available solar radiation changes with season, therefore the average amount of solar energy received by a flat surface vary from month to month depending on the

latitude of the location, surface orientation and tilt angle to the horizontal. The distance and condition of atmosphere the radiation has to pass through greatly affects the amount of solar energy reaching the earth. The more atmosphere or air mass that solar radiation must pass through, the less its energy content, due to the increased absorption and scattering of radiation.

The earth's tilt is responsible for the seasonal variation in weather or solar energy availability. Areas like Nigeria within the tropics are not as seriously affected by seasonal variations in weather due to earth's tilt, because Nigeria lies very close to the equator. The seasonal changes in solar energy availability in Nigeria are mainly due to seasonal changes in atmospheric conditions. The clear sky conditions prevail more during the dry season than during rainy season. Generally solar energy is available all the year round in most tropical areas.

It is clearly seen that the availability of solar radiation on a flat surface on earth is dependent on the latitude of the location, surface orientation tilt angle to the horizontal and season of the year. Availability of solar radiation data is a necessary basis for the design of solar energy devices. Arinze et al. (1990) reported that Nigeria generally has abundant sunshine

with the intensity of daily or monthly available solar energy increasing from the humid south to sub-saharan north.

2.4.5 Free Convection Heat Transfer in Solar Collectors

Free convection in a solar collector is a limiting factor to the collector's efficiency. The mechanism of free (natural) convection is well spelt out by Hollands (1978) as follows:

Heat transfer in a stationary fluid is by conduction, just as in solid, and, under steady conditions. In this case the temperature field satisfies Lapace's equation. For a parallel layer of stationary fluid of thickness t and having temperature T_h on one face and $T_c < T_h$ on the other, the heat flux, q acorss the layer is given by

$$q_s = K \frac{(T_h - T_c)}{t} \quad \ldots\ldots\ldots\ldots\ldots\ldots 2.7$$

where K is the thermal conductivity of the fluid. The heat transfer coefficient, h, across the layer is defined as the heat flux per unit temperature difference:

$$hs = \frac{q_s}{T_h - T_c} = \frac{K}{t} \quad \ldots\ldots\ldots\ldots\ldots\ldots 2.8$$

The subscript s is used to denote the stationary condition.

A temperature variation is initially established by conduction, when a temperature difference is applied across a fluid. Since the density of most fluid depends

on temperature, consequently, a density variation of the fluid is established by temperature difference across the layer. This non-uniform density in turn causes a local imbalance (called the buoyancy force) between the gravity force and the hydrostatic pressure force on a fluid element. The buoyancy force can drive a flow in the fluid and this flow is called free (or natural) convection. Hence free convection is established by only applying external temperature gradient. After the flow of fluid has been initiated by temperature difference, the natural convection is then accelerated by free convective thermal energy mechanism through bulk movement of fluid. In which case the motion of the fluid flow initiated as a result of density variation is resisted by the viscosity (internal friction) of the fluid. The heat transfer by natural convection is influenced by:

i) Gravitational force due to thermal expansion
ii) Viscous drag
iii) Thermal diffusion

The natural convection heat transfer, thus, depends on the gravitional acceleration g, the coefficient of thermal expansion β , the Kinematic Viscosity $V = \mu/\rho$, and the thermal diffusivity $\alpha = k/\rho c_p$. The variables can be expressed in terms of dimensionless number called Nusselt number given by ASHRAE Fundamental

(1977) for horizontal or vertical planes, pipes, rectangular blocks, and spheres as

$$N_u = \frac{hl}{k} = 0.56\ (Gr.Pr.)\ 0.25 \quad \ldots\ldots\ldots\ 2.9$$

for laminar range 10^4 (GR.Pr) 10^8

where

N_u = Nusselt number

h = convective heat transfer coefficient, $wm^{-2}\ k^{-1}$

l=t = characteristic dimension of the geometry of flow (thickness of air layer)m

k = thermal conductivity of fluid, w/mk

Gr = Grashof number

Pr. = Prandle number

The Grashof number is given as shown below by Holman 1981

$$Gr = \frac{g\beta\Delta T l^3}{\mu^2} \quad \ldots\ldots\ldots\ 2.10$$

where

g = acceleration due to gravity, ms^{-2}

β = volumetric coefficient of expansion of air, $1/k$

ΔT = temperature difference between the hot and cold surface, k

L = plate spacing, n

μ = kinematic viscosity, Pa.s

The Prandtl number is also given by Holman 1981 as

$$Pr = \frac{CP}{k} \quad \ldots\ldots\ldots\ 2.11$$

where

C_p = specific heat of the fluid (J/kg k)

The fluid properties, β , k, C_p , μ and density of the fluid ρ (kg/m^3) are all subject to variations with temperature and hence are not constant across the fluid in an enclosure.

It has been found that if $Nu = \frac{hL}{k} = 1$ and Rayleigh number (Ra) slightly greater than 1708, the air will be in motion by natural convection (Dixon and Leslie, 1974). The expressed Rayleigh and Nusselt number are as follows:

$$Nu = 1 + 1.44\left(1-\frac{1708}{Ra}\right) + \left\{\left(\frac{Ra}{5830}\right)^{\frac{1}{3}} - 1\right\} \quad \ldots 2.12$$

and

$$Ra = 2737\,(1 + 2\alpha)^2\ \alpha^4 \Delta T\,(100L)^3\,P^2 \quad \ldots. 2.13$$

where

Nu = Nusselt number

Ra = Rayleigh number

$= \frac{100}{T_m}$

T_m = mean temperature of fluid in collector, ^oK

$T_m = \frac{T_p + T_a}{2}$

T_p = temperature of hot surface (absorber plate), ^oK

Ta = temperature of ambient air, ^oK

P = pressure in atmospher, KPa

L = width of solar collector (absorber surface of the glass cover), m

The air flow rate required to dry some quantity of crops when the optimum temperature difference and the amount of heat to be removed are known is given by ASHRAE (1977) as

$$V = \frac{Q}{\rho C_p \Delta T} \quad \text{..... 2.14}$$

where

V = air flow rate, m^3/min

Q = heat removal rate, W

C_p = specific heat of air at constant pressure, J/kg k

ρ = density of standard air kg/m^3

ΔT = indoor-outdoor temperature difference, k

2.4.6 Flow Due To Wind

In considering the contribution of natural wind forces in producing ventilation, account must be taken of average wind velocity, prevalent wind direction, seasonal and daily variation in velocity and direction, and local wind interference by nearby buildings, hills, trees and other obstructions.

ASHRAE Fundamentals (1971) gave an expression for evaluating the quantity of air passing through ventilation openings due to the wind as:

$$V_w = EAV \quad \text{..... 2.15}$$

where

V_w = volume air flow rate, m^3/s

A = free area of inlet opening m^2

V = wind velocity, m/s

E = effectiveness of openings

= (0.50 to 0.60 for perpendicular winds and 0.25 to 0.35 for diagonal winds)

2.5 Rockbed Thermal Storage

It is recommended that the size of the rock to be used for thermal storage will be between 10 to 50mm with not more than 10% smaller. In order to evaluate the thermal performance of rockbed thermal storage, the following properties of rock have to be known: density, void fraction and specific heat and equivalent spherical diameter.

Duffie and Beckman (1974) sited the correlation on temperature gradient, rock particle size package and the velumetric heat transfer coefficient in the rock bed by the following equation.

$$h_v = 650 \frac{(G)}{D}^{0.7} \quad \text{..... 2.16}$$

where

h_v = volumetric heat transfer coefficient, $W/m^3\ ^oC$

G = superficial mass velocity, $kg/s\ m^2$

D = equivalent spherical diameter of the particles, m

$$D = \left\{ \frac{(6)}{\pi} \frac{(V_p)}{N_p} \right\}^{\frac{1}{3}} \quad \ldots\ldots\ldots\ldots\ldots\ldots 2.17$$

V_p = Net volume of particles, m^3

N_p = number of particles

According to Duffie and Beckman (1974), a well-designed bed would have particle size small enough to minimise temperature gradients in the particles. To achieve this the Biot Criterion for sphere of radius R and thermal conductivity k is applied. Hence the Biot number $\frac{hR}{k}$ is less than 0.1, thermal resistance within the particles (and thus internal temperature gradients) can be considered negligicle. Particle sizes should be uniform enough as to obtain large void fractions and thus, minimise pressure drop. h in the given Biot number is the usual heat transfer coefficient per unit area. h is related to h_v of Equation (2.9) by

$$h_v = \left(\frac{A}{V}\right)h \quad \ldots\ldots\ldots\ldots\ldots\ldots 2.18$$

where

A = surface area of the bed material, m^2

V = volume of bed material, m^3

h_v = volumetric heat transfer coefficient, W/m^3 k

h = heat transfer coefficient, W/m^2 k

2. 6 Gas-Fired Heat Exchanger for Hybrid Crop Dryer

2. 6.1 Introduction

The hybrid crop dryer consists of solar dryer and a Gas-fired heat exchanger. Heat exchangers are characterized by the way fluids at high or low temperature flow through them. For the purpose of this project work, parallel and counter flow heat exchangers are considered. Fan (blower) performance for driving the fluid passing through the heat exchanger is also reviewed. The thermal calculation of heat exchanger and the estimation of the effectiveness are presented.

2. 6.2 Thermal Calculation

Okhotin et al. (1987) give the heat transfer equation for a heat exchanger as:

$$Q = Q_1 - Q_2, \qquad \text{..... 2.19}$$

and

$$Q_1 = Q_2 + Q \qquad \text{..... 2.20}$$

but $Q = TKA$

where

K = average overall heat transfer coefficient for the entire surface of the heat exchanger, W/m k

Q = heat power of the heat exchanger, W

T = average temperature difference between fluids in the heat exchanger, k

A = area of heating surface, m^2

Q_2 = heat power absorbed by the cold fluid, W

Q_1 = heat power given off by the hot fluid, W

Q = heat loss, W

The overall heat transfer coefficient K is given by:

$$K = \frac{1}{\frac{1}{\alpha 1} + \frac{1}{\alpha 2} + \frac{\Delta x}{k_t}} \quad \ldots\ldots\ldots\ldots\ldots\ldots 2.21$$

α^1 and α_2 = average heat transfer coefficient for the hot and cold surface of the separating wall, respectively, W/m K

Δx = wall thickness m

K_t = thermal conductivity of the material.

The heat loss can be minimized by applying thermal insulation, so that Q is much lower than Q_1. Neglecting Q Equation (2.20) becomes

$$Q_1 = Q_2 = Q \quad \ldots\ldots\ldots\ldots\ldots\ldots 2.22a$$

and

$$Q = G_1 (h_1' - h_1'') = G_2 (h_2'' - h_2') \ldots\ldots\ldots 2.22b$$

where

G_1 and G_2 are the mass flow rates, respectively, of the hot fluid (1) and cold fluid (2), and h_1', h_1'' and h_2', h_2'' are the enthalpy of hot and cold fluid, respectively, at the heat exchanger inlet and outlet.

2. 6.3 The Log Mean Temperature Difference

The log mean temperature difference is an important parameter required to calculate the surface area for heat transfer, overall heat-transfer coefficient as well as the heat transfer through the plane walls of the heat exchanger. The log mean temperature difference is found from the following relationship according to Holman (1981):

$$q = UA \Delta Tm \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 2.23$$

where

q = quantity of heat transfer through the plane walls of area A for the heat exchanger, W

ΔT_m = log mean temperature difference, K(^{o}C)

U = overall heat transfer coefficient for the heat-exchanger, W/m^2 K

But $$q = \frac{T_h - T_c}{\frac{1}{h_1 A} + \frac{\Delta x}{KA} + \frac{1}{h_2 A}} \quad \ldots\ldots\ldots\ldots\ldots\ldots 2.24$$

T_c and T_h = the hot and cold fluid temperatures on each side of the plane wall, respectively

h_1 and h_2 = the convection heat transfer coefficients on each side of the wall respectively.

K = thermal conductivity of the heat exchanger wall W/m k

A = surface area of heat transfer wall, m^2

Δx = thickness of the wall, m

The overall heat transfer coefficient, U, is given as

$$U = \frac{1}{\frac{1}{h_1} + \frac{\Delta x}{k} + \frac{1}{h_2}} \qquad \ldots\ldots\ldots\ldots\ldots\ldots 2.25$$

The parameters are as defined in equation 2.24.

The log mean temperature defference is also given by:

$$T_m = \frac{(Th_2 - Tc_2) - (Th_1 - Tc_1)}{\ln (Th_2 - Tc_2)/(Th_1 - Tc_1)} \qquad \ldots\ldots\ldots 2.26$$

This log mean temperature difference (ΔTm) is also denoted by the symbol (LMTD).

2. 6.4 Effectiveness of Heat Exchangers

Heat exchanger effectiveness is derived as the ratio of the actual heat transfer to the maximum possible heat transfer. That is

$$\mathcal{E} = \frac{q_A}{q_m} \qquad \ldots\ldots\ldots\ldots\ldots\ldots 2.27$$

where

$\mathcal{E}$ = effectiveness of heat exchanger

q_A = actual heat transfer, W

q_m = maximum possible heat transfer, W

The actual heat transfer may be computed by calculating either the energy lost by the hot fluid or the energy gained by the cold fluid.

For parallel flow exchanger

$$q_a = M_h C_{p_h} (Th_1 - Th_2) = M_c C_{p_c} (Tc_2 - Tc_1) \quad \ldots 2.28$$

For counter flow exchanger

$$q_a = M_h C_{p_h} (Th_1 - Th_2) = M_c C_{p_c} (Tc_1 - Tc_2) \quad \ldots 2.29$$

where

q_a = actual heat transfer

Th_1 = hot fluid flowing out of the heat exchanger

M_h = mass flow of hot fluid

Th_2 = hot fluid flowing in the heat exchanger

C_{p_h} = specific heat of hot fluid

Tc_1 = temperature of cold fluid flowing in the heat exchanger

M_c = mass flow of cold fluid

Tc_2 = Temperature of the cold fluid flowing out of the heat exchanger

C_{p_c} = specific heat of cold fluid

For maximum possible heat transfer it is given that the fluid which might undergo this maximum temperature difference is the one having the minimum value of MC, since the energy balance requires that the energy received by one fluid be equal to that given up by the other fluid, thus:

$$q_{max} = (Mc)_{min} (Th_{inlet} - Tc_{inlet}) \quad \ldots\ldots\ldots\ldots 2.30$$

The minimum fluid may be either the hot or cold fluid, depending on the mass-flow rates and specific heats. For the parallel flow exchanger

$$\varepsilon_h = \frac{M_h C_{p_h} (Th_1 - Th_2)}{M_h C_{p_h} (Th_1 - Tc_1)} = \frac{Th_1 - Th_2}{Th_1 - Tc_1} \quad \ldots\ldots\ldots 2.31$$

$$\varepsilon_c = \frac{M_c C_{p_c} (Tc_2 - Tc_1)}{M_c C_{p_c} (Th_1 - Tc_1)} = \frac{Tc_2 - Tc_1}{Th_1 - Tc_1} \quad \ldots\ldots\ldots 2.32$$

where

ε_h = effectiveness when the hot fluid is the minimum

ε_c = effectiveness when the cold fluid is the minimum.

Other parameters are as defined in Equations (2.28) and (2.29).

For the counter flow exchanger

$$\varepsilon_h = \frac{M_h C_{p_h} (Th_1 - Th_2)}{M_h C_{p_h} (Th_1 - Tc_2)} = \frac{Th_1 - Th_2}{Th_1 - Tc_2} \quad \ldots\ldots\ldots 2.33$$

$$\varepsilon_c = \frac{M_c C_{p_c} (Tc_1 - Tc_2)}{M_c C_{p_c} (Th_1 - Tc_2)} = \frac{Tc_1 - Tc_2}{Th_1 - Tc_2} \quad \ldots\ldots\ldots 2.34$$

The symbols are similarly defined as in Equations 2.28) and (2.29).

2.7 Basic Principles of Crop Drying

2.7.1 Introduction

One of the basic considerations in drying agricultural crops is the role of moisture in the crop Heldman and Singh, (1980). The chemical, physical and thermodynamic properties of bound water indicate that three types of bound water may exist in crops, namely:

i) Water molecules which are bound to ionic groups uch as carboxyl and amino groups.

ii) Water molecules which are hydrogen bonded to hydroxyl and amide groups.

iii) Unbound free water found in interstatial pores in which capillary forces and soluble constitents cause lowering of vapour pressure.

The moisture is removed with a certain degree of difficulty during the drying process, depending on the classification within which it falls. The above type of bound moisture are listed in order of decreasing difficulty of moisture removal. In addition, they are listed in reverse order in which moisture would be removed as the moisture content of the crop is decreased. This means that the free water would be evaporated and removed first, followed by the water molecules that are hydrogen bounded and finally, the moisture which is bounded to ionic groups. Each of the three groups of water in crops require different amount of energy for removal. The nature of moisture content of crops is the major focus in design and operation of crop dryers.

2.7.2 Crop Drying Theory

2.7.2.1 Introduction

Drying is a process of simultaneous heat and mass transfer. The heat is required to evaporate the moisture which is removed from the drying product surface by the external drying medium, usually air. Crop drying is a function of two basic features, namely: The properties of the drying air, often known as external characteristics and the properties of the product known as the internal characteristics.

2.7.2.2. Properties of Drying Air

1. Relative Humidity

By definition, the Relative Humidity of moist air is the ratio of water vapour pressure in moist air at any temperature to the partial pressure of water vapour at saturation. This is given by the equation

$$RH = \frac{Pv}{Pvs} \qquad \text{..... 2.35}$$

where

RH = relative humidity, %

Pv = water vapour pressure in moist air

Pvs = partial pressure of water varpour at saturation.

The partial pressure of water vapour at saturation is calculated from the following equations according to Brooker et al.,(1974). Considering the fact that the temperature of moist air employed for drying agricultural products is far from the critical point of water vapour, the equation below holds.

$$\frac{dPv}{dTabs} = \frac{hfg}{Tabs\ Vv} \qquad \text{..... 2.36}$$

where

hfg = latent heat of vaporization kJ

Tabs = absolute dry-bulb temperature, K

Vv = volume occupied by water vapour, m^3

The latent heat of vaporization (hfg) has to be calculated at the saturation condition and is given by Brooker et al. (1974) as

$$hfg = 1075.90 - 0.57\ (Tabs - 459.69) \quad ..... \quad 2.37$$

2. Saturation Pressure

The saturation pressure of water vapour in a moist air sample is given by Brooker et al. (1974) as

$$Pvs = \exp\ (54.63 - \frac{12301.69}{Tabs} - 5.17\ \text{In}\ Tabs) \quad .. \quad 2.38$$

For $200^{\circ}F > T \geq 32^{\circ}F$

and

$$Pvs = \exp\ (23.39 - \frac{11286.65}{Tabs} - 0.46\ \text{In}\ Tabs) \quad .... \quad 2.39$$

For $0^{\circ}F < T < 32^{\circ}F$

The pressure of vapour in equilibrium with a pure liquid at a given temperature is referred to as the vapour pressure of the liquid. Brooker et al. (1974) gives the mathematical relationship as

$$Pv = \frac{WvRvTabs}{Vv} \quad ..... \quad 2.40$$

where

Pv = water vapour pressure, N/m^2 (Pa)

Wv = weight of water vapour, N

Rv = gas constant for water vapour

Tabs = absolute dry-bulb temperature, K

V_v = volume occupied by water pressure, m^3

3. Humidity Ratio

Humidity ratio of moist air is defined as the weight of water vapour per unit weight of dry air. From ASHRAE Fundamental (1977) the humidity ratio is given by

$$HR = \frac{0.622\ RH\ Pvs}{(P - RH\,Pvs)} \quad \ldots\ldots\ldots 2.41$$

where

HR = humidity ratio (kg water/kg of dry air)

RH = relative humidity

Pvs = pressure of water vapour at saturation N/m^2

P = Barometric pressure = total pressure of moist air, N/m^2

The total energy content of a moist air sample per unit mass of dry air is known as the specific enthalpy.

4. Dry-Bulb and Wet-Bulb Temperatures

The dry-bulb temperature (Tdb) is the temperature of moist air indicated by an ordinary thermometer in free atmosphere, while the wet-bulb temperature (Twb) is the temperature of moist air indicated by the thermometer when the bulb is covered with a wet wick. The wet bulb can also be cooled by evaporation when humid air mass flows through the bulb.

5. Dew-point Temperature

Dew point temperature is the temperature at which the condensation of water vapour begins if a misture of air and water vapour is cooled.

6. Eathalpy

With the aid of a psychrometric chart, the external characteristics of drying air so far explained can be directly identified from the chart, when any two of the properties given above are known.

2.7.2.3 Properties of the Product (Internal Characteristics).

1. Equilibrium Moisture Content

When the rate at which the product losses moisture to the surrounding environment is identically equal to the rate at which it absorbs moisture from the surrounding air, the moisture content of the product under this condition is referred to as the equibilibrium Moisture Content. Henderson and Perry (1976) expressed the equilibrium moisture content relationship mathematically as:

$$1 - RH = e^{-CTM_E^n} \qquad \ldots\ldots\ldots\ 2.42$$

where

RH = equilibrium relative humidity, decimal

M_E = equilibrium moisture content, dry basis, %

T = temperature, k

c, n= constants depending on the product.

Equilibrium moisture data can, therefore, be reported in terms of the constants c and n. The values of these constants for some materials are given in Table A-1 in Appendix A.

The equilibrium moisture properties of materials are important in storage and drying. If the relative humidity of the air in contact with a material is higher than the equilibrium relative humidity of the material at its current moisture content, the material will increase in moisture content, the moisture content at the air relative humidity being the value approached. An air relative humidity lower than the equilibrium will cause the moisture contact to decrease (drying the product).

2. Latent Heat of Vaporization

Latent heat of water is needed to evaluate the energy that will be supplied for evaporation of the amount of water from the wet crop to a desired moisture content. It is given as:

$$hfg = \frac{M_a C_p \Delta T}{M_w} \qquad \text{..... 2.43}$$

where

hfg = latent heat of vaporisation of water, J/kg

M_a = mass of dry air flow rate through the crop, kg/hr

C_p = specific heat of air at constant pressure, J/kg k

ΔT = temperature difference between drying air in phenum above and below the crop, ^{o}C

M_w = mass of the water evaporated, kg

3. Resistance of Grain to Air Flow

When air flows through a layer of grains, there is a pressure drop due to resistance to the air flow. The pressure drop is accompanied by energy lost through friction and torbulence. The pressure drop depends on the air flow rate through the grain mass. Therefore, the static pressure developed in the drying grain is a function of the air flow rate, depth of the material, type, shape, size, orientation, packing and configuration of the voids.

Brooker et al. (1974), gave the following expression for air flow range of 0.0102 m^3/sec. m^2 to 0.204 m^3/sec.m^2 (2.0 to 40.0) c/m per sq.ft., the pressure drop ΔP is

$$\Delta P = \frac{a\, Q_a^{\,2}}{\ln (1 + b\, Q_a)} \qquad \text{..... 2.44}$$

where

ΔP = pressure drop,(psi)

Q_a = air mass flow, ($lb/sq.in$)

a and b = material constants (for shelled corn a = 0.00065 and b = 0.156)

4. Resistance of Perforated Grain Bed to Air Flow

When air is introduced into a grain mass through a perforated metal floor, a pressure drop develops across the metal floor. This is expressed by the equation (Brooker et al., 1974).

$$P = \frac{10^{-6}}{9} \left(\frac{Q_a}{\ell f_o}\right)^2 \qquad \text{..... 2.45}$$

where

P = pressure drop (inches of water per foot deep)

Q_a = air mass flow rate lb/in^2

ℓ = void space in grain (percent or decimal)

f_o = percentage opening in floor (decimal)

5. Internal Moisture Migration

Internal moisture migration is controlled by diffusion, capillarity and pressure gradient due to Shrinkage. The general equation for diffusion of liquid through a porous solid Brenndorfer et al. (1987).

$$\frac{dM}{dt} = D \frac{d^2 M}{dx^2} \qquad \ldots\ldots\ldots\ldots\ldots\ldots 2.46$$

where

M = moisture content, dry basis

t = time

D = diffusion coefficient

X = distance from the particle surface

6. Drying Rate

The capacity of a thermal dryer depends on the rate of heat transfer and moisture (mass) transfer. Since water vapour must be removed during a drying process, heat of vaporization is supplied to achieve this. The material to be dried determines the quantity of heat to be supplied.

For biological materials, at the initial stage of drying, the rate of moisture migration to the surface of the drying product is high enough to keep the surface completely wetted. In this condition, the rate of drying is controlled by the rate of evaporation from the surface. This is known as Constant Rate Drying Period.

The constant drying rate is arrived at by the following equation (Henderson and Perry, 1976).

$$\frac{dM}{dt} = h_p A (P_w - P_a) \quad \text{..... 247}$$

$$\frac{dM}{dt} = \frac{h_c A}{L} (T_a - T_w) \quad \text{..... 248}$$

where

$\frac{dM}{dt}$ = drying rate kg of water/sec

h_p = water vapour transfer coefficient kg/sec m^2

A = water surface area m^2

p_w = water vapour pressure at T_w; kg/m^2

p_a = water vapour pressure at T_a; kg/m^2

h_c = thermal conductance of air film W/m^2 k

L = latent heat of vaporization J/kg

T_a = temperature of hot air ^oC

T_w = temperature of wet surface ^oC

As the constant rate drying period progresses, an intermediate period could be attained. This is the period at which part of the surface is dried while part is still wet. The dry part continues to increase, while the wet part decreases. At this stage the rate of drying is governed partly by the rate of moisture evaporation from the wet parts and partly by the rate of internal moisture migration within the particle. The proportion of the dry surface increases until the surface becomes completely dry

and internal moisture migration becomes the rate controlling factor. This brings in the second stage of the drying rate called Falling-Rate Drying Period.

7. Falling-Rate Drying Period

As drying proceeds, a point is reached at which the rate of transfer of moisture within the material to the surface is less than the rate of evaporation from the surface and the surface begins to dry out. At this point the falling rate drying period starts, and the moisture content of the crop is known as the critical moisture content.

A number of methods have been used to characterize drying at the falling rate. This include the empirical methods. Falling rate drying period of corn is given by Henderson and Perry (1976), as

$$t = A \text{ Ln } MR + B \text{ Ln } (MR)^2 \quad \ldots\ldots\ldots\ldots\ldots 2.49$$

$$\text{But } MR = \frac{M - Me}{M_o - M_e} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots 2.50$$

$$\text{Also } A = 1.862 + 0.00488T$$

$$B = 427.364 \text{ Exp } (-0.03301T)$$

where

t = time to dry to critical moisture content

MR = moisture ratio

M = moisture content

M_o = initial moisture content

M_e = equilibrium moisture content at relative humidity of the drying air, %

T = drying air temperature

A and B = constants.

8. Rate of Water Removal From the Drying Crop and the Energy Supply to Heat the Air

Drying with heated air is an adiabatic process, the energy for moisture evaporation being supplied by a reduction in temperature of the air. The wet-bulb (adiabatic humidification) lines of the psychrometric chart shown in Figure A.1 in Appendix A, can be used to calculate the water removal rate and the energy that must be supplied to heat the air Henderson and Perry(1976).

9. Rate of Water Removal

Air initially at dry-bulb temperature t_1 and humidity ratio W_1 is heated to a dry-bulb temperature t_2 and humidity ratio $W_2 = W_1$, the heated air is then passed through a material to be dried. The state point moves up the wet-bulb line and the air exhausts at dry-bulb temperature t_3 and humidity ratio W_3. The water removal rate Wm is:

$$Wm = \frac{V_a}{v_h}(W_3 - W_2) \qquad \text{..... 2.51}$$

where

W_m = water removal rate, kg/sec. m^2 sectional area of air flow

V = air flow rate m^3/sec. m^2

v = humid volume of air at point of rate measurement, m^3/kg-dry air

Total water removed from a product is given by

$$W_t = \left(\frac{M_i - M_f}{100}\right) DM \qquad \ldots\ldots\ldots\ldots\ldots 2.52$$

where

W_t = total water removed kg

M_{i_d} = initial moisture content (before drying) dry basis

M_{f_d} = final moisture content (after drying) dry basis.

D_m = dry matter (bone dry) kg

9. Heat Energy to be Supplied

The energy that must be supplied to heat the air can be found with the help of the psychrometric chart shown in Figure A.1 in Appendix A. Represented mathematically as

$$Q = \frac{VA}{v_h}(h_2 - h_1) \qquad \ldots\ldots\ldots\ldots\ldots 2.53$$

where

Q = quantity of heat energy required per time kJ/s = kW

A = cross-sectional area of air flow m^2

h_1, h_2 = specific enthalpy at atate 2, respectively, kJ/kg-dry air

10. Thin Layer Drying

In thin layer drying, the drying product is said to be drying uniformly at given boundary conditions. There is no gradients assumed during the drying rate. Vegetables and fruits which have high moisture content are normally dried in thin layers. Henderson and Perry (1976) expressed thin layer drying by the equation:

$$\frac{M - M_E}{M_o - M_E} = A e^{-kt} \qquad \text{..... 2.54}$$

where

M = moisture content, dry nasis, % after a period of time t

M_E = equilibrium moisture content, %

M_o = moisture content, dry basis, % at the beginning of the drying period, at time zero.

K = Drying constants

t = time, hr

A = materials (particles) shape constant.

11. Deept Bed Drying

A deep bed dryers may be defined as one in which there is a finite moisture gradient through the drying layer at any time, except time zero. Material depths of 0.152m and above may be considered to constitute deep beds. However, depths of as dsmall as 0.025m can provide an evidence of the existence of moisture gradient and thus may be deep beds.

2.7.3 Fan Performance

In most dryers, the fan is the primary mover of air. It then becomes necessary to consider fan performance in relation to the dryer performance. According to Henderson and Perry (1976), the power output of a fan is expressed in terms of air power, which represents work done by the fan and it is given as:

$$hp_A = Q \gamma H \quad \text{..... 2.55}$$

where

hp_A = air power, W

Q = volume of air delivered per unit time, m^3/s

γ = specific weight of fluid (air), kg/m^3

H = total head, m

The total head against which the fan works is given by Church (1972) as:

$$H = \frac{K^1 \gamma v^2}{g} \quad \text{..... 2.56}$$

K^1 = overall pressure coefficient

v^2 = velocity of the air, m/s

g = accelerature due to gravity, m/s^2

Church (1972) gave the value of K^1 as:

$$K^1 = \frac{1}{2\bar{\phi}^2} \quad \text{..... 2.57}$$

where

ϕ = overall head coefficient at the point of maximum efficiency, which takes the value from 0.9 to 1.20.

Wallis (1961) expressed the shaft power as follows:

$$hp_s = 2\pi Tn \quad \text{..... 2.58}$$

where

hp_s = fan shaft power, W

T = torque, N-m

n = speed, rps

Henderson and Perry (1976) state that the total mechanical fan effciency is

$$\eta_t = \frac{hp_A}{hp_s} \quad \text{..... 2.59}$$

where

η_t = total mechanical efficiency of fan

hp_A = air horse power (hp)

hp_s = fan shaft horse power (hp)

Henderson and Perry (1976) also explained that since static efficiency is based upon static power which is always less than total power, the static efficiency is not a true index of maximum performance, therefore it's use is not recommended.

The maximum recommended stress for most materials from which fan components are made is of the order of $\frac{1}{4}$ to 1/5 of the ultimate breaking stress, as stated by Osborne (1966) and the maximum shear stress is taken as about $\frac{1}{6}$ of the maximum permissible direct stress. Bearing this in mind a simplified approach to the mechanical design of fan is out lined as follows:

A. Impeller

The back plate and shrould of a centrifugal fan may be stressed by application of the following equations as recommended by Osborne (1966).

$$\delta r\,(max) = \frac{\rho 2}{4g} \quad (\sigma + 3)\,(\gamma_2 - \gamma_1)^2 \quad \ldots\ldots 2.60$$

$$\delta n(max) = \frac{2}{4g} \quad (\sigma + 3) \quad \frac{2}{2} + (1 - \sigma)\,\gamma_1^2 \quad \ldots 2.61$$

where

δr = direct radial stress N/m^2 (pa)

δn = direct tengential stress N/m^2(pa)

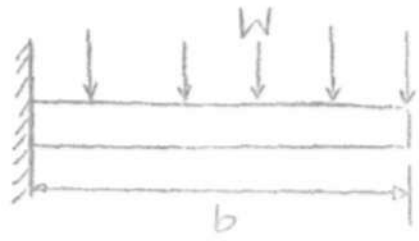
ρ = density kg/m^3

σ = poission ratio

$1'\ 2$ = internal and external radius of the impeller, m

B. Blade

The blades may be considered as beams with rigid support at back plate and shrould. The maximum bending moment is given as:



$$M_b = \frac{M_b}{12} \quad \text{..... 2.62}$$

where

M_b = maximum bending moment, N-m

W = total distributed load on the blade, N

b = blade width, m

The total distributed load on the blade comprises the centrifugal forces and the pressure differences across the blade.

In most practical cases the force F is of greater significance.

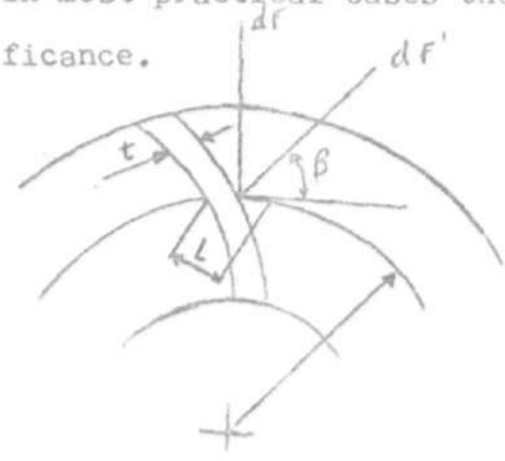


Figure 2.2: Force on Fan Blades

Considering an element of the blade of width, b thickness t and length L as shown in Figure 2.2, the force normal to the element is given by Osboine,(1966).

$$dF^1 = dF \cos\beta = bt\,L \frac{\rho}{g} w^2 r \cos\beta \qquad \ldots\ldots 2.63$$

where

L = blade length, m

b = blade width, m

ρ = density of blade material kg/m^3

w = angular speed Rev/sec.

γ = blade rotation radius reference to fixed position, m

β = blade angle (degrees)

t = thickness of blade, m

g = acceleration due to gravity, m/s^2

The maximum bending moment is given by

$$M_{max} = \frac{dF^1 b}{12} = \frac{b^2 t}{12} \frac{\rho}{g} w^2 \gamma L \cos\beta \qquad \ldots\ldots 2.64$$

All the symbols are as defined in equation 2.47.

The section modulus Z is

$$Z = \frac{2\,t^3 L}{12t} = \frac{t^2 L}{6} \qquad \ldots\ldots\ldots\ldots\ldots 2.65$$

Thus, the maximum bending stress is

$$M_{max} = \frac{b^2 \rho \gamma w^2 Z \cos\beta}{2tg} \qquad \ldots\ldots\ldots 2.66$$

The symbols are similarly defined.

If the blades are welded to the shrould and back, and the stress in the weld is

$$\tau = \frac{\rho w^2 \gamma}{g} 2 L Lw \cos 45 \quad \ldots\ldots\ldots 2.67$$

where

τ = stress in the weld

ρ = density of blade material, kg/m^3

w = angular speed Rev/sec.

γ = blade rotation radius reference to fixed position, m

L = blade length, m

Lw = weld length, m

g = acceleration due to gravity, m/s^2

C. Fan Shaft

The fan shaft may be treated as a beam carrying the impeller as point loads if the shaft is long. The stress situation in the shaft must be considered in three different ways (Hall, et al., 1980).

i) Maximum bending stress

$$\delta_{(max)} = \frac{32 M_b d_o}{\pi (d_o^4 - d_1^4)} \quad \ldots\ldots\ldots 2.68$$

ii) Maximum shear stress

$$\tau_{(max)} = \frac{16}{\pi d_o^3 (1-k^4)} \sqrt{(K_b + F_a d_o (1+k^2))^2 + (K_t + M_t)^2} \quad \ldots 2.69$$

iii) Critical speed, which should be at least $1\frac{1}{2}$ times the running speed.

For Equations (2.47) and (2.48).

$\tau_{(max)}$ = Maximum shear stress N/m^2

$\sigma_{(max)}$ = maximum bending stress, N/m^2

M_b = bending moment, N-m

d_o = shaft outside diameter, m

d_i = shaft inside diameter, m

k = ratio of shaft inside diameter to shaft outside diameter di/do

k_b = combined shock and fatigue factor applied to bending moment.

k_t = combined shock and fatigue factor applied to torsional moment.

α = column action factor = unity

Fa = axial load, N

M_t = torsional moment, N-m

D. Pressure Head

Kazantsev (1977) gave a relationship by which total pressure head developed by a centrifugal fan, at standard atmospheric pressure of 760mm Hg, 50% relative humidity and temperature of $20^{o}C$, can be calculated.

$$H^{\frac{3}{4}} = \frac{n\ V^{\frac{1}{2}}}{n_{sp}} \qquad \ldots\ldots\ldots\ldots\ldots 2.70$$

carried out in Nigeria, her climate and its effect to the farming system is studied.

Nigeria has a very wide range of climates, broadly divided into Equatorial and Savanna regions .Leong and Adeleke (1978). Under the Equatorial region lies forest vegetation, which is further subdivided into mangrove, in the riverine area, water forest, huge and dense forest as well as forest regrowth zones. Equatorial region covers Oyo State down to riverine area of the southern part of Nigeria. The Equatorial region is characterized by the mean monthly temperature of around 27^{o}C, with very little variation Leong and Adeleke (1978). Cloudiness and heavy rains help to moderate the daily temperature. Precipitation is heavy between 1254mm and 2699mm and are well distributed throughout the year Webster, and Wilson (1966). There is no month without rains and the relative humidity is constantly high-over 80% most of the time. It is reported that because of the high relative humidity and constant rain fall, plant growth of all sizes as well as macro and micro-organisms are continuous throughout the year.

The Savanna region is said to cover the remaining part of Nigeria, extending from Kwara and Benue States to the rest of the northern states Leong and Adeleke (1978). This vast area is also divided into Desived or

Guinea Savanna, Sudan Savanna and lastly Sahel Savanna. From the investigation it is found that Guinea Savanna extends to some parts of Anambra State. Kano State is cited as a good example of Sudan Savanna, while parts of Sokoto State fall under Sahel Savanna zone. The climatic feature of savanna region is one of hot rainy season and cool dry season Williamson and Payne (1982). In Sudan Savanna the hot rainy season normally begins in May and lasts until September. Generally the annual rain fall in the savanna region is 710mm to 1214mm. The wind is always very strong and moves with high speed, mostly dust-laden during the dry season. In the dry season, the relative humidity seldom exceeds 30%. The monthly temperature hovers between 21^{o}C and 32^{o}C. Day time is hot during the hot season with temperature ranging up to 38^{o}C and above. At night the clear sky which promotes intense heating during the day also causes rapid radiation in the night such that the temperature can fall down to 10^{o}C. Hence there is wide range of temperature gap in the savanna region Leong and Adeleke (1978).

Crop planting does not start at the same time in Nigeria because of the climatic variations. As a result crops in the south mostly mature during the rainy season between July and September, the wettest months. Likewise

some early maturing crops in the north are harvested during the rains. Hence a means of heating the relatively humid air artificially to permit drying of crops is therefore, needed. It has been found that Nigeria generally has abundant sunshine all the year round. This indicates that solar crop dryer is also needed (even in the north) as to alleviate the drying problems.

Considering the climatic differences of Nigeria (tropics) and its effect on crop drying, the project that can provide dryers suitable for effective crop drying in these different locations must be justifiable. Suffice it to say that this project aims at providing these dryers, that is, solar crop dryers and artificially heated air system or hybrid crop dryers for use in different parts of the savanna region.

Different types and sizes of dryers have been constructed, ranging from small to large scale natural convection solar dryers to forced convection artificially heated-air systems. These dryers are associated with some short comings. For instance, in advanced countries these dryers are normally constructed with the large scale well to do farmers in mind. Therefore, the high financial investment has limited the importation of these

dryers for very few large scale Agro-allied industries here in Nigeria. As a result, to an average Nigerian farmer small scale solar or firing system crop dryers are more appropriate. On the other hand, most of the dryer project constructions done in this country have been revolving around solar grain dryers, mainly located in the areas of abundant sunshine of northern parts of Nigeria. Besides climatic differences, for any project on dryers to be useful to all farmers in this country, the size of farmers has to be well known. To this end Ijere (1986) defined the size of farmers as follows:

1. Small Scale Farmers: This group of farmers are those who normally cultivate from 0.10 to 6 hectares in one year. They constitute about 81 percent of all farm holdings. Their income per capital is always very low and they are mainly located in the rural areas.

ii. Medium Scale Farmers: This set of farmers are those who can farm on area of 6 to 10 hectares per year, and are made up of about 14 percent. They operate with higher capital than the small scale farmers.

iii. Large Scale Farmers: There are those that farm from 10 hectares and above. They constitute about 5 percent of all farm holding. They operate with large capital and can afford to purchase and maintain complex mechanized farm equipment.

The effort of the government to improve rural life by making it possible for installation of motorized agricultural equipment, such as forced convection system dryer, is hereby noted. Nwafor et al, (1982) reported that developments in the electricity and industry have included the rapid expansion of programme for the electrification of the rural areas.

The above points therefore, justify any project which can embark on construction of crop dryers suitable for all categories of farmers, ranging from small to large scale farmers located in different ecological zones in this country. Hence the project in question also gives special consideration on the size of farm holdings in the developing countries. Thus the crop dryers to be constructed under this project are such that all scales of farmers can easily obtain and maintain the and the dryers can are function all the year round.

CHAPTER THREE

3. DESIGN CONSIDERATIONS

3.1 Design Calculations of Solar Crop Dryer

3.1.1 Determination of Dryer Capacity

The result of the Rapid Rural Appraisal (RRA) method of interview conducted among the farmers in the identified areas of Niger and Kaduna States showed that the crop that imposes highest drying problem is the early maturing maize. The farmers in expressing their great need for a mechanized dryer pointed out that it was unfortunate that the maize which matures early during the rains was the best variety, both in quality and yield. The interview also showed that the mánor maize producers are on 150 kg (1.5 bags) production level, while major maize producers indicated 1000 kg to 6000 kg (10 to 60 bags) of threshed maize production level. Among all the

farmers interviewed from the various villages, only two medium scale farmers were identified who said that each one of them produced an average of 10,000kg (100 bags) of shelled maize per year. The small and medium scale farmers further said that they dry about 100 to 200kg of unthreshed fresh maize at a time, and that it took them eight to ten sunny days for a complete batch drying.

The capacity of the dryer of this project is directly related to the quantity of unthreshed fresh maize the farmers can dry at a time. Based on the above findings, the optimum required dryer capacity is chosen to be 400kg of unthreshed fresh maize.

3.12 Calculation of the Collector Area

The collector area must have direct relationship with the determined dryer capacity of 400kg of unthreshed fresh maize. Therefore the following calculations are made as to arrive at the collector area.

Mature and fresh maize grain is assumed to have moisture content as high as 25%, wet basis, when harvested in the rains. If it is to be dried with the cobs, the overall moisture content is estimated at 27%, wet basis.

Having established that the optimum dryer capacity is 400kg of unthreshed maize at the estimated 27% moisture content the water removed by drying the maize from 27% moisture content to the safe storage 12% moisture content is calculated as follows:

$$D_m = W_m = \frac{W_m \, MC_{iw}}{100} \quad \ldots\ldots\ldots\ldots 3.1$$

where

D_m = dry matter of the maize, kg

W_m = weight of wet maize, kg

MC_{iw} = initial moisture content of maize, wet basis, %

If W_m = 3400kg and

MC_{iw} = 27%

Then

$$D_m = 400 - \frac{400 \times 27}{100} = 400 - 108 = 292 \text{ kg}$$

The quantity of water removed is given as

$$W_t = \frac{MC_{id} - MC_{fd}}{100} \, D_m \quad \ldots\ldots\ldots\ldots\ldots 3.2$$

where

W_t = quantity of water removed, kg

D_m = dry matter weight, kg

MC_{id} = initial moisture content of product, dry basis, %

MC_{fd} = final moisture content of product, dry basis, %

The inital dry basis moisture content is

$$MC_{id} = \frac{27 \times 100}{100 - 27} = 36.99\% \text{ dry basis}$$

and the final dry basis moisture content is also

$$MC_{fd} = \frac{12 \times 100}{100 - 12} = 13.64\%, \text{ dry basis.}$$

The quantity of water to be removed in drying from the initial to final moisture content is therefore,

$$W_t = (\frac{36.99 - 13.64}{100}) \times 292$$

$$= 68.182\text{kg of water}$$

Thus, 68.182kg of water is to be removed in order to dry 400kg of unthreshed maize from 27% moisture content, wet basis, to 12%.

The heat energy required to evaporate the calculated 68.182kg of water is the collector useful energy grain. It can be calculated by applying the sensible heat added to the material and the heat of evaporation, given by Severns (1937) as shown in the following equations 3.3

$$E = E_1 + E_2 = W_m Cp_m (T_2 - T_1) + L_v W_t \quad \ldots 3.3a$$

ie $$E_1 = W_m Cp_m (T_2 - T_1) \quad \ldots\ldots\ldots\ldots\ldots\ldots 3.4$$

$$E_2 = L_v W_t \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 3.5$$

where

E = collector useful energy gain, kJ

E_1 = sensible heat added to the material (maize), kJ

W_m = weight of material (wet maize), kg

Cp_m = specific heat of material (maize), kJ/kg ^oC

T_2 = temperature of air inside dryer, ^oC

T_1 = collector inlet temperature, ^oC

E_2 = heat of evaporation, KJ

L_v = heat of vaporization, (kJ/kg) at the temperature T_2

W_t = weight of water to be removed, kg.

From the meteorological data for a period of ten years (10 yrs.), 1980 to 1989, the average maximum daily temperature during the months (June to September) of heavy rains in Zaria, is found to be 29.45^oC (see Table B-1 in the Appendix). Based on this average temperature, the collector inlet temperature T_1 is assumed to be 30^oC.

ASHRAE (1977) gave the safe drying temperatures, in batch and continuous flow dryers for various grains for various uses as shown in Table 3.2, from which the temperature of inside dryer (T_2) is chosen to be 45^oC.

From Equation (3.4) and for Cp_m of 2.2401 kJ/kg ^{o}C,

E_1 = 400kg x 2.2401 kJ (45 - 30) ^{o}C

= 13440.6 kJ

Table 3.1: Safe Drying Temperatures in Batch and continuous Flow Dryers for Various Grains for Various Uses (FAO, 1978)

Grain	Uses	Air Temperature ^{o}C
Corn (maize)	Seed	43.3
Sorghum	Milling	71.1
Wheat	Feed	82.2
Soybeans	Milling	15.6 to 37.8
	Feed	15.6 to 37.8
Groundnut (Peanuts)	Milling	35 (batch drying)
	Feed etc.	
Rice	Milling	35 (Batch drying)
	Feed etc.	35 to 54 continuous flow
Barley	Seed	40.6
	Milling	40.6

From Table A.3 in Appendix A the value of heat of vaporization at the temperature T_2 is L_v = 2394.1518 kJ/kg, and from Equation (3.5)

$$\therefore \dot{E}_2 = 2394.1518 \text{ kJ} \times 68.182 \text{ kg}$$

$$= 163238.06 \text{ kJ}$$

Also from Equation (3.3a)

$$\therefore \dot{E} = 13440.6 \text{ kJ} + 163238.6 \text{ kJ}$$

$$= 176678.66 \text{ kJ}$$

Thus 176678.66 kJ heat energy is required to dry 400 kg of maize from 27% moisture content, wet basisto 12%. The farmers said that it takes 8 to 10 sunny days to dry 100 to 200 kg of unshelled fresh maize. Considering the length of time the farmers normally take to dry their crops any dryer that will take about 50% of the time (4 days) to dry 400kg of fresh maize seems justifiable. Therefore heat energy required per day is

$$\frac{\dot{E}}{4} = \frac{176678.66}{4}$$

Q_u = 44169.66.5 kJ/day

Assuming 8 hours daily sunshine, the energy requirement per hour becomes

Q_u = 44169.665 kJ x 8 hours

= 5521.2081 kJ/hr

= 1.534 kW

= 1534 W

The average monthly total horizontal solar radiation I_H during the crop harvest period at July to September is approximately 490 w/m^2 for Zaria location Arinze and Obi (1984). Assuming that the ambient air and collector inlet are temperature are the same, the solar collector area required to supply the useful energy (1534 W), for drying the crop can be determined approximately for a horizontal collector as Duffie and Beckman (1974).

$$Q_u = A_c F_R (\tau\alpha)_e I_H \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad 3.6$$

where

F_R = heat removal factor (approximately 0.7 for an air-cooled collector)

$(\tau\alpha)_e$ = effective transmittance-absorptance product (approximately 0.7 for the single glass cover and black painted surface)

The required collector area A_c is therefore given by

$$A_c = \frac{Q_u}{I_H \tau\alpha_e F_R}$$

$$= \frac{1534}{490 \times 0.7 \times 0.7}$$

$$= 6.4m^2$$

For maximum solar energy collection all through the year, the collector should be inclined to the horizontal at the latitude angle of a given location Arinze and Obi (1984). The solar collectors in this study were inclined at an angle of 14^o and the project sites selected for this study lie between 9^o and 14^oN latitude. For this small angle of inclination the difference between the solar radiation on the tilted collector surface and that on a horizontal surface would be little. To take into account the reduction in solar energy collection due to the tilting of the collector, the calculated collector area was divided by the average tilt factor (0.9), R_b, for the 14^o inclined collectors and for the drying period by July to September. This gives a collector area of approximately $7.1m^2$.

3.2 Design Calculations for Solar Crop Dryer II

3.2.1 Dryer Capacity and Amount of Moisture To be Removed from the Product.

Solar crop dryer II is mainly for drying vegetables and fruits. It is for on-farm use by the farmers. The interview conducted around Zaria Local Government Area in Kaduna State revealed that in vegetable and fruit handling the local farmers have the greatest problems in drying tomatoes. This is because tomatoes have high moisture content and need to be dried at a short time as to avoid spoilage. The difficulties in drying tomatoes forced the farmers to dry only about 15 to 20kg of tomatoes at a time, and this takes about 10 to 15 days for drying a batch. Based on these facts the capacity of Solar Crop Dryer II is chosen to be 40kg of fresh tomatoes.

Lutz, Hardenburg (1967) said that tomatoes that are firm riped have a moisture content of about 94.1%, wet basis, while the mature green tomatoes have the moisture content of about 93%, and that the average safe storage moisture content of dried tomatoes is about 7%, wet basis. The initial moisture content of tomatoes the local farmers dry is therefore, taken to be 93.5% wet basis.

The dry matter D_m of the 40kg of tomatoes is obtained from Equation (3.1) as

$$D_m = W_o - \frac{W_o M_{ci}}{100}$$

$$D_m = 40 - \frac{40 \times 93.5}{100}$$

$$= 40 - 37.4 = 2.6\text{kg}$$

The qunatity of water W_t removed is obtained from Equation (3.2) as:

$$W_t = \left(\frac{M_{ci}}{1} - M_{cf}\right) D_m$$

$$W_t = \left(\frac{1328.57}{10} - 7.53\right) 2.6$$

$$= 34.35\text{kg}$$

34.35kg of water is to be removed in order to dry 40kg of tomatoes from 93% moisture content, wet basis to 7% moisture content wet basis.

3.2. Calculation of Dryer II Collection Area

Kordylas (1990) recommended that temperature range of between 35°C and 63°C are quite satisfactory for drying fruits and vegetables. It is worth noting that most enzymes are destroyed at temperatures of above 60°C. This project aims at constructing fruit/vegetable dryer that will generate 55°C drying air. To obtain such a high

drying air temperature, from solar dryer constructed with local materials, black rockbed collector are used. Rocks have higher specific heat than air, therefore it can boost the temperature generated by solar radiation, and can also retain the heat for a longer period. Because of the rockbed heat storage system this dryer has a longer drying time.

The heat energy required to evaporate the calculated 34.35kg of water in the collector useful energy gain. Following the procedure presented in Section 3.1.2 the collector areas required was approximately obtained as $2m^2$ assuming the tomatoes would dry in 4 consecutive days in the natural convection solar dryer.

3.3. Design Calculations for the Hybrid Crop Dryer.

3.3.1 Determination of Hybrid Crop Dryer Capacity

The hybrid crop dryer consists of a dryer section, solar collector, gas-fired heat exchanger and a blower (fan). The dryer section capacity is the determinant factor for design parameters of other sections of the hybrid dryer. The hybrid dryer is designed to meet the needs of both small and medium scale faremers who dry

300 to 400kg of product in a batch. The dryer capacity is chosen to be 600kg of fresh ear maize.

3.3.2 Calculation of Air Flow Rate

The fan or blower is the primary mover of air in a forced convection drying system. The blower air flow rate is directly related to the dryer capacity (600kg). In order to determine the required flow rate the amount of water to be removed from the product from 27% initial moisture content, wet basis, to 12% is calculated first.

The dry matter is

$$D_m = 600kg - \frac{600kg \times 27}{100}$$

$$= 438kg$$

The dry basis initial and final moisture contents are

$$M_{cf_d} = 36.9863$$

$$M_{cf_d} = 13.6364$$

The amount of water to be removed is

$$W_t = \frac{(36.9863 - 13.6364)}{100} 438$$

$$= 102.273kg$$

Following the method presented earlier, the total energy required to remove the water from the product, E is approximately 265018kJ. Convection constant air flow rate to dry the maize. Assuming it will take

about 6 hours continuous operation to dry the product the required useful energy for drying is calculated as

$$Q_u = \frac{265018 \text{ kJ}}{6 \times 3600}$$

$$Q_u = 12.2694 \text{ kJ/s}$$

$$Q_u = 12.2694 \text{ kW}$$

From Equation (3.13) the mass flow rate is determined by

$$M_a = \frac{Qu}{C_p (T_2 - T_1)}$$

M_a = mass flow rate of air, kg/s
Qu = useful energy gain flow rate, kJ/s
C_p = specific heat of air at T_2, kJ/kg ^oC
T_2 = temperature of the drying air inside the hybrid dryer, ^oC
T_1 = ambient temperature ^oC

$$\therefore M_a = 12.2694 \frac{kJ}{s} \times \frac{1}{1.015 \frac{kJ}{kg}{}^oC} \times \frac{1}{45^oC - 30^oC}$$

$$= \frac{12.2694 \text{ kg}}{1.015 \times 15 \text{ s}}$$

$$= 0.81 \text{ kg/s}$$

The density of air ρ at T_2 is 1.077 kg/m^3

The volumetric flow rate of air at the drying section is

$$V = \frac{M_a}{\rho} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad 3.7$$

where

V = required volume air flow rate in the drying section.

Ma = required mass air flow rate

ρ = density of air at T_2

$$\therefore \quad V = 0.81 \frac{kg}{s} \times \frac{m^3}{1.077\ kg}$$

$$= 0.7521\ m^3/s$$

Giving an allowance of 10% for losses resulting from lickage, the actual air flow rate is

$$V_a = 0.7521\ m^3/s \times 1.1$$

$$= 0.82731\ m^3/s$$

A radial-type centrifugal fan with 8 blades was designed and constructed in this study to circulate air for the hybrid dryer. The fan runs at 1420 rpm and is driven by a 1.5 kW electric motor. At wide open condition and free delivery, the centrifugal fan produces 5000 m^3/h or 1.39 m^3/s of air. Plate 3.1 shows the centrifugal fan.

3.4 Detailed Description of the Dryers

Three different types of dryers were constructed. These are Solar Crop Dryer I, Solar Crop Dryer II and the Hybrid Crop Dryer. The detailed description of these dryers are as follows:

3.4.1 Description of Solar Crop Dryer I

The solar Crop Dryer I is a direct mode dryer of three different models:

A - mud type

B - metal type

C - wooden type

These solar crop dryers are characterized by their large size and are mainly for drying grains,nuts and tubers. These dryers are located in the field for on-farm use by the farmers at Jere in Kaduna State, New-Wuse and Kwaka in Niger State. At Jere one mud and one wooden type solar crop dryers were built at a site about 1.5km from Kaduna - Abuja road. One mud and one metal type solar crop dryers were also built at New-Wuse some 300 metres from Kaduna - Abuja road. Also at Kwaka on Suleja - Minna road two dryers were built, one mud-type and one metal-type.



PLATE 3.1: CENTRIFUGAL FAN



PLATE 3.2: MUD TYPE SOLAR CROP DRYER AT JERE VILLAGE (KADUNA STATE)



PLATE 3.3: MUD TYPE SOLAR CROP DRYER AT NEW-WUSE VILLAGE (NIGER STATE)



PLATE 3.4: MUD TYPE SOLAR CROP DRYER AT KWAKA VILLAGE (NIGER STATE)

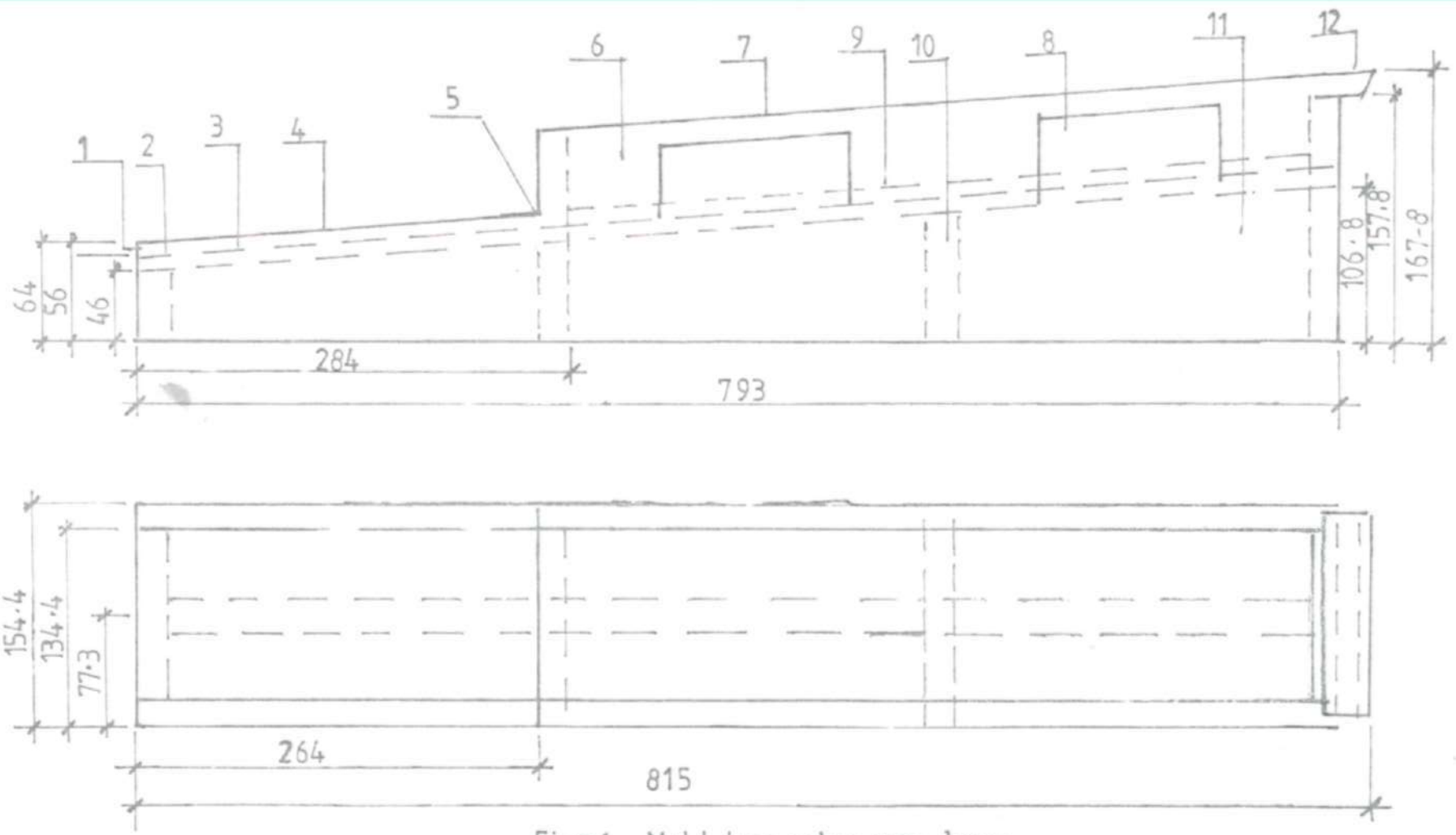


Fig3.1. Muld type solar crop dryer

Figure 3.1 : MUD TYPE SOLAR CROP DRYER

No. of Parts	Name of Parts
1	Air inlet space
2	Air gap
3	Reinforced floor/Heat collector surface
4	Glass cover
5	Collector air outlet/Drying section air inlet space
6	Drying section space
7	Glass cover
8	Wooden door
9	Expanded metal crop bed
10	Support walls
11	Side support wall
12	Dryer air outlet guide

Scale 1:400/Dimensions in mm

These dryers are all direct mode type. That is the dryer section, where crops are placed for drying is covered by a transperant material so that the crop absorb solar radiation directly. Both the mud-type, wood-type and metal-type dryers operate in the smae way so that their structural features are the same, except that mud was mainly used for building the mud dryer, metal sheet was used in constructing the metal dryer, and wood plank was the major material in wood dryer. The top cover for both the solar collector and drying section for these dryers is transperant glass material.

The mud dryers located at Jere, New-Wuse and Kwaka were built alike. The mud type dryer is shown in Figure 3.1 and Plates 3.2, 3.3 and 3.4 for the mud dryer in Jere, New-Wuse and Kwaka, respectively. Figure 3.1 shows that air at ambient air temperature enters the collector section through the collector air inlet opening (1) and flows along the air gap (2). The air movement is induced by thermal forces resulting from the temperature difference between inside and outside the dryer. Crops for drying are placed in the dryer section (6) with perforated metal screen (9). The perforated metal screen is strong enough to hold about 400kg of fresh maize. There is air plenum under the crop-bed. This was created for even distribution

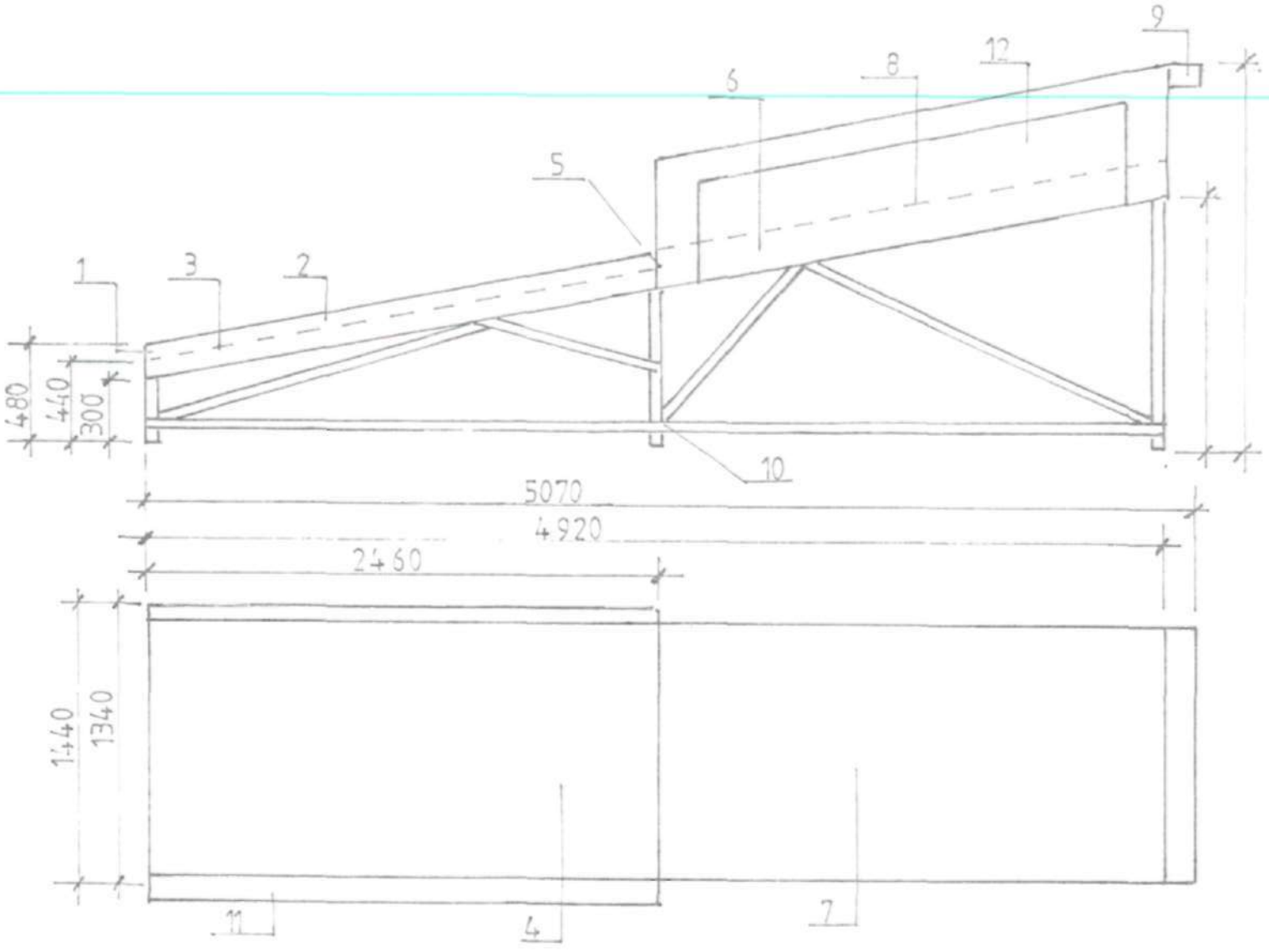


Fig. 2.2 Wood type solar dryer

Figure 3.2: MEDIUM SCALE WOOD TYPE DIRECT MODE SOLAR CROP DRYER

No. of Part	Name of Parts
1	Air inlet space
2	Air gap
3	Collector plate
4	Glass cover (collector section)
5	Collector air outlet/drying section air inlet space
6	Air planum
7	Glass cover (Drying Section)
8	Expanded metal crop bed
9	Dryer air outlet guide
10	Support legs
11	Insulator
12	Wooden door

Scale 1:300/Dimensions in mm

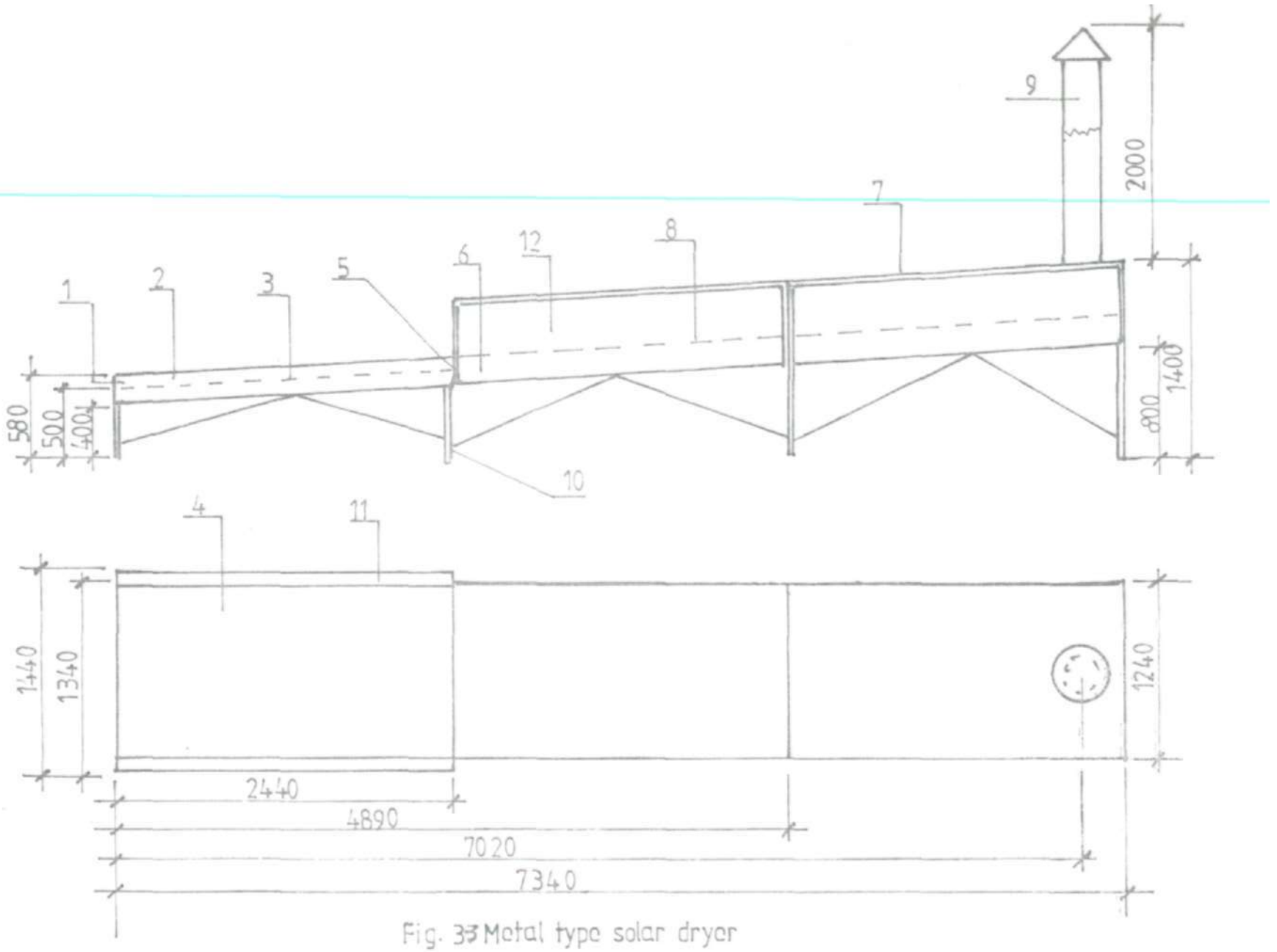


Fig. 33 Metal type solar dryer

Figure 3.3 : METAL TYPE SOLAR DRYER

No. of Parts	Name of Parts
1	Air inlet space
2	Air gap
3	Collector Plate
4	Glass cover
5	Collector air outlet/Dryer section inlet space
6	Air Planum
7	Glass cover
8	Expanded metal crop bed
9	Chimney
10	Support legs
11	Insulator
12	Metalic door

Scale 1:400/Dimensions in mm

of the heated air from the collector so that the crops can dry more or less uniformly. Dryer support wall (11) was constructed to carry the whole structure. Four doors (8) were fixed by the side of the drying section for loading and off-loading crops. Dryer section air outlet guide (12) was constructed such that rain water will not enter into the dryer. The foundation base was made of inside supporting walls (10) which has eight wall appartments or support walls. Eight pieces of planks were positioned at equal enterval on top of the dryer as glass support, and the dryer was finally covered with glass (7).

The wooden dryer shown in Figure 3.2 takes the same shape as the mud type already described, except that the support legs (10) were made of wood plants, and one door (12) was fixed at one side of the drying section. Other parts are the same as described for mud type dryer.

The metal type dryer (See Figure 3.3) is like the mud type dryer, except that metal sheets, pipes and angle iron were used in the construction. Other differences are chimney (9) that was fixed at the end of the dryer section 7 and two doors (12) were inserted at one side of the dryer for loading and off-loading crops. The support legs (10) keep the dryer in an inclined position.

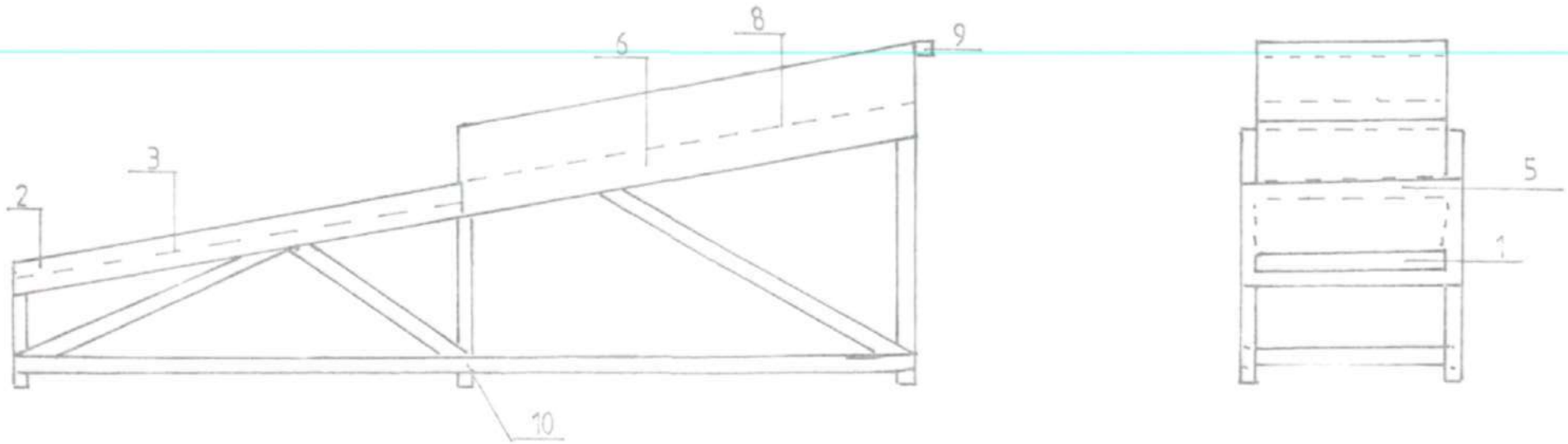
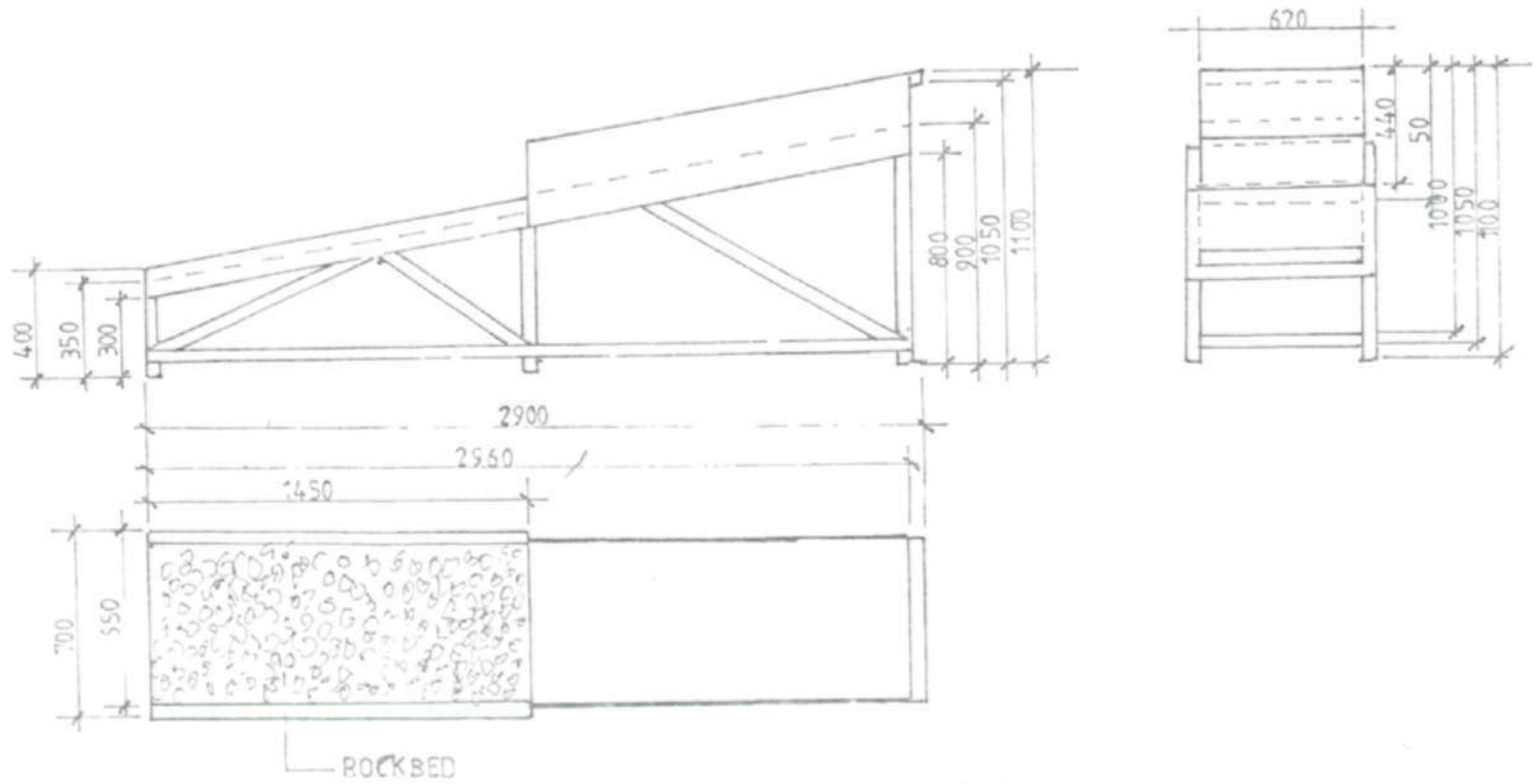


Fig 4a Vegetable / Fruit dryer without rockbed



Figs4b Vegetable /Fruit dryer with rockbed

Figure 3.4A: SMALL SCALE SINGLE COMPARTMENT WOOD TYPE VEGETABLE/FRUIT SOLAR DRYER WITHOUT ROCKBED HEAT STORAGE (PLAN, SIDE AND END VIEWS)

No. of Parts	Name of Part
1	Air inlet space
2	Air gap
3	Collector plate (Absorber surface)
4	Glass or polytehene cover
5	Collector air outlet/drying section air inlet space
6	Air Plenum
7	Glass or polythene lid
8	Nylon netting crop bed
9	Dryer air outlet guide
10	Support legs
11	Insulator scale 1.200 Dimensions in mm

Figure 3.4B: SMALL SCALE SINGLE COMPARTMENT WOOD TYPE VEGETABLE/FRUIT SOLAR DRYER WITH ROCKBED HEAT STORAGE (PLAN, SIDE AND END VIEWS

The construction, name of parts and the size (scale) of this dryer is exactly the same as indicated in Figure 4A

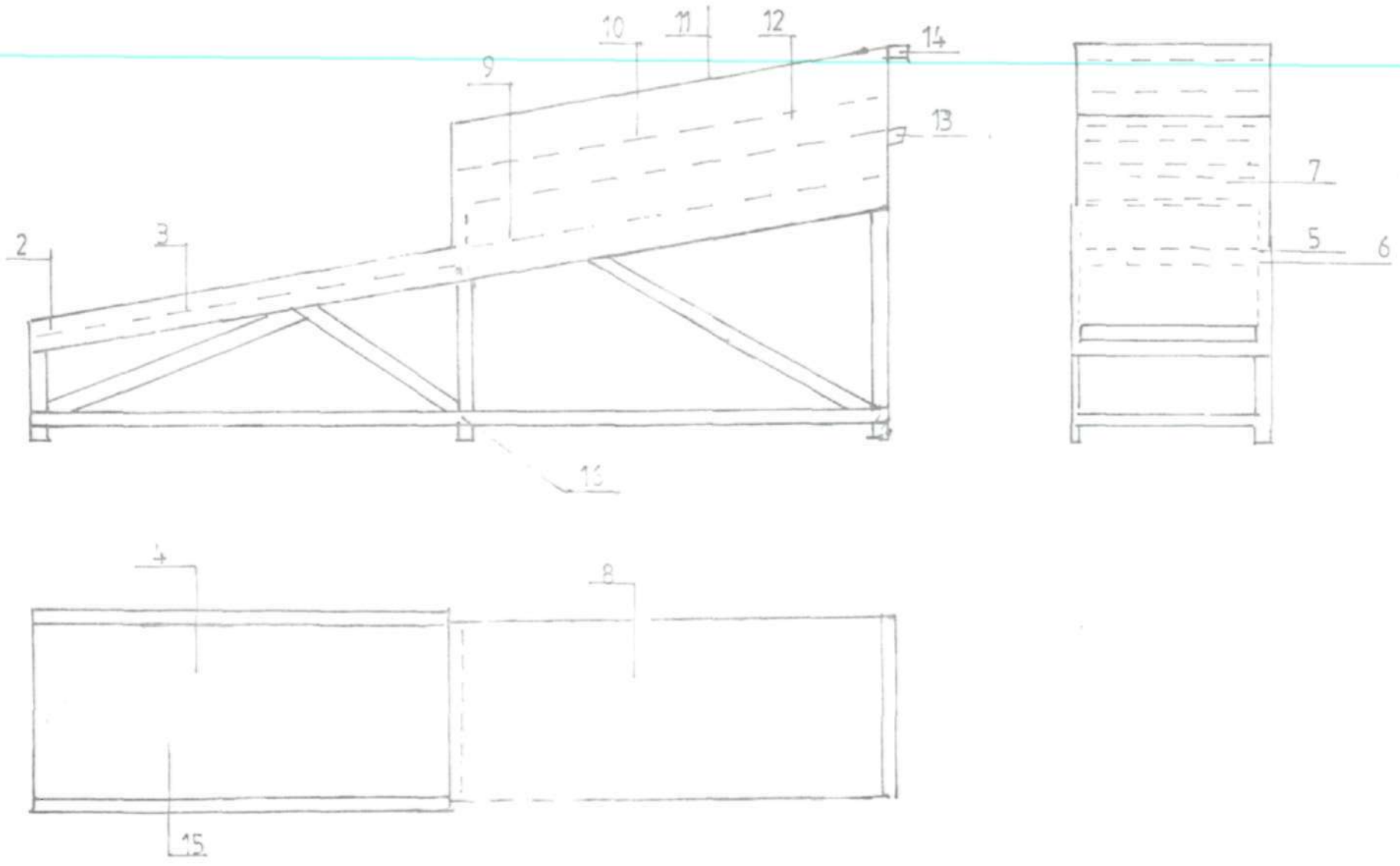


Fig35A Vegetable/Fruit dryer double layer

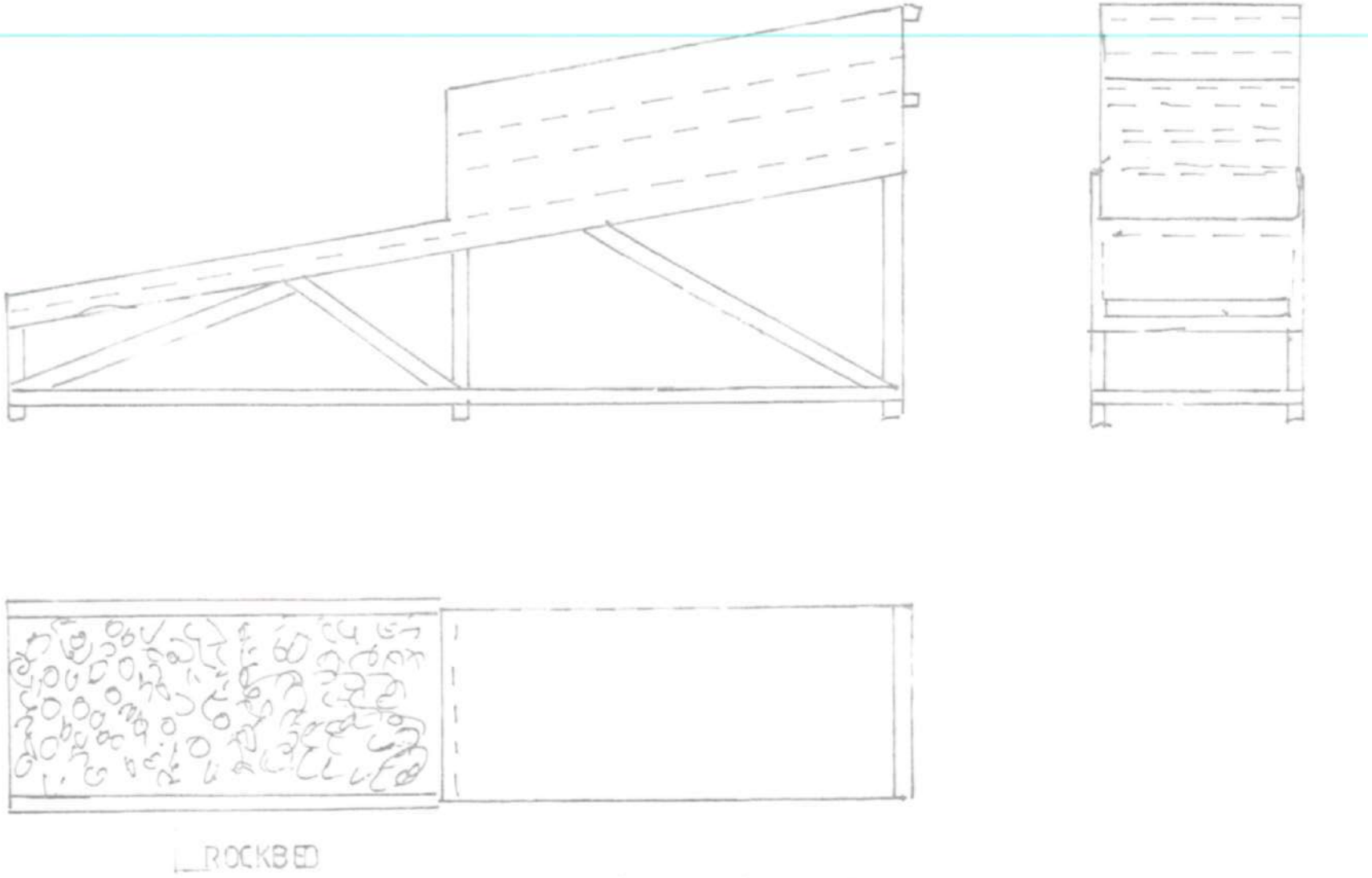


Fig35B Vegetable/Fruit dryer — double layer

Figure 3.5A: MEDIUM SCALE DOUBLE COMPARTMENT WOOD TYPE VEGETABLE/FRUIT SOLAR DRYER WITHOUT ROCKBED HEAT STORAGE(PLAN, SIDE AND END VIEWS

No. of Parts	Name of Parts
1	Air inlet space
2	Air gap
3.	Collector Plate
4.	Glass or polythene cover
5	Collector air outlet space
6	Lower compartment drying section
7	air inlet space
7	Upper compartment drying section
	air inlet space
8	Glass and Polythene lid
9,10	Lower and Upper compartments nylon netting crop beds Respectively
11,12	Lower and Upper compartments air
	plenum respectively
13,14	Lower and Upper compartments dryer
	air outlet guides respectively
15	Insulator
16	Support legs

Scale 1: 200/Dimensions in mm

Figure 3.5B: MEDIUM SCALE DOUBLE COMPARTMENT WOOD TYPE VEGETABLE/FRUIT SOLAR DRYER WITH ROCKBED HEAT STORAGE (PLAN,SIDE AND END VIEWS

The construction, name of parts and the size (scale) of this dryer is exactly the same as indicated in Figure 5A

3.4.2 Description of Solar Crop Dryer II

These dryers are mainly for drying vegetables and fruits. They consist essentially of a drying section which takes only a thin layer of crops and a solar collector. Some drying sections have two compartments, one directly below the top cover and the other below the first compartment. The solar collector of some of the dryers has a rockbed as the absorber plate while others have black painted plywood as absorber. These vegetable and fruit dryers have the same features and principle of operation as that of the wood dryer described previously in Section 3.4.1.

Figure 3.4a shows a dryer with one compartment only for the drying section and without a rockbed. Figure 3.4b shows a dryer as above but with a rockbed absorber plate for the solar collector. Figure 3.5a shows a dryer with two compartments for the drying section and without rockbed, while Figure 3.5b shows the same dryer with rockbed absorber for the solar collector. The rockbed increases the heat capacity of the absorber plate.

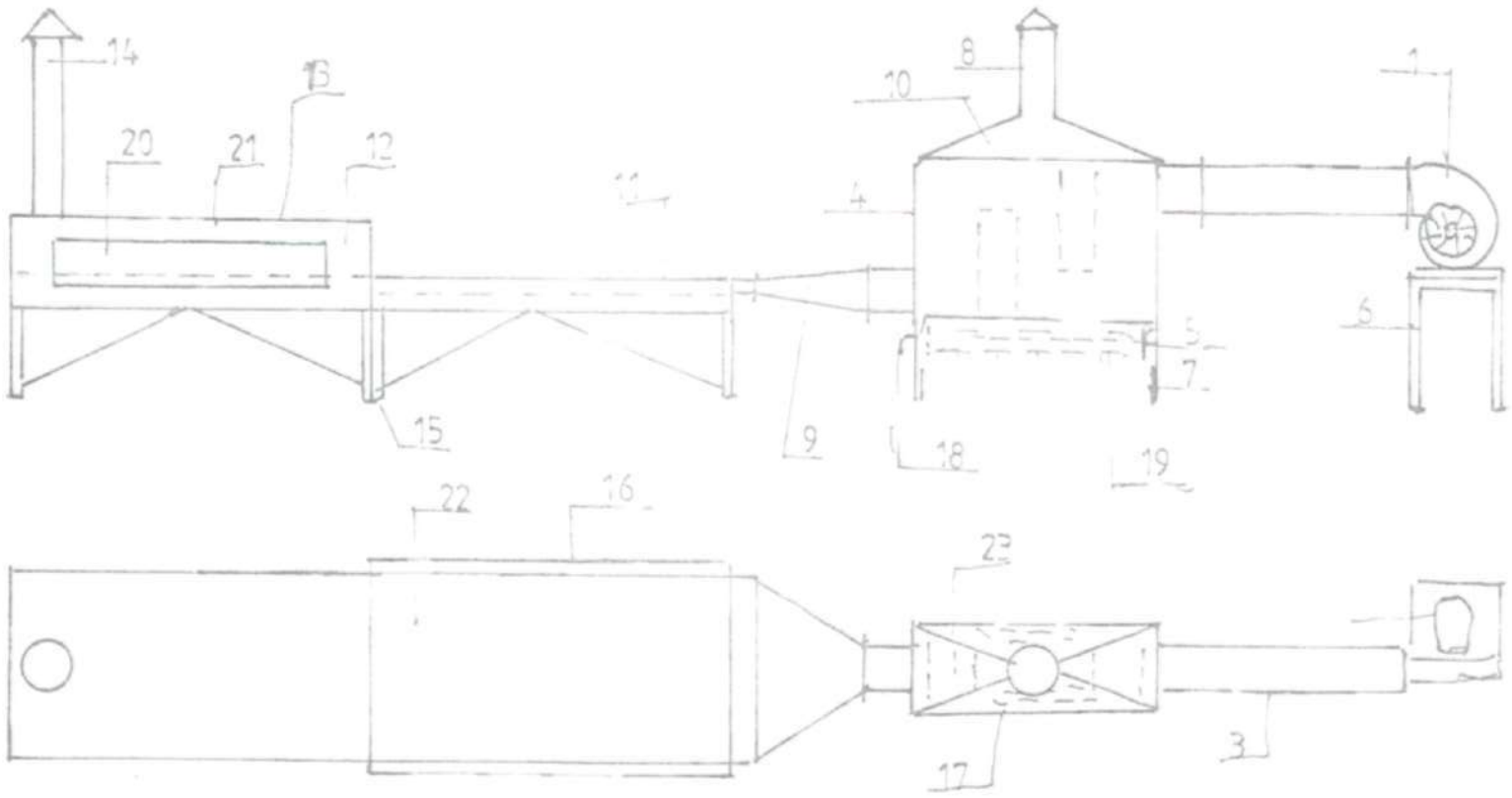


Fig36 Hybrid dryer

Figure 3.6: MEDIUM SCALE HYBRID CROP DRYER

No. of Parts	Name of Parts
1	Centrifugal fan
2	Electric motor
3	Air connection duct
4.	Heat exchanger
5	Furnace
6	Blower stand
7	Heat exchanger stand
8	Flue vent
9	Hot air connection duct
10	Flue convergent
11	Solar collector section
12	Drying section
13	Expanded metal crop bed
14	chimney
15	Dryer collector legs
16	Collector section insulator
17	Heat exchanger insulator
18.	Gas hose connector
19	Gas borners
20.	Metal door
21	Dryer section glass cover
22	Collector section glass cover
23	Heat exchanger air pipe

Scale 1.500/Dimension in mm

3.4.3 Description of Hybrid Crop Dryer

The component parts of this dryer are as shown in Figure 3.6. A 1.5 kW single phase 1420 rpm electric motor (2) drives a centrifugal fan (1). The fan together with the electric motor were bolted on a blower stand (6). The radial-type centrifugal fan is made of eight blades. Air at ambient temperature entering the fan flows out through the air connecting duct (3) to the gas-fired heat exchanger (4). The air is heated by the heat generated in the furnace (5) where natural gas is burnt. The burnt gas flows out through the flue vent (8). Air blown by the centrifugal fan and the burnt gass are not contacted. The drying air contacts only with the heat exchanger metal plate. As the air blown by the fan swirls through the heat exchanger, it is heated, and the hot air flows to the dryer through the ducts (9).

On sunny days, air temperature from the furnace is boosted when it flows through a solar collector (11). Eventually the hot air flows under the crop bed (13) in the drying section (12), and finally flows out through the chimney (14) after drying the crop inside the drying section. The dryer stands (15), heat exchanger stands (7) and the blower stand (6) keep the hybrid dryer in position.

CHAPTER FOUR

4. EXPERIMENTAL INVESTIGATION AND CONSTRUCTION OF DRYERS

4.1 Feasibility Study on Farmers' Acceptability of Mechanized Dryers.

Mechanized system of crop drying such as solar crop dryers and artificially heated-air crop dryers are new to Nigerian local farmers. Before fully embarking on this project, the farmers were interviewed to know their willingness to accept the new technology on crop drying. To this effect a study was under taken to access the crop drying needs of typical Nigerian farmers, and the acceptability of solar and hybrid crop dryers by small scale and large scale farmers.

To achieve this objective Rapid Rural Appraisal (RRA) method was used. This is the system where by the researchers integrate and interact informally with the local farmers, with the aim of finding out the farmers problems, the way they have been trying to solve their problems and openly suggesting a new method to the farmers on how they can solve their problems with little extemal help, and allow the farmers to freely take decision whether to accept this new method or not.

RRA methodology is a quick and accurate way of determining the farmers actual drying needs without the use of questionnaires. Zaria and Jere in Kaduna State and New-Wuse and Kwaka in Niger State, were chosen as areas for the RRA research study. Climates in these areas fully represent tropical climates. Jere, New-Wuse and Kwaka are areas of heavy rains and they simulate well with Southern Nigeria climates, while Zaria is a good example of Northern Nigeria climates. Dryers that work well in these locations will be generally acceptable in any other developing tropical countries.

Having chosen these areas, the RRA research team comprised of engineers, two socio-economists, and a local interpreter native to the study area launched out for the interview. The team first paid a courtesy call to the Emir of Suleja (one of the study areas) who endorsed his approval for carrying out such a project in his local Government Area. This he showed by taking us to the Ministry of Agriculture for formal introduction and instructing them to give us all necessary cooperation to make sure that the natives understood what the project was all about. We proceeded to visit the farmers in groups at Suleja, Kwaka, Bwari, Zuba, Gwagalada, Dikko and New-Wuse all in Niger State, Abuja Federal Capital Territory, as well as Jere, Kateri and Dokka in Southern part of Kaduna State and finally

farmers in Zaria Local Government Area in the norther part of Kaduna State.

Among these areas, Jere, New-Wuse and Kwaka were selected as areas for siting grains, nuts and tuber crop dyrers because they produce these crops extensively as indicated in Table 4.1. Zaria Local Government Area was chosen for locating vegetable/fruit crop dryers, because they produce a lot of vegetables and fruits all year round.

From the result of the RRA interview the following findings were made. The major crops grown in the villages of souther Kaduna State and Suleja local government area in Niger State are similar. The most important ones as ranked by the farmers are as presented in Table 4.1

Table 4.1: Crops Farmed in the Visited Villages

	Kwaka	New-Wuse	Dikko	Jere
a.	Yam	Yam	Guinea Cron	Maize
b.	Guinea Corn	Rice	Maize	Guniea Corn
c.	Maize	Maize	Red Beans	Yam
d.	Groundnut	Groundnut	Groundnut	Groundnut
e.	Rice	Guinea corn	Yam	Red beans
f.	Red beans	Red beans	Cassava	Cassava
g.	Soyabean	Cassava	Rive	Sugar Cane
h.	Cassava	Sweet potato		

Maize, groundnut and red beans are generally harvested during the rains. The crops that give the greatest drying problems are ranked as follows.

Kwaka	New-Wuse	Dikko	Jere
Maize	Maize	Maize	Maize
Groundnut	Red beans	Red beans	Groundnut
Read beans	Groundnut	Groundnut	

Farmers in these villages pointed out that they face a lot of difficulties drying their crops by traditional methods, which normally result to losses and low quality of the harvested crops. Some of these local methodsof crop drying are:

1. Drying the crops in the sun inside their compound, or in open space such as by the road side.
2. Leaving the crops to dry in open sun in the field.
3. Smoke-drying of crops by hanging crops on ropes over the cooking area in the kitchen.
4. Hanging crops on ropes outside but underneath the roof.
5. Putting crops inside calabash or pot containers and hanging them near cooking areas in the kitchen.

Some of these crops particularly, red beans and maize, become brownish or dark in colour when dried by smoking. The crops are generally contaminated before they are dried, because they are exposed to the contaminants.

The farmers are mainly small scale faremrs who produce below 5000kg (50 bags) of maize in one planting season. Only two farmers were identified who produce an average of about 10,000kg (100 bags) of maize per year. They can therefore, be grouped as medium scale farmers. Production level of other crops are not as high as maize generally.

Crops that give the greatest drying problems to farmers as indicated above normally mature for harvest between August and September which is still the period of heavy rains. Depending on weather conditions (relative humidity, temperature, wind speed and solar radiation intensity), and the quantity of crops, the number of days it takes the farmers to dry their crops varies between two days and twenty days.

The small scale farmers dry not more than 200kg (2 bags) of maize at a time. The medium scale farmers dry not more than 400kg (4 bags) of maize at a time. Farmers lose about 20 to 50% of their crops during drying, due to inadequacies of traditional drying methods.

Farmers in Zaria area mainly grow maize, cowpea, guinea corn, millet, sorghum, yam, tomatoes, okra, garden eggs, pepper and other crops which are produced in small quantities. The grains mature for harvesting from middle of November when dry season is already setting in. Grain crop drying does not give much problems except for few early maturing varieties that are harvested during the rainy season.

The farmers in this area indicated that their greatest problem was in drying vegetables and fruits. These are tomatoes, okra and leafy vegetables. Tomatoes which have very high moisture content prove to be the most difficult in drying and it changes to dark clour after the traditional open-sun drying. The farmers normally dry not more than 20kg of tomatoes at a time and it takes 10 to 15 days to dry. Due to the prolonged period of drying, the quality of the dried tomatoes is very low. The farmers dry their crops in this area.

The farmers generally indicated that drying problems affect their crop production level. The more crops the farmer produce, the more they lose due to drying problems because the qunatity they dry at a time is limited.

Farmers expressed the eagerness to use a better drying methods if available. But they wanted to see this method demonstrated to them before deciding how much they would be willing to invest in such an equipment. Many of the farmers said that they would increase their crop production level if faster drying facilities were made available to them. To this end the farmers generally expressed willingness to co-operate with us to see to the successful implementation of the project.

4.2 Construction of the Dryers

4.2.1 Mud-type Solar Crop Dryers

As shown in Figure 3.1, the mud dryer was built with available and affordable local materials. 900 mud blocks, each measuring 320 x 200 x 130mm were used in building each of the three mud dryers in the field at Jere, New-Wuse and Kwaka. At the foundation level, solignum was thoroughly applied to avoid termites attack. The native labourers from each of these villages were employed to work on the construction of the dryer with close supervision. The blocks were laid in the traditional way as they used to do in building their houses. Eight partition walls were built to support the decked floor. Twenty six pieces of 0.025m by 0.305m by 1.29m solignum threated planks were used for reinforcing the decked floor. The decked mud floor formed the collector and dryer section floor of thickness 0.1m. The solar collector was 1.22m wide and 2.44m long. The internal width of the dryer section was also 1.22m and 5.20m long. The overall length of the dryer was 7.83m with the external width of 1.58m. Four doors 0.45m wide and 0.61m long were constructed and fixed in pairs at each side of the dryer section. The walls were finally plastered with cement,

and the floors were also plastered and smoothened. Air dryer outlet opening was constructed with wood. The opening is 0.305m wide, 1.29m long and 0.025m high. The air outlet opening structure was positioned such that, it extended out to prevent water from entering inside the dryer when it is raining. The extension was 0.27m. 0.038m by 0.025m by 1.29m planks were fixed on top of the collector and dryer sections to support the glass cover, The glass cover formed 0.075m air gap in the collector section, while in the drying section a 0.51m gap was created between the crop bed and top cover.

The crop bed was constructed with black afra wood planks and expanded metal screens. The glass joints were sealed with felt adhensive as well as the sides of the top covers.

4.2.2 Metal-type Solar Crop Dryer

This dryer was constructed by welding 1.5mm thick galvanized steel sheet to box-like shape of internal dimensions 1.22m wide and 2.44m long and external dimensions 1.32m by 2.44m. Polystrene insulation of 0.05m thick was used for the collector. The top was covered with 3mm thick plain glass. The metal absorber plate for the solar collector was painted with flat-black oil paint.

The dryer section was constructed with 1.5mm thick galvanised sheet and the internal dimensions are 1.22m wide and 5.20m long. There is no insulation for the dryer section. A chimney was fixed at the end of drying section to aid natural convection air circulation through the dryer. Two doors constructed with galvanized sheet, each 2.5m long and 0.50m wide were fixed on one side of the dryer. Crop bed of internal dimensions 1.2m wide and 5.15m long was constructed and fixed inside the dryer section. The top of the dryer section was covered with glass and sealed with felt adhensive.

4.2.3 Wood Type Solar Crop Dryer

Black afra wood planks of thickness 25mm were used to construct the outside body of the collector section while plywood of 5mm thick was used to construct the collector absorber plate. The dimensions were the same as those of the metal type dryer collector section. For this wood dryer, the dryer section was constructed with interior dimensions of 1.22m wide and 2.60m long. The crop bed is 1.2m wide and 2.55m long and was constructed with wood planks and expanded metal screen. One door of 2.4m long and 0.5m wide was fixed on one side of the dryer.for loading and off-loading crops. A dryer air outlet opening was constructed with

galvanized steel sheet and positioned as to prevent rain water from entering the dryer.

4.2.4 Vegetable/Fruit Solar Crop Dryer

The same procedure employed in constructing the wood-type dryer explained in dryer I was used in constructing dryer II, except that the size of dryer II was constructed to smaller scale based on the farmers need. The vegetable/fruit dryers were of metal-type and wood-type.

i. Metal-type Dryer: The metal-type vegetable/fruit dryer was constructed with galvanized steel sheet, angle irons, flat bars, polystrene insulation, expanded metal screen, and 3mm thick plain glass.

ii. Wood-type Dryer: Wood type vegetable/fruit dryers were constructed with black afra planks, plywood of 5mm thick for absorber, plate, polystrene insulator and extended metal screen. With these materials, two single compartment dryers were constructed with polythylene cover. Rockbed absorber for the collector was

incorporated in one of these two dryers. Another two single compartment dryers were constructed with glass cover, and rockbed heat storage system was introduced in one of the two.

Twelve small model dryers were also constructed with polythrene cover. Rockbed heat storage was attached in eight of these small dryers.

Two double compartment dryers were fabricated with polythrene cover, one of these two had rockbed absorber for the collector.

4.2.5 Hybrid Crop Dryer

Fabrication of this blower (centrifugal fan) for the hybrid dryer was carried out in Department of Agricultural Engineering workshop. The detailed component parts fabrications are as follows:

The impeller plate on which the blades were attached was cut to 0.45m in diameter from a mild steel sheet of 5mm thick. A hole of 0.042m was drilled at the centre of the impeller.

Eight blades, the parts that sweep the air, was constructed from mild steel sheet of 3mm thick. The size of each blade was 0.204m long and 0.14m wide, with side radius of curvatur of 0.082m at one end of the

blade which was cut to a shorter width of 0.05m.

The fan casing was made of three parts welded together, that is two sides and top covers. The side covers were cut to identical shape. The outer side has an inlet opening of diameter 0.45m cut for the impeller entrance and the inner casing has 0.06m diameter opening cut for the shaft sitting. The side covers were cut to an involute shape of radius 0.37m. Galvanized steel sheet of 1.5mm thick was used for the casing sheet.

The top cover which was folded on the involute shape was cut to 1.8m long and 0.21m wide.

The control damper which is an air inlet adjustment gate, was constructed for controlling air flow rate. This was constructed from galvanized steel sheet of 1.5mm. Five circular plates of the same external diameter and internal diameters of 0.06m, 0.12m, 0.18m, 0.24m and 0.30m, respectively, were constructed from galvanised steel sheet of 1.5mm thick.

The whole parts were assembled together and keyed on an electric motor of capacity 1.5kW.

The air duct (23) which makes indirect contact with the burning gas through metal sheets was constructed with mild steel of 5mm thick. The construction of this duct was such that air blown from the centrifugal fan

recirculates three times in the heat exchanger zone, thus allowing enough time for the air to be heated up before flowing out to the dryer. The air flowing inside the air passages does not mix with the burning gas. The side cover of the heat exchanger (4) was constructed with 3mm galvanized sheet impregnanted with fibre glass insulation (7). The flue vent (10) was constructed with galvanized sheet, in such a way that the burnt gas will be safely channeled to the atmosphere. The gas burner (19) was not fabricated under this project, but was adapted to meet the firing of the heat exchanger furnace. The air connecting duct (3) was constructed by folding galvanized sheet.

A chimney of 2m high and 0.28m diameter was constructed with galvanised sheet and fixed at the outlet end of the dryer section. The collector and dryer section construction were as described for metal type dryer. This hybrid crop dryer was completely constructed and assembled in the Department of Agricultural Engineering.

4.3 Scale of Various Dryers

The following dryers on which laboratory test were conducted, were constructed in the department of Agricultural Engineering, Ahmadu Bello University, Zaria.

a) small-scale wood-type direct mode solar dryer with rockbed heat storage.
b) small-scale wood-type direct mode solar dryer without rockbed heat storage.
c) small-scale metal-type direct mode solar dryer without rockbed heat storage.
d) small-scale single compartment wood-type vegetable/fruit solar dryer without rockbed heat storage.
e) small-scale single compartment wood-type vegetable/fruit solar dryers with rockbed heat storage.
f) medium-scale double compartment wood-type vegetable/fruit solar dryer without rockbed heat storage.
g) medium-scale double compartments wood-type direct mode solar dryer, with rockbed heat storage.
h) medium-scale hybrid crop dryer.

Dryers a, b, c and h were designed and fabricated in such a way that they can function well in thin or deep layer batch drying. On the other hand, dryers d, e, f and g were specifically designed for drying

vegetables and fruits, which were normally dried in thin layers. Dryers a to g operate by natural convection air circulation, while dryer h which is gas-fired in combination with solar energy operates by forced convection air circulation.

The field tests were conducted on the dryers located at Jere in Kaduna State, New-Wuse and Kwaka in Niger State. The dryers are:

i) Large-scale mud-type direct mode solar crop dryer.
j) Medium-scale wood-type direct mode solar crop dryer.
k) Large-scale mud-type direct mode solar crop dryer.
l) Large-scale metal-type direct mode solar crop dryer.
m) Large-scale mud-type direct mode solar crop dryer.
n) Large-scale metal-type direct mode solar crop dryer.

Dryers i and j were located at Jere, dryers k and l were located at New-Wuse, while dryers m and n were located at Kwaka. Dryers i to n located in the field were designed mainly for drying cereals and tubers. Crops can be dried in these dryers in thin or deep layer batch drying process.

4.4 Instrumentation and Data Collection

Plate 4.1 shows a mercury-in-glass wet and dry bulb thermometers of range -5°C to 50°C. The dry bulb thermometer was used to measure the ambient temperatures. With the measured values of wet and dry bulb thermometers the ambient relative humidity was read directly from the psychrometric chart.

Plate 4.2 shows copper-constantine thermocouple wires connected to a 24 channel selector switch onto a digital Omega Readout Thermometer Model 450. This instrument was first calibrated with mecury-in-glass thermometer of range -10°C to 100°C and it has an accuracy ±0.5 percent. This instrument was used to measure the temperature at different locations in the collector section, drying section and the heat exchanger section. The inlet and outlet air temperatures in these sections were also measured. Four probe thermometers (Plate 4.3) with temperature range of 0°C to 100°C were also used to measure the inlet and outlet collector and drying sections air temperatures.

HAENI SOLAR 118 DELTA Instrument, a digital instrument with sensor output, shown in Plate 4.4 was used to measure the total solar radiation. This instrument was inclined at the same slope angle as the collector or dryer top surface facing south.



PLATE 4.1: MERCURY IN GLASS WET AND DRY BULB THERMOMETERS



PLATE 4.2: COPPER - CONSTANTINE THERMOCOUPLE



PLATE 4.3: PROBE THERMOMETER



PLATE 4.4: HAENI SOLAR 118 DELTA INSTRUMENT



PLATE 4.5: OMEGA HYDROMETER - THERMOMETER



PLATE 4.6: VANE ANEMOMETER

Plate 4.5 shows an Omega Hygrometer-Thermometer Model RH 610 with digital readout and a probe for relative humidity and temperature ranges 2 to 98%, and -10°C to 60°C, respectively, with an accuracy of ±2% RH. This was used to measure the relative humidity of the humid air flowing out through the drying section.

A Vane Anemometer was mounted to measure atmospheric wind speed near the dryer (see Plate 4.6). The moisture contents of the crops were determined at hourly intervals by A MOISTURE METER DOLE MODEL 400

Other instruments used are:

Karl Kolb Weighing balance of scale range 0.01 to 150kg used to obtain the weight of crops loaded for drying in the dryers. Mettler Balance, a sensitive weighing balance of range 0 to 1200g, was employed to obtain the weight of samples dried in the oven for moisture content determination. Shermond Oven of Model 2000 and serial number 80625 with the temperature range of 10°C to 210°C was used in oven drying to obtain moisture content of the samples. A gas regulator for controlling gas flow rate was also used to determine the quantity of gas burnt at a given time. Vibratak Tachometer, sensitive within the limit of 0 to 21,000 rpm was used to obtain the centrifugal fan impeller/blades speed. Static pitot-tubes of 4mm and

5mm internal and external diameters, respectively, and 150mm long, with a range of 0.508 to 17.78 m/s was employed to measure the air velocity along the air duct and in the drying section.

CHAPTER FIVE

5 TESTS, RESULTS AND DISCUSSION

5.1 Introduction

Laboratory and field performance tests were conducted on the solar and hybrid crop dryers described in chapter three. The results were also critically discussed.

5.2 Testing Methodology and Results

Dryers a, b and c were tested from May 16th 1990 to June 16th 1990. Yellow maize grain of variety SI-23 (grown in IAR/ABU Farm) was soaked in water for 21 hours (12.00 noon to 9.00 a.m.) to raise the moisture content to 20.6%, wet basis. The quantity of maize weighed and placed in each of these three small-scale dryers was 25kg, and was spread to a depth of 50mm in the drying chamber (drying section). The same quantity of maize and layer thickness was spread in a perforated tray for open sun-drying.

Thermocouple wires for monitoring temperatures at various locations in the dryers were fixed to measure collector air inlet and outlet temperatures, drying section air outlet temperature, surface temperature of the drying product and the ambient temperature. These wires from different junction point on the dryers were

connected to a 24-outlet switch and the switch was in turn connected to the digital readout thermometer. Solar insolation at the inclination of the dryers were measured with time. Relative humidity was measured with an Omega Hygrometer with digital readout. Dry bulb and wet bulb thermometers were used to find the surrounding dry and wet-bulb temperatures. Air velocity and grain moisture content were measured with manometer and moisture meter, respectively. The inlet and outlet ends of the dryers were left open even at night throughout the drying operation.

Figure 5.1 shows the maize grain drying curves, while Table B.1 shows the detailed data collected during the batch drying process.

Within two and half days, the maize dried from initial 20.6% moisture content wet basis to 10.9% for dryer a, 12.9% for dryer b, 12.0% for dryer c, and 14.1% for open sun drying.

Subsequent test performance on these three small-scale dryers were conducted with exactly the same method and instrumentation as previously described. On 5th June, 1990, 50kg of the same variety and breed of maize grain already cited, was introduced in each of the three small-scale dryers, after soaking and raising the moisture content to 33.3%, wet basis.

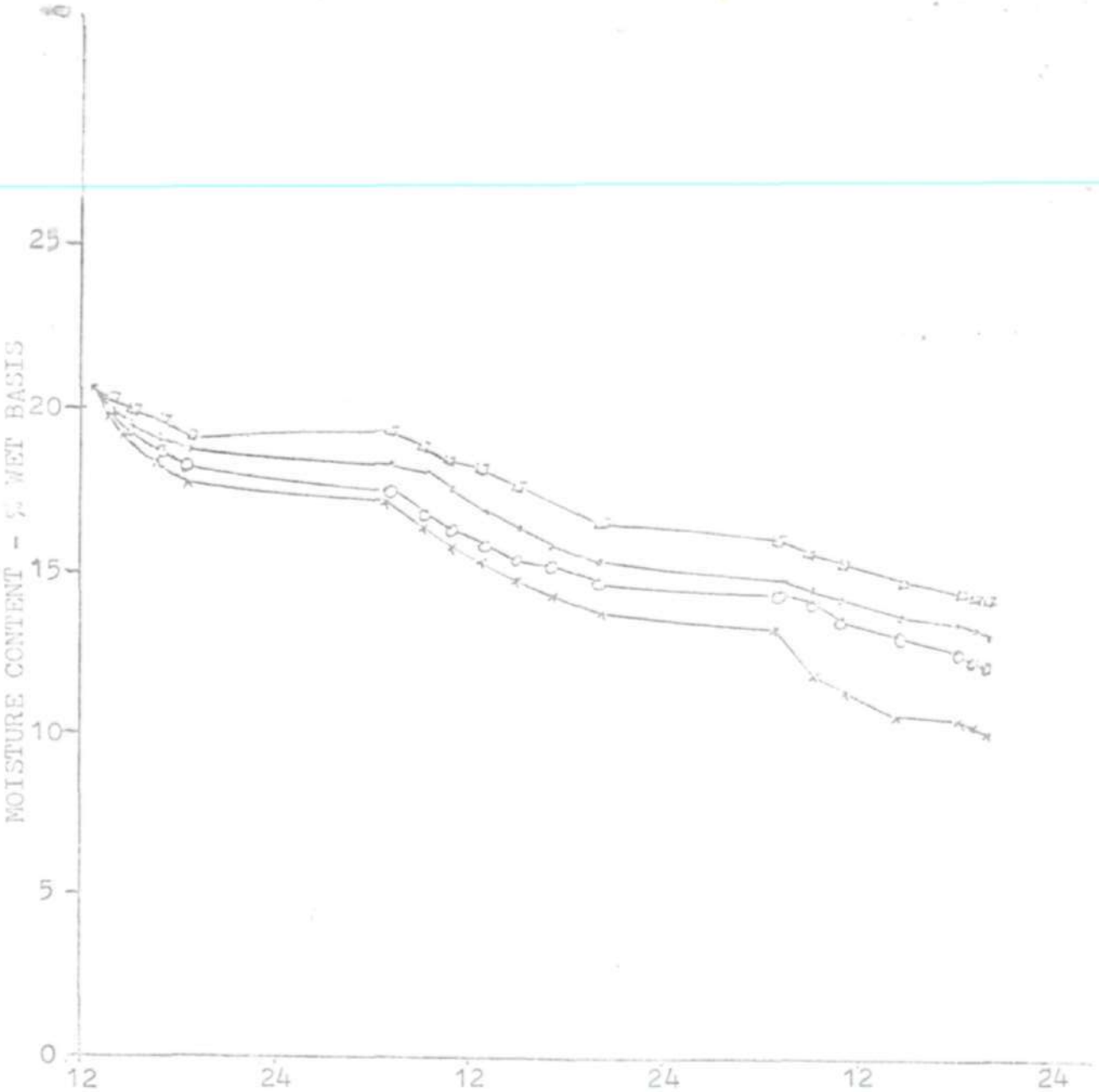

25
20
15
10
5
0
MOISTURE CONTENT - % WET BASIS
12
24
12
24
12
24
TIME OF THE DAY - HOURS

FIGURE 5-1

FIGURE 5-1 Drying curves for rewetted maize versus Time of the days with Dryers A, B, C and open sun drying.

Explanation of Signs

□ = maize moisture content dried with open drying %

, = maize moisture content dried with dryer B - %

○ = maize moisture content dried with dryer C - %

× = maize moisture content dried with dryer A - %

Quantity of product = 25kg

Depth of maize layer = 50mm

Initial m.c. = 206% wet basis

Final m.c. =

Drying dates = May 16th to May 18th 1990

Place of drying = IAR/ABU - Zaria.

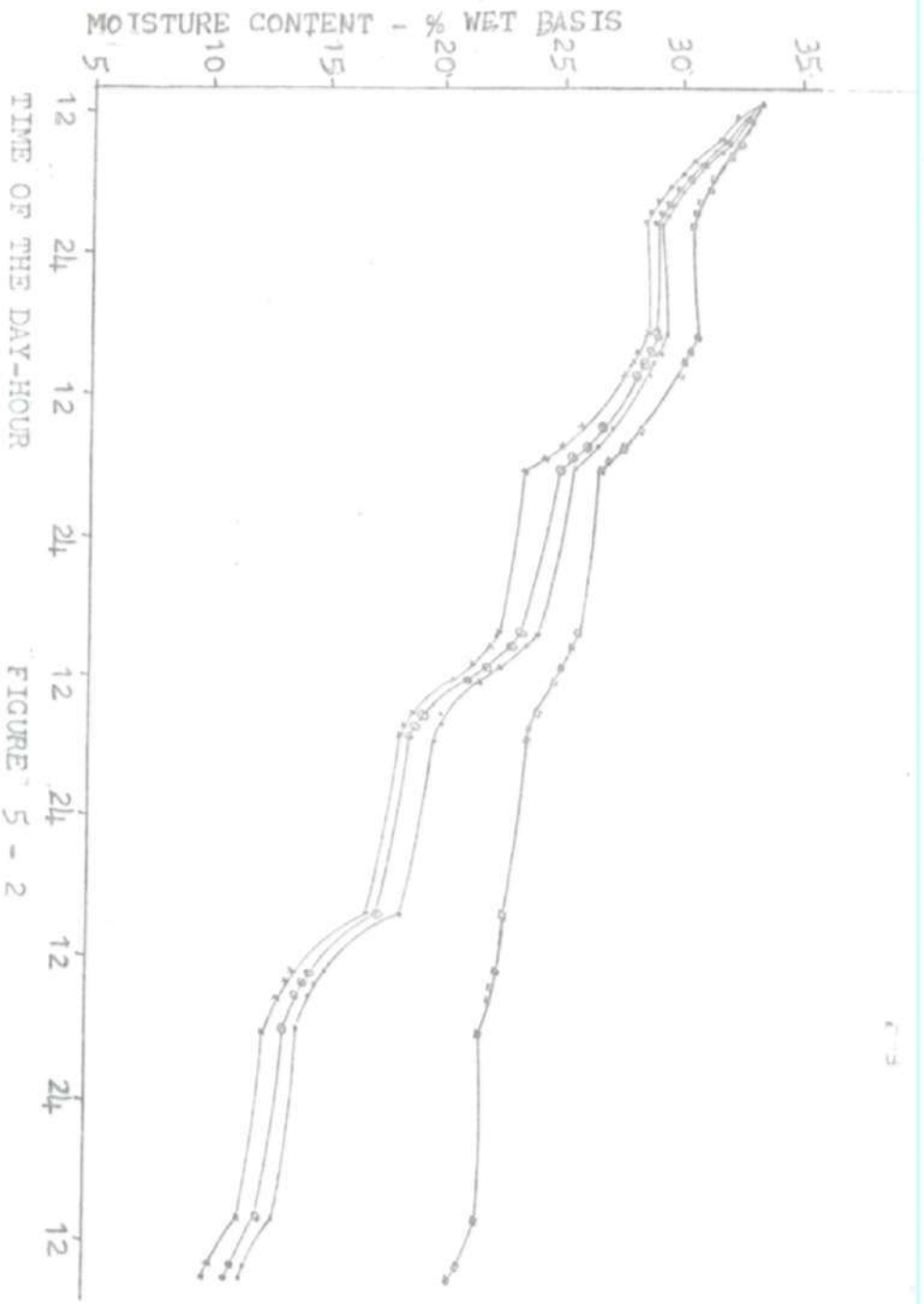

MOISTURE CONTENT - % WET BASIS
5
10
15
20
25
30
35
TIME OF THE DAY-HOUR
12
24
12
24
12
24
12
24
12

FIGURE 5 - 2

FIGURE 5-2 Drying curves for rewetted maize versus Time of the day, with Dryers A, B, C and open sun drying.

Explanation of Signs

□ = maize moisture content dried with open sun drying - %

. = maize moisture content dried with Dryer B - %

⊙ = Maize moisture content dried with Dryer C - %

× = maize moisture content dried with Dryer A - %

Quantity of product = 50kg

Depth of maize layer = 100mm

Initial m.c. = 33.3% wet basis

Final m.c. =

Drying dates = June 5th to June 9th 1990

Place of drying = IAR/ABU - Zaria.

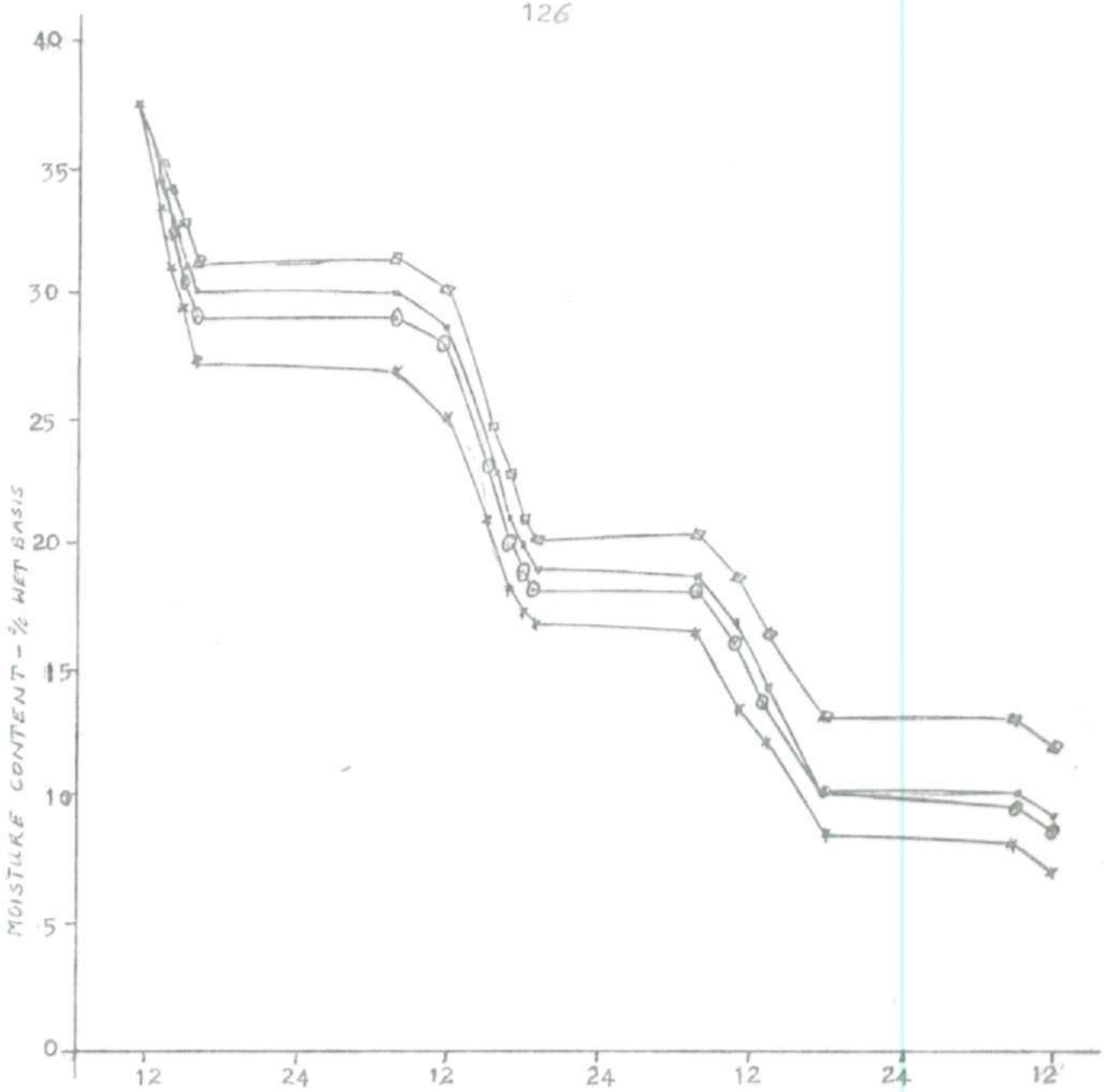

40
35
30
25
20
15
10
5
0
MOISTURE CONTENT - % WET BASIS
12
24
12
24
12
24
12
TIME OF THE DAY - HOURS

FIGURE 5-3

FIGURE 5-3 Drying curves rewetted Groundnut versus Time of the day, with Dryers A, B, C and open sun drying.

Explanation of Sign

□ = Groundnut moisture content dried with open sun drying - %

• = Groundnut moisture content dried with Dryer B - %

× = Groundnut moisture content dried with Dryer A - %

Quantity = 19kg

Depth of groundnut layer = 50mm

Initial m.c. = 37.5% wet basis

Final m.c. =

Drying dates = June 13th to June 16th 1990

Place of drying = IAR/ABU - Zaria

The maize was spread in the dryers to a layer depth of 100mm. This quantity was the maximum grain each of these small scale solar dryers could take. The same quantity and depth of layer of maize was placed for open sun drying. After five days of continuous drying, the maize grain dried from initial 33.3% moisture content, wet basis to 9.2% for dryer a, 10.6% for dryer b, 10.4% for dryer c and 18.5% for open sun drying. The drying curves is shown in Figure 5.2, and the data including other parameters in drying performance is shown in Table B.2 in Appendix B

Groundnut pods of variety Samaru 61 was on June 13th, 1990 weighed and placed in three small-scale dryers, after soaking and raising the moisture content to 37.5%, wet basis. The quantity of groundnut pod in each of the dryers was 19kg, and the layer thickness was 50mm. Measurements were made as usual. The results are shown in figure 5.3 and table B.3. Within two and half days, the groundnut pods dried from 37.5% moisture content, wet basis to 7.0% for dryer a, 9.3% for dryer b, 8.7% for dryer c and 12% for open sun drying.

During the time these drying tests were conducted, newly harvested maize and groundnut were not available. That is why the crops were soaked to raise the moisture content for the batch drying processes.

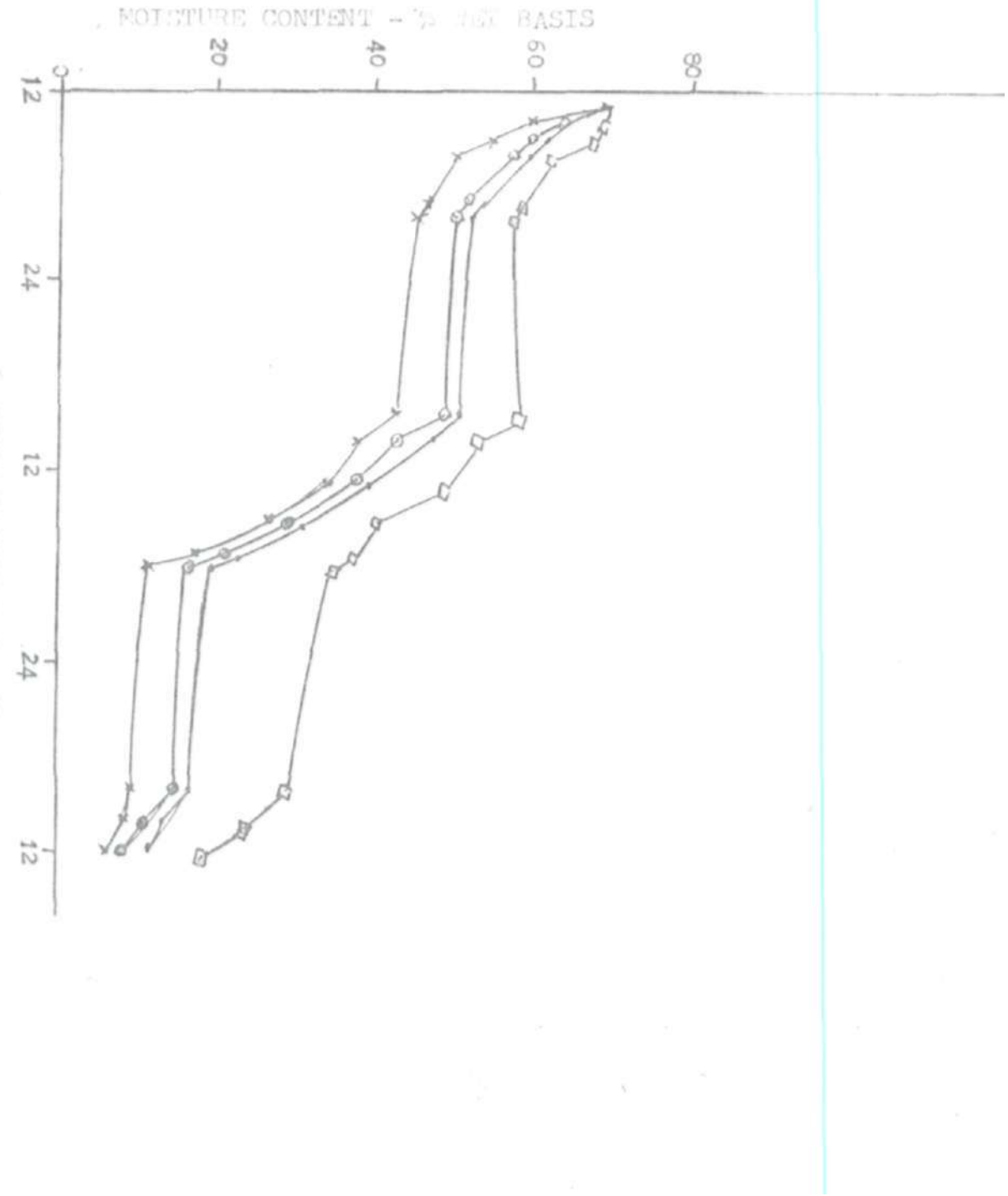

MOISTURE CONTENT - % WET BASIS
0
20
40
60
80
12
24
12
24
12
TIME OF THE DAY - HOURS

FIGURE 5-4

FIGURE 5.-4 Drying curves for single layer sliced fresh Okro versus time of the day with Dryers A, B, C and open sun drying

Explanation of Signs

□ = Okro moisture content dried with open sun drying - %

• = Okro moisture content dired with Dryer - B - %

O = Okro moisture content dried with Dryer - C %

× = Okro moisture content dired with Dryer A -%

Initial m.c. = 70% wet basis

Final m.c. =

Drying dates = May 31st to June 2nd 1990

Place of drying = IAR/ABU - Zaria.

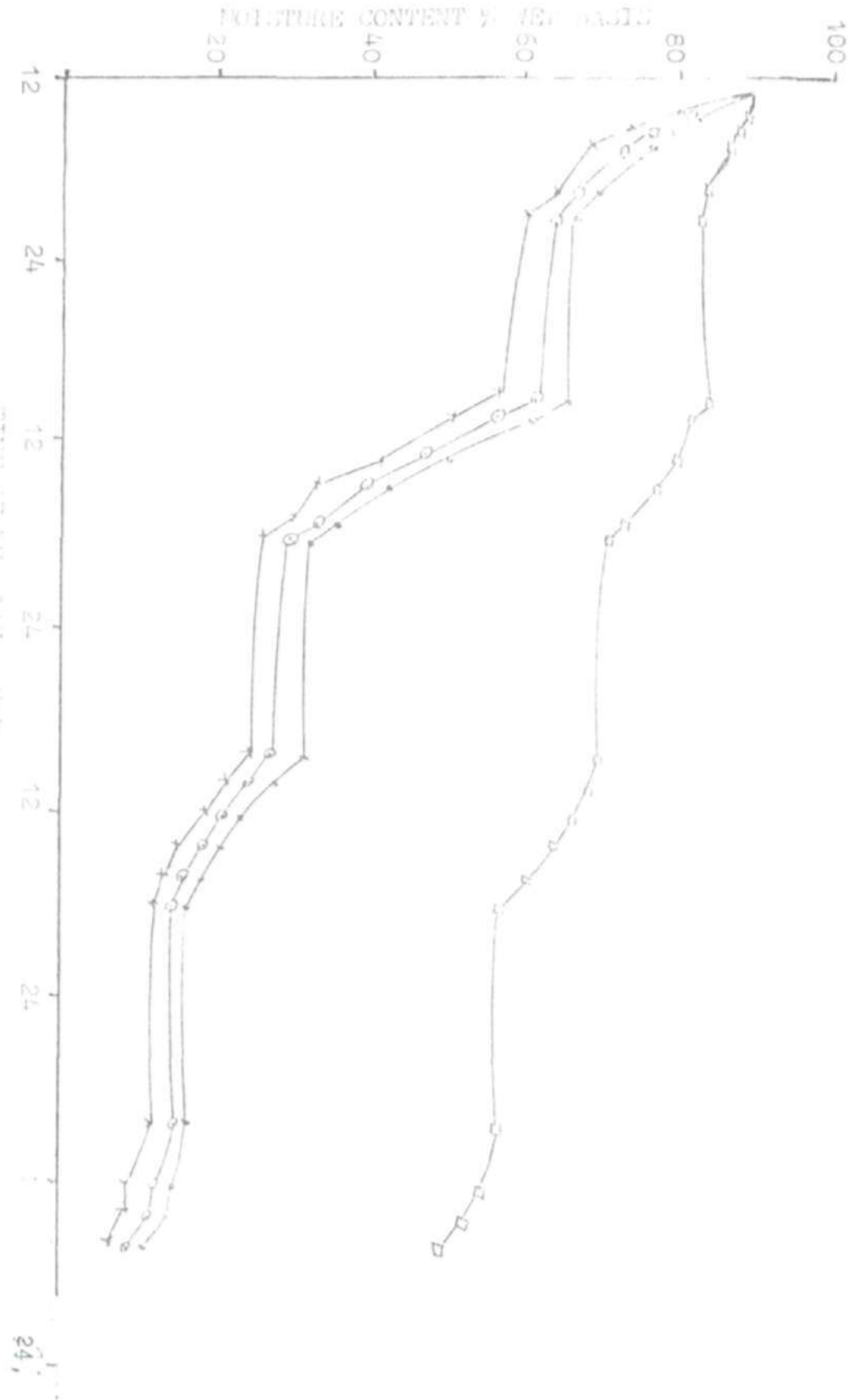

20
40
60
80
100
12
24
12
24
12
24
24

FIGURE 5-5 Drying curves for single layer sliced Tomatoes versus Time of the day, with Dryers A, B, C and open sun drying

Explanation of Sigan

□ = Tomatoes moisture content dried with open sun drying - %

• = Tomatoes moisture content dried with Dryer B - %

⊙ = Tomatoes moisture content dried with Dryer C - %

X = Tomatoes moisture content dried with Dryer C - %

Initial moisture content = 90%

Final moisture content

Drying dates = May 31st to June 3rd 1990

Place of drying = IAR/ABU - Zaria

Newly harvested fresh okro and tomatoes were also dried with the three small scale solar crop dryers. Okro at 70% initial moisture content, wet basis, was sliced to about 15mm thick and dried in single layer in the dryers. The drying data were collected and analysed as shown in Figure 5.4 and Table B.4 in the Appendix. The drying lasted for two and half days. At this time the okro dried from 70% initial moisture content, wet basis, to 6.8% moisture content, for dryer a, 9% for dryer b, 8% for dryer c and 20% for traditional open sun drying (not in the perforated tray).

Tomatoes identified as Ronita cultivar was sliced in two halves and introduced in single layer in the dryers. Figure 5.5 and Table B.5 in the Appendix show the detailed drying performance. During the drying period of three and half days the sliced fresh tomatoes dried from initial 93% moisture content, wet basis, to 7% for dryer a, 11% for dryer b, 9% for dryer c and 49% for traditional open sun-drying.

As soon as the construction of the dryers d, e, f and g were completed, their drying tests performance were conducted from June 5th to 8th, 1991. Newly harvested fresh okro was sliced to about 15mm thick and dried in single layer in the four dryers as well as in traditional open sun-drying. The measurements were made for performance



TIME OF THE DAY - HOURS

FIGURE 5-6

FIGURE 5-6 Drying curves of single layer sliced fresh Okro versus time of the day with Dryers D, E, F, G and open sun drying

Explanation of Signs

P_1d = Okro moisture content dried with Dryer - F(down layer) - %

P_1u = Okro moisture content dried with Dryer F (upper layer) - %

P_2 = Okro moisture content dried with Dryer - D - %

P_3d = Okro moisture content dried with Dryer G - (down layer) - %

P_3u = Okro moisture content dried with Dryer G - (upper layer) - %

P_4 = Okro moisture content dried with Dryer E - %

P_5 = Okro moisture content dried with open sun drying

Initial moisture content = 88% wet Basis

Final moisture content =

Drying Dates = June 5th to June 7th 1991

Place of drying = IAR/ABU - Zaria

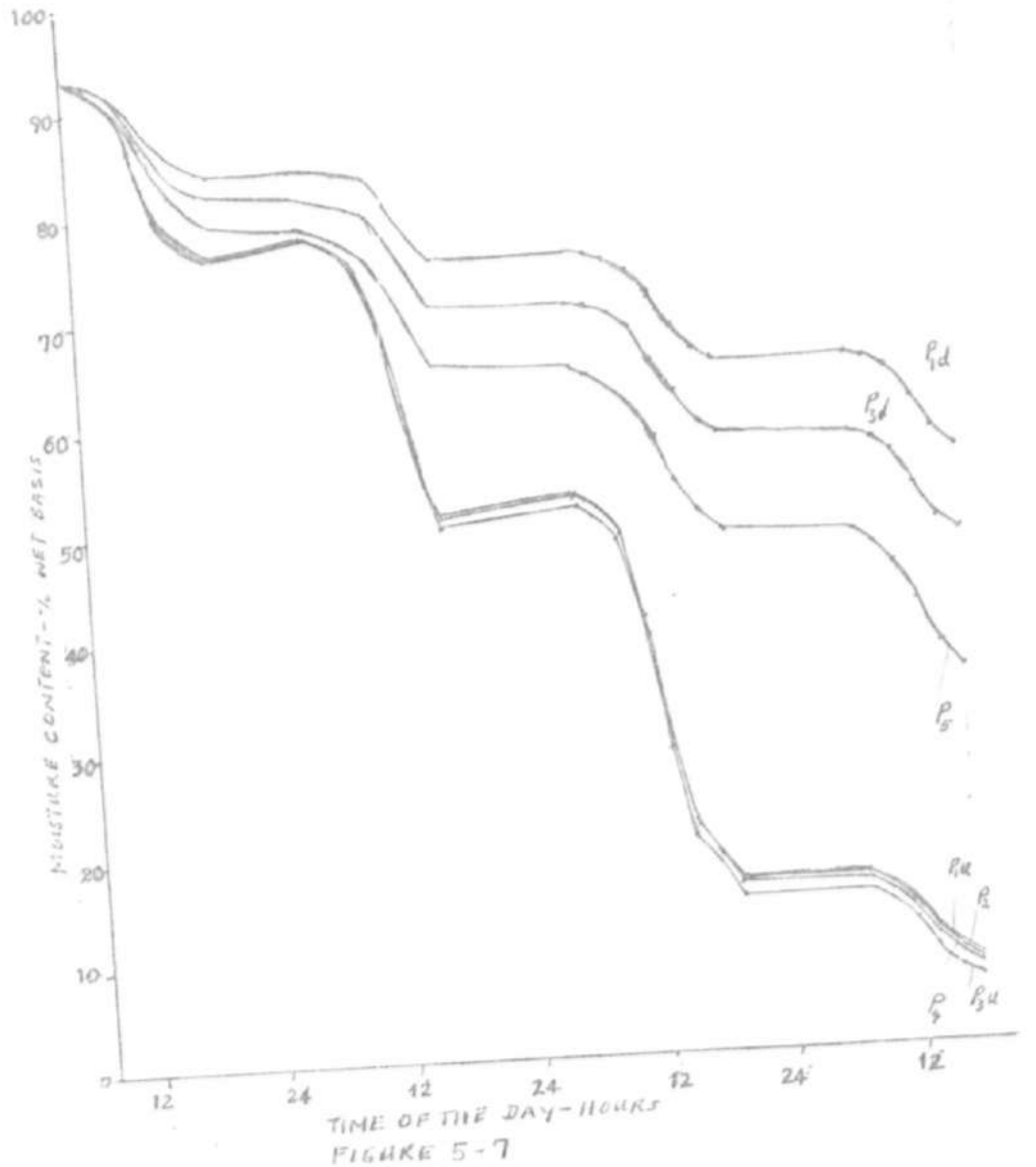

100
90
80
70
60
50
40
30
20
10
0
MOISTURE CONTENT - % WET BASIS
P_1d
P_3d
P_5
P_1u
P_2
P_4
P_3u
12
24
12
24
12
24
12
TIME OF THE DAY - HOURS

FIGURE 5-7

FIGURE 5-7 Drying curves of single layer sliced fresh Tomatoes versus time of the day with Dryers D, E, F, G and open sun drying

Explanation of Signs

P_1d = Tomatoes moisture content dried with Dryer - F(down layer) - %

P_1u = Tomatoes moisture content dried with Dryer - F(upper layer) - %

P_2 = Tomatoes moisture content dried with Dryer - D - %

P_3d = Tomatoes moisture content dried with Dryer - G (down layer) - %

P_3u = Tomatoes moisture content dried with Dryer G -(upper layer) - %

P_4 = Tomatoes moisture content d with Dryer E - %

P_5 = Tomatoes moisture content dried with open sun drying

Initial m.c. = 94% wet basis

Final m.c. =

Drying dates = June 5th to 8th June 1991

Place of drying = IAR/ABU - Zaria

data collection and the results and the quantity of okro in each dryer are shown in Figure 5.6 and Table B.6 in the Appendix. Within two and half days the okro dried from initial 88% moisture content, wet basis, to 7% for dryer f upper compartment, 40% for the lower compartment, 7.5% for dryer d, 6% for dryer g uper layer and 35% for the lower compartment, 6.8% for dryer e, and 30% for traditional open sun drying.

Also newly harvested 'Ronita cultivar' tomatoes were sliced in two halves and dried in the four vegetable/ fruit dryers. After three and half days the tomatoes dried from initial 94% moisture content, wet basis to 7.7% for dryer f upper compartment, 55% for the lower compartment, 8% for dryer d, 6% for dryer g upper compartment and 48% for the lower compartment, 7.1% for dryer e and 35% for traditional open sun-drying. The detailed results including the quantity of tomatoes introduced in each dryer are shown in Table B.7 in the Appendix, while the drying curves are shown in Figure 5.7.

Dryer H-Hybrid crop dryer - was tested from April 25th 1991 to April 26th 1991. At this period of the year, newly harvested maize was not available. Therefore White Dent maize variety of second tier breed was soaked in water to raise the moisture content to 33%, wet basis.

On April 25th 1991, the hybrid dryer was set up for drying test performance. The connection during the test was as described in Chapter 3. The air part and joints were made air-tight to avoid or minimize air and heat losses. The thermocouple wires were fixed at the junction points which measured the following temperatures: Heat exchanger air inlet temperature (air temperature in the duct connecting the blower and the heat exchanger), collector air inlet/heat exchanger air outlet, collector air outlet/drying section air inlet, drying section air outlet, collector plate glass cover, heat exchanger body, flue gas above flame temperature and finally air temperature through the duct. The thermocouple wire from these junction points were connected to a 24-outlet switch, and the switch was connected to the digital readout thermometer. Other parameters such as the pressure of the burning gas, air flow rate, pressure drop, solar irradiation, wet-bulb and dry-bulb temperatures, ambient temperature and the grain moisture content were measured with the appropriate instruments already specified.

40kg maize grain of the elevated moisture was spread to depth of 50mm in the hybrid drying section. Solar irradiation was eliminated from the collector and drying sections of the hybrid dryer, by covering these sections with 10cm thick polystrene foam insulation. The blower

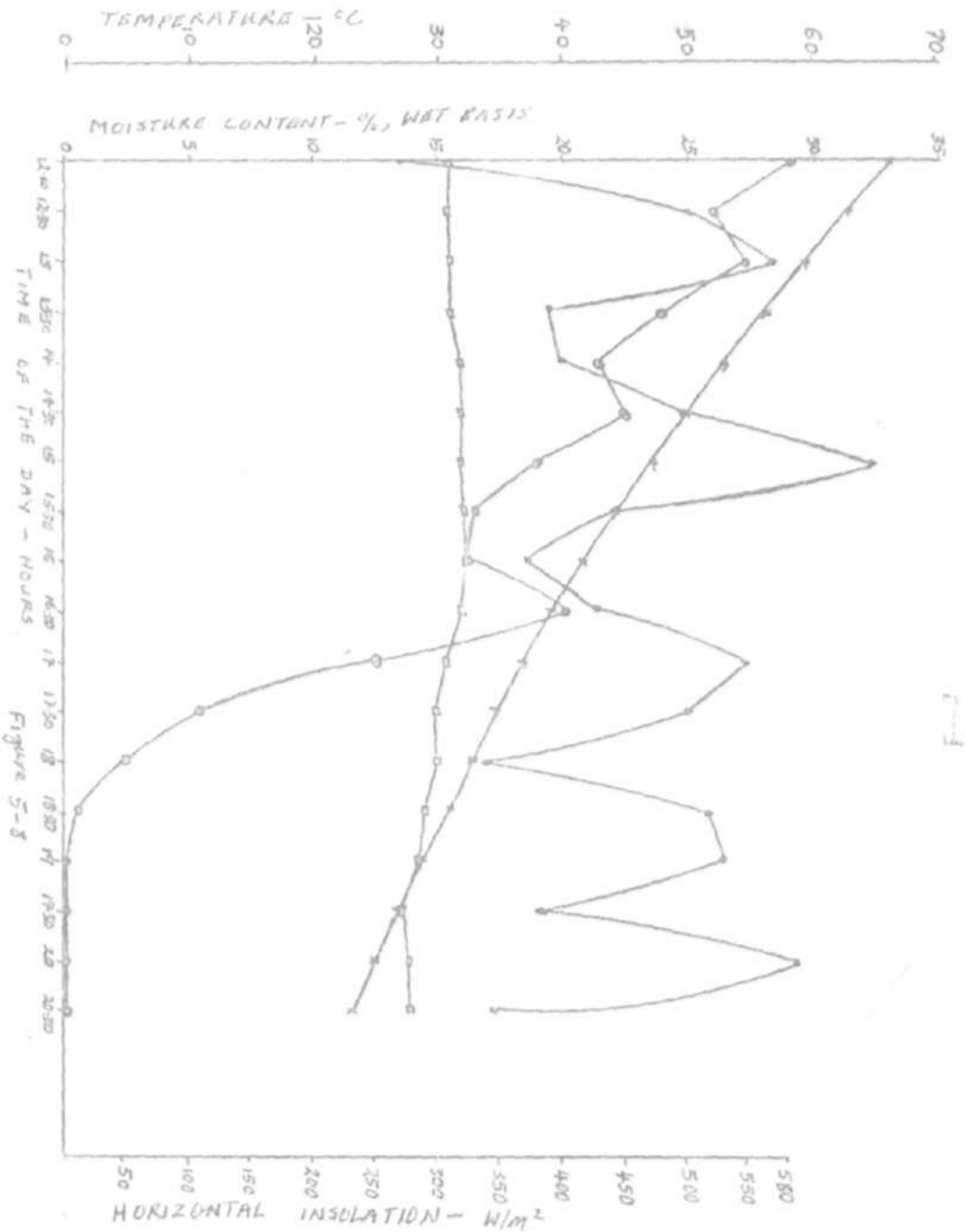

TEMPERATURE °C
0
10
20
30
40
50
60
70
MOISTURE CONTENT - % WET BASIS
0
5
10
15
20
25
30
35
TIME OF THE DAY - HOURS
0800
0900
1000
1100
1200
1300
1400
1500
1600
1700
1800
HORIZONTAL INSULATION - W/m²
50
100
150
200
250
300
350
400
450
500
550
600

Figure 5-8

FIGURE 5-8 Drying curve for maize solar in solation, Dryer air outlet temp. and Ambient temp. versus time of the day for Dryer - H (without solar energy)

Explanation of Signs

χ = Rewetted maize moisture content %

σ = Solar insolation - $w/_{m^2}$

$\cdot$ = Dryer air outlet temp. - ^{o}C

$\Box$ = Ambient temp. - ^{o}C

Quantity of product = 40kg

Depth of maize layer = 50mm

Initial m.c. = 33%

Final m.c. = 11·6%

Drying dates

Place of drying = IAR/ABU - Zaria

operated by electricity was switched on and the gas burner in the heat exchanger lighted. The drying temperature was monitored, thus the gas was switched off when the dryer air inlet temperature became high, and switched on when the air cooled down. The blower supplied constant air flow rate throughout the drying period. Firing time is when the gas was actually burning in the heat exchanger. With the aid of the gas pressure gauge connected to the gas cylinder, the quantity of gas used during the drying period was calculated (see Appendix B). Figure 5.8 shows the drying curve and the corresponding temperature and insulation curves, while Table B.8 in the Appendix shows the detailed result of the drying performance.

The same variety and breed of maize grain was soaked to initial moisture content of 33% wet basis, on April 26th, 1991. The same quantity (40kg) of maize grain was measured and placed in the hybrid dryer. All the measuring systems and the junction points remain same as explained. The collector and the drying sections were exposed to direct solar irradiation. Thus the drying process was a combination of solar energy and gas-firing system. The drying operation lasted for seven hours at which the maize dried to 11.6% moisture content, wet basis. The quantity of gas used for the drying was

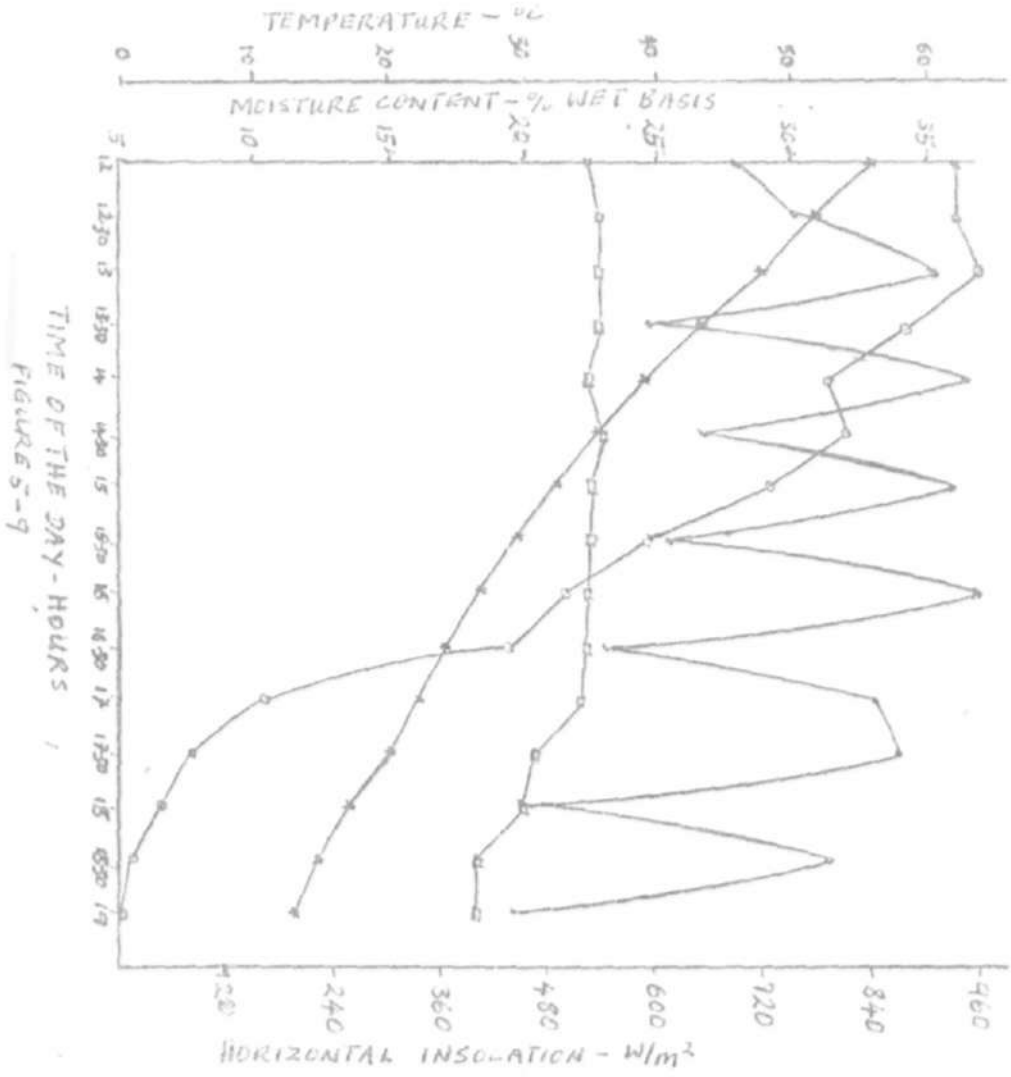

TEMPERATURE - °C
0
10
20
30
40
50
60
MOISTURE CONTENT - % WET BASIS
5
10
15
20
25
30
35
TIME OF THE DAY - HOURS
12
1200 IST
1500 IST
1800 IST
2100 IST
2400 IST
0300 IST
0600 IST
0900 IST
1200 IST
HORIZONTAL INSOLATION - W/m²
120
240
360
480
600
720
840
960

FIGURE 5-9

FIGURE 5-9 Drying curve for maize solar insolation, Dryer air outlet temp., and Ambient temp. versus time of the day for Dryer - H (with solar energy)

Explanation of Signs

X = Rewetted maize moisture content - %

θ = Solar insolation - w/m^2

$\bullet$ = Dryer air outlet temp. - ^{o}C

$\Box$ = Ambient temp. - ^{o}C

Quantity of product = 40kg

Depth of layer = 50mm

Initial m.c. = 33%

Final m.c. = 11.6 %

Drying dates

Place of drying = IAR/ABU - Zaria

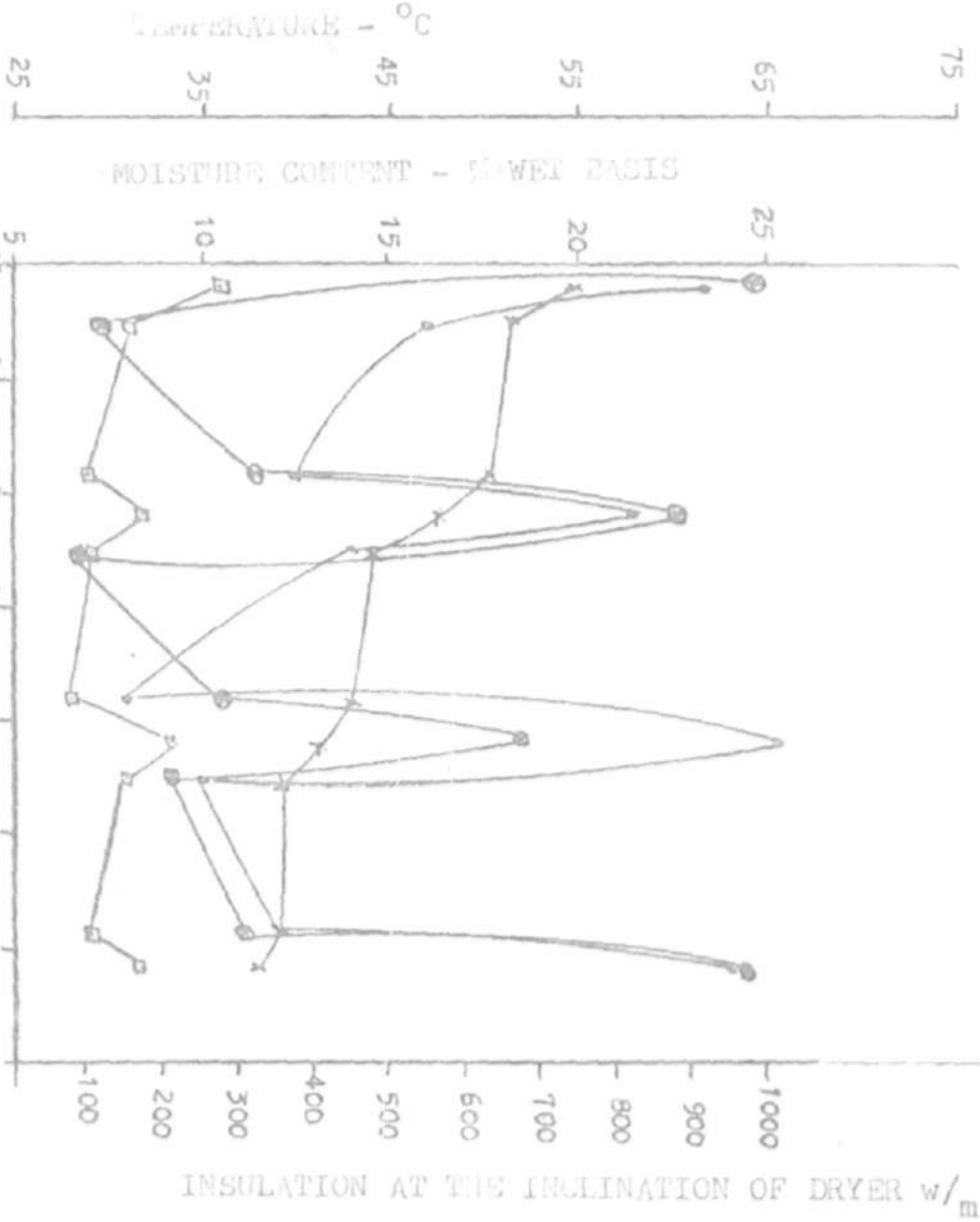

TEMPERATURE - °C
25
35
45
55
65
75
MOISTURE CONTENT - % WET BASIS
5
10
15
20
25
TIME OF THE DAY - HOURS
12
24
12
24
12
24
12
INSULATION AT THE INCLINATION OF DRYER w/m2
100
200
300
400
500
600
700
800
900
1000

FIGURE 5-10

FIGURE 5-10 Drying curve for fresh unthreshed maize, solar insolation, Dryer air outlet temp. and Ambient temp. versus Time of the Day for [illegible]er J

Explanation of Signs

x = unthreshed maize moisture content - %

θ = solar insolation - w/m^2

$\cdot$ = Dryer outlet temp. - ^{0}C

Π = Ambient temp - ^{0}C

Quantity of product = 100kg

Initial m.c. = 20%

Final m.c. = 11.5%

Drying Dates = Sept. 15th to Sept. 16th 1990

Place of drying = Jere village in Kaduna State.

calculated as indicated in Appendix B. Figure 5.9 shows the drying temperature and solar irradiation curves and Table B.9 in the Appendix shows the comprehensive result of the drying performance.

In the field, the metal-type dryers J, L and n were first constructed at Jeze, New-Nuse and Gwako, respectively. Dryer J (wood-type) was on September 13th, 1990 loaded with newly harvested ear maize of about 150kg. The initial moisture content was 20%, wet basis. The owner of the maize was a farmer living in that village. The drying rate was monitored every four hours. It took three days to dry down to 11.5%, wet basis. The rate of drying, solar irradiation and temperatures are shown graphically in Figure 5.10, and all the data collected during the batch drying process are indicated in Table B.10 in the Appendix.

On September 8th, 1990, dryer 1 was tested by loading in shelled groundnut, unshelled and shelled maize brought by the village farmers. The initial moisture content at which the crops were introduced in the dryer were 19%, 24% and 27% wet basis for shelled groundnut, shelled maize and unshelled maize, respectively. Also the crops dried after one and half days, two and half days and three and half days in the same order to

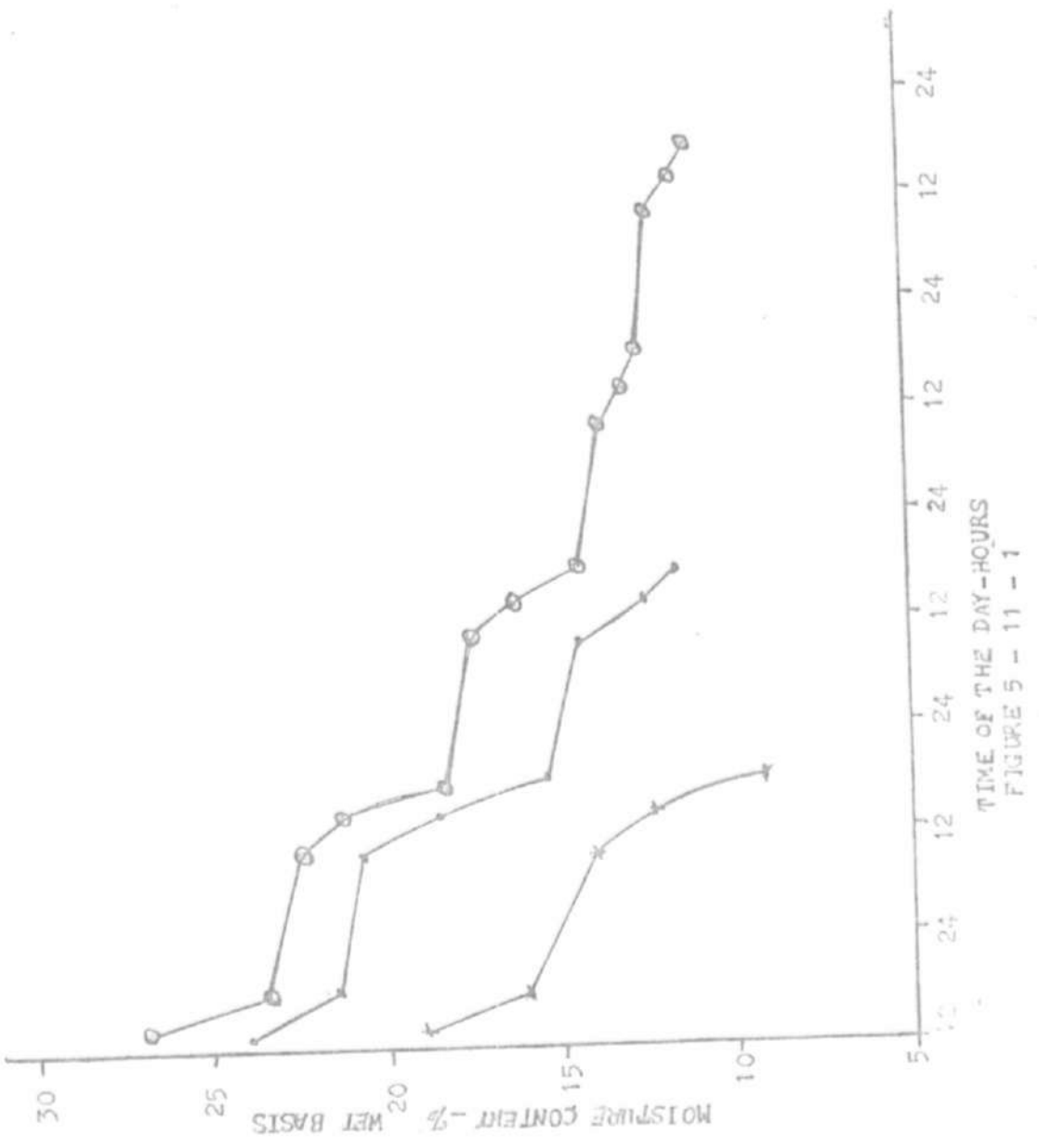

MOISTURE CONTENT - % WET BASIS
30
25
20
15
10
5
12
24
12
24
12
24
12
24
12
TIME OF THE DAY-HOURS

FIGURE 5 - 11 - 1

FIGURE 5-11: Drying curves for unthreshed and threshed maize and the shelled groundnut moisture content curves taken at the end of the day, for day 1.

Explanation of Signs

ϕ = unthreshed maize moisture content curve.

ρ = threshed maize moisture content curve.

χ = Shelled groundnut moisture content curve.

Quantity of product

unthreshed maize = 250kg

shelled groundnut = 26kg;

Initial m.c.27% Final m.c. = 11·6 %

Drying dates = Sept. 8th to Sept. 12th 1990

Place of drying = New-Wuse village in Niger State.

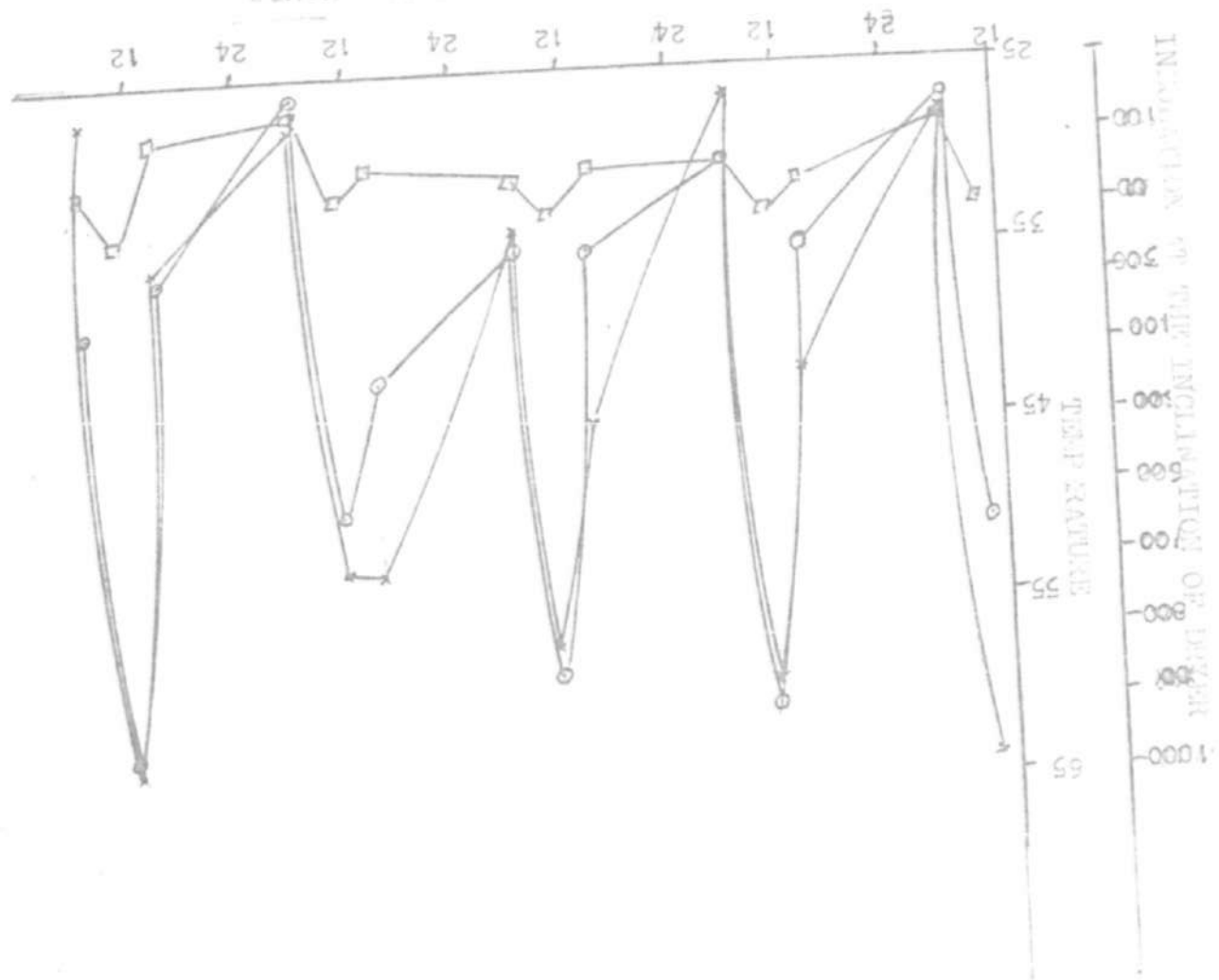

TIME OF THE DAY - HOURS
12
24
12
24
12
24
12
24
12
INTENSITY OF SOLAR RADIATION
100
200
300
400
500
600
700
800
900
1000
AMBIENT TEMP. DEGREE
25
35
45
55
65

FIGURE 5-11-2

FIGURE 5 :- Drying curves for solar insolation, Dryer air outlet temp. and ambient temp. versus time of the day for Dryer 2

Explanation of Signs

x = Solar insolation curve - W/m^2

○ = Dryer air outlet temp. curve - ^oC

□ = Ambient temp. curve - ^oC

Drying dates :- Sept. 8th to Sept. 12th 1990

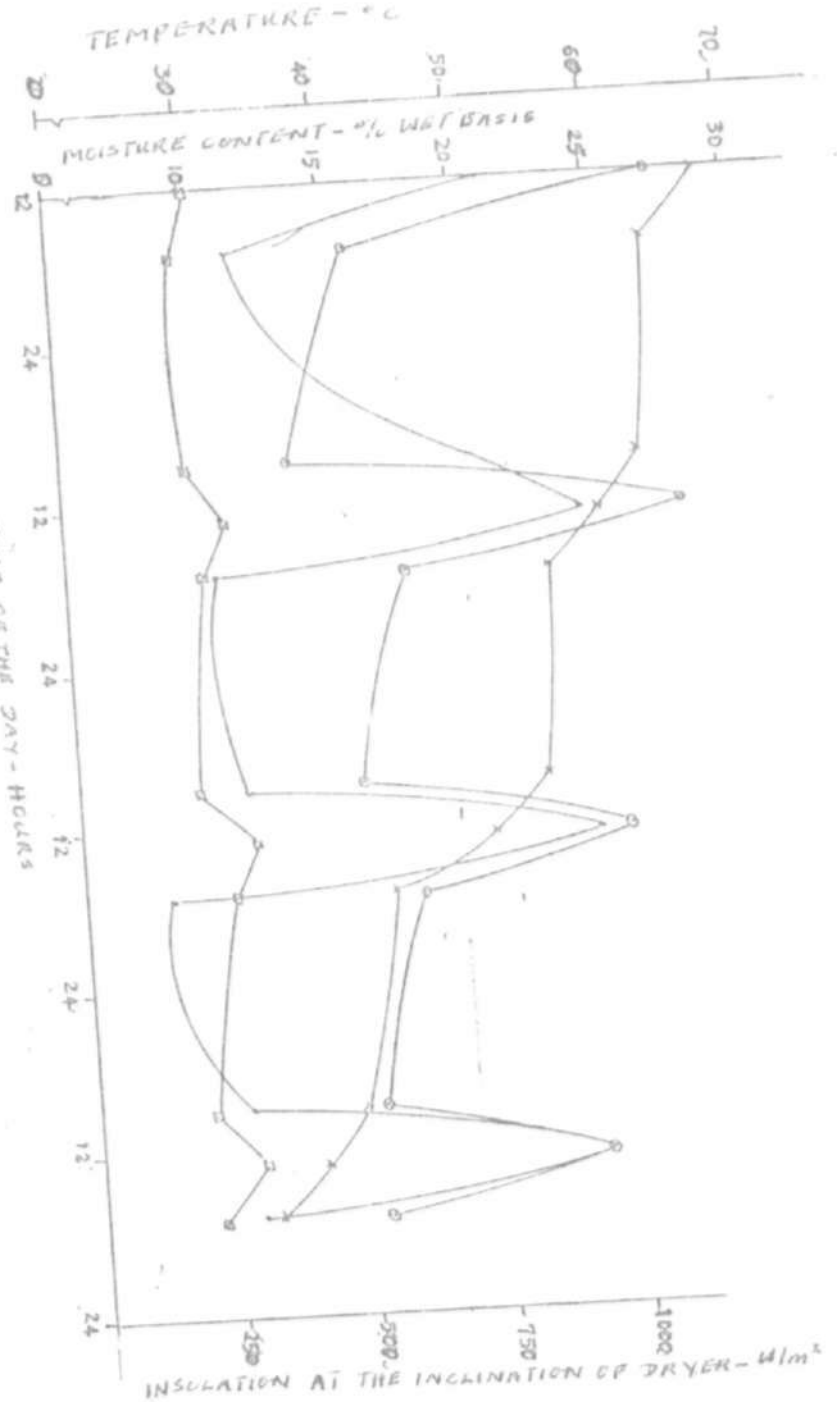

TEMPERATURE - °C
0
30
40
50
60
70
MOISTURE CONTENT - % WET BASIS
0
10
15
20
25
30
TIME OF THE DAY - HOURS
12
24
12
24
12
24
250
500
750
1000
INSOLATION AT THE INCLINATION OF DRYER - W/m²

FIGURE 5-12-1

FIGURE 5-1-1 Drying curve for Groundnut solar insolation, outlet Dryer temp. and Ambient temp. Vs Sun Time of the day for Dryer N -

Explanation of Signs

X = Groundnut moisture content % wet basis

θ = Dryer outlet temp. - ^{o}C

I = Solar Insolation - w/m^2

Π = Ambient temp. - ^{o}C

Quantity of product = 75.5kg

Depth of Groundnut layer = 40mm

Initial m.c. = 29%

Final m.c. = 7.5%

Drying dates = Sept. 8th to Sept.11th 1990

Place of drying = Kwaku village in Niger State.

9%, 11.7% and 11.6% moisture contents respectively. Table B.11 in the Appendix shows the data collected. Figure 5.11a shows the drying curves for these crops while the corresponding temperature and solar insolation curves are indicated in Figure 5.11b.

Dryer n was tested from September 5th, 1990, to September 12th, 1990 with about 73.5kg unshelled groundnut from the farmers. Within these days the groundnut pods dried from 29% initial moisture content, wet basis, to 7.5% moisture content wet basis. The groundnut pods was spread to a layer depth of 40mm. The results are shown in Figure 5.12a and Table B.12a in the Appendix.

Further testing was carried on dryer n from September 13th 1990 to September 16th 1990. The dryer was loaded with 100.2kg groundnut pods from the farmers and spread to a layer of 55mm thick. Within the batch drying process the groundnut pods dried from 30% initial moisture content, wet basis, to 7.8%. The detailed results for the test are shown in Figure 5.12b and Table B.12b in the Appendix.

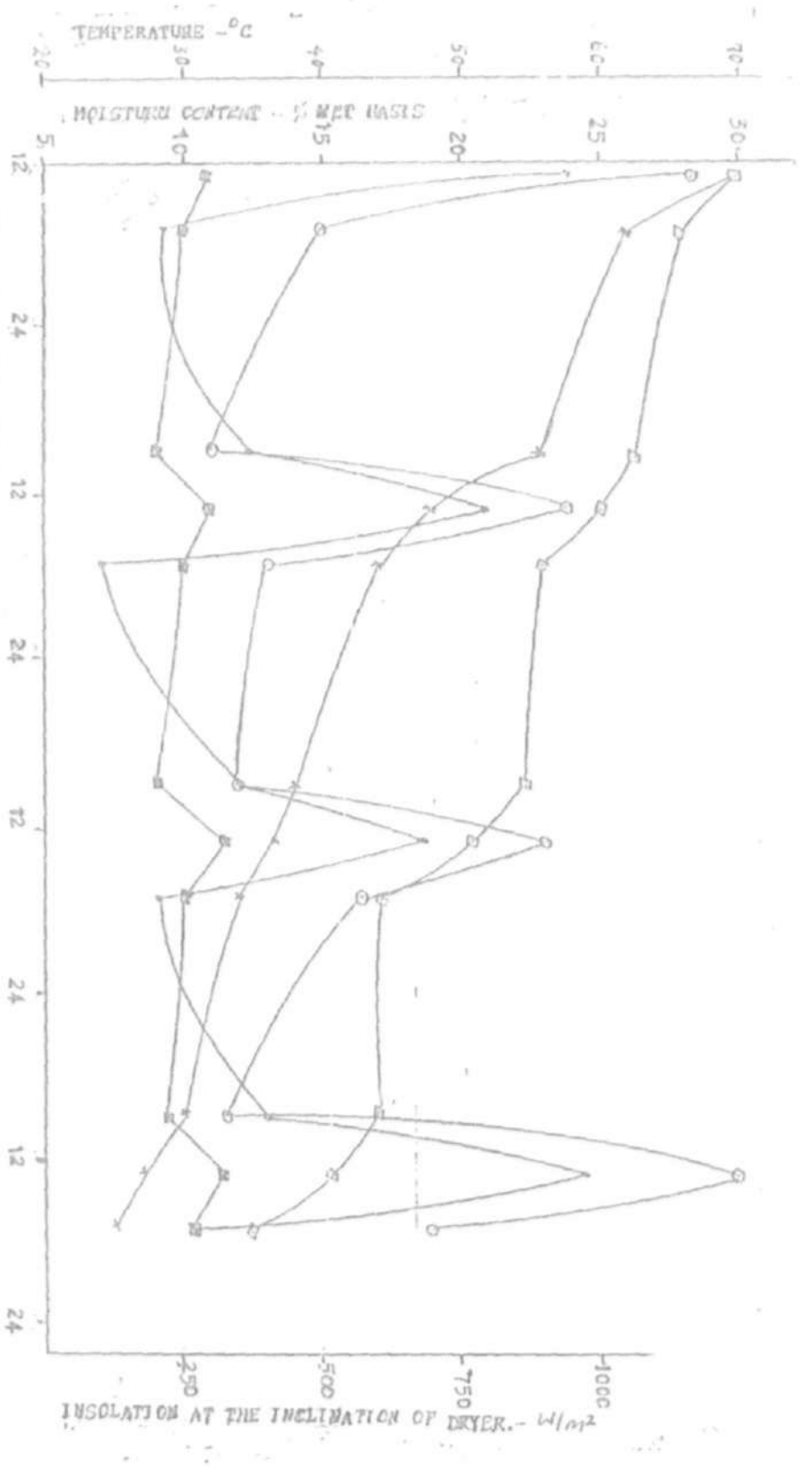

TEMPERATURE - °C
20
30
40
50
60
70
MOISTURE CONTENT - % WET BASIS
5
10
15
20
25
30
TIME OF THE DAY - HOURS.
FIGURE 5.12-A
12
24
12
24
12
24
250
500
750
1000
INSOLATION AT THE INCLINATION OF DRYER.- W/m²

FIGURE 5-12-2 Drying curves for groundnut

Solar kerosene, open sun

drying and ambient temp.

versus time of the day for

Dryer -

Explanation of lines

x = groundnut moisture content curve for metal dryer

σ = groundnut moisture content curve for open sun drying

θ = Dryer outlet temp. curve - ^{o}C

$\bullet$ = Solar insolation curve W/m^2

$\blacksquare$ = Ambient temp. curve - ^{o}C

Quantity of product = 10 .5kg

Depth of groundnut layer = 5.5mm

Initial m.c. = 30 %

Final m.c. = 78 %

Drying dates = Sept. 13th to Sept. 16th 1990

Place of drying = Kwaka Village in Niger State.

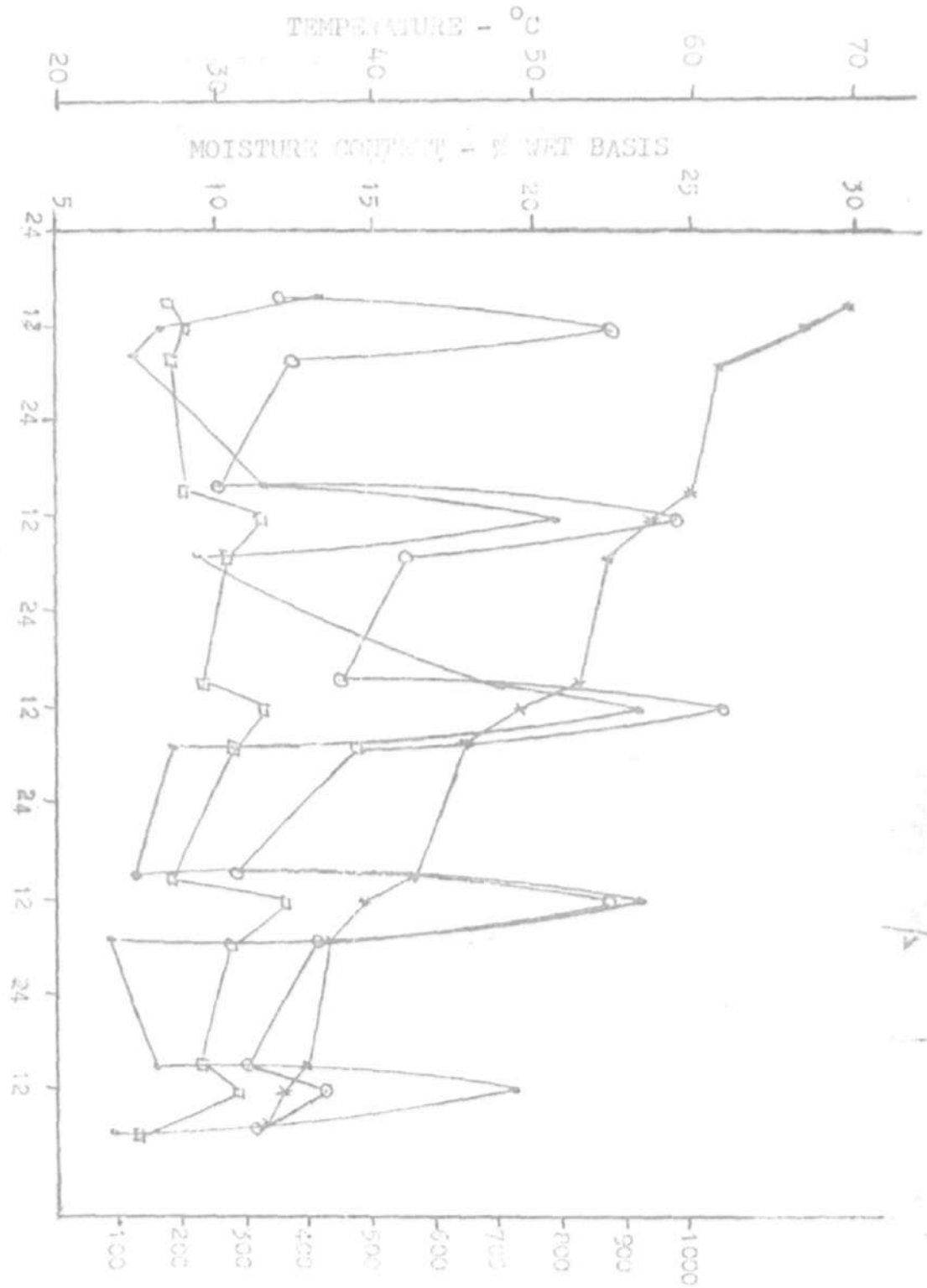

TEMPERATURE - °C
20
30
40
50
60
70
MOISTURE CONTENT - % WET BASIS
5
10
15
20
25
30
TIME OF THE DAY - HOURS
24
12
24
12
24
12
24
12
100
200
300
400
500
600
700
800
900
1000
INSOLATION AT THE INCLINATION OF DRYER - w/m2

FIGURE 5-13

FIGURE 5-11 Drying curves for maize, solar insolation, Dryer outlet air temp. and ambient temp. versus time of the day, for dryer I

Explanation of Signs

χ = maize moisture content curve - %

O = Dryer outlet air temp. curve - ^{o}C

$\square$ = Ambient temp. curve - ^{o}C

$\diagup$ = Solar insolation curve - ^{o}C

Initial m.c. = 30%

Final m.c. = 11.5%

Drying dates = May 14th to May 19th 1991.

Place of drying = Jere village in Kad. State.

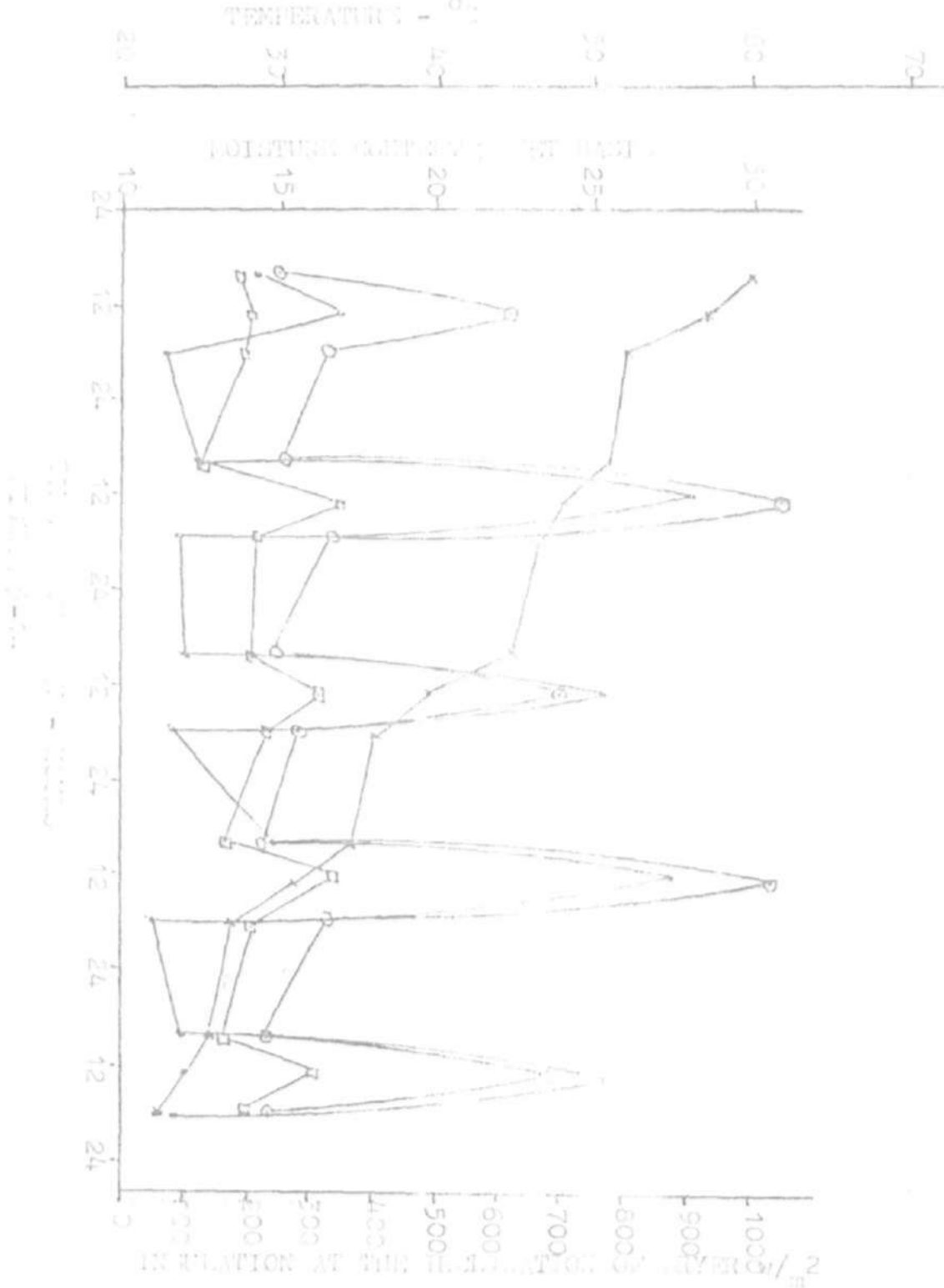


FIGURE 5-14 Drying curve for maize, solar insolation dryer air outlet temp. and Ambient temp. versus time of the day for dryer - B.

Explanation of Signs

x = maize moisture content curve - %

θ = Dryer air outlet temp. curve - ^{o}C

ρ = Solar insolation curve - W/m^2

Π = Ambient temp. curve - ^{o}C

Initial moisture content = 20% wet basis

Final moisture content = 11.2%

Drying dates - May 14th to May 18th 1991

Place of drying New-Wuse village in Niger State.

Dryers i, k and m were built at Jere, New-nuse and Kwaka, respectively. These dryers were identical in size and function. These dryers were ready for testing at off harvesting season. Therefore newly harvested maize and other cereal or tuberous crops were scarce. Few cobs of newly harvested fresh maize from the farmers irrigated farm were used for testing the dryers. The drying of the newly harvested unshelled maize started on dryer i from May 14th, 1991 to May 18th, 1991. Within this period, the maize dried from 30% initial moisture content wet basis to 11.5%. The details of the drying rate and other drying parameters are as indicated in Figure 5.13 and Table B.13 in the Appendix.

Dryer k was also tested with the newly harvested maize cobs from May 14th, 1991 to May 18th, 1991. The maize dried from 30% initial moisture content wet basis to 11.2%. The detailed results are shown in Figure 5.14 and Table B.14 in the Appendix.

5.3 Performance Evaluation of the Crop Dryers

The performance of the four dryers were evaluated by considering their drying efficiencies, dried product quality and the construction materials cost.

5.3.1 Calculation of Dryer Efficiencies

The related drying efficiencies calculated are:

i) System Drying Efficiencies

ii) Collector (Dryer) Efficiencies

iii) Thermal Efficiencies

5.3.1.1 System Drying Efficiencies

This is expressed by the formula

$$\eta_{SD} = \frac{M_w L_v}{I A_{ce} t} \qquad \ldots\ldots\ldots\ldots\ldots\ldots 5.1$$

where

η_{SD} = system drying efficiencies, %

M_w = weight of water evaporated, kg

L_v = latent heat of vaporization, J/kg

I = average daily insolation incident on collector, W/m^3

A_{ce} = effective collector area, m^2

t = drying time, s

The average daily insolation (I) incident on the collector was found from the data collected during the crop drying for dryer a to be 491.5 W/m^2. The latent heat of vaporization (Lv) of water is given (ASHRAE, 1977) as

2401000 J/kg and 2425[illegible].4 J/kg at temperatures $42^{o}C$ and $31^{o}C$ respectively.

The system drying efficiencies of the dryers are calculated as follows:

Given 25kg of maize grain at 20.6% initial moisture content, wet basis, Dryer a dried this grain to 10.9% moisture content wet basis.

Thus $$\eta_{SD} = \frac{M_w Lv}{IA_{ce}t}$$

but

$$M_w = (\frac{MC_{id} - MC_{fd}}{100}) \times D_m \quad \ldots\ldots\ldots\ldots 5.2$$

and

$$D_m = W_p - W_p MC_{iw} \quad \ldots\ldots\ldots\ldots 5.3$$

ie

$$D_m = 25 - 25 \times 0.206$$

$$= 19.85kg$$

$$\therefore M_w = (\frac{25.95 - 12.24}{100}) \times 19.85$$

$$\approx 2.72kg$$

AC_e for Dryer a = 0.3904 m^2

L_v = 240100 J/kg

I = 491.5 w/m^2

t = 2.5 days of 12 hours effective daily drying time.

ie t= 2.5 x 12 x 3600 = 108000 sec.

Substituting the values in equation (5.1)

$$\eta_{SD} = \frac{2.74 \times 240100}{491.5 \times 0.3904 \times 108000}$$

$$= 31.0\%$$

Following the above method of calculating system drying effectiencies, and from the data obtained during the drying processes, the valued in Table 4.1 are generated for different dryers tested.

5.3.12 Collector (Dryer) Efficiencies

Collector (Dryer) Efficiencies are calculated for the large scale dryers in the field. The dryers are similar in size and operation. The inlet and outlet collector temperatures are relatively the same. Therefore their collector efficiencies are calculated as

$$\eta_{ce} = \frac{M_a \, Cp_a (T_o - T_i)}{A_{ce} I} \qquad \ldots\ldots\ldots\ldots\ldots\ldots 5.4$$

where

η_{ce} = collector (dryer) efficiency, %

M_a = air mass flow rate, kg/s

Cp_a = specific heat of air, J/kg ^oC

A_{ce} = effective collector area, m^2

I = average daily insolation incident on collector, J/m^2

T_o = dryer outlet temp., ^oC

T_i = dryer inlet temp., ^oC

But

$$M_a = \frac{AV\rho E}{T_i} \qquad \text{..... 5.5}$$

where

A = collector air inlet area, m^2

V = wind velocity, m/s

E = effectiveness of openings (given as 0.5 to 0.6 for perpendicular winds and 0.25 to 0.35 for diagonal winds)

T_o = average dryer temp. (collector air outlet temp.), ^oC

T_i = collector air inlet temp. ^oC

ρ = air density, kg/m^3

for A = 0.078 m^2

V = 1.78 m/s

E = 0.[illegible]

T_o = [illegible] °C

T_i = 31 °C

= 1.[illegible] kg/m³

the mass flow rate of air is

$$M_a = \frac{0.[illegible] \times 1.[illegible] \times 0.[illegible] \times [illegible] \times 1.[illegible]}{31}$$

= 0.[illegible] kg/s

Also for

Cp_a = [illegible] J/kg °C

A_{ce} = 0.[illegible] m²

I = [illegible] w/m²

the collector (active) efficiency is

$$\eta_{ce} = \frac{0.[illegible] \times 100[illegible] \times ([illegible] - 31)}{0.[illegible] \times [illegible]} \times 100$$

= 29.[illegible]

5.3.13 Thermal Efficiencies

This is calculated from the formular

$$\eta_T = \frac{M_w Lv}{Mf\ hf} \qquad \ldots\ldots\ldots\ldots\ldots\ldots 5.6$$

where η_T = thermal efficiency, %

M_w = weight of water evaporated, kg

Lv = latent heat, J/kg

Mf = weight of fuel used, kg

hf = heating value of fuel, J/kg

For the hybrid dryer and for the values of the following parameters:

M_w = 9.684 kg

Lv = 2401000 J/kg

M_f = 5.852 kg

hf = 45770000 J/kg

the thermal efficiency is

$$\eta_T = \frac{9.684 \times 2401000}{5.852 \times 45770000} \times 100$$

$$= 8.7\%$$

When drying with the hybrid dryer with the collector and dryer top cover shaded, for the values of the following parameters:

M_a = 9.61 kg

Lv = 2401000 J/kg

M_f = 9.557 kg

hf = 45770000 J/kg

the thermal efficiency is

$$\eta_T = \frac{9.61 \times 2401000}{9.557 \times 45770000}$$

$$= 5.3\%$$

Table 5.1: Dryers System Drying Efficiencies with Relation to Different Crops and Quantities

Dryer	1	2	3	4	5	6	7	8	9
A	25	19.85	2.72	0.39h_4	10[illegible]	20.6	10.9	Maize	31.5
B	25	19.85	2.2	0.39h_4	10[illegible]	20.6	12.9	Maize	25.5
C	25	19.85	2.4	0.39h_4	10[illegible]	20.6	12.1	Maize	27.8
T_s	25	19.85	2.4h_4	0.39h_4	151200	20.6	12	Maize	12.7
A	50	33.35	11.3	0.39h_4	216000	33.3	9.2	"	77.0
B	50	33.35	12.7	0.39h_4	216000	33.3	10.6	"	73.6
C	50	33.35	12.3	0.39h_4	216000	33.3	10.4	"	75.2
T_s	50	33.35	12.4h	0.39h_4	518400	33.3	11.9	"	24.8
A	19	11.88	6.3h	0.39h_4	129600	37.5	7.0	G/nut	60.2
B	19	11.88	5.9	0.39h_4	129600	37.5	9.3	"	56.9
C	19	11.88	6.0	0.39h_4	129600	37.5	8.7	"	57.9
T_s	19	11.88	6.1	0.39h_4	194400	37.5	8.0	"	32.3
A	4	1.2	2.72	0.39h_4	86400	70	6.8	Okro	39.4
B	4	1.2	2.67	0.39h_4	86400	70	10	"	38.6
C	4	1.2	2.7	0.39h_4	86400	70	8	"	39.1
T_s	4	1.2	2.7	0.39h_4	1[illegible]	70	8.1	"	9.6
A	5	0.5	4.4h	0.39h_4	151200	90	7	Tomatoes	37.2
B	5	0.5	4.4h	0.39h_4	151200	90	11	"	36.7
C	5	0.5	4.45	0.39h_4	151200	90	9	"	39.9
T_s	5	0.5	4.4h	0.39h_4	151200	90	7.5	"	11.8
D	15	1.8	13.0	1.22h_4	108000	88	7.5	Okro	47
E	15	1.8	13.1	1.22h_4	108000	88	6.8	"	48.2
F(Lower layer)	15	1.8	12	1.22h_4	108000	88	40	"	23.5
F(upper layer)	15	1.8	13.1	1.22h_4	108000	88	7	"	25.7
G (lower layer)	15	1.8	12.2	2.31	108000	88	35	"	24.0
G (upper layer)	15	1.8	13.1	2.31	108000	88	6	"	26.5
T_s	15	1.8	12.5	2.31	172800	88	6.8	"	15.9
D	10	0.6	9.3h7	2.31	172800	94	8	Tomatoes	21.6
E	10	0.6	9.4	1.22h_4	172800	94	7.1	"	23.2

Table 5.1 Cont'd.

F(Lower layer)	10	0.6	8.67	1.224	17[illegible]	94	55	Tomatoes	13.6
F(upper layer)	10	0.6	9.39	[illegible]	17[illegible]	94	7.7	"	11.7
G(lower layer)	10	0.6	8.89	[illegible]	17[illegible]	94	48	"	10.7
G(upper layer)	10	0.6	9.6	[illegible]	17[illegible]	94	6	"	12.8
T_s	10	0.6	9.2	[illegible]	60[illegible]	94	7	"	4.3
I	50	35	10.5	[illegible]	[illegible]	30	11.5	Unthreshed maize	[illegible]
J	150	120	[illegible]	[illegible]	151[illegible]	20	11.5	"	[illegible]
K	50	35	10.64	8.712	216000	30	11.2	"	[illegible]
L	250	182.5	43.62	8.712	172[illegible]	27	11.6	"	[illegible]
L	50	38	[illegible]	8.712	108000	34	11.7	"	[illegible]
N	73.5	62.19	17.1	8.712	172800	29	2.5 G/nut pod		[illegible]
N	100.2	70.14	24.1	8.712	151[illegible]	30	2.8	"	[illegible]

1 = Wt of product before drying (Wp)
2 = Wt of dry matter (Wm) kg
3 = Wt of water removed mc (Ww)
4 = Effective drying area (Ae) m^2
5 = Drying time (t) sec.
6 = Initial m.c wet basis (MC_{wi}) %
7 = Final M.C wet basis (MC_w) %
8 = Name of crop
9 = System drying efficiencies lose %

5.4 Product Quality Analysis

The Food Science and Technology Department of IAR/ABU - Zaria analysized the Nitrogen (N_2) and the Protein content of the fruits (Okro and Tomatoes) dried in the vegetable/fruit dryers. The result of the analysis is shown in table 5.2. The percentage of the nutrient content was calculated per unit weight of the analysized samples. Fresh Okro and Tomatoes were also tested wet.

Table 5.2: Nitrogen and Protein value of Fresh/ Dried Okro and Tomatoes

Materials	Nutrient value	
	% N_2	% Protein
Okro		
Fresh	0.27	11.19
Dried in upper compartment of dryer - F	1.95	12.31
Dried in upper compartment of dryer - F	2.52	15.75
Dried in dryer - D	2.38	14.88
Dried in lower compartment of dryer - G	2.01	13.08
Dried in upper compartment of dryer - G	2.57	16.06
Dried in dryer - E	2.45	15.31
Dried by traditional open sun drying	1.1	13.0

Table 5.2 Cont'd

Tomatoes		
Fresh	0.19	1.19
Dried in lower compartment of dryer - F	2.97	21.69
Dried in upper compartment of dryer - F	4.05	26.98
Dried in dryer - D	4.52	27.88
Dried in lower compartment of dryer - G	3.11	23.60
Dried in upper compartment of dryer - G	4.57	28.30
Dried in dryer - E	4.22	28.0
Dried by traditional open sun drying	3.01	22.0

Okro and Tomatics dried in direct mode vegetable/fruit dryers with or without rockbed heat storage showed remarkable high nutrient value because they dry taster than the traditional open sun drying.

The same sample by weight of both the dried and the fresh Okro and Tomatoes were used in the nanalysis of the nutrient value.

5.5 Cost Analysis of the Dryer

The total estimated cost of each of the dryers are shown in Table 5.3. In appendix C the detailed costs of the materials for each dryer were specified.

Table 5.3: Price of Dryers Based on the Average Market Cost Price in Zaria, Jere and Suleja Between November 1989 and June 1991.

	Type of Dryer	Total Material Cost ₦ k
1.	DRYER-A- small scale wood-type direct mode solar dryer with rockbed heat storage.	519.00
2.	DRYER-B- small scale wood-type direct mode solar dryer without rockbed heat storage.	516.00
3.	DRYER-C- small scale metal-type direct mode solar dryer, without rockbed heat storage	732.00
4.	DRYER-D- small scale single layer wood-type vegetable/fruit solar dryer without rockbed heat storage.	444.50
5.	DRYER-E- small scale single layer wood-type vegetable/fruit solar dryer with rockbed heat storage.	450.65
6.	DRYER-F- medium scale double layers wood-type vegetable/fruit solar dryer without rockbed heat storage.	871.75

Table 5.3 cont'd.

	Type of dryer	Total material cost ₦
7.	DRYER-G- medium scale double layers wood-type vegetable/fruit solar dryer with rockbed heat storage.	882.35
8.	DRYER-H- medium scale hybrid crop dryer.	12,782.50
9.	DRYER-I- large scale mud-type direct mode solar crop dryer	4,458.40
10.	DRYER-J- medium scale wood-type direct mode solar crop dryer	1,793.00
11.	DRYER-K- large scale mud-type direct mode solar crop dryer	4,458.50
12.	DRYER-L- large scale metal-type direct mode solar crop dryer	8,043.00
13.	DRYER-M- large scale mud-type direct mode solar crop dryer	4,458.40
14.	DRYER-N- large scale metal-type direct mode solar crop dryer	8,043.00

Labour cost is not included in the total cost given, because labour prices are very flexible and depends on many factors, but the materials for the dryers components are fairly constant in price over a period of time.

5.5.1 Payback Period And Percentage Cash Flow Gain

The payback period of the various dryers and their percentage cash flow gain the traditional drying method are given in table 5.4. The detailed calculations of the payback period and the percentage cash flow gain for each dryer are worked out in Appendix C-2

Table 5.4 Dryers Payback Period and the Percentage Cash Flow Gain

DRYERS	Assumed life of the dryers (yr)	Estimated cost of dryers (₦)	Size of dryer and capacity (kg)	Payback period of the dryers (yr)	Dryer percentage cash flow gain advantage over traditional drying method (%)
DRYER-A	5	519.00	Maize,500	1.5	35.89
DRYER-B	5	516.00	maize,500	1.47	36
DRYER-C	15	732.00	maize,500	1.86	42.74
DRYER-D	5	444.50	Tomatoes,400	1.37	18.81
DRYER-E	5	450.65	Tomatoes,400	1.39	18.69
DRYER-F	5	871.75	Tomatoes,600	1.66	19.84
DRYER-G	5	892.35	Tomatoes,600	1.7	19.68

Table 5.4 cont'd

DRYER-H	15	12,782.50	maize,6000	2.42	46.17
DRYER-I	10	4,488.40	maize,6000	0.71	60.49
DRYER-J	5	1,703.00	maize,1,500	2.43	26.25
DRYER-K	10	4,488.40	maize,6000	0.71	60.49
DRYER-L	15	8,013.00	maize,6000	1.35	55.74
DRYER-M	10	4,488.40	maize,6000	0.71	60.49
DRYER-N	15	8,013.00	maize,6000	1.35	55.74

5.6 Discussion

From the data collected during the anyday test analysis, the following observations were made.

The small scale dryers and the vegetable/fruit dryers with rockbed heat storage dried the crops faster than those without rockbed heat storage. But the rocks increased the weight of the dryers, which affected the transportability.

Tomatoes dried at the lower compartment of the double compartment dryers rottened before it dried. This is because at the time of the drying operation, the atmospheric relative humidity was high. Also the lower compartment is an indirect mode drying component. At such drying conditions the lower compartment section of the double compartment dryer cannot dry high moisture content crops, such as tomatoes.

It was observed that within the drying period, the products generally increased slightly in moisture content over the night. This might be due to the fact that the collector air inlet space and the drying section air outlet space were usually kept open even in the night. This then allowed the high relative humidity air, which characterizes the night weather condition, to flow to the drying product in the dryers.

There was no difference in drying performance between the dryers covered with $\frac{4}{4}$ transparent polythene and the ones covered with transparent glass of 3mm to 5mm thick. As the testing continued, the transparence of the polythene deminished, even when it was cleaned, it was not as transparent as the new one. The polythene was found to be very soft at high dryer temperatures. This normally occured between 11.00 a.m. and 4.00 p.m. in a clear weather. High temperatures have advance effects on the polythene, one of which is that the polythene can easily tear or puncture. On the other hand the glass always retains its transparence whenever it is cleaned. The glass easily breaks when it is heated and moved with slight force during the noon time. Therefore, transportation of glass under high vibrations and temperatures should be avoided.

The temperature of the dryers with rockbed heat storage increased by about $5^{o}C$ higher than those without rockbed heat storage when tested under the same conditions. In the morning the dryers with rockbed experienced some time lag to heat up the collector section. But the rock took a longer time to cool down to ambient temperature after sunset.

The metal-type dryers generated more heat than the wood type dryers without rockbed but they cooled down very quickly after sunset.

Different dryer operating slopes were tried with the laboratory small model dryers. It was found that the best operating slope for the natural convection dryer without chimney is between 11° and 15°. During the test when the slope of 15° was exceeded, the crops put in for drying rolled and piled at down side of the drying chamber. The inclination of the dryer should therefore not exceed the angle of respose of the crops.

Okro dried faster than tomatoes. This may be on the ground that okro has more heat absorption capacity which made okro drying surface temperatures to be always higher than those of tomatoes. Besides okro has internal and external corrugated surface and this might have enhanced faster removal of internal moisture from the pores. The internal water binding force of tomatoes to is/my opinion relatively higher and as a result the drying took longer time.

Groundnut in the small and large scale dryers dried faster than maize. Although the moisture content of newly harvested groundnut was found to be normally greater than the moisture content of the newly harvested maize, yet the groundnut dried faster than maize under the same

conditions. This is likely to be due to the relatively higher solar absorptance of groundnut as explained by Arinze (1978), and also for the higher internal moisture holding force of maize.

It has to be pointed out here that the vegetable/fruit (okro and tomatoes) nutrient test showed that the dried okro and tomatoes increased in Nitrogen and Protein per unit weight than the wet product. The increase in nutrient value can be as a result of high nutrient concentration due to reduction in moisture content, especially as the design of the dryer ensured that the products dried at the optimum temperature (45°C to 55°C). The vegetables dried by traditional open sun drying and in the lower compartment of the double layer dryer dried at such a low drying rate that they were affected by enzymatic reaction and mould attack which caused nutrient value deterioration.

When testing the hybrid dryer, it was observed that at constant gas burning rate, the heat exchanger air outlet temperature increased as the fan air inlet opening was reduced. Thus, a decrease in fan air inlet opening means a reduction in air mass flow rate, and increase in outlet air temperature. Also when the fan air inlet opening was increased the heat exchanger air outlet temperature decreased as well. From the adjustments an

optimum fan air inlet space of 200mm diameter was found and used for drying the maize crop. At 200mm fan air inlet diameter 0.64 kg/s air mass flow rate was generated, which at a burning gas flow rate of 9.953×10^{-4} kg/s raised the drying air temperature to 44.4°C. When operated within the explained drying conditions, 75% of the maize tested in the hybrid dryer was viable after drying. The viability was tested by planting 20 maize grains after drying them in the hybrid dryer. Also 20 maize grains of the same maize type (variety and breed) from which the soaked maize grains were measured out, were planted and 90% were viable. 75% viability of the maize dried with the hybrid dryer may be due to the fact that it was soaked in water for 21 hours and dried again.

Field tests results for dryers in the field were critically analysed. After the installation of the metal and medium wood-type dryers at Jere, New-Nuse and Kwaka, the use of the dryers were explained to the farmers. Besides, some quantity of the farmers' products were bought and dried in the dryers. When the farmers observed that the crops dried faster than their normal traditional method of open sun drying and that the system of operation of the dryers were very simple, the farmers brought their crops for drying.

At Kwaka, farmers brought their main crop (groundnut). The farmers were excited to find out that it took two to three days to dry newly harvested groundnut pods. When asked, the farmers said that it normally took them 5 to 7 days to dry the same quantity of fresh groundnut pods. At New-Wuse and Jere the farmers were educated on how to use the dryers. The farmers brought their fresh maize which dried within 3 to 4 days with the solar dryers. The farmers confirmed that it normally took them about 7 to 10 days to dry similar quantity of maize.

Usually the moisture content of the crops being dried were monitored by measuring the initial moisture content and at intervals until the crops dried to the safe storage moisture content.

The farmer appreciated the fact that the drying crops in the dryer can be left outside over the night or even when it is raining.

Construction of the mud-type dryers was finished and ready for testing at the off harvesting season. In order to demonstrate the performance of the mud-type dryers to the farmers, some ear-maize of newly harvested fresh maize from the farmers' irrigated farm were purchased and dried. It took 4 days to dry.

The aim of building the mud-type dryers was to teach the farmers how to construct the dryer with locally available and affordable materials. The farmers were intgrated in the mud dryer construction by employing them

to build the mud dryer walls in the same way they build their mud houses. Initially the mud dryer walls were plastered with cement-sand ratio of 1 bag to 12 headpans (normal plastering mixture). This ratio of cement and sand mixture was found not to be strong enough as to withstand heavy rains, which beat directly on the mud dryer structure. The mud dryer wall was later plastered with the cement-mud mixture ratio of 1:6, and this made the walls to become stronger and water resistant.

The system drying efficiencies of the dryers was found to increase as more crops were introduced in the dryers for a batch drying. Therefore, it is advisable to maximize the use of the dryers by drying threshed crops at the layer depth of about 50 to 100mm covering the entire space of the drying crop bed.

It was found that labour cost increases two to three times between May and November when compared to the period between December and April. The later is the off planting or harvesting seasons. Also there is good weather condition for construction work in the field between December and April.

From table 5.4 the large scale mud grain dryer have the highest annual percentage cash flow gain advantage over the traditional open sun drying. This is due to the relatively low dryer cost with large drying capacity.

CHAPTER SIX

6. CONCLUSIONS AND RECOMMENDATIONS

Small and large scale natural convection solar crop dryers and hybrid crop dryers were successfully designed and constructed. The experimental laboratory and field results showed that the performance of the metal-type, wood-type and mud-type direct mode dryers are very encouraging when compared to open sun traditional drying. 50 to 99% savings in drying time were achieved with natural convection solar crop dryers and the hybrid crop dryer when compared with the traditional open sun drying method.

Up to 60% crop dryer percentage cash flow gain advantage over the traditional drying method was realized. Dryers cost analysis and their payback period showed that the designed dryers are within the farmers reach and that it is more economically profitable than the usual traditional open sun drying method. The medium and large scale farmers will be encouraged to establish their own large scale mud-type and hybrid dryers.

The mud-type dryers are now receiving high demand by the farmers in the villages where they have been built and demonstrated to the farmers. For better performance and reliability, the structure of the mud-type dryers can be improved by:

1. Reinforcing the soil used either for moulding the mud blocks or for moulding the mud dryer walls directly.
2. The plastering mixture will be of ratio 1 bag of cement to 6 headpans of sand.
3. The drying structure (dryer) can be constructed with cement blocks.

Field solar crop dryer construction work is best done between December and April. The hybrid dryer can be operated as a forced convection solar crop dryer without supplementary heating. The drying chamber of the hybrid dryer can be increased to a large scale dryer while still operating with the same fan whose air inlet space is adjustable. The insulation of the heat exchanger walls needs to be improved.

Further, vegetables and fruits nutrient tests that will include vitamin test for different drying mechanism is recommended. For high moisture content vegetables/ fruits drying, the dryer should have rockbed heat storage for effective fast drying.

Glass of 5mm thick is preferable to the glass of 3mm thick, because the later breaks so easily.

This project is of great help to the small and large scale farmers. Therefore the extension service on educating the farmers on how to use and build the solar dryers, for themselves should be intensified, and popularized.

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APPENDIX A

Equilibrium Constants and the Metological Data for Ten Years for Zaria Weather.

APPENDIX A

Table A.1: Values of Equilibrium Constants C and n for Some Materials

Material	c	n
Shelled corn	1.10×10^{-5}	1.90
Wheat	5.59×10^{-7}	3.03
Sorghum	3.40×10^{-6}	2.31
Soybeans	3.20×10^{-5}	1.52
Flaxseed	6.89×10^{-6}	2.02
Raisins	7.13×10^{-5}	1.02
Dried peaches	4.11×10^{-4}	0.564
Dried prunes	1.25×10^{-4}	0.865
Cotton	4.91×10^{-5}	1.70
Wood	5.34×10^{-5}	1.41
Spray-dried eggs	2.95×10^{-5}	2.00
Natural clay	7.53×10^{-5}	1.72

Table A.7: Meteorological data, 5 year mean (years [illegible])
for Larnia (from Dept. of Soil Science
Lab/AUB, Larnia, [illegible]).

Year 1959

Month	Max. Temp. °C	Min. Temp. °C	Wind speed KM/24 hr	Dry bulb temp. °C	Wet bulb Temp. °C	Relative Humidity %
Jan.	31	11.0	1.h.1o	[illegible]	1.1	1o
Feb.	[illegible]	15.6	1o1.2[illegible]	[illegible]	[illegible]	[illegible]
March	35.[illegible]	18.8	[illegible]6.7[illegible]	[illegible]	1o.1	[illegible]
April	3o.[illegible]	[illegible]1.9	1o[illegible]	[illegible]	[illegible]	3[illegible]
May	33.0	21.3	[illegible]35.33	[illegible]	23.8	[illegible]
June	3o.3	19.8	2[illegible]o.o[illegible]	[illegible]	[illegible]	[illegible]
July	28.7	1[illegible].o	1[illegible]o.[illegible]	[illegible]	22.o	[illegible]
Aug.	[illegible]	1[illegible].[illegible]	[illegible]1..[illegible]	[illegible]	[illegible]	[illegible]
Sept.	[illegible]	1[illegible].[illegible]	[illegible]1.[illegible]	[illegible]	[illegible]	[illegible]
Oct.	[illegible]	15.3	[illegible].	[illegible]	[illegible]	[illegible]
Nov.	[illegible]	1[illegible].[illegible]	[illegible]1.1[illegible]	[illegible]	[illegible]	[illegible]
Dec.	[illegible]	11.7	[illegible]1.[illegible]	[illegible]	11.[illegible]	[illegible]

Table A.2 Cont'd.

Year 1981

Month	Max. Temp. ^{o}C	Min. Temp. ^{o}C	Wind Speed KM/24 hr	Dry bulb Temp. ^{o}C	Wet bulb Temp. ^{o}C	Relative Humidity %
Jan.	28.2	11.5	158.46	20.9	10.4	10.3
Feb.	32.4	15.4	167.5	25.2	12.1	14.1
March	34.8	18.9	132.37	29.3	16.3	20.7
April	36.0	20.1	192.94	30.1	20.4	40.7
May	31.9	20.8	179.73	27.2	23.2	68.9
June	30.7	20.5	193.1	26.1	22.4	71.5
July	28.1	19.5	175.86	24.0	21.9	82.2
Aug.	28.4	19.5	127.43	24.4	22.5	82.4
Sept.	30.1	19.4	113.87	25.4	22.6	76.9
Oct.	32.5	17.3	85.15	28.0	22.1	60.1
Nov.	29.1	14.2	142.01	24.8	14.0	23.6
Dec.	30.3	12.7	113.29	24.9	13.2	20.5

Table A.2 Cont'd.

Year 1982

Month	Max. Temp. ^{o}C	Min. Temp. ^{o}C	Wind Speed km/24 hr	Drv bulb Temp. ^{o}C	Wet Bulb Temp. ^{o}C	Relative Humidity %
Jan.	29.7	13.9	127.37	23.6	12.5	18.7
Feb.	31.3	15.1	151.6	24.6	13.1	19.3
March	34.6	19.8	162.1	28.9	16.3	21.5
April	35.5	21.5	200.52	29.5	22.3	53.0
May	33.5	21.8	206.71	27.8	23.3	67.2
June	30.8	21.0	197.13	25.9	22.6	75.1
July	29.5	19.9	167.85	24.5	21.8	78.8
Aug.	28.0	19.5	134.38	24.2	22.7	82.4
Sept.	29.6	19.5	105.07	25.5	22.7	77.8
Oct.	31.1	18.7	101.26	26.5	22.5	69.7
Nov.	30.0	13.3	112.37	25.1	13.9	21.3
Dec.	30.0	13.6	139.38	24.4	12.5	16.1

Table A.2 Cont'd.

Year 1983

Month	Max. Temp. °C	Min. Temp. °C	Wind Speed km/24 hr	Dry Bulb Temp. °C	Wet Bulb Temp. °C	Relative Humidity %
Jan.	30.6	13.8	253.54	17.7	14.5	20.8
Feb.	32.4	18.1	173.78	26.7	13.3	12.0
March	33.0	17	197.22	27.1	13.9	14.4
April	37.5	19.9	155.0	32.2	18.4	22.4
May	34.7	21.6	240.28	28.9	23.5	62.6
June	31.9	19.6	230.73	2o.1	22.6	72,6
July	28.8	23.4	186.70	24.3	21.9	81.0
August	28.4	16.7	116.36	24.3	22.0	81.2
Sept.	29.9	17.3		25.5	22.5	76.3
Oct.	31.8	14.3	91. 03	27.6	17.6	35.4
Nov.	32.0	12.6	73.94	27.4	14.9	19.4
Dec.	31.0	12.9	90.81	24.7	12.9	17.0

Table A.2 Cont'd.

Year 1984

Month	Max. Temp. ^{o}C	Min. Temp. ^{o}C	Wind Speed km/24 hr	Dry Bulb Temp. ^{o}C	Wet Bulb Temp. ^{o}C	Relative humidity %
Jan.	28.3	11.8	137.43	21.0	10.4	16.4
Feb.	31.7	14.8	143.4	24.9	11.9	11.7
March	35.0	20.7	148.94	29.5	17.6	11.0
April	35.0	22.7	184.71	29.5	21.0	45.9
May	31.9	21.3	225.16	27.1	22.7	67.4
June	31.5	20.5	209.10	26.3	22.5	70.8
July	28.9	19.2	160.4	24.5	21.9	79.0
Aug.	29.8	19.5	143.62	25.3	22.3	77.1
Sept.	29.5	19.2	89.74	25.1	22.0	75.0
Oct.	30.5	18.6	66.60	26.5	21.1	60.9
Nov.	31.2	13.6	87.13	26.7	15.5	25.0
Dec.	27.6	12.8	138.81	21.4	11.5	22.0

Table A.2 Cont'd.

Year 1985

Month	Max. Temp. ^{o}C	Min. Temp. ^{o}C	Wind Speed km/24 hr	Dry Bulb Temp. ^{o}C	Wet Bulb Temp. ^{o}C	Relative Humidity %
Jan.	31.6	14.4	142.93	24.8	13.2	18.4
Feb.	29.5	14.3	198.06	22.9	10.8	12.8
March	35.1	21.2	186.20	28.6	18.4	35.2
April	34.5	21.8	148.97	29.2	17.8	29.0
May	35.5	22.2	254.06	27.6	23.1	66.0
June	30.0	18.7	236.94	25.3	22.2	75.5
July	27.8	17.3	175.34	23.3	21.8	86.3
Aug.	28.8	15.5	137.29	24.4	22.1	81.3
Sept.	29.3	17.8	109.31	25.0	22.2	77.6
Oct.	31.2	15.5	82.66	27.1	18.7	42.6
Nov.	32.3	13.0	85.02	27.5	16.5	23.2
Dec.	28.3	13.3	143.98	21.8	12.1	24.6

Table A.2 Cont'd.

Year 1986

Month	Max. Temp. ^{o}C	Min. Temp. ^{o}C	Wind Speed km/24 hr	Dry Bulb Temp. ^{o}C	Wet Bulb Temp. ^{o}C	Relative Humidity %
Jan.	29.6	12.7	137.00	21.7	11.8	23.1
Feb.	34.6	15.9	122.69	26.9	14.5	18.8
March	35.5	18.9	133.26	29.0	18.9	35.4
April	37.5	21.4	205.58	30.4	23.6	54.6
May	34.4	21.7	207.5	28.8	23.0	59.8
June	30.0	20.5	242.05	26.0	22.2	71.2
July	27.9	19.7	206.54	23.5	21.4	82.1
Aug.	28.6	18.8	135.20	23.4	21.4	81.7
Sept.	28.9	19.1	117.65	25.1	22.1	75.6
Oct.	31.1	17.6	82.0	27.4	21.2	56.8
Nov.	31.5	14.2	94.36	26.3	17.5	36.1
Dec.	27.0	12.6	14.2.48	21.0	11.8	25.0

Table A.2 Cont'd.

Year 1987

Month	Max. Temp. ^{o}C	Min. Temp. ^{o}C	Wind Speed km/24hr	Dry Bulb Temp. ^{o}C	Wet Bulb Temp. ^{o}C	Relative Humidity %
Jan.	30.5	12.5	110.66	23.1	12.5	21.4
Feb.	33.1	16.3	108.76	26.7	13.1	11.8
March	34.9	19.6	150.59	29.0	17.4	26.7
April	36.3	21.7	173.38	31.0	18.5	18.5
May	36.7	22.2	196.65	30.4	22.4	50.6
June	30.7	21.1	173.06	25.9	20.0	76.5
July	30.1	20.2	154.34	25.2	22.7	79.8
Aug.	29.2	19.8	108.68	24.2	22.4	85.4
Sept.	30.4	20.4	98.70	26.3	23.2	75.9
Oct.	31.0	17.5	86.0	27.1	20.5	53.9
Nov.	31.8	12.4	78.35	27.1	19.4	22.7
Dec.	29.9	12.5	99.76	23.6	13.3	24.0

Table A.2 Cont'd.

Year 1988

Month	Max. Temp. °C	Min. Temp. °C	Wind Speed km/24 hr	Dry Bulb Temp °C	Wet Bulb Temp °C	Relative Humidity %
Jan.	28.9	13.5	127.40	21.9	11.7	22.1
Feb.	31.9	15.7	138.14	24.9	12.8	17.8
March	35.9	20.9	160.56	29.8	16.7	21.5
April	36.1	22.2	179.85	30.0	21.5	47.6
May	34.8	22.5	184.27	28.7	23.0	60.0
June	30.7	20.1	185.65	25.9	22.6	75.4
July	28.1	19.5	171.01	23.9	21.8	83
Aug.	27.4	19.4	139.40	23.6	21.6	83.3
Sept.	29.3	19.3	112.49	25.7	22.6	76.9
Oct.	31.0	15.7	89.93	27.2	19.6	47.8
Nov.	31.7	12.0	77.32	27.0	15.4	23.4
Dec.	28.2	11.8	103.97	22.4	12.5	24.7

Table A.2 Cont'd.

Year 1989

Month	Max. Temp. °C	Min. Temp. °C	Wind Speed km/24 hr	Dry Bulb Temp. °C	Wet Bulb Temp. °C	Relative Humidity %
Jan.	25.2	10.1	155.13	18.2	9.7	25.6
Feb.	28.0	13.4	170.90	21.5	11.7	17.5
March	34.7	17.5	131.25	28.5	14.8	15.5
April	36.8	20.0	172.16	30.8	20.3	37.0
May	33.1	20.4	183.39	27.6	22.3	61.8
June	30.7	20.0	188.82	25.7	22.2	72.3
July	29.4	19.6	155.42	24.6	22.0	78.9
Aug.	28.0	19.3	129.11	24.2	21.9	81.7
Sept.	29.8	19.2	95.85	24.9	22.3	78.4
Oct.	30.6	16.5	88.90	26.4	19.6	51.9
Nov.	31.1	12.7	102.34	25.6	14.3	19.3
Dec.	28.6	12.9	127.27	22.9	12.8	19.3

Table A.3: Thermal Properties of Materials

Materials	Moisture Content	Specific heat Btu/lb-°F (Source)
Corn dried	10.5	0.28 } Mohamin, 1980
Corn green	73.9	0.79 }
Tomatoes		}
Mature-green	93.0	0.94 } Lutz and Hardenburg, 1967
Firm ripe	94.1	0.95 }
Air density at	40°C = 1.092 kg/m³	} Heldman, 1980
	50 = 1.057 kg/m³	}

T_2 = 45 by Interpolation 5 = x - 1.092

5 = 1.057 - x

∴ n = 1.077 kg/m³

Heat of vaporization at 45°C = 1029.3 Btu/lb (ASHRAE, 1977)

but 1 Btu/lb = 2.326 kJ/kg

∴ 1029.3 Btu/lb x 2.326 kJ/kg = 2394.1518 kJ/kg

The average specific heat of corns and tomatoes were taken

Thus, Cp_m = 0.535 Btu/lb - °F

But 1 Btu/lb - °F = 4.187kJ/kg °C

∴ Cp_m = 2.2401 kJ/kg

Likewise Cp_o = 0.945 Btu/lb°F = 3.956715 kJ/kg

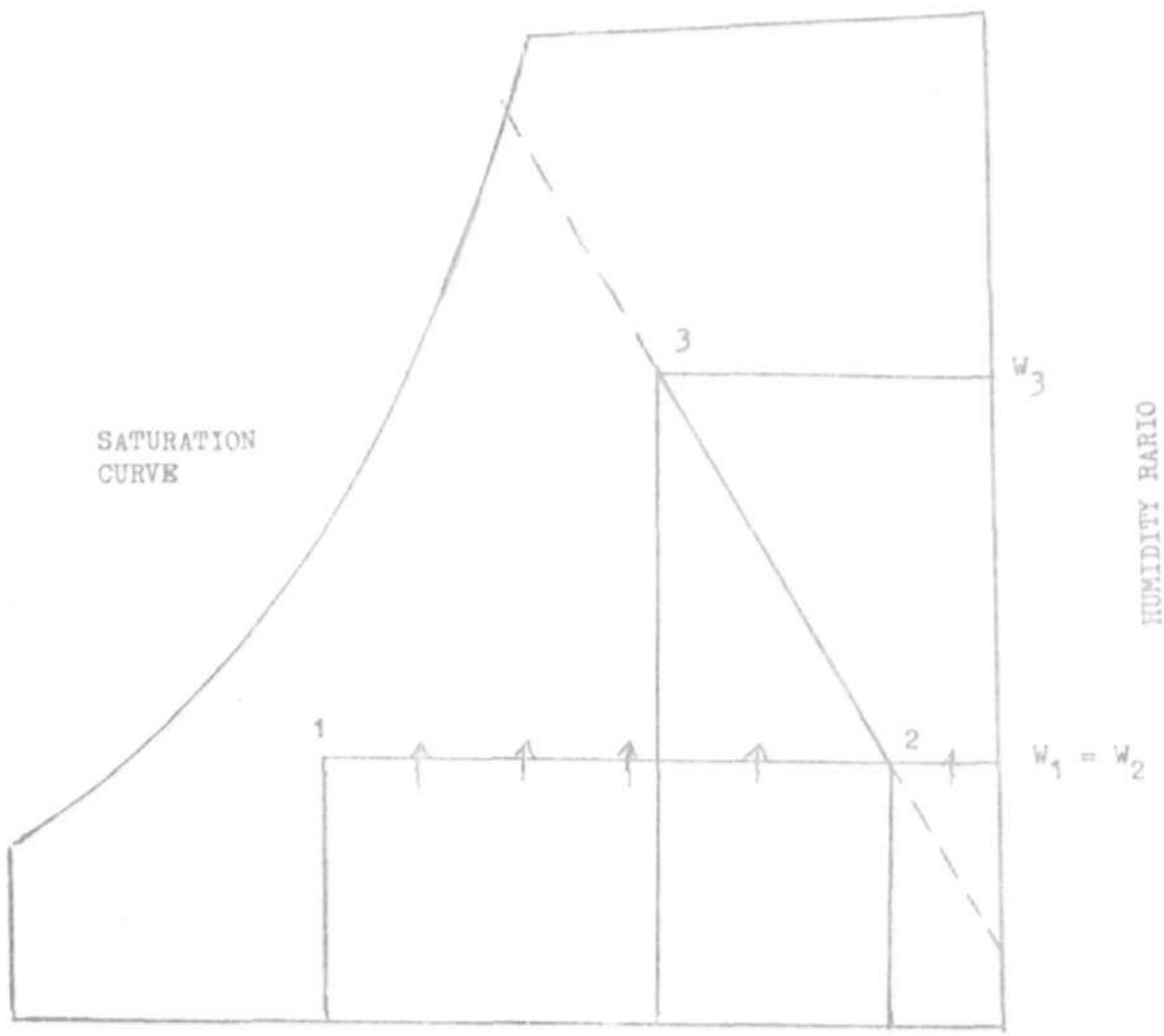


Figure A.1

Psychrometric process for heating and dehumidifying (Air state change for a drying process). The air state change (2) to (3) for a drying process.

CALCULATION OF THE GAS FLOW RATE

An imperial unit pressure gauge was used to measure the pressure of the gas following to the gas burner. With the aid of the pressure gauge, the pressure of the burning gas was ed at 0.25 bar throughe the drying period. Valve of the pressure gauge, through which the gas flows to the hose-gas burner is 2mm i. diameter.

It is given that:

1 bar = 100,000 N/m^2

Propane gas density = 2.0073 kg/m^3

but N = mass x accelerati to gravity

= kg x m/s^2

0.25 bar = 25000 N/m^2

= 25000 $\frac{kg.}{m^2}$ m/s^2

= 25000 $kg/m.s^2$

Gass velocity flowing through the pressure , which generated a pressure of 0.25 bar is found from the formula

$$Pg = \frac{\rho v^2}{2}$$

where

P = velocity pressure, N/m^2

g = acceleration due to gravity, m/s

ρ = density of gas, kg/m^3

V = velocity of gas ejected through the pressure gauge valve, m/s

Pg = 25000 $kg/m.s^2$

ρ = 2.0073 kg/m^3

$$\therefore 25000\ kg/m.s^2 = \frac{2.0073\ kg/m^3 \cdot V^2}{2}$$

$$\therefore V = \frac{2 \times 25000\ kg/m.s^2}{2.0073\ kg/m^3}$$

$$= \frac{50000\ m^2}{2.0073\ s^2}$$

$$= 157.83\ m/s$$

The value gas outlet area is given as

$$A = \frac{\pi \left(\frac{2m}{1000}\right)^2}{4}$$

$$= 3.14159 \times 10^{-6}\ m^2$$

The volume flow rate is

$$V_a = VA = 157.83 \times 3.14159 \times 10^{-6}$$

$$= 4.95825 \times 10^{-4}\ m^3/s$$

Mass flow rate is given as

$$M_a = V_a \rho$$

$$= 4.95825 \times 10^{-4}\ m^3/s \times 2.0074\ kg/m^3$$

$$= 9.953 \times 10^{-4}\ kg/s$$

With this mass flow rate, gas consumption shown in tables B-8 and B-9 were worked out.

APPENDIX 3

DETAILED TABULATED DRYING PERFORMANCE OF VARIOUS DRYERS' DATA

APPENDIX B

DRYING CHARACTERISTICS AND LATEX DRYING PERFORMANCE OF V-RIDGE DRYERS DATA

Table B.11 Data on Testing Single Layer Rewetted Rubber, over Open Mat Version, Wood and Metal Type Street Wide Roller Dryers, at 140°C, Trial.

Time	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W
16/8/82																							
1.45 pm	31	31	30.8	34	36	38	46	47	43	37	37	37	33	20.6	20.6	20.6	20.6	940	61	26	32	32.7	2.5
1.35 pm	33.5	32.8	33.4	40	39	40	45	51	48	36	37	35	33.8	19.7	19.9	19.9	20.3	776	69.9	25.5	32	32.8	2.8
2.30 pm	33.1	33	33.3	34	42	39	45	44	43	36	34	40	34	19.2	19.6	19.4	20.0	813	64	25	31.8	33	2.17
3.45 pm	34	34	34	34	38	37	43	43	41	36	34	34	34	18.7	18.7	18.3	19.1	18.7	19.6	345	65	25	31.5	32	1.67
4.45 pm	30	31	30	34	38	37	43	43	41	36	34	34	34	18.4	18.7	18.6	18.7	19.1	20	87	31	32.5	32	2.33
17/8/82																							
7.30 am	34	34	34	33	34	33	33	34	33	34	34	34	33	17	18.4	17.5	19.1	110	87	21	33	34	2.83
9.30 am	28	28	28	28	32	35	37	41	41	33	35	34.7	35.6	16.5	18.2	16.9	19.9	440	60	22.5	37	38	1.83
11.00 am	31.3	31.6	31.4	38	40	40	39	37	37	37	38	40	34	15.9	17.5	16.4	18.6	810	40	24.5	36	31	0.92
1.00 pm	34	34	34.4	43	42	47	48	48	47	45	47	47	35.8	15.3	16.9	15.8	18.1	730	37	24.5	35.5	33.5	0.75
3.00 pm	36	37.7	35.8	47	46	44	52	46	47.4	50	40	43	36.4	14.8	16.3	15.5	17.7	340	40	25	33	35	0.50
5.00 pm	32.5	32.4	32.4	42	39.5	39	52	39.5	40	41	38	39.5	35	14.3	15.7	15.1	17.1	170	44	23.8	31	32.1	0.33
8.00 pm	29	29	29	37	30	28	29	25	28	29	28.8	28	26	13.9	15.1	14.8	16.5	3	89	22.5	29	29	1.58
18/8/82																							
7.30 am	24.5	24.5	24.5	24	25	33	30	29	31	28	28	28	23	13.3	14.6	14.3	16.0	250	76	22	27	27	2.10
9.30 am	30	30.6	30.3	34	3535	35	43	49	41	40	45	37	31	12.9	14.3	14	15.6	687	69.5	23	29	30	1.93

Table 8.1 Contd.

Date/Time	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	Time	Quantity of product dried in each dryer = 25kg	Initial moisture content = 20.6% wet basis
11.30 am																										
1.30 pm	37	37.4	37.8	33	60	50	58	53	44	39	50	51	40	11.8	14.8	3.0	14.8	810	43.7	25	34.5	33.8	0.92			
4.30 pm	31	31	31	14	38	36	40	28	14	40	34	31	34	11.4	11.5	12.5	14.6	40	43	24.6	30	31	0.67			
8. am	24	24	24	24	24	24	24	24	24	24	24	24	24	10.9	11.2	10.7	14.1	3	70	23	28	28	0.99			

EXPLANATION:

The Subscript 1 refers to small scale wood type dryer with rockbed heat storage.

The subscript 2 refers to small scale wood type dryer without rockbed heat storage.

The subscript 3 refers to small scale metal type dryer without rockbed heat storage.

The subscript 4 refers to traditional method of drying.

A - C = C_1IT, C_2IT, C_3IT = Collector air inlet temp. ^oC

D - F = C_1OT, C_2OT, C_3OT = Collector air outlet temp. ^oC

G - I = DS_1OT, DS_2OT, DS_3OT = Drying section air outlet temp. ^oC

J - M = P_1ST, P_2ST, P_3ST, P_4ST = Drying product surface temp. ^oC

N - Q = P_1MC, P_2MC, P_3MC, P_4MC = Drying product moisture content - wet basis.

R = Irrad. = Irradiation = solar insulation, W/m^2

S = R.H. = Relative Humidity, %

T = Wet bulb = Wet bulb temp. ^oC

U = Dry bulb = Dry bulb temp. ^oC

V = AMT = Ambient temp. ^oC

W = Wind speed - m/s

Time = Time of the day-hours

Quantity of product dried in each dryer = 25kg

Initial moisture content = 20.6% wet basis

Table 5.21 Data on Drying Deep Layer Rewetted Paddy, with Open,Sun Dryer, Wood and Metal Type Direct Mode Solar Dryers

Time Date	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	X	T	U	V	W
5/6/90																							
11.30 am	32	32	31.8	45	41	42	45	43	43	44	41	41	38	31.3	31.3	33.3	33.3	993	61	25.5	31	32	0.58
1.00 pm	32	32.7	34.1	47	47	43	47	44	50.2	44.2	41	41	39	35.2	35.2	32.5	32.5	807	50	27	33	33.7	1.67
3.00 pm	31	32	33.4	43	47	43.9	45	44.3	48.9	33	45	43.6	37	37.4	37.4	34.8	34.4	756	60	26.5	33	34	0.67
5.00 pm	34	34.7	34.85	49	44	48.9	38.4	44.3	50	42	47	42	38	37.4	37.4	37.5	37.5	612	49	26.5	32.9	33.6	0.92
6.00 pm	33.8	33.6	33.4	49	37	36	50	37	36	37.8	37	38	35	29.8	30.7	29.9	31.6	370	50	26	32.5	33	2.00
7.00 pm	33	33	46	38	36	47	38.3	37.2	37	36	36	36	34	29.4	30.3	28.6	31.4	319	48	24	31.6	32	1.67
7.30 pm	33	33	32	33	31	31.4	35	35.7	35.1	31	30.5	30	29	22.1	23.5	23.2	25.6	326	80	24.5	28.5	30	2.00
7.00 am	28	28	28	27	29	27	27.5	28	28	29	30	31	28	22.6	24.1	23.6	25.9	340	83	24.5	27.5	28	1.67
9.00 am	30.3	30	30.5	33.3	33	33	35	35.7	35.1	31	30.5	30	29	22.1	23.5	23.2	25.6	326	80	24.5	28.5	30	2.00

Product turned for uniform drying

Door open - Loose material on paddy sample collected from the opened portion

Door closed on the surface of moisture glass lid at the drying section

Dew still on the glass lid. Product turned.

Table 8.2 Contd.

11.[illegible] am	33	31.6	33.2	41	42	40.8	42	40	42	43	44	42	43	37	21.5	23.4	22	24.3	856	60	25	31	32	1.83
12.[illegible] noon	33.6	32	34	57	49	57	59	60	52	48	45	48	39	20.8	21.7	21.3	24.3	893	30.2	25.5	33	33.5	0.92
1.[illegible] pm	27	27	28	31	32	32	33	32	34.1	33	33	33.2	33	18.9	20	19	23.9	442	37	24.5	28	29	0.42

It rained from 1.. pm to 4.25pm.

4.[illegible] pm	25	25	25	32	24	24	24	24	24	25	24.3	24	24	16.2	22	12	23.9	16	7	22	23	25	2.58
5.00 pm	23	23	23	30	24	23.9	24.2	24	23	23	25	24.8	25	18.5	19.9	18.9	23.7	41	97	25	26	26	1.83

8/4/90

1.[illegible] pm	33	33.1	33.1	41	39	37.7	38	38	38	38.7	37	39	39	28	17.9	18.6	18.3	23.9	687	80.2	24.5	29	29	0.33
2.00 pm	34	33.1	33.6	39	39	39	39	40	38	38	38	39.4	38	17.9	18.3	18.2	23.9	688	80	24.5	27.7	32.6	1.00
3.00 pm	34	33.2	33.6	44	44	43.8	43	43	43.6	42	43	43	35	17.1	14.9	15.1	23.9	693	40	24.5	31.8	34.2	0.17

8/4/90

4.[illegible] pm	32	32.1	32.6	37	32	31.3	32	32	32	32	34	31.8	30	15.7	14.0	13.7	21.8	143	51	24	31	32	2.5

9/4/90 It rained heavily.

9.[illegible] am	28	28	28	33	28	27.7	28	28.3	27.8	27	27.6	25	24	11.7	13.1	12.8	21.8	700	85	23.5	26	28	2.17
2.00 pm	34	34	34	59	49.8	50	50	51	54	49	47	45	40	10.5	11.9	11.4	20.0	879	44	24.5	33	33.7	1.67
3.45 pm	34	33.9	33.9	56	49.0	51	52	50	51	49	48	48	40	10.1	11.8	11.1	19.5	708	44	24.5	33	33.8	0.67
4.00 pm	33	32.1	33.9	41	38	37	38	38	38	35	36	34	35	9.8	11.3	10.8	18.8	435	48	24.5	32	32.9	0.83
5.00 pm	33	33	33	39	34	35	33.5	33.0	39	37	36	35	30	9.2	10.6	10.4	18.5	219	50	24.5	32	32.5	0.92

Table B.2 Cont'd

DEFINITIONS

The subscript 1 refers to small scale wood type dryer with rockbed heat storage.

The subscript 2 refers to small scale wood type dryer without rockbed heat storage.

The subscript 3 refers to small scale metal type dryer without rockbed heat storage.

The subscript 4 refers to traditional method of drying.

A - C = C_1IT, C_2IT, C_3IT = Collector air inlet temp. - ^oC

D - F = C_1OT, C_2OT, C_3OT = Collector air outlet temp. - ^oC

G - I = DS_1OT, DS_2OT, DS_3OT = Drying section air outlet temp - ^oC

J - M = P_1ST, P_2ST, P_3ST, P_4ST = Drying product surface temp - ^oC

N - Q = P_1MC, P_2MC, P_3MC, P_4MC = Drying product moisture content - % Wet basis.

R = Irra. = Irradiation = Solar insulation - W/m^2

X = R.H. = Relative humidity - %

T = Wet bulb = Wet bulb temp. - ^oC

U = Dry bulb = Dry bulb temp. - ^oC

V = AMT = Ambient temp. - ^oC

W = Wind speed - m/s

Time = Time of the day-Hours

Quantity of product dried in each dryer = 50kg

Initial moisture content 33.3% Wet basis.

Table 4.4: Data on Drying Single Layer Knotted Groundnut, with Open Sun Drying, Wood and Metal Type Direct Mode Solar Dryers, 4 Jul/4PM, Ferix.

Time	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	X	T	U	V	W
13/6/90																							
11.30 am	31	31	31	47	40	47	45	47	46	39	39	39	37.0	37.5	37.5	37.5	37.5	980	60	24.5	28.0	31	1.67
1.00 pm	32	32.5	32.7	45	42	46	47	47	50	40	39	39.6	38	34	35	34	35.7	298	62	26.5	31.0	30	1.00
2.00 pm	37	32	31.8	46	42.5	43	51	46	48	39.5	37	38	37	31.0	33.5	33	34.4	430	57	24	31.5	31.5	1.83
3.00 pm	32	32	32	47	43	43	49	44.5	45	40	38	38	36	29.6	31.6	30.5	32.7	530	54	25.5	31.5	30	0.67
4.00 pm	31.5	31	30	47	39	31	37	33	31	36	34	33	32	27.3	30.1	29	31.2	210	68	25	30	30.8	1.18
14/6/90																							
9.00 am	35	34	34	50	45	50.5	50	49	51	44	44	43	41	37	39	39	41.5	450	67	23.5	30	32	2.00
11.00 am	30.5	31	30.7	47	38	46	47	47	48	46	46	47	38	25.7	28.5	28	30.3	480	77.5	26	35	30.3	2.58
1.00 pm	33	31.5	33.4	47	47	49	49	47	48	48	47	43	37	21.3	23.2	22.8	24.8	744	55.5	24.5	31	30	0.92
3.00 pm	32	31.5	31.8	47	35	43	47	42	41	35	36	32	30	18.2	21	20.2	22.7	334	45	24	30	31.5	0.83
6.00 pm	31	31.2	30.6	39	32	39	44	43	40	34	33	28	26	17.3	19.7	19.5	21	87	56.5	24	30	31	1.67
7.00 pm	28.1	28	28.1	35	28.2	36	41	37.5	37	32	29	28	28	16.8	19	18.2	20.3	3	71.5	23.5	27	28	0.25
15/6/90																							
8.00 am	26	26	26	35	29	30	37	33	34	31.5	30	31	30	16.7	18.8	18.1	20.4	385	98.7	23	26	26	2.1
11.00 am	32.6	3.25	32.3	35	31.5	36	41	41	37	47	45	48	35	14.5	16.9	16.1	18.8	658	70.8	25	30	31.5	1.37
1.00 pm	34	34.3	34.1	46	40	45	51	47	48	50	46	46	38	12.3	14.3	13.8	16.5	820	46	25	31.5	33	1.17
15/6/90																							
6.00 am	26	26.7	26.5	33	26	25	30	27	27	36	27	27	27	8.5	10.1	10.1	13.1	80	99	23	26	26	0.83
16/6/90																							
9.00 am	28.8	28.3	28.6	29	31	34	34	36	36	34	35	37	30	8.2	10.3	9.8	13.1	418	80.5	24	28	28.8	2.00
12.00 noon	30.5	30.1	30.9	38	37	39	42	39	40	44	40	44	37	7.0	9.3	8.7	12.0	539	70	24.5	30	30.7	0.75

Table B.3 Cont'd.

DEFINITIONS

The subscript 1 refers to small scale wood type dryer with rockbed heat storage.

The subscript 2 refers to small scale wood type dryer without rockbed heat storage.

The subscript 3 refers to small scale metal type dryer without rockbed heat storage.

The subscript 4 refers to traditional method drying.

A - C = C_1IT, C_2IT, C_3IT = Collector air inlet temp - ^oC

D - F = C_1OT, C_2OT, C_3OT = Collector air outlet temp - ^oC

G - I = DS_1OT, DS_2OT, DS_3OT = Drying section air outlet temp - ^oC

J - M = P_1ST, P_2ST, P_3ST, P_4ST = Drying product surface temp - ^oC

N - Q = P_1MC, P_2MC, P_3MC, P_4MC = Drying product moisture content - % wet basis.

R = Irra = Irradiation = solar insulation - W/m^2

X = R.H. = Relative humidity - %

T = Wet bulb = Wet bulb temp - ^oC

U = Dry bulb = Dry bulb temp - ^oC

V = AMT = Ambinent temp - ^oC

W = Wind speed = m/s

Time = Time of the day-hours

Quantity of product dired in each dryer = 19kg

Initial moisture content = 37.5% wet basis

Depth of layer = 6cm

Table B.41 Data on Tomato Variety Evaluation [illegible], with Open Sun Drying,
Wood and Solar Direct Type Dryers, at ARI/ARU - Zaria

Time Date	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W
31/5/90																							
1.00 pm	33	33	33	45	[illegible]					30.4	29.9	29.8	28	70	70	70	70	736	44	21.5	35.5	33	1.33
[illegible]																							
3.00 pm	35	34	34	47	47						33.6	33.6	33	69	65	62	60	68.5	707	30	27		34	33	0.67
4.30 pm	35	34	34.4	48	46						34.5	3	30	27	60.8	57	55.9	62.0	439	35	25		36.1	35	1.5
7.00 am	33	33	33	31	32						33.2	27	27	28	47.7	55	52.8	59	3	40	24		29	29	-
9.00 am	29	29	29	44	45						29.2	25	25	43.4	51	49	59	326	93	24.5	[illegible]		26	0.83
[illegible]																							
11.30 am	34	33.6	34	47	45.4						34.4	33	33	38	32.7	39	37.8	47.5	928	48	24.5	32	33	3.00
1.30 pm	35	34	34	49	49						34	33	49	42	23.9	30	39	40	588	50	26		33.5	34	0.50
5.00 pm	34	34	33.8	45	46						34.7	33	33	32.5	17.8	22	20.8	37.9	269	44	25		33	34	0.17
6.00 pm	37	37	34	38	37						37	33	33	30	15.2	20	18.8	35.9	69	46.8	24		37	37	0.05
2/6/90																							
8.00 am	27.6	27.6	27.6	26	26						24	24	24	24	13.5	18.5	17.1	34.2	266	33	23		27	28	2.83
10.00 am	33	33	33	39	38						32	33	45	38	11.6	16.4	15	32.3	811	67	25		30.5	33	2.17
12.00 noon	35	34	34.6	46	44						38	41	46	41	10.5	14.7	13.1	30	930	51	25		37.5	34	1.33
2.00 pm	35.5	34.5	35.5	50	47						48.9	48	47	34.5	8.6	12.9	10.9	27.9	730	60	25		34	34.5	1.00
4.00 pm	34	34.1	34.5	48	40						48.5	48	46	47	34	6.8	10	8	20	600	45	24.5	33	34	0.58

Table B.4 Cont'd.

DEFINITIONS

The Subscript 1 refers to small wood type dryer with rockbed heat storage.

The subscript 2 refers to small scale wood type dryer without rockbed heat storage.

The subscript 3 refers to small scale metal ty: rockbed heat storage.

The subscript 4 refers to traditional method drying.

A - C = C_1IT, C_2IT, C_3IT = Collector air inlet temp - ^oC

D - F = C_1OT, C_2OT, C_3OT = Collector air outlet temp - ^oC

G - I = DS_1OT, DS_2OT, DS_3OT = Drying section air outlet temp - ^oC

J - M = P_1ST, P_2ST, P_3ST, P_4ST = Drying product surface temp - ^oC

N - Q = P_1MC, P_2MC, P_3MC, P_4MC = Drying product moisture content - % Wet basis.

R = Irrad. = Irradiation = Solar insulation - W/m^2

X = R.H. = Relative humidity - %

T = Wet bulb = Wet bulb temp. - ^oC

U = Dry bulb = Dry bulb temp. - ^oC

V = AMT = Ambient temp. - ^oC

W = Wind speed m/s

Time = Time of the day - hours

Initial moisture content = 70% W.B.

Table 3.4: Drying of Single Layer Sliced Tomatoes, with Open Top

Drying, Loaded and Partially Dried in the Solar Dryer

Time Date	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	X	T	U	V	W
1/5/90																							
5 pm	30.5	31	32	42	40	44	45	44	40	38	33	34	36	40	43	46	50.5	448	35	31	33	33.5	1.10
4.30 pm	35	34	34	35	40	44	43	43	39	34	30	30	33	34	40	37	38.5	401	30	25	34	35	0.97
4.30 pm	35	34	34.5	50	48	48	46	49	50	46.6	35	40	35	48	76	71	87.3	438	35	25	34.5	35	1.5
7.00 pm	29	29	28	35	30	38	33	40	31	29.2	28	28	29	44	69	45	51	3	66	24	29	29	-
8.30 pm	28	28	28	30	34	34	34	37	28	30	31	33	29	41	47	42	51.5	4	65	23	28	28	-
1/6/90																							
8.30 am	26	24	26	25	24	27	25	26	31	29	27	28	28	47	44	42	84	126	91	22.5	24.5	26	2.33
11.0 am	29	29	29	30	32	34	32	34	40	40	37	43	38	47	49	50	80.4	120	74	23.5	28	28.5	2.17
12.30 pm	34	33.5	32	40	38.5	44	38	42	48	50	40	41.4	34	47	64.7	48	81.5	90.5	69	24.5	32	33	2.00
3.30 pm	35	34	34	36	38	42	40	42	50	49	42	46	36	54	63	60	78.0	168	72	26	33.5	34	0.92
5.30 pm	34	34	34.5	45	40	44	42	44	48	46	38	38	34	50	56	52	75.9	249	44	24	33	34	0.67
6.30 pm	31	31	31	34	34	37	34	36	38	38	31	40	32	44	49.5	44	71.5	69	14.8	24	31	31	0.58
8/5/90																							
8.00 am	27.5	27.5	27.5	28	28	30	29	30	27	28	27	28	31	37	39	34	71.5	168	93	23	27	28	2.33
10.30 am	33	33	33	34	35	37	34	36	38	38	34	38	35	51	69.5	57	84.2	311	67	25	30.5	33	2.17
12.30 noon	35	34	34	46	44	47	44	47	50	48	41	47	39	70	93.5	76	97	930	94	25	32.5	34	1.33
2.00 pm	34.5	35	34.5	50	47	49	48	51	53	49	37.5	37.5	33	57	91	78.5	94	730	60	25	34	35.5	1.00
4.00 pm	34	34	34.5	48	40	44	41.5	47	48.5	47	37	37	33	43	58	56	78	600	45	24.5	33	34	0.58

Table 5.3 Contin.

6.00 pm	31.5	31.5	31.5	43	32	37	41	40	40	40	40	39	30	17.0	16	15	57	76	50	23.5	31.5	31.5	0.33
10.00 am	35	34	34	48	47	43	51	53	55	50	47	48	37	11.5	12	14	57	889	49	25.5	34	34	1.25
2.00 pm	36	34	35.5	53	43	48	63	54	54.5	60	48	48.5	34	8.5	14	12	53	826	45	25.5	34	35	0.83
4.00 pm	33	32	32	50	39	40	53	47	47	48	47	48	33	7.0	11	9	49	496	40	25.0	32.5	33	0.67

DEFINITIONS

The subscript 1 refers to small scale wood type dryer with rockbed heat storage.

The subscript 2 refers to small scale wood type dryer without rockbed heat storage.

The subscripts 3 refers to small scale metal type dryer without rockbed heat storage.

The subscript 4 refers to traditional method of drying.

A-C = C_1IT, C_2IT, C_3IT = Collector air inlet temp. - ^{o}C

D-F = C_1OT, C_2OT, C_3OT = Collector air outlet temp. - ^{o}C

G-I = DS_1OT, DS_2OT, DS_3OT = Drying section air outlet temp. - ^{o}C

J- M = P_1ST, P_2ST, P_3ST, P_4ST = Drying product Surface temp. - ^{o}C

N- Q = P_1MC, P_2MC, P_3MC, P_4MC = Drying product moisture content %

R = Irradiation = Solar insulation - W/m^2

X = RH = Relative Humidity - %

T = Wet bulb = Wet bulb temp. - ^{o}C

U = Dry bulb = Dry bulb temp. - ^{o}C

V = AMT = Ambient temp. - ^{o}C

= Time = Time of the day - hours

W = Wind speed - m/s

= 7.73%

DRYER - A percentage cash flow gain advantage over the traditional drying method

= 43.62% - 7.73%

= 35.89%

The same method employed in calculating the Payback period and the dryer percentage cash flow gain advantage over the traditional drying method for DRYER - A was exactly followed in calculating for the remaining dryers.

Table 3.61: Data on Drying Single Layer Newly Harvested Okro, with Open Sun Drying, Single and Double Layer Wood Type Direct Ride Dryers at IAR/AMU, Zaria.

Time	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
[illegible]	28.1	28.1	28.3	28.6	32	30	[illegible]	[illegible]	[illegible]	33	39	47.6	46	[illegible]	34	27	26	34.5	27.2	34	34.8
[illegible]	29.4	29.3	29.5	29.7	30.4	34	[illegible]	[illegible]	[illegible]	40.6	39	44.6	44.4	47	41	43	41	33	46	44	33
[illegible]	32.7	30.3	33	33	47	47	[illegible]	[illegible]	[illegible]	48	46	47	48	47.3	50	51	50	40.8	47	45	34.5
[illegible]	33.1	33.5	34.1	34.4	48	47	[illegible]	[illegible]	[illegible]	48	48	49	49	[illegible]	38	34.5	34	42.4	44.5	48.1	37
[illegible]	33.4	33.9	34	34	48	47	[illegible]	[illegible]	[illegible]	47	48	48	48	49.1	42	42	49	43.1	41	47.2	36
[illegible]	33.9	33.9	34.8	35	33	33	[illegible]	[illegible]	[illegible]	33	34	33	34	34	39	30	35.6	34	35.6	43	38.2	31
[illegible]	34	34.5	27.6	27.5	27.6	27.3	31	32	[illegible]	27.4	27.3	29.8	30	29	27.5	28	28	29	30	29	27
[illegible]	27	27	27	27	26.8	26.8	[illegible]	27	[illegible]	26.7	26.6	27.5	27.1	27	27.5	27.6	27	27.7	27.1	27	27
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	32.4	32.6	32.7	32.8	32.6	33.5	33.4	33.7	34.5	34.5	34.6	26.5	26.6	26.6	26.6	26.9	26.8	26.7	32.3	32	32
[illegible]	26.5	26.4	26.6	26.5	26.6	26.3	26	[illegible]	26.8	26.8	26.6	26	26.7	26.6	26.6	26	26	26	26	26	26
[illegible]	28.5	28.6	28.9	28.5	31	30.4	31.6	30.9	28	33.7	34	34	36	35	29.6	35.9	34.3	34.2	38	37	29
[illegible]	39.1	39.2	[illegible]	[illegible]	39.1	39.4	39.4	39	38	39	39.2	39.7	40	[illegible]	30.8	32	45	45.1	37.7	[illegible]	[illegible]
[illegible]	41.5	41.6	[illegible]	[illegible]	43	[illegible]	[illegible]	[illegible]	42	42	[illegible]	[illegible]	[illegible]	[illegible]	40.7	43	43	44.9	44.6	43	44
[illegible]	43.3	43.7	[illegible]	[illegible]	47	47	[illegible]	[illegible]	[illegible]	46.2	46	[illegible]	[illegible]	[illegible]	41.9	51.7	49	51.5	51.8	49	48.6
[illegible]	44	44	44	44	46	46	47	[illegible]	[illegible]	46.7	47.4	35	33	34.8	39.2	34	36	36	33	37	36.8
[illegible]	45	45	45	45	46	46	47	[illegible]	[illegible]	47	47	47	47	47	47	47	47	47	47	47	47
[illegible]	47.3	47.3	47.6	47.6	47.4	47	47	[illegible]	[illegible]	47.5	47	47.5	47.4	47.7	47.1	47.7	44	45	[illegible]	[illegible]	46

Time	22	23	24	25	26	27	28	29	30	31	32	33	34
[illegible]	88	88	88	83	88	85	88	138	79	24	27.5	28	1.5
[illegible]	87.1	86.9	87	87.1	86.7	86.8	87	235	77	25	28	28.9	0.37
[illegible]	84.9	83.7	83.8	84.8	83.6	81.6	84.7	711	64	26.5	30	32	0.37
[illegible]	81.7	77.1	77.2	84.5	76.9	77	79.7	584	67	26	29.5	31	0.9
[illegible]	76.9	69.9	69.1	75.2	68.1	68.8	74	334	68	27	30	32.1	0.9
[illegible]	72.6	61.2	61.1	71.0	60.5	61.1	69.2	42	66	25.5	30	30.1	1.87
[illegible]	70.7	57.8	58	68.8	57.1	57.7	66.9	3	72	24	27.5	27.9	0.37
[illegible]	69.2	55.6	55.8	67.2	55.1	55.6	65.2	3	71	23.8	27	27	-
[illegible]	70.2	56.7	56.9	68.4	56.7	56.4	66.6	15	53	23	24.5	24.5	-
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	68.3	54.1	54.4	66.4	53.1	54.1	62.5	194	75	23.5	26	26.5	1.6
[illegible]	60	48.7	49.1	61.9	48.1	48.7	59.8	30.1	72	23.8	25.4	25.5	1.2
[illegible]	[illegible]	47.6	47	57.7	46.6	47.4	54.7	748	61	25	26	26.3	0.76
[illegible]	[illegible]	31.7	31.1	51.3	30.9	31.5	48.2	760	64	26	27.5	27.5	1.65
[illegible]	49.2	21.3	21.7	45.2	20.3	21.1	41.2	400	65	25	32	33	1.5
[illegible]	[illegible]	15.1	15.5	41.2	14.2	14.9	37.3	4	75	22	24	24	1.86
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	23	[illegible]	[illegible]	-
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	23.5	[illegible]	26.3	1.2
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	23.5	[illegible]	29	0.37
[illegible]	47.7	8.1	8.6	37.2	7.1	7.9	32.3	640	77	25	[illegible]	31.5	0.85
[illegible]	46	7.2	7.4	35	6.6	6.8	30	640	46	24.8	[illegible]	29	-

Table B.6 Cont'd.

DEFINITION OF TERMS

Subscripts 1 = Medium scale double layer vegetable/fruit wood type dryer without rockbed heat storage

2 = Small scale single layer vegetable/Fruit wood type dryer without rockbed heat storage.

3 = Medium scale double layer vegetable/fruit wood type dryer with rockbed heat storage.

4 = Small scale single layer vegetable/fruit wood type dryer with rockbed heat storage.

5 = Traditional drying method

d = Lower layer for double layer dryers (Indirect Mode)

U = Upper layer for double layer dryers (Direct mode)

1 - 4 = C_1IT, C_2IT, C_3IT, C_4IT = Collectors air inlet temp. ^oC

5 - 8 = C_1OT, C_2OT, C_3OT, C_4OT = Collectors air outlet temp. ^oC

9 -14 = DS_1OTd, DS_1OTU, DS_2OT, DS_3OTd, DS_3OTU, DS_4OT = Drying sections air outlet temp. ^oC

15 -21 = PST_1d, PST_1U, PST_2, PST_3d, PST_3U, PST_4, PST_5 = Drying product surface temp. ^oC.

22 -28 = P_1MCd, P_1MCU, P_2MC, P_3MCd, P_3MCU, P_4MC, P_5MC = Product moisture content, % wet basis.

29 = Irrad = Irradiation = solar insulation, W/m^2

30 = R.H. = Relative humidity

31 = Wet bulb = Wet bulb temp. ^oC

32 = Dry bulb = Dry bulb temp. ^oC

33 = AMT = Ambient temp. ^oC

34 = Wind speed, m/s

Initial moisture

Content = 88% wet basis

Quantity of product in each drying layer:
Dryers 1 and 3 = 0.51 kg
Dryers 2, 4 and 5 = 0.32 kg

Time = Time of the day -- hours

Drying dates June 5th to June 7th 1991.

Table 5.7: Data on Drying Single Layer Newly Harvested Tomatoes, with Open Sun Drying, Single and Double Layer Wood Tyre Direct Mode Dryers at IAR/ABU - Zaria.

Time	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
5/6/91	28.3	28.1	28.3	28.5	32	30	35.6	34	31	33	32	30.6	36	35	34.5	33	35	34.5	35	35	35
8.00																					
10.00	29.4	29.3	29.3	29.7	35.4	34	38.9	36	32	40.6	39	33.5	43.9	41	30	41	40	38	45	42	33
12.00 noon	35.8	37.3	38	33	42	39	46	42	39	48	46	47	55	51.9	37	50	49	39	57	53	55
2.00 pm	33.	32.5	34.1	34	46	42	53	47	40	50	49	43	60	54	38	53	51	40	64	57	37
4.00 pm	33.9	33.9	34	34	46	41	58	50	45	49	46	44	59.5	54	40	50	46.5	41	60	56	36
6.00 pm	30.3	30.7	31.1	30.9	43	37	52	38	35	34	33	35	44	39	38	36.5	33	34	47	48	30
8.00 pm	27.5	27.5	27.5	27.5	27.5	30.1	41	30	27..	27.4	27.3	29.8	30	29	27.5	27.4	27.3	29	30	29	27
9.00 pm	27	27	27	27	26.8	26.9	27.5	27	26.8	26.7	26.5	27.5	27.2	27	27	27	27	27	27.7	27.3	27.3	27
6/6/91																					
6.00 a	24.3	24.5	24.7	24.5	24.5	24.5	24.5	24.5	24.5	24.5	24.5	24	24.5	24.5	24.5	24.5	24.5	24.5	24.5	24.5	24.
8.00 a	5	26.4	26.4	26.5	26.2	26.1	26	26	26.8	26.8	26.6	26	26.8	26.4	26	26	26	26	26	26	26
10.00 a	5	28.4	28.5	28.5	31	30.4	31.5	30.9	28	33.7	34	34	35	35	30	34	33.9	33	38	36	29
	5	29.2	29.2	30	39.4	36.6	43.8	40	28	39	43.2	42.1	51	51	33.9	50	45	39	56	54	32
2.	.3	33.4	33.5	33.8	48	44	57	50	41	54	51	45	61	58	40	59	53	47	69	63	38
4.00 pm	33.3	33.1	33.7	33.4	47	43	59.2	52	40.8	48.4	44.5	42	61	56	41	49.5	46.2	49	64	58	38
5.30 pm	24	24	24	24	25	25	35	30	24.7	24.9	24.7	35	33	29.5	25.7	25	25	35	32.5	29	24.
7/6/91																					
6.00 am	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25
8.00 am	26.3	26.5	26.1	26.3	32.5	30	31	30	30	38	33	31	40	37.7	29	40	37	29	42	39	26
10.00 am	31	30.5	31	31	37	34.1	36.5	36	32	41	38.9	34	47.3	41.6	31	45	40.3	32	48.8	44.3	33
12.00 noon	33.3	33	33.6	33.4	43	41	48.2	46	39	58	42	45	60	50.5	32	52.8	44.8	33.4	59.4	57	35
2.00 pm	33.6	33.1	33.8	33.3	47.4	45	56	51	45.6	53	48.5	47	62.5	55.4	34.1	58.1	49.2	43	62	58	37

22	23	24	25	26	27	28	29	30	31	32	33	34
34	34	34	34	34	34	34	336	79	24.0	27.5	26	1.5
33.8	33.1	33.3	33.1	33.7	33.9	33.3	335	771	25	29	28.9	0.57
49.9	41.1	40.4	40.3	40.6	40.8	41.5	711	64	26.5	32	30	0.67
40.5	37.1	37	38.6	38.6	36.9	38.4	691	61	26	32.5	33	0.5
37.8	37.4	37.8	37.4	38.6	38.8	38	731	69	27	32	32.5	0.9
36.9	35.7	37.4	37.3	37.7	37.7	37.7	67	68	25.5	30	30.4	1.87
36.5	36.9	37	37	36.6	36.9	36.3	3	70	24	27.5	27.5	0.37
34.2	34.7	34.8	34.7	34.4	34.8	34.6	3	71	23.8	27	27	-
34.3	34	34.1	34.1	34.2	34.2	34.2	15	87	23	24.5	24.5	-
34.2	33.2	33.3	34.3	33.1	33.4	33.6	104	85	23.5	26	26.5	1.6
33.9	33.8	33.9	33.7	33.4	33.8	33.6	341	70	23.8	28.4	28.5	1.0
33.7	33.8	33.8	33.4	33.7	33.7	33.1	348	61	25	29	29.3	0.76
30.3	29.8	29.7	30.5	29.1	29.6	31.6	760	60	24	31.5	30.5	1.86
33.4	32.4	32.1	33.3	32.4	32.9	33	400	65	25	30	32	1.5
35.4	30.9	31	31	30.0	30.6	35.3	4	75	22	24	24	3.86
25	25	25	25	25	25	25	10	84	23	25	25	-
35.2	31.9	32	32	30.9	31.6	33.7	380	80	23.5	26	26.3	1.2
34.8	29.6	29.8	29.5	28.6	29.3	32.6	474	80	23.5	26.5	29	9.67
33.8	31.1	31.2	32.2	30.1	31	30.9	40	73	25	29.5	31.5	0.25
31.1	31.6	31.9	32.2	30.3	31.2	32.5	660	65	24.8	29.8	32	-

Table B.6a Drying of Single Layer Rewetted Maize with Hybrid Dryer without Solar Energy

Initial M.C. = 33% WB, Quantity = 40kg; Depth of Layer 5cm

Time	FT min.	Qg kg	Irra W/m^2	HEIT °C	CIT °C	COT °C	DOT °C	CPT °C	GT °C	$HWIT_1$ °C	$HWIT_2$ °C	$HWOT_1$ °C	$HWOT_2$ °C	FTF °C	FTD °C	Wet bulb °C	Dry bulb °C	AMT °C	PMC %
25/4/91 12 noon	12.15		580	28	28.3	27.9	27	27.5	27.1	30.8	30.8	30.8	30.8	30	30.6	24	30	31	33
12.30	12.45	1.792	520	28.5	55	54.9	50	33	37	450	445	60	55	460	433.4	24	30	31	31.6
1.00	=30		550	30	71	70	57	42	37	500	490	66.7	58.5	515	474	24.5	31	31.5	29.9
1.30			480	30	42.5	42	39	33	46	50	45	38.5	34	43	38.5	24.5	30	31.5	28.1
2.00	2.15		431	31	41.5	41	40	32.9	34	46	43	33	32	42	31.5	26	31	32	26.5
2.30	2.45	1.792	456	32	60	60	50	35	43	420	409	58.4	43.8	436	408	26	31	32	25
3.00	=30		380	31	70	70	65	44	45	490	478	67.7	51.4	505	465	25.5	31	32	23.7
3.30			331	32	46.3	46	44	30	40	146	130	53.9	40	156	140	25.5	31	32.5	22.1
4.00	4.15	2.389	326	31	38	38	37	32.8	35	54	50	39.4	34.5	40	33	24.5	30	32	20.8
4.30	4.55 =40		407	32	50	50	43	40	39	107	92	40.0	37	430	410	24	30	31	19.8
5.00			250	32	62	61	55	49	46	480	467	64.3	53	500	472	24	29.5	30	18.7
5.30			110	31	56	54.2	50.2	40	40	350	34.5	45.6	39.5	260	235	24	29	30	17.4
6.00	6.15	1.792	56	30	35.4	35	34	31	35	69	68	37	36	60	53	23.8	29	29	16.7
6.30	6.45 =30		12	29	55.8	55.6	51.7	39	41	153	137	41	37	475	447.5	23.8	28.7	29	15.8

Table B.8 Cont'd.

24/4/91																		
7.00	7.35		3	28	57	56.1	53.1	42	45	360	343	55.8	40	490	461.7	23.8	28.5	28.5	14.4
7.30	8.05	1.792	3	28	36.8	36.8	36	32	38	70	68	33	32	65	55.9	23.5	28.5	28.5	13.4
8.00	=30		3	27.5	61	62	59	43	40	470	465	63	55	489	455.5	23	28	28	12.7
8.30			3	27.5	35.1	35	34.7	34	35	66	63	34	32.5	62	54.6	23	28	28	11.8

DEFINITION OF THE SUBSCRIPTS

FT = Firing time - minutes

Qg = Qunatity of gas used - kg

Irra. = Irradiation = solar insulation - W/m^2

HEIT = Heat exchanger air inlet tempr. - ^oC

CIT = Collector air inlet temp. - ^oC

COT = Collector air loutlet temp. - ^oC

DOT = Drying section air outlet temp. - ^oC

CPT = Collector plate temp. - ^oC

GT = Glass cover temp. - ^oC

$HWIT_1$ = Heat exchanger inside down wall temp. - ^oC

$HWIT_2$ = Heat exchanger inside up wall temp. - ^oC

$HWOT_1$ = Heat exchanger outside down wall temp. - ^oC

$HWOT_2$ = Heat exchanger outside up wall temp. - ^oC

FTF = Flue temp. above flame - ^oC

FTD = Flue temp. through the duct - ^oC

Wet bulb = Wet bulb temp. - ^oC

Dry bult = Dry bulb temp. - ^oC

AMT = Ambient temp. - ^oC

PMC = Drying product moisture content - % Wet basis.

Table 3.9: Drying of Single Layer Sweetcut Maize with Petrid Dryer with Solar Energy

INITIAL M.C. = [illegible]; Quantity = [illegible]; Depth of Layer 5cm.

Time	ET min	ΔW kg	Irrg. w/m²	TIT °C	BIT °C	ADT °C	BOT °C	CAT °C	GT °C	MXIT$_1$ °C	MXIT$_2$ °C	MXOT$_1$ °C	MXOT$_2$ °C	XTF °C	XTD °C	Wet bulb °C	Dry bulb °C	AMT °C	RHC %
26/4/94																			
12.00 noon			490	33	31	47	36	53	43	35	35	35	35	34	34	26	34	35	33
12.30 pm	12.25 to		905	34	40	46	38	56	44	237	218.5	50	46.7	440	400	26	34	37.4	31
1.00	1.01 = 36	0.15	900	30	41	48	41	61	43	400	369.1	61	57	490	429.8	26	34	35	29
1.30			880	33	36	44	39	56	42	82	78.9	39	37	60	55	26	34	35	26.9
2.00	2.10 to		700	31	34	38	43	65	42	430	400	16.9	58	450	400.5	25.5	33.8	36	26.8
2.30	2.40 = 30	0.079	815	33.5	37	42	43	63	42	62	56	37	35.9	46	43	25.5	34	33.4	29
3.00	3.10 to	109	779	33	40.6	39	46	76	42	450	430.8	60.5	57.8	460	410.5	25.5	34	36	31.4
3.30	3.40 = 30	0.097	693	30.5	42	48	40	65	46	85	74.1	41	37.3	70	62.5	25	33.8	33.4	30.0
4.00	4.10 to		557	30.5	43	53	41	65	46	463	439.5	62.3	58.9	480	430	25	33.5	33.5	28.6
4.30	4.40 = 30	0.067	445	32	44	54	47	67	38	44	39.5	16	14.1	45	38	25	33.8	34	31.4
5.00	5.10 to		163	31	43	54	46	66	43	380	360	66.4	53.4	405	345	25	33	37	34.2
5.30	5.40 = 30	0.174	85	29	34	38	38	55	50	410	417.4	60.0	56.7	410	360	23.7	28.7	34.7	21.0
6.00	6.10 to		58	28	31	34	37	57	37	55	50	33	35.6	78	62	23.7	28.7	37	23.7
6.30	6.40 = 30	0.027	17	27	43	43	53	60	39	390	368	61	54.9	405	373	23.5	28	34.5	17.4
7.00			3	27	30	35	37.5	37	33	63	59	33	31.8	90	86	23.5	28	28	11.6

Table B.9 Cont'd

DEFINITION OF THE SUBSCRIPTS

FT = Firing Time - minutes

Qg = Quantity of gas used - kg

Irra. = Irradiation = Solar insulation = W/m^2

HEIT = Heat Exchanger air inlet tem. - ^oC

CIT = Collector air inlet temp. - ^oC

COT = Collector air outlet temp. - ^oC

DOT = Drying section air outlet temp. - ^oC

CPT = Collector plate temp. - ^oC

GT = Glass cover temp. - ^oC

$HWIT_1$ = Heat exchanger inside down wall temp. - ^oC

$HWIT_2$ = Heat exchanger inside up wall temp. - ^oC

$HWOT_1$ = Heat exchanger outside down wall temp. - ^oC

$HWOT_2$ = Heat exchanger outside up wall temp. - ^oC

FTF = Flue temp. above flame - ^oC

FTD = Flue temp. through the duct - ^oC

Wet bulb = Wet bulb temp. - ^oC

Dry bulb = Dry bulb temp. - ^oC

AMT = Ambient temp. - ^oC

PMC = Drying product moisture content - % Wet Basis

Table B.10: Data on Drying of Newly Harvested Maize with Medium Scale Wood Type Dryer at Jere in Kaduna State

Time	CIT ^{o}C	COT ^{o}C	DOT ^{o}C	PMC %	Irrad. W/m^2	Wet bulb ^{o}C	Dry bulb ^{o}C	AMT ^{o}C	Wind speed m/s
13/9/90									
2.30 pm	35	57	62	20	981	26	33.8	34	0.5
6.30 pm	31	46	48	18.3	101	24	30	31	1.83
14/9/90									
10.30 am	29	37.5	41	17.7	318	23.8	29	29	1.5
2.30 pm	33	51	58	16.3	891	25	32.7	33	0.17
6.30 pm	30	46	44	14.5	94	24	30	30	2.00
15/9/90									
10.30 am	28	30	30	14	275	23.7	28	28	1.67
2.30 pm	34	59	66	13.1	680	26	33.8	33.9	0.25
6.30 pm	31.5	35	36	12.2	200	24.1	30.8	31	1.37
16/9/90									
10.30 am	29.5	36	39	12.1	302	23	28	29	0.67
2.30 pm	34	57	63	11.5	966	25.5	33	33.5	0.27

Quantity of Product (Unthreshed Maize) = 150kg

Initial Moisture Content - 20% Wet Basis

Definition of the Subscripts for Table

Time = Time of the Day-Hours
Irrad. = Irradiation = Solar Insulation - W/m^2
CIT = Collector air inlet Temp. - ^{o}C
COT = Collector air outlet Temp. - ^{o}C
DOT = Drying Section air outlet Temp. - ^{o}C
Wet bulb = Wet bulb Temp. - ^{o}C
Dry bulb = Dry bulb Temp. - ^{o}C
Wind speed = m/s
AMT = Ambient Temp. - ^{o}C
PMC = Drying Product Moisture Content - % Wet Basis

Table B.11: Data on Drying of Newly Harvested Maize and Groundnut with Large Scale Metal Type Dryer at New-Wuse, Niger State.

Time	CIT ^{o}C	COT ^{o}C	DOT ^{o}C	PMC_1 %	PMC_2 %	PMC_3 %	Irra. W/m^2	Wet bulb ^{o}C	Dry bulb ^{o}C	AMT	Wind speed m/s
8/9/90											
1.00 pm	34	54	51	27	24	19	989	25	32	33	1.58
6.30 pm	28	28	29	23.5	21.5	16	56	23	28	28	1.83
9/9/90 10.30 am	29	33	35	22.5	20.9	12.4	425	23.7	30	31	0.5
2.30 pm	35	58	60	21.3	18.7	9	888	24.6	32	33.5	0.25
6.30 pm	30	30.5	31	18.4	15.3		44	24	31.5	32	1.67
10/9/90											
10.30 am	28.9	34	35	17.5	14.3		500	24.5	29.5	30	1.5
2.30 pm	34	57	59	16.2	12.7		820	25.5	32.5	33	0.38
6.30 pm	31	35	35	14.2	11.7		170	24.1	31	31	1.00
11/9/90											
10.30 am	30	41	42	13.9			703	23	28	30	2.5
2.30 pm	33	45	50	13			700	25	31	32.3	1.67
6.30 pm	28	27	27	12.3			75	22	25	25	2.00
12/9/90											
10.30 am	29	34	36	12.2			260	23	28	28	1.5
2.30 pm	35	59	63	11.6			970	26	34	35	0.28

Quantity of Product

Mazie: Unthreshed = 250kg; Initial, M.C. = 27%
Threshed = 50kg, Initial, M.C. 24%
Groundnut: 20kg, Initial M.C. 19%

Definition of the Subscripts for Table
Time = Time of the Day-Hours
Irrad. = Irradiation = Solar Insulation - W/m^2
CIT = Collector air inlet Temp. - ^{o}C
COT = Collector air outlet Temp. - ^{o}C
DOT = Drying Section air outlet Temp. - ^{o}C
Wet bulb = Wet Bulb Temp. - ^{o}C
Dry bulb - Dry Bulb Temp. - ^{o}C
Wind speed - m/s
AMT = Ambient Temp. - ^{o}C
PMC_1 = Drying Product (Unthreshed Maize) Moisture Content - % Wet Basis
PMC_2 = Drying Product (Threshed Maize) Moisture Content - % Wet Basis
PMC_3 = Drying Product (Groundnut) Moisture Content - % Wet Basis

Table B.12:d Drying Newly Harvested Groundnut, with Large Scale Metal Type Dryer at Kwaka, Niger State

Time	CIT °C	COT °C	DOt °C	PMC %	Irra. W/m²	Wet bulb °C	Dry bulb °C	AMT °C	Wind speed m/s
8/9/90									
12.00	31	58	65	29	820	24	29	30.5	1
5.00 pm	30	41	42	27	340	23	28	29	0.64
9/9/90									
9.00 am	29	35	37	26.5	760	23	29	29	1.5
1.00 pm	32	54	66	25	960	25.6	31	32	0.85
5.00 pm	30	45	45	23	270	24	30	30	1.17
10/9/90									
9.00 am	29.8	40	42	22.6	326	24.3	28	29	2.0
1.00 pm	34	54	61	20.5	970	25.5	32	33	0.67
5.00 pm	31	43	45	16.9	160	24	30	31	1.33
11/9/90									
9.00 am	29	38	41	15.2	290	23.4	29	29	2.67
1.00 pm	33	50	58	13.8	950	26	31.7	32.5	0.17
5.00 pm	29.7	39	41	11.6	230	23.7	29	29	0.92
12/9/90									
9.00 am	28.8	36	36	9.3	120	23	28.3	29	2.00
1.00 pm	33.5	49.5	55.7	7.5	920	25.5	32	32.2	0.17

Quantity of Groundnut 73.5kg

Initial Moisture Content 29% Wet Basis.

Depth of layer 4cm

Definition of the Subscripts for Table

Time = Time of the Day - Hours
Irra. = Irradiation = Solar Insulation - W/m^2
CIT = Collector air inlet Temp. - °C
COT = Collector air outlet Temp. - °C
DOT = Drying Section air outlet Temp. - °C
Wet bulb = Wet Bulb Temp. - °C
Dry bulb = Dry bulb Temp. - °C
Wind speed - m/s
AMT = Ambient Temp. - °C
PMC = Drying Product Moisture Content - % Wet Basis

Table b.12:b Drying of Newly Harvested Groundnut, with Large Scale Metal Type Dryer at Kwako, Niger State

Time	CIT	COT	DOT	PMC_1	PMC_2	Irrn.	Wet bulb	Dry bulb	AMT	Wind speed
	°C	8C	°C	%	%	W/m^2	°C	°C	°C	m/s
13/9/90										
1.00 pm	33	51	67	30	30	950	25	30	32	1.67
5.00 pm	30	39	40	26	28	220	24	29	30	0.17
14/9/90										
9.00 am	28	30	32	23	27.5	366	23.5	27.5	28	0.58
1.00 pm	34	56	58	19	26	800	25	31	32	1.00
5.00 pm	30	33	36	17	23	100	24.8	29	30	0.08
15/9/90										
9.00 am	28.5	31	34	14	22.1	350	24	27.8	28	0.5
1.00 pm	36	52	56	13.6	20.5	699	25	32	33	0.33
5.00 pm	31.5	40	43	12	18.1	200	24	30.5	31	0.83
16/9/90										
9.00 am	29	34	36	10	17	400	23.7	29	29	0.67
1.00 pm	35	58	70	8.7	15.3	985	25	32	33	0.25
5.00 pm	32	47	48	7.8	12.5	263	24	30	31	0.83

Quantity of Groundnut 100.0kg

Initial Moisture Content % Wet Basis

Depth of Layer 5.5cm

Definition of the Subscripts for Table

Time = Time of the Day-Hours
Irrad = Irradiation = Solar Insulation - W/m^2
CIT = Collector air inlet Temp. - °C
COT = Collector air outlet Temp. - °C
DOT = Drying Section air outlet Temp. - °C
Wet bulb = Wet bulb Temp. - °C
Dry bulb = Dry bulb Temp. - °C
Wind Speed = m/s
AMT = Ambient Temp. - °C
PMC_1 = Product Moisture Content Dried with the metal dryer - % Wet Basis
PMC_2 = Product Moisture Content Dried by Traditional Method - % Wet Basis

Table B.13: Drying of Single Layer Newly Harvested Fresh Maize with the Large Scale Mud Type Dryer at Jere, Kaduna State

Time	Irrad. W/m^2	CIT ^oC	COT ^oC	DOT ^oC	Wet bulb ^oC	Dry bulb ^oC	Wind speed m/s	AMT ^oC	PMC %
14/5/91 9.00 am	411	27.5	29.5	34	23	27	1.17	27.5	30
12.00 noon	154	30	41	55	25	26.8	0.67	28	28.5
5.00 pm	108	31.5	33	35	23.5	29.2	-	27	25.8
15/5/91 9.00 am	320	28.4	29	30	23.7	26.8	1.5	28	25
12.00 noon	790	34	52	59	24.6	32	0.23	33	23.9
5.00 pm	211	30.8	38	42	23	29	0.11	30.8	22.2
16/5/91 9.00 am	706	29.1	33	38	23	27.1	0.99	29	21.5
12.00 noon	884	33.8	54	62	26	31.5	0.25	33	19.7
5.00 pm	183	32	36	39	24	28.7	-	31	17.8
17/5/91 9.00 am	110	27.5	30	31.6	22.8	27	1.85	27	16.1
12.00 noon	930	35	52	58	25.9	33.5	0.76	34.5	14.8
5.00 pm	76	31	34	37	24	29	1.8	31.2	13.6
18/5/91 9.00 am	150	29	30	32	23.1	28	1.67	29	13
12.00 noon	741	32	43	37.5	24	30.3	0.83	31.8	12.3
5.00 pm	88	25	31	33	22.6	24.5	0.99	24.5	11.5

Definition of the Subscripts

Time = Time of the Day-Hours
Irrad. = Irradiation = Solar Insulation - W/m^2
CIT = Collector air inlet Temp. - ^oC
COT = Collector air outlet Temp. - ^oC
DOT = Drying Section air outlet Temp. - ^oC
Wet bulb = Wet Bulb Temp. - ^oC
Dry bulb = Dry Bulb Temp. - ^oC
Wind Speed - m/s
AMT = Ambient Temp. - ^oC
PMC = Drying Product Moisture Content, - % Wet Basis

Table B.14: Drying of Single Layer Newly Harvested Fresh Maize, with the Large Scale Mud Type Dryer at New-Wuse, Niger State.

Time	Irrad. W/m^2	CIT ^oC	COT ^oC	DOT ^oC	Wet bulb ^oC	Dry bulb ^oC	Wind speed ^oC	AMT ^oC	PMC %
14/5/91									
8.00 am	210	27.5	28	30	23	27	1.33	27.5	30
1.00 pm	350	30	38	45	23	25	1.4	28	28.8
6.00 pm	51	30	32	33	24	29	1.05	27.9	26
15/5/91									
8.00 am	110	25	29	30	22.7	25	1.9	25	25.3
1.00 pm	913	34.9	56	62	26	33	-	34	24
6.00 pm	181	28.5	30	33.5	24	28	0.97	28.2	22.1
16/5/91									
8.00 am	195	28	29	29.6	23.5	28	0.83	28	21.4
1.00 am	783	33	42	48	24	31	0.67	32.7	19.9
6.00 am	66	29.2	30	31	23.2	28.5	-	29	18
17/5/91									
8.00 am	230	26.7	28	29	23	26.3	1.8	26.6	17.2
1.00 pm	881	34.3	54	61.8	25.3	32	0.74	33.8	15.6
6.00 pm	48	28.5	33	33	24.1	28	-	28	13.4
18/5/91									
8.00 am	91	26	29	29	22.4	26	0.11	26	12.9
1.00 pm	779	33	41	47	24.9	31	0.7	32.5	12.1
6.00 pm	59	28.4	29	29	24	28	0.82	28	11.2

Definition of the Subscripts

Time = Time of the Day-Hours
Irrad. = Irradiation = Solar Insulation - W/m^2
CIT = Collector air inlet Temp. - ^oC
COT = Collector air outlet Temp. - ^oC
DOT = Drying Section air outlet Temp. - ^oC
Wet bulb = Wet Bulb Temp. - ^oC
Dry bulb = Dry bulb Temp. - ^oC
Wind Speed - m/s
AMT = Ambient Temp. - ^oC
PMC = Drying product moisture content - % Wet Basis

APPENDIX C

DETAILED EXPLANATION OF THE COST
ANALYSIS FOR EACH OF THE DRYERS

Table C.1: Dryer 'A' Cost Estimate Analysis

Materials	Size	Qty.	Net cost
			N k
Black Afra	0.025m x 0.305m x 3.66m	4	150.00
Black afra	0.05m x 0.305m x 3.66m	2	84.00
Plywood	0.0006.5m x 1.2m x 2.5m	0.25	45.00
Glass cover	0.003mx0.61m x 1.22m	2	80.00
Polypr. foam	0.02m x 1.22m x 1.83m	1	20.00
Expanded metal sheet	0.6m x 1.21m	1	60.00
Wire netting	0.6m x 1.21m	1	10.00
Rock			3.50
Nails			10.00
Hinges	5cm	2	5.00
Stapple	5cm	1	2.00
Black paint		0.125 gallon	25.00
Aluminum pant		0.125 gallon	25.00
	TOTAL		₦519.00

Table C.2: Dryer B Cost Estimate Analysis

Materials	Size	Qty.	Net cost
			₦ k
Black afra	0.025m x 0.305m x 3.66m	4	150.00
Black afra	0.05m x 0.305m x 3.66m	2	84.00
Plywood	0.00625m x 1.22m x 2.[illegible]m	½	45.00
Glass cover	0.003m x 0.61m x 1.22m	2	80.00
Polypr. foam	0.02m x 1.22m x 1.03m	1	20.00
Expanded metal sheet	0.6m x 1.22m	1	60.00
Wire gauge	0.6m x 1.22m	1	10.00
Nails			10.00
Hinges	0.05m	1 pair	5.00
Staple	0.05m	1	2.00
Black paint		0.125 gallon	25.00
Aluminum paint		0.125 gallon	25.00
		TOTAL	₦516.00

Table C.3: Dryer C Cost Estimate Analysis

Materials	Size	Qty.	Net Cost
			₦
Galvanized metal sheet	(18 gauge) 1.22mx2.44m	1.5	300.00
Mild steel sheet	(20 gage) 1.22m x2.44m	0.25	75.00
Plain glass	0.003m x 0.61m x 1.22m	2	80.00
Polyur. foam	0.02m x 1.22 x 1.83m	1	20.00
Angle iron	0.05 x 0.05 x 6.1m	1.5	140.00
Expanded metal sheet	0.6m x 1.22m	1	60.00
Wire gauge	0.6m x 1.22m	1	10.00
Filler rods, welding rods, brazing rods and electrods			20.00
Hinges	0.05m	1 pair	5.00
Stapple	0.05m	1	2.00
Black paint		0.125 gallon	25.00
Alluminum pant		0.125 gallon	25.00
		TOTAL	₦732.00

Table C.4: Dryer D Cost Estimate Analysis

Materials	Size	Qty.	Net cost
			₦ k
Black afra	0.025m x 0.305m x 3.66m	3	112.50
Black afra	0.05m x 0.305m x 3.66	1.5	84.00
Plywood	0.00625m x 1.22m x 2.44m	0.4	100.00
Polythene (plain)	0.65m x 2.6m	1	20.00
Polypr. foam	0.02m x 1.22 x 0.55m	1	35.00
Nylon netting	0.5m x 1.22m	1	15.00
Nails			20.00
Hinges	0.05m	1 pair	5.00
Stapple	0.05m	1	3.00
Aluminum paint		0.125 gallon	25.00
Black paint		0.125 gallon	25.00
		TOTAL	₦444.50

Table C.5: Dryer Cost Estimate Analysis

Materials	Size	Qty.	Net cost
			₦ k
Black afra	0.025m x 0.305m x 3.66m	3	112.50
Black afra	0.05m x 0.305m x 3.66m	1.5	84.00
Plywood	0.00625m x 1.22m 2.44m	0.4	100.00
Rock		40.95kg	6.15
Plain polythene	0.65m x 2.6m	1	20.00
Polypr. foam	0.02m x 1.22m x 0.55m	1	35.00
Nylon netting	0.5m x 1.[illegible]m	1	15.00
Nails			20.00
Hinges	0.05m	1 pair	5.00
Stapple	0.05m	1	3.00
Aluminum paint		0.125 gallon	25.00
Black paint		0.125 gallon	25.00
		TOTAL	₦450.00

Table C.6: Dryer F Cost Estimate Analysis

Materials	Size	Qty.	Net cost
			₦ k
Black afra	0.025m x 0.305m x 3.66m	5.5	206.25
Black afra	0.05m x 0.305m x 3.66m	2.5	124.00
Plywood	0.00625m x 1.22 x 2.44m	1.2	300.00
Polythene (plain)	0.[illegible] 3.2m	1	38.00
Polypr. foam	0.02m x 1.0[illegible]	1	79.50
Nylon netting	1.52 x 3.00m	1	30.00
Nails			36.00
Hinges	0.05m	2	5.00
Staple	0.05m	1	3.00
Aluminum paint		0.125 gallon	25.00
Black paint		0.125 gallon	25.00
		TOTAL	₦871.75

Table C.7: Dryer G Cost Estimate Analysis

Materials	Size	Qty.	Net cost
			₦ k
Black afra	(0.025 x 0.305 x 3.66)m	5.5	206.25
Black afra	0.05mx 0.305m x 3.66m	2.5	124.00
Plywood	0.00625m x 1.22m x 2.44m	1.2	300.00
Polythene (plain)	0.97m x 3.2m	1	30.00
Polypr. foam	0.02m x 1.0 x 1.5m	1	73.50
Rock		70.65kg	10.60
Nylon netting	1.52 x 3.00m	1	30.00
Nails			35.00
Hinges	0.05m	1 pair	5.00
Stapple	0.05m	1	3.00
Aluminum paint		0.125 gallon	25.00
Black paint		0.125 gallon	25.00
		TOTAL	₦082.35

Table C.8: Dryer H Cost Estimate Analysis

Materials	Size	Qty.	Net cost
Galvanized metal sheet	gage 18, (1.22x2.44)m	7	4,200.00
Mild steel sheet	gage 20, (1.22mx2.44)m	2	900.00
Mild steel sheet	0.003m x 1.22 x 2.44m	1.5	1,500.00
Mild steel sheet	0.01m x 1.22 x 2.44m	0.25	600.00
Angle iron	0.025m x 0.025m x 6.0m	5	340.00
Angle iron	0.05m x 0.05m x 6.0m	2.5	170.00
Flat bar	0.05m x 6.0m	2	130.00
Metal rod	0.05m x 9.0m	1.5	97.50
Galvanized pipe	0.05 external diameter by 6.0m	0.5	40.00
Galvanized pipe	0.05 internal diameter by 6.0m	0.5	40.00
Glass	0.003 x 0.61m x 1.22m	8	280.00
Expanded metal sheet	1.2m x 2.4m	1	90.00
Wire netting	1.2m x 2.4m	1	40.00
Polypr. foam	0.1m x 1.2 x 2.4m	1.5	140.00
Polypr. foam	0.05m x 1.2 x 2.4m	1.5	75.00
Filler rods, welding rods, brazing rods, and electrods			50.00
Black paint		1 gallon	150.00
Aluminum paint		1.5 gallon	180.00
Electric motor	Single phase, 1.5kW	1	2,900.00
Gas burners	Large size	3	860.00
		TOTAL	₦12.783.50

Table C.9: Dryer J Cost Estimate Analysis

Materials	Size	Qty.	Net Cost
			M k
Black afra	0.025m x 0.305m x 3.66m	6	225.00
Black afra	0.05m x 0.305 x 3.66m	3	168.00
Plywood	0.00625m x 1.22m x 2.44m	0.5	90.00
Polypr. foam	0.05m x 1.22 x 2.44m	1	60.00
Expanded metal	1.2m x 2.4m	1	90.00
Adhensive seal		1 gallon	200.00
Glass	0.003 x 0.6 x 1.2	1.5	525.00
Wire netting	(1.2 x 2.4)m	1	30.00
Soligmum		1 gallon	180.00
Nails			30.00
Aluminum paint		1 gallon	120.00
Black paint		0.5 gallon	75.00
		TOTAL	M1,793.00

Table C.10: Dryer I Cost Estimate Analysis

Materials	Size	Qty.	Net Cost
			₦ k
Mud blocks	0.15m x 0.2m x 0.3m	900	600.00
Cement (Benue)		5	300.00
Black afra	0.05m x 0.305m x 3.66m	8	468.40
Glass	0.005m x 1.2 x 2.4m	3.5	1,400.00
Doors	1.2m x 2.4m	4	800.00
Soligmum		1.5 gallon	270.00
Adhesive seal		1 gallon	200.00
Expanded metal sheet	1.2 x 2.4m	2	180.00
Wire netting	1.2m x 2.4m	2	65.00
Black paint		0.5 gallon	75.00
Nails, sand, soil and water			100.00
		TOTAL	₦4,458.40

Table C.11: Dryer L Cost Estimate Analysis

Materials	Size	Qty.	Net cost
Galvanized metal sheet	18 gage(1.2 x 2.4)m	1.75	4,200.00
Mild steel sheet	20 gage(1.2 x 2.4)m	1.75	787.50
Angle iron	0.005m x 0.05 x 6m	3	204.00
Angle iron	0.005m x 0.025m x 6m	5	340.00
Flat bar	0.05m x 6.0m	3	195.00
Metal rod	0.05m x 9m	1.5	97.50
Galvanized pipe	0.05 internal diameter by 6.0m	0.5	40.00
Galvanized pipe	0.05 external diameter by 6.0m	0.5	40.00
Glass	0.005m x 1.2m x 2.4m	3.5	1,400.00
Expanded metal	1.2m x 2.4m	2	180.00
Wire netting	1.2m x 2.4m	2	60.00
Polypr. foam	0.05m x 1.2 x 2.4m	1	70.00
Adhesive seal		1.25 gallon	240.00
Black paint		0.5 gallon	75.00
Filler rods, welding rods, brazing rods and electrode			90.00
Hinges	0.05m	4	20.00
Stapples	0.05m	2	4.00
		TOTAL	₦8,043.00

Dryers I, K and M are similar in structure and total material cost. Likewise Dryers L and N are similar in structure and total material cost.

APPENDIX C-2

I. Calculation of The Payback Period Of The Solar Crop Dryers And The Hybrid Crop Dryer.

II. Calculation Of The [illegible] And The Traditional Drying Method Percentage Cash Flow Gain.

In order to calculate the payback period of the dryers and the annual percentage cash flow gain, the following points are specified.

- The total estimated cost (initial investment) of each dryer show in Table 5.3 is used.
- The prices of undried and dried crops as well as the labour cost were given by the farmers at Jere, New-Wuse Kwǎka and Zaria - Hunkuiyi at the prevailing market price in 1991.
- The quantity of crops a farmer can produce in a year, the percentage cost due to traditional drying method and the farmers financial capability to purchase any of the given dryers were found through the Rapid Rural Appraisal (RRA) approach.
- The farmers indicated that they dry their crops on the elevated hard surface ground. Therefore the cost of the traditional crop drying container is assumed to be zero.
- Keith (1989) gave the formula applied in calculating the payback period of the dryers.
- The method of calculating the percentage cash cflow gain was assume.

- Tomatoes and maize only were the crops considered in the calculation of the payback period and the percentage crop cash flow gain, because these crops are produced in large quantity and they have the greatest drying problems.
- Each of the farmers produces a number of different crops, and each of the dryers can dry more than one type of crop within a year, but for these calculations, the farmer is assumed to be using only one type of crop (maize or tomatoes) which is dried in one dryer of the size corresponding to his production capacity.

i. Calculation of the Payback Period and the Percentage cash flow gain.

From Keith (1989) the payback period when considering a single system (machine) operation is given as

$$\text{Payback Period} = \frac{\text{Initial investment}}{\text{annual cash flow}}$$

But in this project, two systems (old and new) or operation are considered. Thus traditional drying method (old system) and the crop dryers (new system) Therefore the payback period of the crop dryers is given as

$$\text{Payback period} = \frac{\text{Initial investment}}{\text{Crop dryers advantage over the traditional drying method.}}$$

where

Initial investment is the estimated cost of dryers as indicated in Table 5.3

Crop dryers advantage over the traditional drying method is expressed as

(crop dryer total annual net cash flow)

- (Traditional drying method total annual cash flow)

but crop dryer total annual net cash flow = Annual cash inflow- overall annual cash outflow.

Where overall annual cash outflow= Annual cash out flow + Dryer depreciation.

Dryer annual cash outflow = cost of expected annual quantity of undried crops + annual dryer maintenance cost + annual labour cost.

Depreciation: The straight line method for calculating depreciation of a machine is given by Henderson and perry (1976) as

$$\frac{\text{cost new-salvage value}}{\text{Total expected life in year}}$$

For this project, cost new = Initial dryer investment salvage value of the dryers are assumed to be zero. The expected life in year is indicated for each dryer.

Annual cash inflow = Sale of the expected annual quantity of dried crop.

Traditional drying method total annual net cash flow

= Annual cash inflow - overall annual cash outflow.

where

Overall annual cash outflow = cost of the estimated annual quantity of undried crop + labour cost for drying the crop

Annual cash inflow = Sale of the expected annual quantity of dried crop

ii. Calculation of Crop Dryer Percentage Cash Flow Gain Advantage Over the Traditional Drying Method.

This is given as

(Crop dryer percentage cash flow gain) - (Traditional drying method percentage cash flow gain. Where crop dryer percentage cash flow gain = $\frac{\text{Crop dryer total annual net cash flow}}{\text{Crop dryer overall annual cash outflow}} \times 100\%$

The method of finding the total annual net cash flow and the crop dryer overall annual cash outflow remain same as previously explained.

The traditional drying method percentage cash flow gain is given as

$$\frac{\text{Traditional drying method total annual net cash flow}}{\text{Traditional drying method overall annual cash outflow}} \times 100$$

Calculations

DRYER - A Small-scale wood type dried mode solar dryer with rockbed heat storage.

Initial investment = ₦519.00

Cash Outflow

The farmers that can purchase DRYER-A are those under the production level of 500kg of maize per year.

Annual cost of 500kg maize before drying = ₦800.00/yr

Annual maintenance cost of the dryer = 5% of the initial investment ie. 0.05 x ₦519.00=₦26/yr

The life of this dryer is assumed to be 5 years with no salvage value.

$$\text{Depreciation} = \frac{₦519.00}{5\text{yrs}} = ₦103.80/\text{yr}$$

Labour cost is calculated as follows:

50kg of maize is dried in a batch drying.

500kg will be 10 batch drying

but each batch drying takes 3.0 days

Thus 10 batch drying will take 30 days

It is assumed that the labour for loading and off loading the maize in and out of the dryer as well as turning the maize periodically during the 30 days drying time will cost ₦45.00 i.e. drying labour cost per year. (₦45.00/yr)

Overall annual cash outflow =

₦800.00/yr + ₦26.00/yr +
₦45.00/yr + ₦103.80/yr
= ₦974.80/yr

Annual cash inflow

Sale of the same 500kg of maize after drying ₦1400.00/yr

Crop dryer total annual net cash flow =

₦1400.00/yr - ₦974.80/yr = ₦425.2/yr

-Traditional drying method overall annual cash outflow = Annual cost of 500kg of maize before drying ₦800.00/yr Annual Labour cost: Assuming 50kg of maize is also dried in a batch drying and that each batch drying takes 7 days. Therefore it will take 70 days to dry 500kg. Within this drying period the labour for taking care (spreading in the sun, removing the maize when it is about to rain and driving away animals) of the drying maize is assumed to be ₦175.00 i.e. drying labour cost per year (₦175/yr)

Overall annual cash outflow =

₦800.00/yr + ₦175.00/yr

= ₦975.00/yr

Traditional drting method annual cash inflow.
It was found that in traditional drying method about 25% of grain is lost due to damages by the effect of weather, animals and mould.

$$\text{Annual cash inflow} = 75\% \text{ of } \frac{500kg}{yr} \times ₦2.80/kg$$

= ₦10.50.00/yr

Thus Traditiona drying method total annual net cash flow = ₦1050.00/yr - ₦975.00/yr = ₦350.20/yr

Payback period for DRYER - 1

$$= \frac{₦519.00}{₦350.20/yr} = \frac{₦519.00}{₦350.20} \times \frac{yr}{1}$$

= 1.48 1.5yr

Crop dryer percentage cash flow gain

$$= \frac{₦425.20/yr}{₦974.80/yr} \times 100$$

= 43.62%

Traditional drying method percentage cash flow gain

$$= \frac{₦75.00/yr}{₦970.00/yr} \times 100$$

= 7.73%

DRYER - A percentage cash flow gain advantage over the traditional drying method

= 43.62% - 7.73%

= 35.89%

The same method employed in calculating the Payback period and the dryer percentage cash flow gain advantage over the traditional drying method for DRYER - A was exactly followed in calculating for the remaining dryers.