DEVELOPMENT AND EVALUATION OF AN INTEGRAL PASSIVE SOLAR CROP DRYER

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THESIS SUBMITTED TO THE SCHOOL OF POSTGRADUATE STUDIES IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE AWARD OF THE DEGREE OF MASTERS IN ENGINEERING (M. ENG.), AGRICULTURAL ENGINEERING OF THE FEDERAL UNIVERSITY OF TECHNOLOGY, OWERRI.

Certification

This project is hereby certified adequate in scope and standard and accepted in partial fulfillment of the requirements for the award of the Master of Engineering (M. Eng.) Degree in the Department of Agric Engineering, Federal University of Technology, Owerri.

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DEDICATION

Dedicated to:
my beloved Mother Ezinne Mrs Cecilia Okorondu
and
my most elderly brother Mr Fidelis Okorondu,
both of Blessed Memory.

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I wish to express my profound gratitude to all the people whose contributions have, in any way, helped the accomplishment of this noble programme. My deepest heart-warming thanks go to my lecturer and supervisor Engr. Prof. G.I. Nwandikom, whose close guidance, objectivity and intellectual acumen helped model, propel and realize this research work.

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ABSTRACT

A direct-heated solar crop dryer suitable for rural farmers and households was developed and evaluated. The simple structured dryer was fabricated using square and round pipes, aluminium sheet, Perspex, wire gauze, bolts and nuts. Its performance was evaluated using cassava chips and three cylindrical aluminium chimneys of heights 1200mm, 800mm and 400mm; all of equal diameter. Mature cassava roots were peeled, washed, chopped into flat circular chips of 10mm thickness and spread on racks in the drying chamber of the solar dryer. The dryer with its content was fully exposed in the sun for ten hours daily (8.00 hours to 18.00 hours) for three consecutive days. For comparison, control tests were set up alongside that of the dryer, by drying in open air. The following parameters were monitored on hourly basis (i) in-let air (ambient) temperature, i.e temperature of the air flowing into the solar dryer; (ii) drying chamber temperatures, i.e. temperature of the air inside the drying chamber; (iii) exhaust (exit) air temperatures and (iv) weights of the drying samples of the cassava chips. The observations and results were recorded and systematically analysed. Through a drying period of thirty hours cumulatively, the cassava chips spread in the open air showed moisture loss of up to 396g, while the chips spread inside the solar dryer lost 550g water. Moisture content of the cassava chips spread inside the dryer reduced from $62\%_{(wb)}$ to $9.7\%_{(wb)}$, as against $23.8\%_{(wb)}$ for the chips dried in open air. An average drying efficiency of 95.5% was attained using the aluminium chimney of height 1200mm. Further analyses showed that the variation in chimney height from 0mm to 1200mm had negligible effect on the temperature gain inside the solar dryer; temperatures inside the dryer rose with the daily ambient temperature. Chimney height, however, appeared to have very slight influence on the overall moisture reduction effect on the solar dryer, thus the cassava chips dried using chimney height 1200mm attained a moisture content as low as $9.7\%_{(wb)}$ in 30hours; whereas the chips dried without chimney attained a moisture content of $13.0\%_{(wb)}$. On the other hand, the analyses of variance showed that temperatures inside the solar dryer, drying rate and the overall performance of the integral solar

dryer were more significantly affected by the daily ambient temperatures rather than the chimney height.

CHAPTER ONE

INTRODUCTION

1.1 Background Information.

Harvesting of agricultural products is usually seasonal. In most cases the crops have high water content at harvest. This makes them highly vulnerable to decay and deterioration. During the harvest period there is more than enough of the product but it becomes scarce or even out of stock shortly after the harvest season. Many agricultural products are needed year round, sometimes there might be abnormal increase in demand once the product becomes scarce, causing some economic and market tension. The reason is at harvest high percentage of useful products is either wasted or spoiled, and huge losses are incurred by farmers.

To ensure year – round availability of the harvest and reduction of losses incurred by the hard – toiling farmers, some reliable means of effective preservation and storage are necessary. A most suitable and economically viable and proven method of agricultural product preservation and processing is drying (Osei and Kukah, 1989; Scanlin, 1997; Kerr, 1999; Whitefield, 2000, etc).

Based on the consistency with which eminent researchers and authors appraised and emphasized crop drying it could be asserted that, drying has become a *sine quo non* for sustainable and economically viable agriculture.

Various kinds of drying systems, drying equipment and processes are in use. They include the traditional drying systems; mechanical or conventional dryers, solar energy dryers etc. However both traditional and mechanical drying systems fall short of certain desired qualities needed for their continued adoption. For instance, the traditional sun drying is highly limited by weather conditions, low drying rate, labour intensive, and most at times unhygienic and generally requires large space for spreading. In addition, the crops being dried are prone to contamination, and insects, rodents, birds and pests attack. Hauser and Omar (2000) observed that though mechanical dryers overcome all the problems of traditional drying, they are not well suited for use in developing countries because they need substantial investments, well developed technology and infrastructure to operate. In recommending the solar drying technique they posited that solar dryers combine the merits of traditional and industrial mechanical drying systems, namely, low investment cost and high product quality. The above view is further corroborated by the current effort by modern science and technology to replace the conventional energy (oil, gas, etc) with the renewable and revolutionary "clean" energy (solar, wind, etc). Addressing the conference on Energy solutions on January 31, 2006 the then United States president, George Bush announced his advanced Energy initiative to reduce the United States dependence on foreign energy sources and to move beyond a petroleum – based economy and invest on revolutionary (solar, wind, etc) energy technologies, (Larissa 2006). In Pennsylvania projects worth millions of Dollars are at various stages of accomplishment to advance, perfect and install clean energy systems. The target was to ensure that up to 18% of all energy generated by 2006 came from the clean, advanced and efficient energy sources, particularly the solar energy, (Kathleen, 2006). The story and situation would not be different in other places. It is worthy of note that solar energy occupies the centre stage in discussions of alternative clean energy development and improvement.

The agricultural industry stands better chance of deriving the benefits of this current all – important transition to revolutionary clean energy sources. In the rural areas where most of the practical agricultural activities go on, grid–connected electricity and supplies of the other non– renewable sources of energy are either unavailable, unreliable or relatively too expensive for the peasants. Obviously the design or selection of a mechanical crop drying system that employs motors, fans, electrical heating would be quite inappropriate and not feasible. As observed, the huge initial capital involvement and the concomitant high running and maintenance cost of such dryers powered by fossil fuels are enough to discourage the local low investment farmer who is constrained to look for the cheaper alternatives. Most debilitatating is the artificial scarcity to which most of the fossil fuels, especially the petroleum products are subjected, which has almost become a tradition in Nigeria and many developing nations of the world.

In the face of these daunting circumstances it becomes necessary to go for the cheaper energy sources and a ready solution is the systematic harnessing of the ready available and abundant energy of the sun via the solar energy dryers.

The efficacy of a well made solar dryer is assured especially in the tropics where for several months of the year the mean level of solar insolation upon the ground is more than $0.5kW/m^2$ (measured as a mean over the hours of day light) (Chancellor, 1995). According to Whitefield,(2006) the unfortunate situation is that many of the areas (the tropical countries) that could benefit from solar drying technology lack adequate and necessary information related to the technology of solar dryer construction and application to specific conditions. He observed that the latest developments in solar drying technology as well as achievements made by applying this body of knowledge are not readily available in libraries or the universities of most developing countries in the tropics.

However, solar energy dryers are gradually coming into use in the tropics, though most designs do not so much contain the needs of the rural people /farmers in terms of size, construction material, cost, service and overall performance. More over, some designs of solar dryers cannot maximally tap the abundant solar energy. There is the need for continuous research to develop more efficient solar dryers that would utilize the abundant solar energy to the fullest to enhance production and food preservation. This research work is focused towards this end.

The integral or direct radiation solar dryer is fashioned to maximally expose the products to direct sunlight, thus allowing maximum utilization of the insolation incident on the dryer. The design has been highly simplified to conform to the recommendations of Sablani and Rahmav, 2003 whose work recommended further research to develop simple, easy to use solar dryers.

Perhaps it would be pertinent to point out that one major impediment to the rapid advancement and wide-spread use of the simplified versions of solar drying systems is the arbitrary and abject neglect of and/or lack of confidence in the efficacy of such simple dryers. Arfaoui, 2000 commented that, “Often they (i.e. people or farmers) do not believe that this one (i.e. The simplified design) can be effective, because it looks so simple.” He called for elaborate awareness campaign in the use and management (or even construction and maintenance) of simple solar dryers.

Compared to other versions of solar dryer such as the convectional/ distributed solar dryer which has low thermal conversion efficiency due to heat losses in the separate solar collector plate, the integral solar dryer experiences little or no such losses. This is because the solar radiation falls right on the products without necessarily passing through any intermediate unit. Thus, the dryer would have higher solar energy conversion and utilization, as well as the much desired quick drying characteristic which constitute the “key” requirement of food dryer systems (Whitefield, 2000). In effect, the integral solar energy dryer, though very simple, provides the much needed rapid drying characteristics required for quick and effective drying of freshly harvested high moisture laden vegetables, tuber and root crops such as tomato, yam and cassava which have normal moisture levels of 88%, 67% and 62% respectively, (Lurkey, 1984). Cassava and yam are the target products for the integral solar dryer. This is due to the fact that these crops are among the commonest staple food crops grown in the tropics. Africa accounts for over 50% of total world production of yams (Onayemi, 1982). In Nigeria, cassava production was about 25.95million in 1999, and that increases as the years roll in with production put to about 27million tonnes in 2006 (Nwosu, 2006). There is hardly any household that does not grow yam. It was estimated that about three to four million tones of yam were lost annually due to various handling inadequacies including lack of efficient drying system at the reach of the rural house holds and farmers (Anosike and Ikediobi, 1985). Normally the loss would increase with production. These losses could be avoided if the tubers were sliced and dried so that they can store for longer periods and then processed into yam flour (when needed), which could be used to prepare instant pounded yam (Akambi *et al*, 1996). By drying yam slices and milling them, the drudgery involved in preparing pounded yam is reduced, and the storage life of the dried yam slices / chips prolonged, (Ajiboshin , 2005). The integral solar dryer by its simplicity and size accommodates even domestic applications, and reduces incidence of rot and loss occurring in homes and farm storage facilities.

Cassava is a major source of calories for over 300 million people world over. It is the major staple food for over 75% of the population accounting for more than 50% of the caloric intake in Southern Nigeria (Rickard and Conry, 1981). High yield cultivars have been developed most of which mature in less than twelve months. Cassava is the most widely grown crop cultivated by almost every house – hold in the tropics current production level in Nigeria is 38 million tonnes per annum (Nwosu , 2006) and calculated efforts are being made to double this quantity by the year 2011 (Nwosu , 2006). However, mature cassava roots are hardly stored raw from harvest, except when they are cut into chips and dried. This is traditionally done in the homes by farmers by spreading on the ground for open sun drying which has a lot of disadvantages. The integral solar dryer will be a good relief to this situation, especially during season of surplus production.

Its application is simple and very similar to the traditional technology and it is convenient and efficient (Osei and Kukah, 1989; Ekechukwu *et al*, 1995; Kerr, 1999; Whitefield, 2000). Well dried cassava chips can be stored and, when needed, can be milled to cassava flour which has a lot of domestic and industrial uses, which includes baking.

1.2 Statement of the Problem.

The immense energy from the sun, naturally spread over the universe, can be cheaply harnessed to a large extent, in various forms, and as alternative to the depleting fossil fuels and other non-renewable energy sources. Though solar energy has been proved very effective for the drying of the moisture laden agricultural products most known practicable designs of solar dryers lack the capacity to maximally harness the abundant energy from the sun for rapid drying of freshly harvested crops. Root, tuber and certain vegetable crops such as cassava (Manihot esculenta), yam

(Dioscorea rotunda), etc, are heavy with water when freshly harvested and need to be dried quickly to avoid spoilage, if they were to be stored. The required fast drying rate can hardly be achieved with the distributed – type solar energy dryers, which more or less restrict utilization of the abundant solar energy to only the convectional method.

A cross view of the various designs of solar dryers showed that

i) Solar dryers are usually designed and fabricated with chimneys which differ in height, shape, material of construction, etc. This work, on the one hand, aims to investigate the effects of variation in the chimney height on the performance of the integral solar dryer.

ii) some information necessary for a reliable and practical design procedure are inadequate to afford systematic, logical and rational design and construction (Snigh *et al,* 1987). Hence in spite of all efforts so far expended, most dryer designs hardly find wide acceptance among the targeted end users, for the simple reason that they were constructed on "imported" designs with little or no modifications to suit local conditions; and most dryers currently being designed in parts of the country have very high capacities far beyond the needs and reach of small farmers and domestic users. Tougher situations are met where the operation of the dryer requires specialist training. These increase the running, repair and maintenance costs. There is, therefore, the natural inclination and quest for a simple, drying system which is easy to fabricate, operate and maintain and, which would suit domestic needs and provide services to small farmers (Whitefield, 2000). The achievement of the above goals can simply be realized through the revisiting and refinement of the age – long solar energy drying technology which had suffered neglect over the years. Besides, most solar dryers in use were constructed of wood materials which can hardly withstand adverse weather. Hence continuously intensified research on harnessing solar energy, particularly for crop drying and general agricultural activities is imperative. The integral solar Energy Dryer which will be described in this work has the potentials for achieving faster drying by direct solar heating of the crops. It would ensure greater utilization of the solar energy incident on the dryer, no matter the position / direction of the sun. It can serve the needs of subsistent farmers who would take advantage of strong construction materials that can stand adverse weather.

1.3 Objectives of the Work.

The objectives of this research are to;

1. Design an Integral (direct sun heat and convectional heat) passive dryer for drying of root crops / tuber crops,
2. Construct the dryer, and
3. Evaluate the effects of chimney height on the performance of the dryer using peeled cassava chips.

1.4 Justification.

Traditional open-air crop drying in spite of its numerous demerits is still widely practiced because it offers the extensive exposure of the drying (crop) materials to solar energy, thus ensuring rapid drying of the crop matter. Against this backdrop the integral passive solar dryer is developed to provide better drying conditions for more rapid and efficient drying of the crops, while taking care of the problems and demerits of open-air crop drying.

An over view of the solar dryers (including most mechanical dryers) in common use reveals that some dryers function without chimney, others have chimneys of various heights and configuration. Since the chimney is an essential component of the dryer, the significance of its height to the dryer is worth studying.

Rural dwellers and indeed every household need a mini domestic dryer. The bulky expensive mechanical or electrical or gas-fired dryers would be inappropriate. The simple integral solar dryer described in this work saves the situation.

CHAPTER TWO

LITERATURE REVIEW

2.1 Drying: - General

Generally water can be abstracted mechanically from a substance (usually solid) through any of the following mechanical dewatering methods, namely, centrifugation, filtration, decantation, sedimentation, drying, suction, dehydration, etc. (Odiro, 2004).

Among the above named mechanical dewatering processes it could be asserted that drying is the most common, developed or rather most popular method of water removal from a substance. It seldom requires any special prerequisite operation such as cutting, crushing, compressing etc. The use of heat to remove liquid/water distinguishes drying from other dewatering processes, (McGraw-Hill, 1982). Through the process of drying, it might be possible to approach "Zero" water content in a substance, unlike in filtration, sedimentation, etc.

Many authors and researches have defined and expressed varied opinions about drying. (Ekechukwu *et al*, 1995) summarized drying as "a dual process of

i). Heat transfer to the product from the heating source and,

ii). Mass transfer of moisture from the interior of the product to its surface and from the surface to the surrounding air"

Thus Ekechukwu *et al*, 1995 rather projected drying as a complex mechanical process / phenomenon involving motion and movement of entities in a medium / substance, consequent upon energy transfer and gain.

(Alonge, 1997) described drying as the removal of water from a product through the application of some energy source which can be in the form of direct solar energy or energy from burning fuels or electrical heating. In one of their work, (Kendall and Allen, 1998) asserted that drying is a relatively simple method of food preservation which procedure is not exact. Thus while emphasizing the simple nature of drying, Kendall and Allen nearly contradicted them selves by asserting the 'non- exact' nature of drying which agrees with the complex view of (Ekechukwu, *et al,*1995). Kerr, (1999) also agreed with the simple nature and referred to drying as a "simple ancient skill" (that needed to be learnt in order to practice it effectively). Odiro, (2004) referred to drying as an operation in which a liquid, usually water, is removed from a wet solid or gas. Odiro's (2004) idea gave a wider notion about drying, pointing out that the process, though very much understood or appreciated in solids, also takes place in gases. Thus a gaseous substance can equally be wet or moist, which case it could be dried if so needed.

However different or similar the opinions might sound, drying which is the partial or "complete" removal of water or moisture from a material, has, more often than not, been attributed to agricultural products, most of which are naturally moisture – laden at maturity, and need to be well dried to safe storage levels for domestic and industrial purposes. Thus in one dissertation (Ekechukwu, 1987), stated that the basic essence of drying is to reduce the moisture content of a product to such a level that prevents deterioration within a certain period of time, normally regarded as the "safe storage period"

Drying operation may be done naturally or by some artificial method. Natural method of drying takes the form of exposing the wet products to the action of sun and wind. Artificial dryer systems function by applying heat from combustion of fossil fuels, biomass resources, directly or indirectly, and in both natural and forced convection systems. From the foregoing drying process can be described as a mechanism involving the movement of water out of a substance by air vehicle with the help of heat energy. Thus drying essentially involves the cross movement of heat, air, water through a substance, and in the process, the substance undergoes weight loss.

2.2 Fundamentals of Crop Drying

It has been established that drying of a crop material involves movement or motion of moisture, air and heat energy through and around the material. Thus the process has been visualized in the light of a mechanism, which comprised the dual processes of:

(i) Heat transfer, and

(ii) Mass transfer (Ekechukwu *et al,* 1995).

In the light of the above, the drying process could be ideally summarized as a moisture diffusion mechanism which occurs within and around a (crop) material expressed by the function:

$M_R = f(T,h,t)$, -------------------------- (1)

Which can be translated to $M_R = \frac{M_C - M_{ce}}{M_{co} - M_{ce}} \times 100\ \%$ --------------------------- (2)

Where M_R = Moisture Ratio

M_c = Moisture Content of Material at any level and at any time, on dry basis (%db)

M_{ce} = Equilibrium Moisture Content (%db)

M_{co} = Initial Moisture Content of wet Product (%db)

T = Air Temperature (^oC)

h = Air relative humidity

t = Drying time. (Mojola, 1996).

The primary but direct or standard method of determining the moisture content of a crop material makes use of an oven in which a given sample, of known weight W, is dried at some prescribed temperature for some stated length of time. If the bone- dry weight of the given crop sample is known, then the moisture content of the crop material (as a percentage) can be determined using the relation: (Mojola, 1996):

$M_{c\ (wet\ basis)} = 100(W_i - W_d) / W_i$ (%) -------------------------- (3)

and $M_{c\ (dry\ basis)} = 100\ (W_i - W_d) / W_d$ (%) ------------------ (4)

Where M_c = Moisture content (wet or dry basis)

W_i = initial weight of sample

W_d = bone – dry weigh of material.

Normally as a crop material dries it becomes less easy for the remaining moisture inside the material to diffuse out to the surface of the crop material for removal by evaporation. This fact is better explained or appreciated by observing drying rate curve whose slope is usually steeper near the origin.

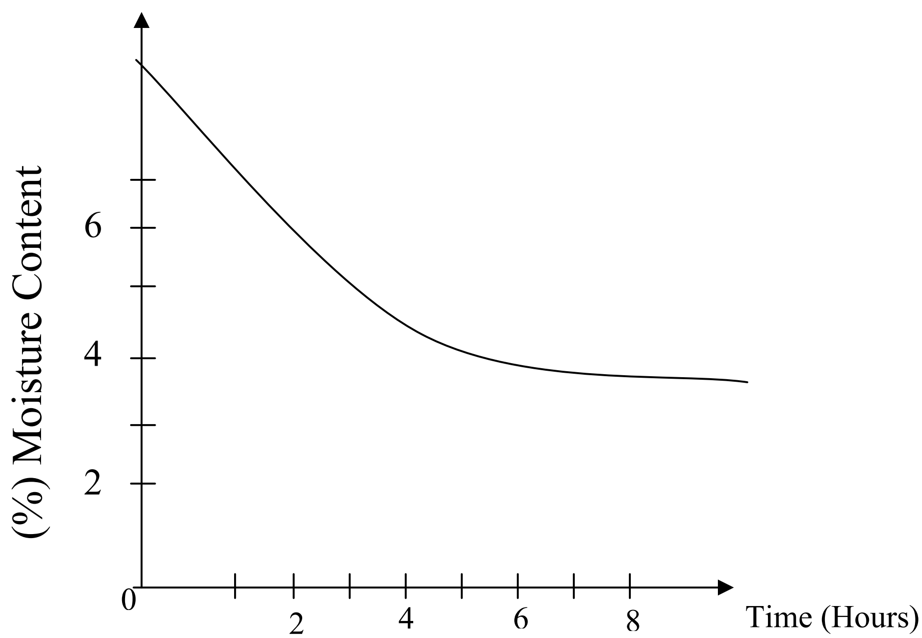


Fig. 1 Typical agricultural product drying rate curve.

Drying of crop material in bit or in bulk involves the loss of moisture at different rates by the discrete materials and the overall bulk. It often takes place within discrete zones, the extent of which depends on the moisture content of the crops and the temperature, humidity and the rate of air movement through the crop. Thus about three main discrete zones can be distinguished in a drying crop bed, namely, the un-dried zone, the drying zone and the dried zone. The range of each of these zones depends on the thickness of the bed as well as the mode, source and direction of dryer heating system and the drying air.

Drying process can be schematically represented as shown in fig. 2.

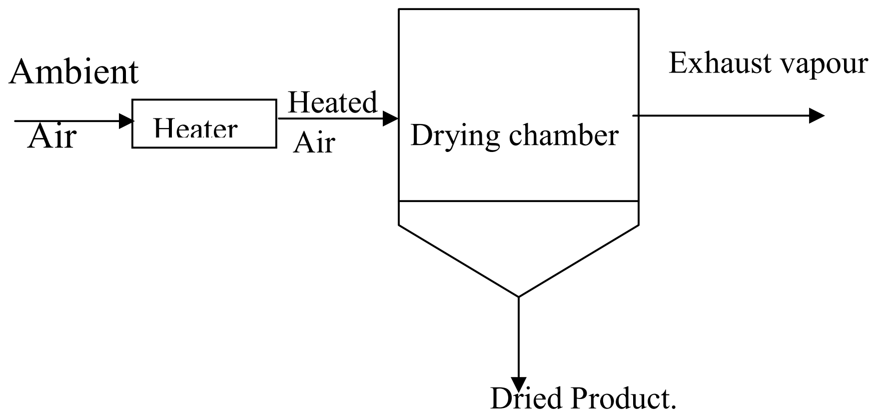


Fig. 2 Schematic diagram of a drying process.

For a drying process, the heat supplied by the drying air mass q_a was estimated by Chakraverty, (1993) using the relation:

$$q_a = (0.24+0.45H_1)\ G^1\ (T_2 - T_3)t_d \text{----------------} \quad (5)$$

where G^1 = rate of air supply / flow (kg /min)

t_d = total drying time (min)

H_1 = Humidity of ambient air (kg/kg)

T_2 and T_3 are the dry bulb temperatures of heated and -exhaust air respectively (^oC).

q_a = heat supplied (kJ).

Similarly the heat required for the evaporation of moisture from a crop material (q_a) was estimated by Chakraverty, (1993) thus:

$$q_1 = W_d (X_1 - X_2) Y \text{ (kJ)} \text{ --------------------- (6)}$$

Where Y = average value of latent heat of vaporization of moisture from the Crop material (kJ/kg)

W_d = total weight of bone – dry crop matter in the dryer (kg)

X_1, X_2 are the initial and final moisture contents of the crop material. And, the sensible heat, q_1 needed to raise the temperature of the crop material and its moisture is determined from:

$$q = W_d C_g (T_{G2} - T_{G1}) + W_d C_w (T_{G2} - T_{G1}) X_1 \text{ ------------------ (7)}$$

Where C_g, C_w are the specific heats of crop material and Water respectively (kJ /kg ^oC_o)

T_{G1}, T_{G2} are the initial and final crop temperatures (^oC)

Hence the heat supplied by the drying air q_a was given by

$$q_a = q_1 + q \text{ -------------------------------(8)}$$

It is worthy of note that if the moisture content m_c of a given quantity Q of crop material is known, then the amount of water contained in the crop material can be calculated by:

$$W_c = \frac{Q.M_c\%}{100+M_c\%} \text{ (kg) -----------------------(9)}$$

(Snigh *et al,* 1987)

Where W_c = water present in the sample (kg)

Q = mass of crop sample (kg)

M_c = moisture content of crop sample (%)

And if the sample is to be dried from the initial moisture content M_i to a final moisture level M_{cf}, then the moisture that would be expelled in the process is given by Singh *et al,* (1987):

$$M_e = \frac{Q\,(M_i - M_{cf})}{(100 + M_i)} \text{ ----------------------------- } (10)$$

Where M_e = moisture expelled (kg),

M_i = initial moisture content (%)

M_{cf} = final moisture content (%)

Thus the heat load of a dryer was calculated using the relation:

q_L = sensible heat gain by crop material and moisture + latent heat of evaporation --- (11)

$$q_L = (Q - W_c)\, C_{pc}\,(T_2 - T_1) + (W_c\, C_{pw})(T_2 - T_1) + M_e Y \quad \text{--------} \quad (12)$$

Where C_{pc} = specific heat of crop material (kj/kg°C)

T_2 = dry crop / product outlet temperature °C

T_1 = crop inlet temperature °C

C_{pw} = specific heat of water (kJ/kg °C)

Y = average latent heat of vaporization of water (at some temperature, usually the outlet temperature is used).

Other parameters retain their meanings.

The performance of a dryer slated for some particular task may also be assessed in terms of its drying efficiency. Three main factors influence or determine drying efficiency:

- those related to the dryer environment, particularly, the ambient air conditions,

- those which are specific to the crop
- those peculiar to the design and operation of the dryer.

There are various ways of expressing the drying efficiency of which the sensible heat utilization efficiency (SHUE), the fuel efficiency, and the drying efficiency are the most useful. Sensible heat utilization Efficiency (SHUE) takes into consideration the sensible heat attributable to the ambient air and any heat added to the air by other systems such as fan, as well as heat supplied by combustion of fuel, solar heating, etc. Sensible heat utilization efficiency (SHUE) is given by the expression in equation (13):

$$\text{SHUE} = \frac{\text{Heat utilized for moisture removal}}{\text{Total sensible Heat in the Drying Air.}} \quad \text{--------------------} (13)$$

The fuel Efficiency method bases only on heat available from the fuel is given by equation (14):

$$\text{Fuel Efficiency} = \frac{\text{Heat utilized for moisture Removal}}{\text{Heat supplied from fuel}} \quad \text{--------------}(14)$$

It is important to note that fuel efficiency can be significantly different for the operations of the same dryer at two locations with widely different ambient conditions. With low temperature drying, particularly in the dry climates, the heat supplied from the fuel may be less than half the total sensible heat and the fuel efficiency may exceed 100%.

Thus direct comparison of the performance of dryers at separate locations is not possible using the fuel efficiency expression. The Drying Efficiency method can be described by the expression in equation (15):

$$\text{Drying Efficiency} = \frac{\text{Heat utilized for moisture Removal}}{\text{Heat available for moisture Removal}} \quad \text{--------} \ (15)$$

The expression for drying efficiency is often used for evaluation of dryer designs or for comparison between dryers, as it is a measure of the degree of utilization of sensible heat in the drying air.

2.3 General Significance of Crop Drying.

Besides the cardinal purpose of moisture removal / reduction, crop material may be dried for several other reasons and a lot of benefits are derivable there from.

Drying has been identified as an invaluable (if not indispensable) process in the field of crop production, utilization and processing. (Whitefield, 2000) observed that dried foods are high in fibre and carbohydrates and low in fat, thus making them the preferred health food choices. Similarly, in her booklet A Review of solar Drying, (Kerr, 1999) hinted that nutritionally dried food is ranked by the United States Food and Drug Agency as better than canned food. Kerr,(1999) further asserted that the tastes were related to the food, but there was some uniqueness in their flavour and taste. Research by Scanlin, (1997), an expert in alternative energies and instructor at Appalachian State University, Boone, indicated that flavour and most of the nutritional values in dried food are concentrated and preserved. Some benefits derivable from crop drying include:

- improved market value
- Enhanced handling and transportation
- Increased product shelf life
- Better preservation and storage

- Improvement in certain desired organoleptic qualities such as taste, colour (as in rabica coffee), flavour (as in roasted bean, fish, Yam, maize, etc.)
- Preservation of healthy seed grains
- Enhancement of further processing and industrial application of agricultural products
- Improvement of the economy and job creation

2.4 General Considerations for Crop Dryer Design / Selection.

Contrary to their generally simple view of the act of drying, (Kendell and Allen, 1998), (Kerr, 1999), the design, selection (and even the application) of a reliable practical dryer for the efficient drying of a given crop matter is quite a rigorous and arduous exercise which needs adequate consideration and blending of the conditions and characteristics listed below:

(1) The environment, nature and conditions of use (climate, prevalent weather, conditions, etc.)

(2) Crop type, nature of crop material (crop physical, thermal, chemical properties, moisture content, etc.)

(3) Energy type (Whether solar energy or conventional energy would be used).

(4) The type or form of drying system / operation applicable (Rotary, conduction, Dryeration, seed grain drying, etc.)

(5) Capacity / size of farm, demand of the post harvest industry

(6) Materials for constructing the dryer (availability, reliability often locally sourced materials are recommended).

(7) Nature (literate and technical levels) of the target end users, and convenience.

(8) Overall cost of investment (construction, operation, repair, maintenance) which should be aimed at the barest minimum, (Snigh *et al,*1987) and (Chakraverty, 1993).

2.5 General Classification of Dryer Systems.

Dryers and drying systems have been classified in several ways using certain distinctive parameters, features and principles. Thus, viewed from the principle and method of heat transfer for moisture removal, Cook and Harman, (1991) grouped drying equipment into three categories:

(i) Direct Heat Dryers,

(ii) Indirect Heat Dryers,

(iii) Radiant Heat Dryers.

DIRECT HEATED DRYERS: In direct heated dryer the heat source and the material(s) being dried are within the same enclosure. The same cabinet harbours them such that the heat generated from the heating source directly warms the materials without passing through any intermediary structure.

INDIRECT HEATED DRYERS: For indirect heated dryers the heat source unit is separate from the drying chamber. An intermediate structure probably a duct connects the heat source and the drying chamber. Through the duct heat is transferred (usually by conduction/convection using blowers, fans, etc.) to the drying chamber. Thus the drying heat in contact with the material is in the form of current air mass.

RADIANT HEAT DRYERS: These employ radiant heat energy (usually from the sun) to accomplish drying.

Based on their operating temperature ranges Ekechukwu, *et al,* (1995) classified drying systems into high temperature and low temperature dryers. HIGH TEMPERATURE DRYERS: The high temperature dryers are used for fast drying operations, especially where the products require brief exposure to the drying heat/air. The operating temperatures are such that the drying air remains in contact with the product until equilibrium moisture level is attained. Due to the likely occurrence of serious over-drying, products would only be dried to just the desired moisture level and later cooled, (Mclean , 1980).High temperature dryers could be of the batch drying type or the continuous flow type, Hall , (1980). Due to the temperature ranges prevalent in high temperature dryers, most known designs are electrically or fossil-fuel powered. Very few practically realizable designs of drying systems are solar energy heated.

LOW TEMPERATURE DRYERS: For the low temperature systems, the moisture content of the product is usually brought to equilibrium with the drying air by constant ventilation, thus low temperature drying tolerates intermittent or variable heat input. It enables crop materials to be dried in bulk and is most suited for long–term storage. Hence low temperature dryers are often referred to as bulk or storage dryers, (Mclean, 1980). Their ability to accommodate intermittent heat input makes them most appropriate for solar energy drying applications.

Practically every author or researcher has some peculiar way or basis for distinguishing or classifying dryers. Danguenet, (1985) distinguished two types of dryers, namely:

- The boiling dryers in which the temperature of product is sufficiently raised so that the vapour pressure of the water it contains equals the total ambient pressure. Boiling dryers use temperatures above 100^0C;
- The “drive” dryers in which the product is placed in an air flow which has vapor pressure inferior to that at its level. Solar energy dryers are grouped under the drive dryers.

Dryer classifications are as varied as even dryer designs (see figure3). Drying systems could be classified into crude /traditional drying, and the scientific/improved/modern dryers considering the level of refinement of the process or system. On the basis of the purpose for which dryers are made or used distinction could be made between domestic/house hold dryers and commercial /industrial dryers. Still more, based on the mode of circulation of the drying air, dryers have been grouped into natural circulation and forced convection dryers. In natural circulation dryers, heated air is made to circulate through the crop by buoyancy forces or by the atmospheric wind pressure, acting either singly or in combination. Forced convection dryers employ fans or pumps to maintain steady current of drying air mass through the product, (Ekechukwu *et al,* 1995). A classification based on size and capacity groups dryers into small-medium-and large-scale dryers. And from the view point of the level of human input or physical involvement in accomplishing a drying process, dryers may be categorized into natural drying and artificial drying. Yet, based on the nature, source or type of heating energy for the drying operation, two broad drying systems may be distinguished, namely:

-Conventional or non-renewable energy drying systems (some what referred to as mechanical dryers) which utilize electricity and the fossil fuels, and

- Renewable energy drying systems which is based on solar energy for its power/operation (though some researchers distinguish solar, wind and biomass).

Dryer classification is quite a herculean exercise which could be inexhaustible. However, Ekechukwu *et al,* (1995) adopted a schematic approach to achieve an acceptable system classification of dryers, Fig. (3).

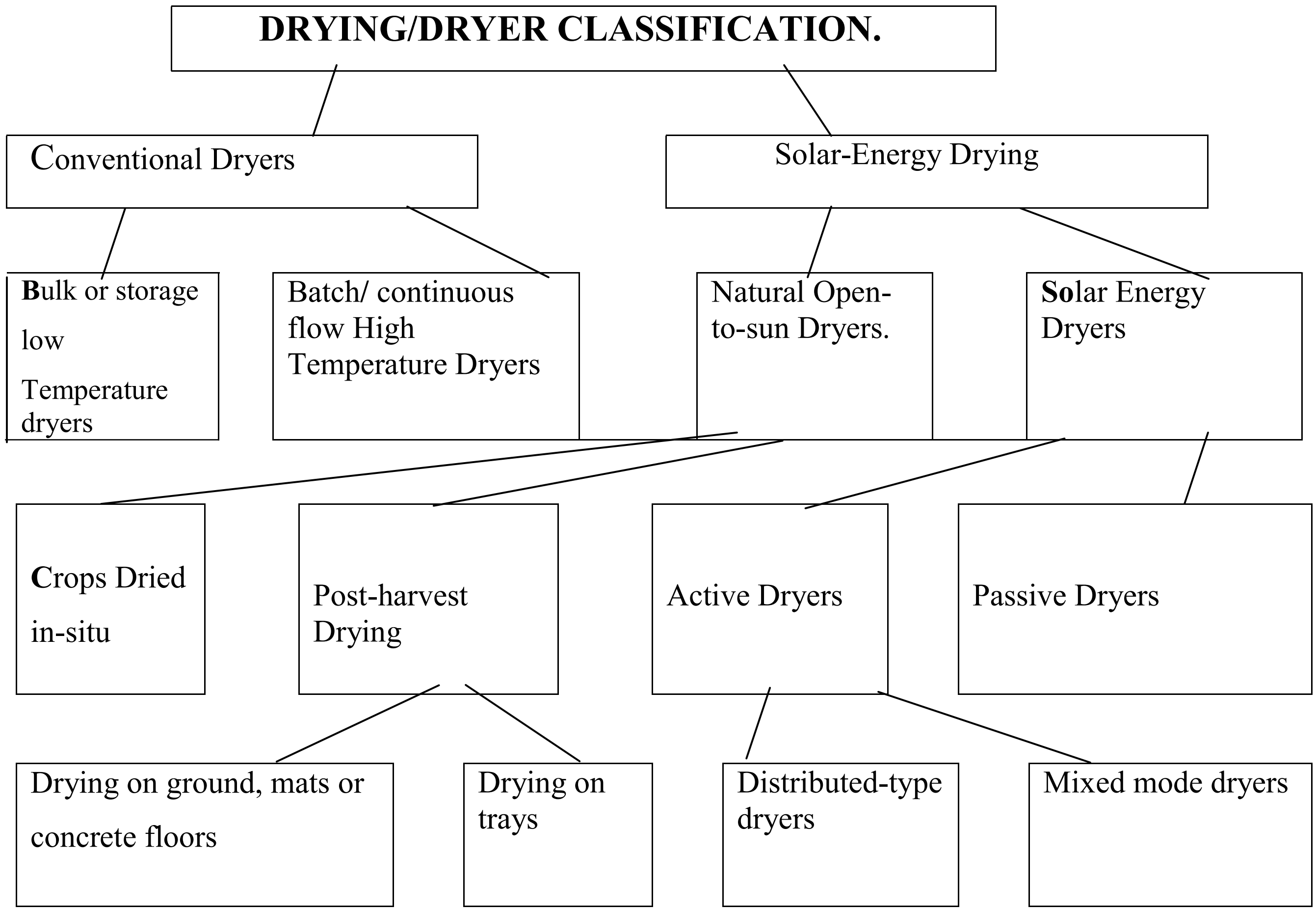


Fig. 3: Classification of dryers and drying modes.

Source: Ekechukwu *et al*,(1995); An overview of solar drying technology. Conference on Renewable and Alternative energy Technologies.

2.6 The Sun and Solar Radiation / Solar Energy Applications.

The sun which occupied a central position in the solar system is nature's-single most abundant primary source of energy which has characteristic natural capacity to radiate such a fierce heat, visible spectrum and other energy levels through space. Structurally, the sun would be described as a spore of fierce hot gaseous matter (including helium oxygen, neon, hydrogen, etc) whose interior region temperature is estimated to range from

$8.00x10^6$ ^0K to $40.0x10^6$ ^0K, with total energy put at $3.86x10^{33}$ energy/sec., (Harold, 1989).

Science and research have shown that virtually every energy source derived directly or indirectly from the sun (see fig. 4). The average distance of the sun from the earth is put at $1.496x10^{13}$cm, equivalent to one Astronomical unit (AU), (Harold, 1989). The rays of the sun have to pass through this distance before striking any surface on earth. Hence not all the suns energy land on the earth. While some percentages of the radiation are reflected off the atmosphere in the form of *earthshine*, some fraction is absorbed by the ozone layer, water vapour, carbondioxide and other gases in the atmosphere, very little percentage actually reaches the earth. The massive and fierce hotness of the sun makes it unapproachable and impenetrable to astronauts. Insolation/radiation from the sun reaches the earth's surface in two main forms, namely,

(i) Direct beam to direct radiation which can fall on a place without any change in directions

(ii) Diffused radiation which might undergo some change in direction due o reflection and the scattering effect.

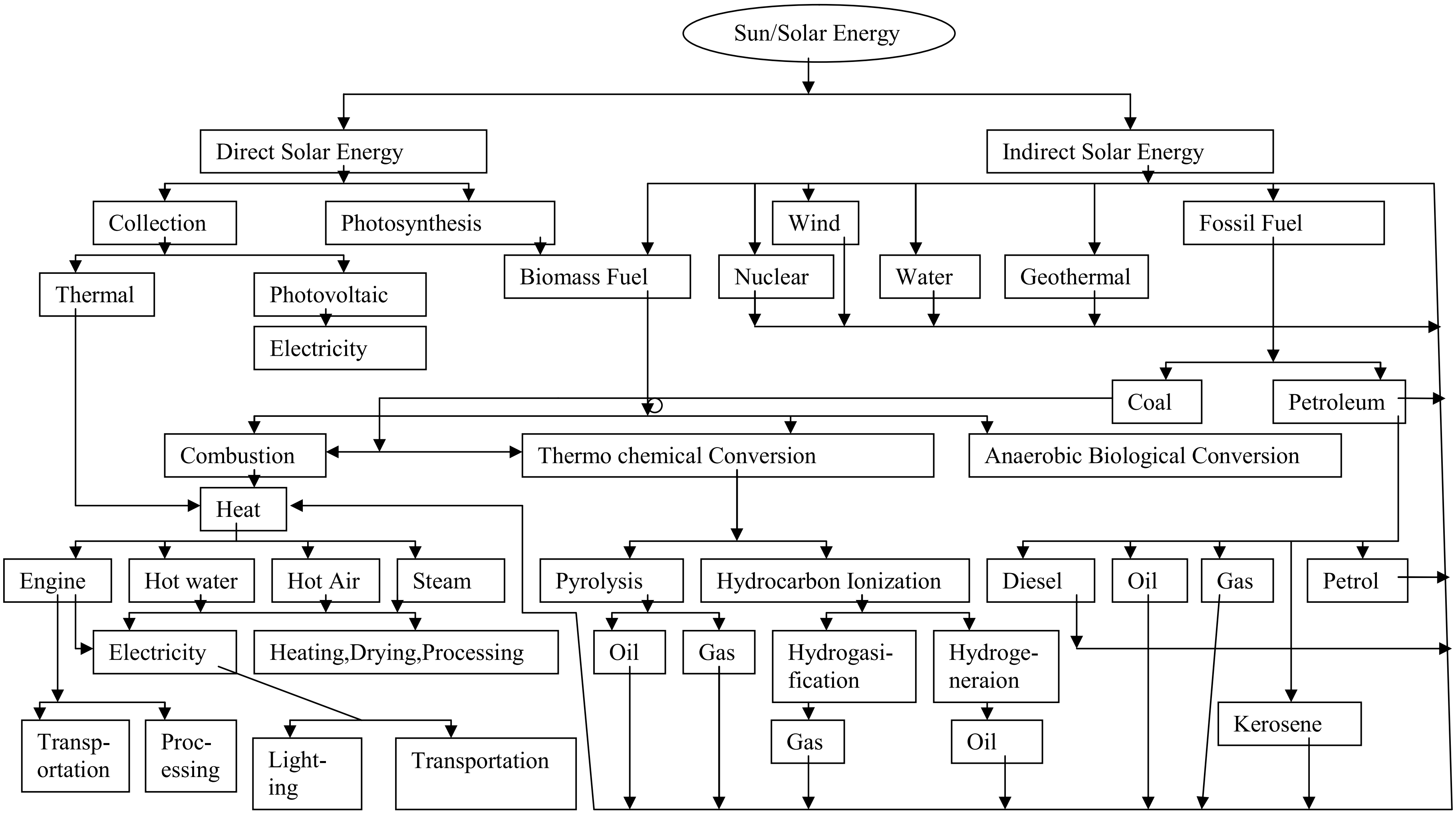


Fig. 4: The solar energy system.

Source: Agricultural Mechanization in Asia and Latin America, volume 26, No 4, p70,1995-1996.

Several attempts have been made and efforts are still being made to estimate or measure solar radiation (s) empirically for given locality. Duffie and Beckman, (1980) stated that the amount of solar radiation available in any given location depends, on latitude, time of the year, hour of the day, angle of inclination of the collector. However, work by Alonge and Oje, (1997) have shown the need to predict the available solar radiation for a location in order to determine if the use of a solar dryer will be effective and economically viable. One such instrument used for predicting or measuring solar radiation is the thermoelectric pyrometer introduced in 1923 by Hobbies and Kinball. In its application, the instrument is positioned to collect solar radiation at right angles to the sun rays, such that scattered radiation is excluded. Irradiance is the amount of solar energy incident on unit surface area per unit time, and is given by the expression in equation (16):

$$\text{Irradiance} = \frac{\text{solar Energy (kJ)}}{\text{Surface Area } (m^2) \times \text{Time (s)}} \quad (kW/m^2) \text{ --------- } (16)$$

The unit of irradiance is Kilo watt per square meter (kW/m^2).

Work by Akor and Zibokere, (1997) suggested another expression for determining the incident solar energy (on a collector/ flat surface, crops spread on some horizontal plane for drying), expressed thus:

$$E_i = \alpha I_c A_c R \Omega \text{ ---------------------------- } (17)$$

Where Ω = Collector heating efficiency

α = absorptions factor

R = transmittance of cover plate

I_c = Average insolation per hour

A_c = Absorber surface area exposed to insolation

Akor and Zibokere's (1997) expression appears very simple and easily applicable.

It may be rightly asserted that the universe is being propelled and sustained directly or indirectly via the energy from the sun which has been described as a clean energy (Kathleen, 2006), see fig. 4. Biologically sun light is an indispensable agent of photosynthesis and plays major role in the regulation of the entropy of the ecosystem (Roberts, 1988).

Relatively substantial human efforts have been and are still being made towards harnessing the solar power as a boost or alternative to the available conventional energy (Kathleen, 2006). Hence, solar energy is currently being used for electric power generation, heating and cooking in the homes, industries; water pumping, waste management, etc.

In the agricultural industry, solar energy is being employed for several purposes and operations including the green house, refrigeration and preservation, irrigation, crop drying, etc. (Goswani, 1986). Apart from photosynthesis, crop drying and preservation constitute an essential direct application of solar energy to agriculture which naturally had been in operation from time immemorial, even before man realized the environment. In the course of time, civilization and progressive research activities have successfully developed our today's solar energy (cabinet) crop dryers.

2.7 Basic Principles of Solar Energy Crop Drying.

The basic principle underlying solar energy crop drying is that the sun supplies abundant heat to raise the temperature of the drying air and the crop materials. This causes moisture migration from the interior to the surface of the crop matter. Then a continuous air flow through the crops evacuates the migrated surface (free) moisture into the atmosphere. This air flow can be in form of wind (for open sun drying), or induced by thermal gradient within and around the dryer (i.e. natural convention) in the case of cabinet dryers, (Ekechukwu,1985). Alternatively, air can be forced to flow through the crops by means of a fan or pump mechanism i.e. forced convention, (Brenndorfer *et al,* 1985).

2.8 Fundamentals of Solar Dryer Design.

The solar energy dryer is a structure designed and constructed for the purpose of utilizing the insolation from the sun to effect controlled drying of material(s) especially agricultural products. Differing from the conventional or mechanical dryers mainly in their source of heat, construction material and structural design, solar energy crop dryers top the world's leading current innovations in agricultural product drying, (Whitefield, 2000). The main components of a solar energy dryer are.

- The drying chamber in which the crop materials are placed
- The solar energy collector /heat exchanger unit,
- The air /moisture section chimney. Sometimes a heat storage unit may be incorporated to improve the efficiency and performance of the system, and also fans or pumps and ducting may be incorporated, (Ekechukwu *et al,*1995)

The Brace Research Institute, (Ekechukwu *et al,*1995) recommended standard guidelines for designing and constructing solar energy dryers. These guidelines include:

- The length of the cabinet should be at least three times the width to minimize shading effects of the side panels,
- An optimal angle of slope for the glazing as a function of the local latitude (applicable to sites both north and south of the equator).

Figure 5 gives this slope as a function of latitude.

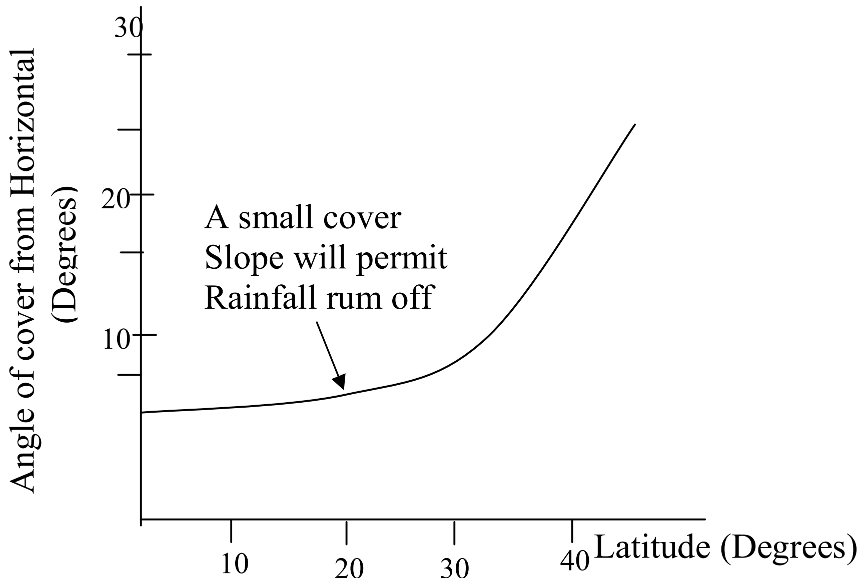


Fig. 5: Optimum tilts angle of a solar cabinet dryer as a function of local latitude.

(Ekechukwu *et al,* 1995).

- The interior walls should be painted black, the crop trays should be placed above the cabinet floor to ensure a reasonable level of air flow under and around the product,
- The top cover glazing, double preferable, should be treated against degradation under ultraviolet radiation,
- The choice of construction materials should be determined by local availability compatible with desired performance and the desired level of sophistication.

The performance and efficiency of a solar dryer which are chiefly determined by the drying rate and product quality depend on.

- Heat transmittance of the cover plate. The cover plate is a transparent material fixed over the solar heat collector plate to protect it from rain drops or moisture. It could be cut from a glass or plastic or nylon sheet. Solar dryer cover plate must be transparent to allow almost the whole rays incident on it to pass through it and fall on the collector or absorber plate.

- Absorption power of the solar heat collector plate. Solar heat collector plate is a metal sheet placed under the cover plate to intercept incident radiation from the sun, gather and absorb the heat therein, then transfer the heat by convention and radiation to the heat storage medium or directly to the crop drying chamber. Thus the collector plate serves as a heat exchanger unit of the solar dryer. Solar energy heat collector, also called heat absorber plate, can be made from zinc, or aluminum or mild steel or other similar metal sheet. Solar heat collectors are usually painted black to improve its heat absorbing capacity.
- Heat transmission ability (transmissivity) of the heat exchanger or the collector plate. This refers to the ease and readiness with which the collector emits the heat it accumulated/ absorbed to the drying chamber.
- Air flow rate and suction power of the chimney.
- Level of insulation. (Ekechukwu *et al,* 1995).

2.9 Classification of Solar Drying Systems / Methods.

Two methods of solar energy drying can be distinguished.

(a) Open sun drying (traditional sun drying)

(b) Solar cabinet systems.

Open sun drying or traditional sun drying is still the most popular practicable method of crop drying in developing countries of the tropics, (Snigh *et al,* 1987). One method employed by local farmers was to allow the crops (especially grains) to dry while standing on the farm after maturity and prior to harvest. Though the method may not need much human labour, it has some attendant limitations. Another major form of natural open sun drying involves spreading the harvested crops on some flat surface, allowing them to dry under the influence of the sun and wind. The idea is simple: the sun provides on appreciable and inexhaustible source of heat to evaporate moisture from the crops, and the velocity of the wind to remove the evaporated moisture is, in many locations, comparable to the air flow in a mechanical dryer and satisfactory. This method though labour intensive has proved very effective in most parts of the tropics where for several months of the year the mean level of solar insolation upon the ground is more than $0.5kW/m^2$ (measured as a mean over the hours of daylight). Thus for a twelve hour day light, this gives approximately $21.6mJ/m^2$, a quantity of heat theoretically sufficient to evaporate up to 9kg of water.

Traditional, open sun drying is highly limited by weather conditions. Besides weather and environmental limitations, natural/ traditional open sun drying is low and grossly inadequate for large scale applications. The system could be unhygienic, labour intensive, etc. During unfavorable weather, natural open sun-drying may be drastically hampered, thus creating an enabling atmosphere for bacteria, fungi and mould, to grow and secrete their enzymes into the moist products, resulting in deterioration and further drop in product quality /value.

Solar cabinet drying systems have been developed to address the problems of traditional open-sun drying, wherein the adverse influence of weather is highly minimized or totally neutralized.

The solar cabinet dryer is structurally a box specially constructed for the purpose of trapping the sun's heat and using same to effect drying of crops materials. The cabinet structure serves to protect the crop materials from inclement weather and pests and rodents attack.

Solar energy cabinet dryers have been classified into two main groups (Ekechukwu *et al,* 1995), namely;

(i) Active solar-energy drying systems (some of which are called hybrid solar dryers) or forced convection dryers)

(ii) Passive solar –energy drying systems generally referred to as natural circulation solar drying systems, (Brenndorfer *et al*, 1985).

A basic feature of active (solar) energy dryer is that the draft / circulation of drying air current is aided by motorized fans, pumps, etc. The passive solar energy dryer has no provision for incorporating fans, pumps to enhance air circulation. Instead air circulation is provided by the warm moist air leaving via the upper apertures under the action of buoyancy forces while the replenishing fresh air is drawn from the base, (Ekechukwu *et al,* 1995).

Furthermore, solar energy dryers (active or passive) may be classified into three distinct sub groups dependent on the design, arrangement of the dryer components, and the mode of utilization of solar heat energy. These classes are as follows:-

* Integral-type solar Dryers

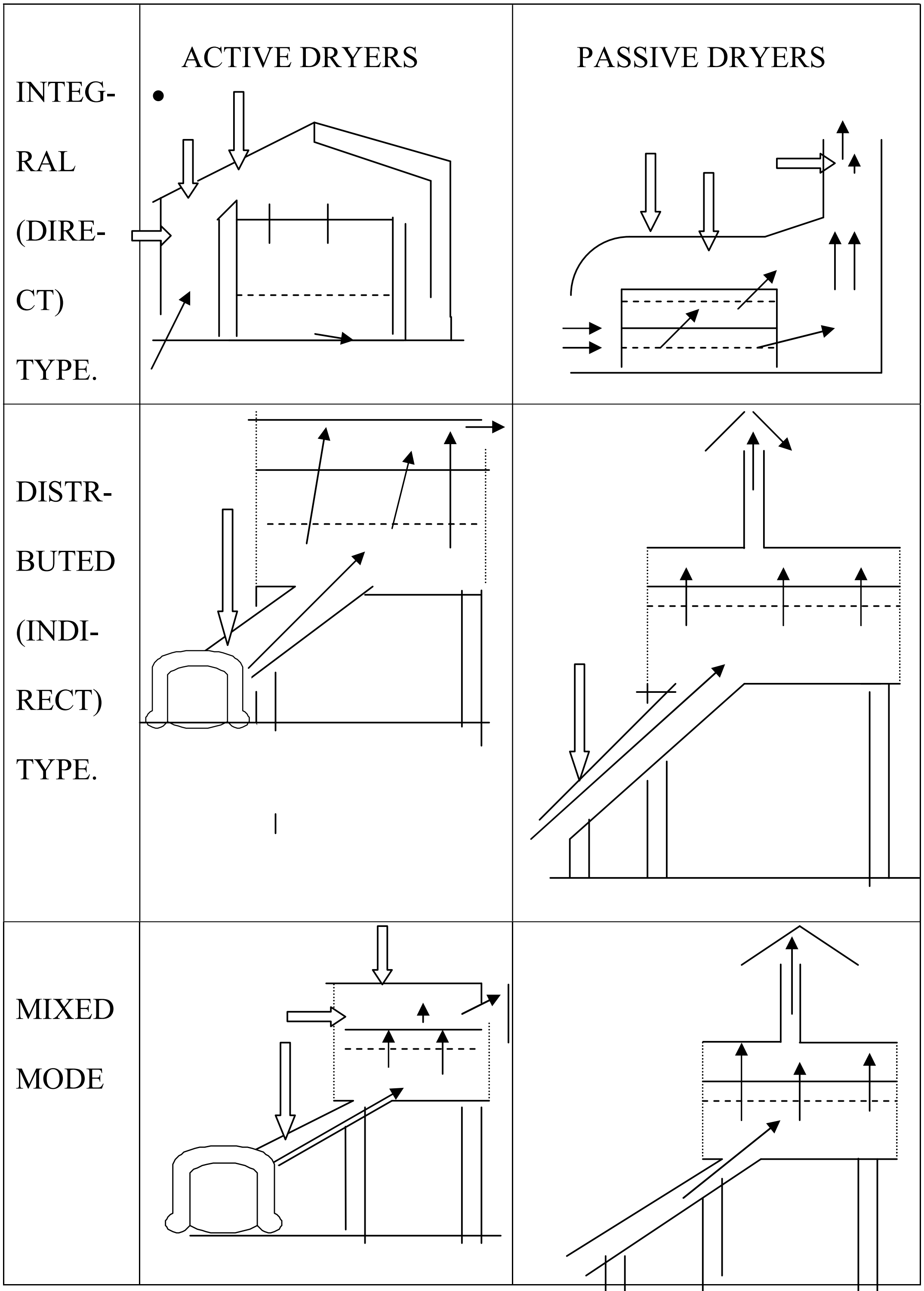
* Distributed –type solar Dryers

* Mixed –mode solar Dryers (Ekechukwu, 1985).

The main features of typical models of the identified classes of solar energy dryers are shown in figure 6.

2.10 Derivations from Solar Energy Crop Drying.

A lot of benefits are derivable from the practice of solar energy drying. Many researchers and authors have confirmed higher product quality of solar energy drying over other drying systems. Ranging from Osei and Kukah, (1989) who in addition to the improved taste and flavor, colour, declared that the keeping/storage quality of fish significantly improved when dried in a cabinet solar energy dryer. Renowned expert on Solar energy drying, (Kerr, 1999) had lauded solar drying technology in every respect.



Solar Radiation: Figure 6: Typical solar-energy dryer designs.

Source: Ekechukwu *et al,* (1995); Overview of solar drying technology.
AIR FLOW → SOLAR RADIATION ⇒

Whitefield, (2000) investigating solar energy drying technology appraised the process in the following key areas:

1. Solar food drying as a very simple skill easily assimilated into most cultures.
2. The use of solar dryer systems to conserve vegetables, fruits, coffee, and other crops is practical economical and environmentally responsive.
3. Solar dryer systems improve the quality of the product, while reducing wasted product and traditional fuels.
4. solar dried food products reduce storage and transportation costs as well as associated problems from climatic effects,
5. solar dryers are a cost – effective solution to food preservation in sunny climates,
6. Implementing the use of solar drying systems will result in significant savings to farmers and will open new markets.
7. Solar dryer systems improve the quality of life.
8. Solar dryer system technology now in existence can be adapted to meet almost every agricultural need.
9. There is an absence of good information about solar dryer technology in the countries where solar food processing is most needed.

Comparing the natural – circulation solar energy cabinet dryers with the traditional drying techniques, Ekechukwu *et al,* (1995) outlined the following distinctions:

- Cabinet dryers using natural circulation require a smaller area of land to dry similar quantities of crop that would have been traditionally dried over large open land area.

- They yield a relatively high quantity and quality dry crops because fungi, insects and rodents are prevented from infesting the crop during drying.
- The drying period is shortened compared with open air drying, thus attaining higher rates of product throughput.
- Protection is afforded to the crops from sudden down – pours of rain.
- Natural-circulation solar cabinet dryers are commercially viable, they have relatively low capital and maintenance cost because of the use of readily available indigenous labour and materials for construction.

It could be showen that food items dried in solar dryers were "superior" to those which were open – sun dried, when evaluated in terms of taste, colour and mould counts. Little wonder many researchers and authors emphasized the necessity to further develop, evaluate, exploit and employ solar dryer systems to utilize the abundant solar energy to the "fullest" and by so doing improve food production and preservation.

2.11 Over View of Solar Energy Systems and Solar Energy Crop Dryers.

The act of drying is as old as life, and crop drying technology had been developing along side agricultural technology, with the (solar) drying and field drying of crops being among the earliest known and / or practiced drying methods applied to most grains. Until recently, about the end of the 18th century when food canning was developed, drying was virtually the only method of food preservation, (Whitefield, 2000). Kerr, (1999) had asserted that food drying is an ancient skill for food preservation. It is worthy of note that in spite of the long standing existence and practice of crop drying, there is, hitherto, a dearth of reliable practicable ideas and information on design of appropriate crop drying systems across the globe, especially in the less developed and developing countries, (Snigh *et al,* 1987). However, documentaries of ancient work on solar energy (drying) can be traced to Syriacus 212BC (Nwakuna, 1990).

Contemporary work leading to the development of solar – energy systems include that of Joseph Priestly in 1774 when he produced oxygen gas by focusing sunlight into some oxide of mercury. His discovery was actually an eye – opener to the versatile uses of the solar energy (Kreider and Kreith ,1981).

Perhaps the greatest application of solar energy is in the agricultural sector wherein apart from photosynthesis; solar energy has been applied to power generation, water pumping, crop drying, irrigation, etc.

The original work by Richard M. and Vincent M. saw the emergence of a solar dryer for coffee and cocoa beans, in 1vory Coast. Their original design was later improved under the auspices of Ghanaian Government and the food and Agricultural Organization (FAO, 1980 and Ekechukwu *et al,* 1995).

Several designs of solar – energy dryers similar in configuration to the Brace institute model have been developed and tested in various parts of the world under a variety of conditions and crops.

Project Development Agency, PRODA, Enugu, Nigeria, 1980 carried out series of research on solar energy drying on thin layer of crops using chimney effect (Arinze and Obi, 1983). Brace Research Institute, Canada, reported the design of a mixed mode solar dryer built and tested by Sharma *et al*. The system which consisted of a bare plate air heating solar energy collector (made from a black – painted metal panel) or corrugated galvanized iron sheet (painted dull black), with hard board or thermopile insulation, and a multi- stacked drying chamber glazed on the front side and at the top. Though the dryer was not equipped with any chimney, the tall column of the drying chamber (about 1.27m) helped to generate the necessary buoyant head for natural convective air flow (Ekechukwu, *et al* 1995). Ekechukwu and Norton, (1995), reported the construction of a more simplified design of solar crop dryer. The drying chamber measured about 6.67m long by 3.0m wide by 2.3m high. The chimney (designed to allow variation in height) has a maximum height of 3.0m above the drying chamber and both drying chamber and chimney were made of galvanized steel frame work clad in transparent polyethylene sheet (which had been treated against degradation under exposure to ultraviolet radiation).

(Salmon *et al*, 2000) articulating mathematical model for designing chimney type indirect solar energy dryers, further emphasized the need for solar energy systems in developing economies.

Forde and Hamadou, (1996) experimented with a natural and forced convection solar energy dryers using meat. Their results showed a higher drying velocity at the beginning and also led to their conclusion of the existence of two phases in the drying process, namely

(i) evaporation of superficial moisture phase,

(ii) extraction and evaporation of the inner moisture contained in the product.

In his work on Home Power Magazine, Scanlin, (1999) offered a wide range of knowledge and information on construction techniques for indirect – type solar energy dryer systems. His work gave a wider insight on the following areas: factors affecting food drying, recommended drying temperatures, relationships between air flow and dryer temperature, possible temperature – related problems, how to get correct temperature , air flow, dryer construction and many other related subjects.

Akor and Zibokere, (1999) designed and developed a universal dryer which jointly used fossil fuels, electricity as well as solar energy. The dryer was tested using maize grains, cassava chips, yam slices and ginger and the results obtained ware quite encouraging and was more or less attributed to the in- built flexibility in the use of varied energy sources.

Alonge, (1997) modified a natural convection solar crop dryer by incorporating a chimney, eliminating the tubes used in conveying the heated air and substitution of perspex with glass. A no – load test of the modified dryer yielded a temperature in the range of $55^{o}C$ and, with the upper section of the chimney, it was observed that moisture condensation problem was considerably checked.

Alonge and Ojo, (1997) undertook the mathematical modeling of an active solar dryer for which it was shown that hourly out flow temperature was highest between 11am and 2pm for all months and it was lowest between 8am and 9am; 5pm and 6pm.

At the Federal University of Technology Owerri, notable research had been carried out on solar Energy utilization technology. Ogueke, (1998) worked on the Heat and mass transfer Analysis of Solar Powered Solid Adsorption Refrigeration. Ondoma, (2002) designed and constructed a Solar Power Supply for Domestic lighting.

Iwuoha, (2004) developed a Solar Assisted Infant Incubator, which worked on the thermo-siphon principle. The incubator which was tested ok raised the temperature of water (in a storage tank) to $50^{o}C$. This was then controlled to maintain the incubator to 37 ^{o}C suitable for the survival of a premature baby. Orji, (1989) designed a natural convection solar energy crop dryer which incorporated a heat storage chamber. His work was later modified and evaluated by Nwakuna, (1990). The modified version showed an improvement of the drying chamber temperature from 40oC to 63oC with better product qualities.

CHAPTER THREE

DEVELOPMENT OF THE DRYER.

In this section the techniques adopted in the conduct of the research has been shown. While showing the method of approach in the development and fabrication of the integral solar dryer, the basic principles of operation of the system are explained. Highlights of the experiments conducted were also given.

3.1 Theoretical Concept.

Solar energy cabinet dryers work by tapping the heat energy of the sun and using the same to evaporate moisture from crop materials until the crop materials attain equilibrium with the surroundings. The cabinet essentially provides shelter to the crop materials.

Integral solar dryers expose the crop materials to direct heat of the sun for increased rate of moisture removal. The dryer is made in such a way that the crop materials inside the drying chamber are exposed to the same amount of sunshine as in open-sun-drying, under better drying conditions.

A major consideration in the design of this dryer was the estimation of the incident solar energy which was available on the dryer ready for transmission to the crop

materials for moisture removal. This energy was estimated by considering the work of Akor and Zibokere, (1995) as given earlier in equation (17):

$$E_i = \alpha I_c A_c R \Omega \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (17)$$

Where, E_i = incident solar energy

α = absorption factor of the absorber plate.

I_c = average insolation per hour per unit area.

A_c = absorber surface area exposed to the sun.

R = transmittance of the cover plate.

Ώ = collector heating efficiency.

Equation (17) was applied to a natural convection solar dryer that has a collector/ absorber unit. However, for the integral (direct radiation and convectional heat) solar dryer, the collector/ absorber unit was eliminated. Incident solar radiation passed through the transparent cover plate and struck directly on and absorbed by the same crop materials inside the drying chamber. Thus, the effects of the absorption factor α, and the collector heating efficiency Ώ, was neglected or assumed unity. In that way equation (17) was modified to the form:

$$E_i = I_c A_d R \qquad \ldots\ldots\ldots\ldots\ldots\ldots (18)$$

Where, A_d = area of the drying chamber exposed to the sun.

In calculating E_i, approximate values of the variables I_c and R were used with

$I_c = 0.5 kW/m^2$ ---------- (Chancellor, 1995).

Approximate values of R was determined by a simple experiment described in section 3.4.

A_d was calculated from the area of the rectangular frame of the dryer.

$$A_d = L \times W \qquad \text{-----------------} (19).$$

Where, L = length of the drying chamber

W = width of the drying chamber.

Under the above heat the crops in the drying chamber steadily lost moisture until equilibrium was attained with the surrounding.

When a crop material is dried from an initial moisture level to final moisture content, some quantity of heat q, must be absorbed by the crop material and the evaporating moisture. This heat which could be referred to as the heat load of the system was calculated using the relation given by Snigh *et al,* (1987) in equations (11 and 12):

Heat load q_L = sensible heat gain by crop material and moisture

+ Latent heat of evaporation of the moisture. ………….. (11)

That is,

$$q_L = C_{pc} (Q - W_c)(T_3 - T_1) + W_c C_{pw} (T_3 - T_1) + M_e Y \quad \text{…………..(12)}$$

where, q_L = heat load (of the dryer),

Q = mass of given sample of crop (kg)

W_c = amount of water contained in the crop sample (kg)

M_e = moisture expelled from the crop sample (kg)

T_1 and T_2 are the inlet and exit air temperatures of the dryer (^oC). T_1 the inlet air temperature was assumed equal to the ambient air temperature.

C_{pc} = specific heat of the crop material (kJ/kg^{o}C)

= 837 to 2930 kJ/kg^{o}C for organic materials, (Eric, 1989).

C_{pw} = specific heat of water = 1kJ/kg^{o}C

Y = average latent heat of vaporization of water at the exit

Temperature

~ 22.5×10^5 J/kg at atmospheric pressure, (Eric, 1989).

The ability of a dryer system to attain the equilibrium moisture under specific conditions is directly related to the thermal efficiency ŋ, of the dryer. Akor and Zibokere, (1997) calculated the thermal efficiency of a solar dryer using the expression:

$$Ŋ = Q_d \div E_i \quad \text{…………………….(20)}$$

Where, Q_d = heat energy used in drying, which is equivalent to q_l, the heat load of the dryer.

E_i = total incident solar energy on the dryer.

That is, the thermal efficiency η, of the integral solar dryer was estimated by applying the same or similar expression:

$$\eta = (Q_d \div E_i) = (q_L \div E_i) \qquad \ldots\ldots\ldots\ldots(21)$$

$$= \{C_{pc}(Q - W_c)(T_1 - T_3) + W_c C_{pw}(T_1 - T_3) + M_e Y\} \div (I_c A_d R) \qquad \ldots\ldots\ldots\ldots(22)$$

3.2 General Design Considerations / Assumptions.

The basic considerations and assumptions adopted in developing the integral solar dryer include:

(i) Possibility of heat loss in the form of:

- reflection of solar radiation by the cover plate,
- conduction and radiation through the walls of the cabinet
- convection and vapor rising through the chimney into the atmosphere,
- convection and vapor escaping through minor openings in the cabinet (the cabinet walls are not air-tight)
- convection and movement of cold air through the inlet air vent into the drying chamber,
- movement of surrounding air in contact with the external walls of the dryer.

(ii) Crop drying might be done at any time or season of the year, the main crop drying season normally runs from late October to March, for most parts of Nigeria. During this period, it is most unlikely to have rain and the atmosphere is less humid.

(iii) Relative humidity remained constant throughout the period of testing the integral solar dryer.

(iv) Reliable daily radiation data are very limited, hence the average daily radiation in the tropics equal to $0.5kW/m^2$, as given by Chancellor, (1995), was adopted

(v) The integral solar dryer constructed can be adapted for use in any part of Nigeria. Better performance would be expected in areas within latitude 5.45^o, the slope angle of the cover plate

(vi) Abundant sunshine/ solar energy, with an average of ten (10) hours of sunshine daily.

3.3 Design Process of the Integral Solar Dryer.

Certain factors were considered in the development and fabrication of the integral solar dryer. These factors affected the selection of materials and the construction of the dryer.

Apart from the inherent economic factors, three basic parameters had been highlighted-

(i) Material factors,

(ii) Dimensional and structural design factors,

(iii) Construction process.

3.31 Material factors.

Selection of the construction materials forms an important aspect of engineering design practice. The choice of the suitable materials for the fabrication of the dryer was guided by:

(i) The service conditions under which the dryer will be used,

(ii) Adaptability of the material to the local construction process,

(iii) Ease of locating the material, especially in the local market,

(iv) Strength and durability of the material. The strength of a material is the resistance of the material to externally applied load or force. The principal forces on the dryer would be due to its weight and weight of the thin layer of the crop materials spread on the drying racks. Square pipe sections (25mm square pipes) and galvanized cylindrical pipes were used to make the frame-work of the dryer. These could withstand the forces that would act on the dryer under normal usage.

Table 1 : Details of the materials used to construct the solar dryer.

S/N	Material	Specificat-ions	Qty.	Function(s)	Remarks
1	25mm square pipe	Mild steel pipe 600×25×25	3 len-gths	Construct-ion of the rectangular frame	Mild steel preferred to wood for its higher strength. Pipe was preferred to solid bar due to its lighter weight and for portability.
2	Ø20mm galvanized pipe	Galvanized mild steel pipe Ø20×6000	1 len-gth	Construct-ion of the detachable stands.	Pipe sections used for their lighter weight compared to solid bar.
3	Ø27mm galvanized pipe	Ø27 ×400	1 len-gth	Female socket for the stands	Cylindrical pipe was used instead of the square pipe for easy coupling.
4	Alumi-num sheet	2400 ×1200 ×0.94thick-ness	1 sheet	Forming the chimneys and the floor of the drying chamber	Aluminum was preferred to mild steel because of its lighter weight and higher resistance to corrosion and heat reflectivity

5	Expended metal mesh	Mild steel wire mesh 750 × 350 ×2thick.	3 pieces	Construction of the drying racks	
6	Perspex	3mm thick 2400× 1200 ×3	1 she-et	For the walls and top cover of the dryer	Perspex used instead of glass for easy handling and construction
7	Particle board	5mm thick 780 × 380 ×5	2	Insulating floor of the drying chamber	The board was paired to make the floor double and increase its insulation effect
8 9	Bolt & nut pair Screws	M8 × 40, mild steel M10 × 30 M6 × 12	 110 4 8pc	For fixing the Perspex, stand, and the particle board	
10	Hinges	50mm (2inches) mild steel hinges	1 pair	Attaching the access door to the main frame	
11	Pvc pipe	Pvc of diameter 110mm	1	Opening for exit air, connects chimney to dryer	
12	Mild steel sheet	1.2mm thick mild steel sheet 600×600	1	Forming brackets and supports, and chimney clip	
13	Electrode	Mild steel electrode G12	1/3 packet	Arc welding of the metal frame	
14	Paint	Black oil paint	1 liter	Painting the metal frame chimney and floor of the dryer Black paint used for its high heat absorption capacity.	

3.32 Dimensional and structural Design of the Drying Chamber.

The integral solar dryer is to dehydrate 1kg of cassava chips at initial moisture content of 62%(wb) to a moisture level of 12.5%(wb) or less.

Dry matter content was obtained thus:

$$D_m = W_i - \{(M_{ci} \times W_i) \div 100\} \qquad (23)$$

Where W_i = initial weight of the cassava sample = 1kg

M_{ci} = initial moisture content (wet basis)% of the cassava

D_m = dry matter content of the sample.

$$D_m = 1kg - \{(62 \times 1kg) \div 100\} = 1kg - 0.62kg = 0.38kg.$$

Moisture content (wet basis)% ,M(wb), was converted to moisture content (dry basis) M(db), thus:

$$M_c(db) = M_c(wb) \div \{1- M_c(wb)\} \qquad (24)$$

Where $M_c(db)$ = moisture content dry basis

$M_c(db)$ = moisture content wet basis = 0.62 and 0.125.

(Komolafe and Osunde, 2005).

For 0.62

$$M_c(db) = 0.62 \div (1- 0.62) = 1.632 \text{ or } 163.2\%(db)$$

And for 0.125 we had

$$M_c(db) = 0.125 \div (1- 0.125) = 0.143 \text{ or } 14.3\%(db)$$

The weight of water to be removed from the sample by the drying process was determined thus:

$$W_w = \{M_{ci}(db) - M_{cf}(db)\} \times D_m \qquad (25)$$

Where W_w = weight of water (kg) to be expelled from the 1kg cassava,

M_{ci}(db) = initial moisture content (dry basis) of the cassava = 1.632

M_{cf}(db) = final moisture content (dry basis) of the cassava = 0.143

$$W_w = (1.632 - 0.143) \times 0.38\text{kg} = 0.566\text{kg}$$

The useful heat required for the drying process was estimated thus:

Equation (12) gave the heat required for crop drying as:

$$q_L = (Q - W_c)\, C_{pc}\, (T_2 - T_1) + (W_c\, C_{pw})(T_2 - T_1) + M_e Y \qquad (12)$$

Where q_L = heat required for crop drying, i.e. heat used by the drying process (kJ),

C_{pc} = specific heat of crop material (which is within the range 837kJ/kg°C to 2930kJ/kg°C)

Q = weight of sample, i.e. initial weight of the fresh cassava chips = W_i = 1kg

W_c = water content of the sample (kg).

= (W_i - D_m) = (1kg - 0.38kg) = 0.62kg

T_1 and T_2 are the averages of inlet air temperature and the air temperature inside the drying chamber respectively (°C),

T_1 and T_2 were assumed equal to 25°C and 47°C respectively

C_{pw} = specific heat of water = 1kJ/kg ^{0}C

M_e = weight of water to be expelled from the sample = W_w = 0.566kg,

Y = average latent heat of vaporization of water ~ 22.5 x10^5J/kg at atmospheric pressure, (Eric, 1989).

$$q_L = (837\text{kJ/kg}\,^{o}\text{C} + 2930\text{kJ/kg}\,^{o}\text{C}) \div 2\ (1\text{kg} - 0.62\text{kg})(47^{o}\text{C} - 25^{o}\text{C})$$
$$+\ 0.62\text{kg}(1\text{kJ/kg}^{o}\text{C})(47^{o}\text{C} - 25^{o}\text{C}) + (0.566\text{kg} \times 2.25 \times 10^3\text{kJ/kg})$$
$$= 15746.06\text{kJ} + 8.36\text{kJ} + 1273.5\text{kJ} = 17028.72\text{kJ}.$$

The useful solar heating power involved was estimated thus:

Ten hours daily sunshine was used and the dryer with its content was exposed for the ten hours of sunshine for three consecutive days.

Total time of exposure to sunshine (in seconds) was obtained thus:

Total time t(s) = (3days x 10hours x 60minutes x 60seconds) (26)

$$= (3 \times 10 \times 60 \times 60) = 108000s = 1.08 \times 10^5 s.$$

Useful heating power was calculated thus:

$$P_s = (q_L \div t) \quad (27)$$

Where P_s = useful solar heating power (kW)

q_L = useful solar heat for the drying = 17028.5kJ

t = time duration of the drying process = 1.08×10^5s

$$P_s = 17028.5kJ \div 1.08 \times 10^5 s = 0.158kW$$

Komolafe and Osunde, (2005) estimated the dimensions of the collector and drying chamber of a free convective solar dryer using the expression:

$$Q_u = A_c F_R T_{\infty ø} I_H \quad (28)$$

Where Q_u = rate of useful heat gain (J/s) = useful solar heat power P_s (kW),= 0.158kW

A_c = collector area (m^2),

F_R = heat removal factor = (0.7),

$T_{\infty ø}$ = effective transmittance absorptive product = (0.79),

I_H = average total horizontal solar radiation, (earlier given in this text as $0.5kW/m^2$).

Equation (28) which is equivalent to equation (17) was modified and used to determine the drying chamber dimensions. The factors F_R and $T_{\infty ø}$ which relate to the collector play little or no role in the integral solar dryer which uses direct heat of the sun. Hence equation (31) transformed to:

$$Q_u = A_c I_H R \quad (29)$$

Equation (29) is the equivalence of equation (18) as equation (28) is to equation (17).

But, $Q_u = P_s = A_d I_H R$

where A_d = drying chamber area (m^2),

R = solar heat transmittance of Perspex ~ 1

With $P_s = A_d I_H R$,

$A_d = \{ P_s \div (I_H R)\}$

$= (0.158kW) \div (1 \times 0.5kW/m^2) = 0.316m^2 = 0.32m^2$.

Using the relation:

X, 0.733X and 1.5X; Komolafe and Osunde, (2005) determined respectively the solar collector length, width and drying chamber length of a free convective solar dryer. But for the integral solar dryer, the drying chamber also serves as the collector so that the above relation was used to determine the drying chamber dimensions as follows:

Area of drying chamber, $A_d = L \times W$ as earlier given in equation (19).

Where, A_d = area of the drying chamber of the integral solar dryer (m^2),

L = length of the drying chamber (m),

W = width of the drying chamber (m),

i.e. $$A_d = (1.5X) \times (0.733X). \quad (30)$$

$0.32\ m^2 = 1.0995X^2$

$X = \sqrt{(0.32 \div 1.0995)} = 0.5395 \sim 0.54m$.

Thus the length of the drying chamber was calculated as:

$$L = 1.5X \quad (31)$$

$= 1.5 \times 0.54m = 0.809m \sim 0.80m$.

And the width was calculated as:

$$W = 0.733X \quad (32)$$

$= 0.733 \times 0.54m = 0.395 \sim 0.40m$.

Conversely, the height of the drying chamber above the ground, that is, the height of the stand was selected to:

(i) improve the user's comfort, by minimizing bending down by the user;

(ii) Protect the drying materials from rain drops, insects, rodents, etc.

A simple rectangular configuration was adopted in constructing the dryer considering the limited construction facilities within reach.

3.33 The Construction.

The dryer was made in a way that the construction facilities can easily be obtained and the fabrication done in any metal workshop using simple workshop processes.

3.4 Determination of the Approximate Transmittance of the Perspex.

Solar transmittance of the Perspex used in constructing the integral solar dryer was approximately determined by simultaneously monitoring the temperature profiles of water in two cups. One of the cups was placed below a sheet of the Perspex; the other cup was kept in open sun.

PROCEDURE: Two similar plastic cups were filled with equal volumes of water and placed of a wooden bench. A thermometer was dipped in each cup. One of the cups was placed beneath a large sheet of Perspex in such a way that it received sunlight through the Perspex only. The other cup was kept in open sun so that it received direct sunlight.

Readings on the thermometer were monitored and recorded on hourly intervals until a drop in temperature was noticed. Before each reading was taken, the water in the cup was stirred thoroughly for uniformity. The experiment was repeated trice. For each pair of reading the hourly solar transmittance of the Perspex was calculated using the relation:

Hourly solar transmittance, $r = T_p / T_\bullet$ ……………………(33)

Where, T_p = hourly thermometer reading under the Perspex

$T_\bullet$ = corresponding hourly thermometer reading in open sun

The mean of these values of r obtained for all the pairs of values of T_p and $T_\bullet$ was estimated using the relation:

$$R = \Sigma^{n}_{i=1}(r)/n \qquad \ldots\ldots\ldots\ldots(34)$$

Where, R = approximate solar energy heat transmittance of the Perspex,

r = hourly solar energy heat transmittance of the Perspex

n = number of pairs of readings of $T_p/T_\bullet$ used in the estimation

Σ = summation sign.

The results obtained are given in table 2.

3.5 Construction of the Integral Solar Dryer.

Engineering construction is the transformation of an engineering design into physical structure. In the development of the solar dryer, the construction processes and facilities involved were considered. Selection of one of the major construction materials- the Perspex- for instance, involved extensive consideration of the critical construction work on the material. In that case the critical construction work on the Perspex was drilling of holes by means of which the perspex boards were fixed. Perspex was used instead of glass for the reason that it was easier to drill and has less handling risk than glass. Major construction processes involved in the fabrication of the solar dryer included: cutting, drilling, folding, simple joining, welding and various finishing operations. The main components of the dryer are:

(i) Main frame work or metal skeleton, (ii) Detachable stands,

(iii) Access door (for loading and unloading of the crop materials),

(iv) Drying racks, (v) Suction chimney.

(i) **Main frame work**: This was formed with the 25mm or 1 inch square pipes which was cut to the design sizes and joined by arc welding process to form a rectangular metal skeleton / box, 800mm×400mm×550mm.

(ii) **Detachable stands**: Was made from the 20mm diameter galvanized pipe cut into four pieces, each of 750mm and drilled on one end for M10 ×30 bolt

(iii) **Access door frame**: 350mm x 350mm, formed with the 25mm square pipe.

(iv) **Drying racks**: Formed with wire mesh 720mm x 345mm, the edges trimmed with the 1.2mm mild steel sheet.

(v) **Suction chimney**: formed with 0.93mm aluminum sheet folded to form the frustum of a cone of diameters 117mm by 127mm. For the purpose of evaluating the dryer, three chimneys were formed of heights 1200mm, 800mm, and 400mm. The chimneys were used to investigate the effects of chimney height on the performance of the integral solar dryer.

(vi) FINISHING: The above listed components were polished with black oil paint and allowed to dry. The Perspex was fixed followed by the chimney which was held firm with the chimney clips / straps fixed on the chimney support.

3.6 EVALUATION.

Performance tests were conducted on the dryer to establish the functionality of the system on the basis of the heat utilization capacity, and quality of the dried products.

3.61 Preliminary Test: This was done to ascertain the functionality of the dryer. Freshly harvested, peeled cassava tubers, cut into circular flat chips of 10mm thickness were spread on the drying racks in the drying bin. The dryer with its content was kept in the sun. A control test was set up by spreading equal weight of cassava chips on a similar rack, placed in open sun. The experiment was monitored and records of the observations kept on hourly intervals. Records of the hourly ambient temperature, drying bin temperature, exit air temperature (from the chimney), weight loss of the cassava chips, were documented.

3.62 Investigation of the Effects of Variation in Chimney Height on the Performance of the Integral Solar Dryer.

FACILITIES AND MATERIALS USED:

(i) Three chimneys of heights 1200mm, 800mm, 400mm, labeled A, B, C respectively. The chimneys were made of aluminum sheet and painted black to improve the thermal properties.

(ii) Three thermometers

(iii) Two drying racks, labeled D and S

(iv) Weighing scale

(v) Freshly harvested, peeled cassava roots/tubers of average intermittent diameter 40mm.

PROCEDURE: The cassava tubers were peeled, washed and kept in a basket for 10minutes for the surface water to drain out. The tubers were cut into circular flat chips of 10mm thickness. Equal weights of the cassava chips were spread on the two racks D and S. Rack D with its content was placed in the drying bin, while rack S with its content was placed on a wooden stand. Rack S with its content served as the control experiment. Chimney A was fixed on the dryer. The experiment which was carried out at the Imo State Technological Skills Acquisition Institute (TESAI), Orlu in the October 2007, was set up in the field to ensure good exposure of both the dryer and rack S to the sun from 8.00 a.m. to 18.00 hours, (6.00 p.m.) daily, and monitored on hourly intervals.

(1) Temperatures were monitored at three different locations:-

(i) Ambient temperature recorded from a thermometer placed near the inlet air vent of the dryer,

(ii) Drying bin temperature recorded from a thermometer placed in the drying chamber,

(iii) Exit air temperature measured near the top of the chimney through the openings for exit air.

(2) The cassava chips in the racks were weighed and reweighed on hourly basis to obtain hourly weight loss.

At the end of each drying day, i.e. at 6.00 p.m. (18.00 hours), the whole set-up was moved to a veranda to shield the content of rack S from dews. The experiment was continued the following day from 8.00 hours to 18.00 hours for three consecutive days. Samples of the dried cassava chips were taken from both racks D and S analyzed for moisture content and other physical qualities e.g. appearance.

The experiment was repeated three times with each of chimneys A, B, C, and then without the chimney. The observations made were recorded and analyzed.

CHAPTER FOUR

RESULT ANALYSES AND DISCUSSION.

In this chapter the results of the tests and experiments done in the course of this project are presented. General assessment and discussion of the tests, observations and results are given. In making the analyses, the observed physical characteristics of the cassava chips dried in the integral solar dryer were compared with those of the chips dried in open air. The following parameters were determined:

(1) Moisture content of the dried cassava chips, M_c (%),

(2) Percentage volume shrinkage of the dried cassava chips,

(3) Drying efficiency of the integral solar dryer.

Details of the tests, experiments, observation and results are given below.

4.1 Estimating Approximate Transmittance of the Perspex.

In the experiment to estimate the approximate light energy transmitting power of the perspex used in making the integral solar dryer, the following data were obtained:

Table 2 : Observed Hourly Temperatures of the waters in the two cups

Time of the day	Thermometer Readings °C Open air (T_o)	Under the perspex (T_p)	Temperature Ratio (T_p/T_o)
8.00 a.m.	22.2	22.2	1.0000
9.00 a.m.	23.0	23.0	1.0000
10.00 a.m.	26.5	27.8	1.0491
11.00	30.2	32.0	1.0596
12.00 Noon	33.0	34.8	1.0545
1.00 p.m.	34.7	36.2	1.0432
2.00 p.m.	36.6	37.8	1.0356
3.00 p.m.	36.3	37.5	1.0331
2nd Day			
8.00 a.m.	22.3	22.3	1.0000
9.00 a.m.	23.0	23.3	1.0130
10.00	26.0	28.0	1.0769
11.00	29.5	32.8	1.1119
12.00	33.0	35.2	1.0667
1.00 p.m.	34.4	36.7	1.0669
2.00 p.m.	36.3	38.0	1.0468
3.00 p.m.	36.0	37.7	1.0472
3rd Day			
8.00a.m.	22.2	22.2	1.000
9.00	23.2	23.6	1.0172
10.00	26.7	27.7	1.0375
11.00	29.8	32.5	1.0906
12.00 noon	33.1	34.8	1.0514
1.00 p.m.	34.6	36.6	1.0578
2.00	36.4	37.9	1.0412
3.00	36.1	37.7	1.0443

Table 3: Averages of the hourly temperatures of the water in the cups .

Average Temperatures (^oC) for days 1,2,3		Temperature ratio (T_p/T_o)
Open air (T_o)	Under perspex (T_p)	
22.2333	22.2333	1.0000
23.0667	23.3000	1.0101
26.4000	27.8333	1.0543
29.8333	32.4333	1.0872
33.0333	34.9333	1.0575
34.5667	36.5000	1.0559
36.4000	37.9000	1.0412
36.1333	37.6333	1.0415

In figure 7 the curve T_p lies above the curve T_o. This shows a higher rise in the temperature of the water under the perspex over that of the water kept in open sun. This also implies that the water under the perspex received more heat than the water placed in open sun for exposure to the sun. Thus it could be stated that the perspex boosted the radiant heat from the sun.

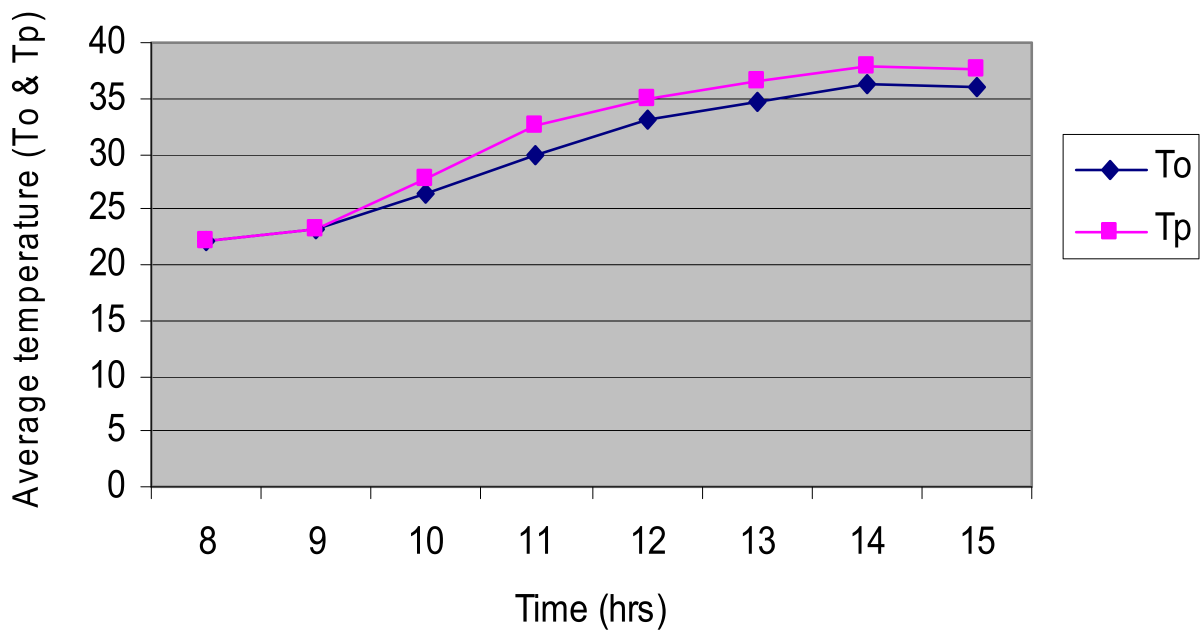


Fig.7: Plot of Average temperatures (To & Tp) against time (See table 3)

A measure of this property of the perspex referred to as the solar heat coefficient of perspex (in this text) was estimated graphically by plotting the graph of average T_p against average T_o as shown in figure 8, and the slope of the straight line graph determined; or by calculating the mean of the ratios (T_p/T_o) for the thermometer readings obtained. The graph of average T_p against average T_o (figure 8) gave a slope of 1.034 which is almost equal to the calculated value of the ratios of average T_p and average T_o which gave a value of 1.0435. However, 1.034 was adopted as the solar heat coefficient of perspex, designated as R in this work.

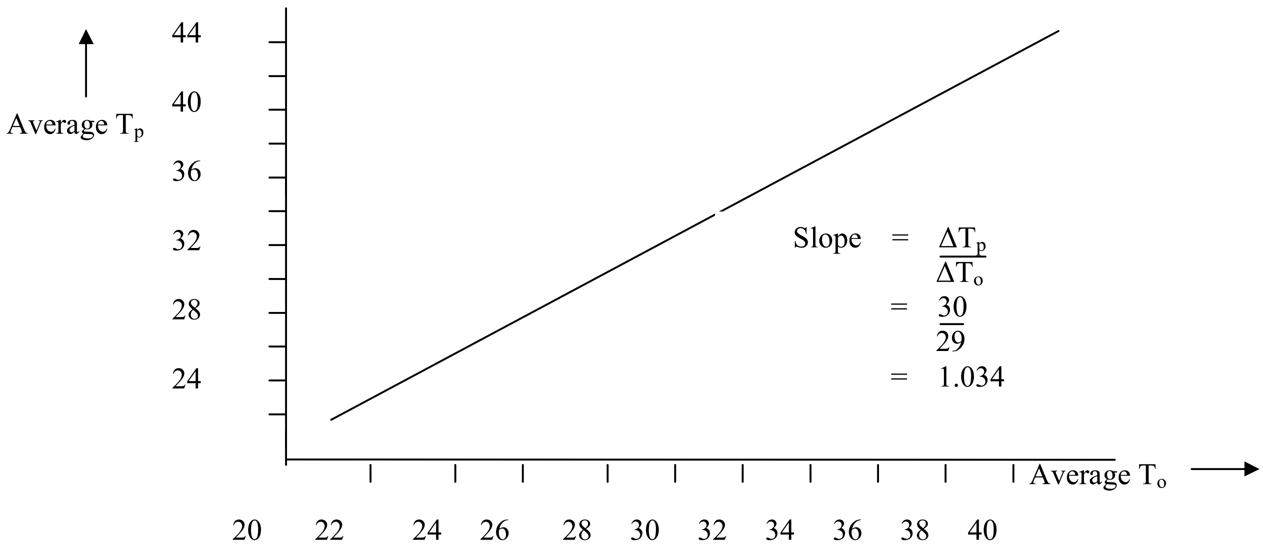


Fig. 8 : Plot of the average temperatures of the water under the perspex T_p, against average temperatures of the water in open sun T_o.

The plot of the ratios (T_p/T_o) against time, in figure 9 showed a sharp rise in (T_p/T_o) during the morning hours. This trend declined through the afternoon due to general atmospheric air warm up.

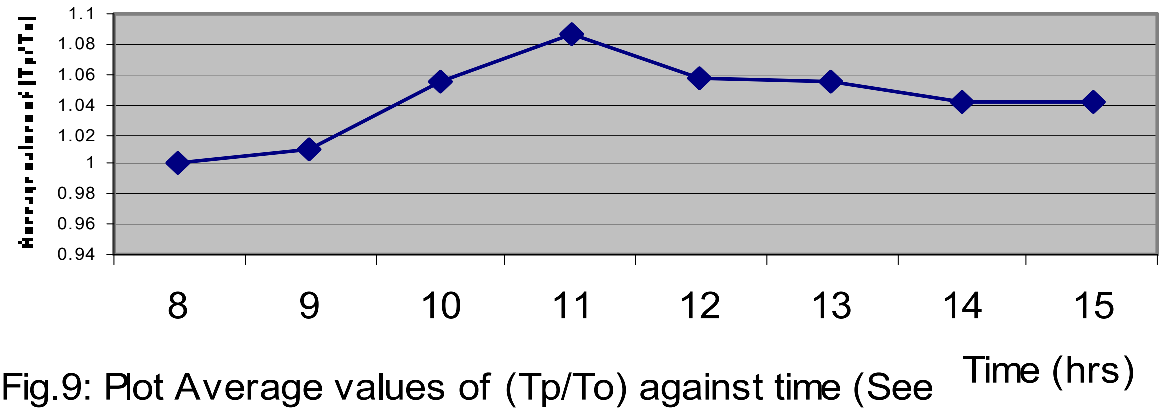


Fig.9: Plot Average values of (Tp/To) against time (See table 3)

4.2 Preliminary Tests.

Preliminary tests were made on the integral solar dryer using freshly harvested cassava chips. 1kg of the chips was spread in the dryer, and another 1kg spread on a rack placed in open sun serving as the control test. Both set ups were kept in the field to certify they had the same rate of sun shine for three consecutive days. Within this period the chips in side the dryer lost up to 550g of water, while the chips in open sun lost about 400g of water. This shows that the solar dryer is effective and faster than open sun drying. Table 4 shows the observations recorded during the tests.

Table 4: Observed hourly temperatures and weights of drying samples of cassava chips

Time of day	Thermometer Reading (°C)			Weight of cassava chips (g)	
	Air-in-let T_a	Drying chamber T_d	Exit air T_e	Open air	Drying bin
Day 1					
8.00 am	26.4	26.8	26.4	1,000	1,000
9.00 am	28.0	33.5	28.5	992.6	990.1
10.00	29.9	39.1	35.1	980.2	971.8
11.00	31.5	42.6	38.0	963.1	944.8
12. noon	33.7	46.0	42.1	942.1	910.0
13.00	35.2	51.0	43.3	918.4	872.8
14.00	36.7	57.8	46.8	891.7	829.5
15.00	36.0	54.0	45.9	865.5	784.8
16.00	33.8	49.2	44.4	841.6	751.3
17.00	31.4	42.6	40.0	827.0	729.6
18.00	29.3	38.1	36.1	820.9	716.3
Day 2 8.00	26.5	27.0	26.6	805.6	694.1
9.00	27.8	37.8	28.8	805.6	694.1
10.00	30.2	40.0	37.4	795.4	680.3
11.00	31.6	45.3	40.0	779.6	658.8
12.noon	33.3	47.9	41.6	761.5	634.8
13.00	35.8	53.1	43.0	741.1	607.5
14.00	36.4	58.1	44.1	715.6	579.0
15.00	35.9	54.7	43.5	693.9	551.0
16.00	33.6	52.2	42.0	674.7	527.8
17.00	30.4	48.6	39.5	663.9	513.9
18.00	28.3	45.0	37.8	659.2	506.8
Day3 8.00	26.7	27.0	26.8	652.8	499.4
9.00	27.5	38.2	30.3	652.8	499.4
10.00	30.1	42.0	36.4	649.3	495.6
11.00	31.9	45.9	38.7	644.2	491.0
12.noon	33.0	49.8	42.5	638.3	480.6
13.00	35.6	53.1	44.0	631.3	469.4
14.00	37.1	58.6	45.0	622.7	456.7
15.00	35.5	55.2	44.6	616.6	444.9
16.00	32.8	51.9	42.0	611.0	438.7
17.00	30.1	48.2	38.1	609.7	435.9
18.00	28.5	44.8	36.0	608.4	434.5

Table 5: Averages of the hourly temperatures obtained during preliminary tests.

Time of day	Average thermometer readings (^oC)		
	Air in-let (Ambient)	Drying chamber	Exit air
8.00 a.m.	26.53	26.93	26.60
9.00 a.m.	27.77	35.50	29.20
10.00 a.m.	30.07	40.37	36.30
11.00 a.m.	31.67	44.60	38.90
12.00 noon	33.33	47.90	42.07
13.00 p.m.	35.53	52.40	43.43
14.00 p.m.	36.73	58.17	45.30
15.00	35.80	54.63	44.67
16.00	33.40	51.10	42.80
17.00	30.63	46.47	39.20
18.00 p.m.	28.70	42.63	36.63

The comparative plot of the ambient temperatures, drying bin temperatures and exit air temperatures against time in figure 10 showed a faster and higher rise in the drying bin temperature Td over the ambient and exit air temperatures Ta and Te, respectively. The three curves attained their peak temperatures about the same hour (i.e. 14.00 hours or 2.00pm). Beyond these peaks curves Te and Ta showed steeper downward slopes than Td. It was also observed that the temperature inside the drying chamber remained appreciably higher than the ambient and exit air temperatures, thus maintaining a temperature gradient for drying to continue a few hours after sun set.

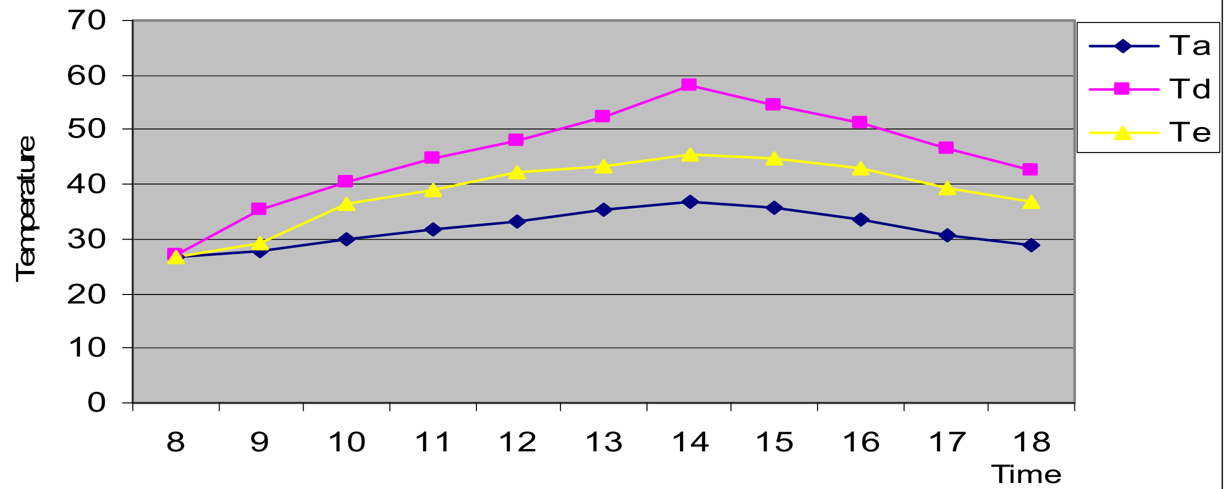


Fig.10: Plot of temperatures against time for preliminary test (See table 5)

4.3 Effects of Variation in Chimney Height.

In this experiment four conditions were investigated on the solar dryer:

1. Drying using chimney A of height 1200mm
2. Using chimney B of height 800mm
3. Using chimney C of height 400mm
4. Drying without chimney attached.

Time of day	Temperature (^oC)			Weight of drying cassava (g)	
	Air in-let T_a	Drying chamber T_d	Exit air T_e	Open air	Drying bin
Day 1					
8.00	26.4	26.8	26.4	400	400
9.00	28.0	33.6	29.3	393.0	395.7
10.00	30.0	38.8	35.4	391.6	383.9
11.00	31.4	41.9	38.0	386.8	365.8
12 noon	33.1	45.8	40.0	376.4	344.1
13.00	35.8	52.0	42.8	363.0	319.2
14.00	36.6	57.3	43.5	345.3	290.8
15.00	35.1	53.1	42.9	329.8	270.8
16.00	32.5	48.8	40.0	320.2	254.3
17.00	30.3	45.0	37.5	314.4	247.0
18.00	27.8	39.8	33.0	310.0	244.9
Day 2					
8.00	26.6	27.9	26.7	302.3	239.5
9.00	27.4	35.0	30.8	301.0	238.8
10.00	29.5	40.8	36.0	297.1	234.7
11.00	31.9	44.5	39.1	286.4	228.7
12 noon	33.0	47.6	40.6	274.5	221.9
13.00	35.0	53.6	41.4	262.3	212.0
14.00	36.0	58.0	43.0	250.8	200.1
15.00	34.1	56.4	42.7	242.0	190.3
16.00	31.8	54.2	41.6	236.7	186.0
17.00	31.0	52.5	39.9	231.9	181.9
18.00	29.0	47.1	36.0	229.5	180.0
Day 3					
8.00	27.0	27.6	27.0	224.2	178.8
9.00	27.7	35.5	30.4	224.2	178.8
10.00	31.9	42.1	35.3	220.7	177.3
11.00	32.6	45.3	38.8	217.4	176.0
12 noon	33.0	49.5	41.0	214.6	174.7
13.00	35.4	55.0	41.8	210.8	172.9
14.00	36.6	58.8	42.5	205.4	170.4
15.00	35.4	55.5	41.0	200.6	169.0
16.00	33.0	54.1	40.2	199.7	168.4
17.00	31.2	51.7	38.2	199.5	168.3

18.00 p.m.	28.7	47.4	34.5	199.5	168.3

Table 6: Temperature profiles and weight of drying samples of cassava using chimney A120mm high

Table7:Temperature profiles and weights of drying samples of cassava chips using chimney B 800mm high.

Time of day	Temperature (^oC)			Weight of drying cassava (g)	
	Air in-let	Drying chamber	Exit air	Open air	Drying bin
Day 1					
8.00	26.3	26.4	26.3	400	400
9.00	27.7	32.8	29.8	393.0	395.3
10.00	30.0	38.5	35.8	391.4	385.4
11.00	32.0	42.0	37.5	386.3	370.0
12 noon	33.4	46.3	41.3	375.9	357.1
13.00	34.6	50.2	42.4	362.7	338.2
14.00	36.8	56.8	43.0	345.0	301.8
15.00	35.3	54.0	41.8	330.1	289.3
16.00	34.0	48.0	39.3	321.8	272.5
17.00	31.1	42.2	37.2	314.3	263.6
18.00	28.7	38.8	33.0	310.0	257.0
Day 2 8.00	26.5	27.2	26.5	303.1	253.9
9.00	27.4	36.1	29.9	302.3	253.1
10.00	32.1	41.0	36.0	297.3	248.4
11.00	32.6	45.3	39.0	286.8	243.5
12 noon	33.1	47.5	40.1	275.1	236.7
13.00	34.0	52.5	42.8	263.9	225.8
14.00	35.6	58.2	44.5	251.6	210.6
15.00	34.9	55.0	43.8	242.7	200.4
16.00	32.6	53.0	41.8	236.4	193.8
17.00	31.0	50.8	39.6	232.0	188.0
18.00	28.3	46.6	35.9	230.3	185.2
Day 3 8.00	26.0	27.0	26.5	224.8	182.0
9.00	27.8	35.5	30.8	224.8	182.0
10.00	32.0	41.2	36.6	221.0	180.4
11.00	32.8	46.0	38.5	217.9	179.7
12 noon	33.4	49.8	42.1	214.6	177.8
13.00	35.1	54.2	43.0	210.5	175.7
14.00	36.5	59.0	44.7	205.8	173.3
15.00	34.6	55.6	43.6	201.0	172.1
16.00	32.3	54.4	42.0	199.8	171.8
17.00	30.0	52.7	40.5	199.3	171.6
18.00	28.4	48.1	36.2	199.3	171.6

Table 8: Temperature profiles and weights of drying samples of the cassava chips using chimney C of height 400mm

Time of day	Temperature (^oC)			Weight of drying cassava (g)	
	Air in-let	Drying chamber	Exit air	Open air	Drying bin
Day 1					
8.00	26.5	26.8	26.5	400	400
9.00	28.0	33.4	28.6	392.8	396.2
10.00	31.1	38.5	35.5	390.9	385.0
11.00	32.5	42.6	38.0	386.0	371.6
12 noon	3.6	45.1	41.0	375.1	357.3
13.00	35.0	51.4	42.5	360.8	339.0
14.00	36.6	57.1	44.3	341.2	302.5
15.00	33.0	54.0	43.7	327.8	283.0
16.00	30.8	48.6	41.5	319.7	269.6
17.00	29.8	44.6	39.2	313.1	260.5
18.00	28.5	38.7	35.5	309.9	254.2
Day 2					
8.00	26.0	26.8	26.1	301.8	251.2
9.00	27.2	37.5	29.5	300.3	250.5
10.00	30.4	40.6	336.1	296.9	246.2
11.00	31.9	45.8	39.4	286.3	240.9
12 noon	33.6	47.2	41.8	275.0	234.1
13.00	35.5	53.8	43.4	263.4	223.2
14.00	37.1	58.8	45.9	259.7	209.0
15.00	34.7	55.2	43.8	242.3	200.3
16.00	32.2	53.3	42.5	236.2	194.1
17.00	30.5	50.8	39.8	230.9	189.5
18.00	28.3	46.4	36.2	228.3	187.0
Day 3					
8.00	26.4	27.3	26.5	225.0	184.0
9.00	27.8	35.6	31.0	225.0	184.0
10.00	30.2	40.8	35.9	221.3	182.8
11.00	32.6	45.4	40.4	217.9	182.2
12 noon	34.0	49.7	42.0	214.8	180.4
13.00	36.3	54.0	43.6	211.0	178.2
14.00	37.0	58.8	46.2	205.9	176.7
15.00	34.8	55.8	45.4	201.2	175.4
16.00	32.5	54.5	44.4	199.9	174.5
17.00	30.2	51.8	41.7	199.4	173.8
18.00	28.0	47.6	36.8	199.4	173.5

Table 9: Temperature profiles and weights of drying samples of the cassava chips using no chimney, D

Time of day	Temperature (^{0}C)			Weight of drying cassava (g)	
	Air in-let	Drying cha.	Exit air	Open sun	Drying bin
Day 1					
8.00	26.7°C	26.7°C	26.7°C	400g	400g
9.00	28.0	32.0	28.4	393.2	396.8
10.00	29.6	38.4	35.1	391.6	384.9
11.00	32.5	40.9	38.6	385.8	370.4
12 noon	33.9	45.3	42.2	376.1	356.0
13.00	35.3	51.6	42.8	361.5	338.4
14.00	36.8	56.8	43.5	342.5	301.6
15.00	35.0	53.0	42.9	328.8	280.8
16.00	33.7	48.5	40.7	319.8	267.0
17.00	30.2	46.3	37.4	313.6	258.7
18.00	28.0	39.5	33.1	310.3	252.2
Day 2					
8.00	26.4	27.1	26.7	301.6	249.1
9.00	27.8	36.6	29.9	300.6	248.8
10.00	30.0	40.8	36.7	297.2	244.4
11.00	31.9	46.0	41.4	286.0	239.1
12 noon	33.0	48.3	43.0	275.1	232.3
13.00	35.4	54.1	43.6	263.4	222.6
14.00	36.0	58.5	45.3	258.8	208.4
15.00	34.3	55.7	44.0	243.0	199.7
16.00	32.6	54.3	43.0	236.5	194.5
17.00	29.9	50.1	40.7	231.2	190.1
18.00	28.4	45.7	36.0	228.8	187.8
Day 3					
8.00	27.0	27.6	27.0	225.2	184.7
9.00	28.1	36.0	30.3	225.2	184.7
10.00	30.7	41.1	36.7	220.8	184.0
11.00	31.4	45.2	42.0	218.1	182.8
12 noon	32.6	50.4	43.5	214.6	181.0
13.00	33.9	55.8	45.0	210.3	178.9
14.00	35.8	57.8	45.7	205.0	177.4
15.00	34.2	55.8	44.5	201.4	176.0
16.00	32.0	55.0	43.8	199.8	175.6
17.00	29.7	53.6	40.5	199.2	175.0
18.00	28.1	48.8	35.8	198.9	174.8

Tables 6,7,8 and 9 show the results of the drying tests using the three chimneys labeled A, B, C, and then D-without chimney. Each table contains;

i) Temperatures of the drying bin (T_d) measured hourly,

ii) In let air (ambient) temperatures (T_a) on hourly basis,

iii) Temperatures of the exit air(T_e) measured hourly,

iv) Weights of drying cassava chips measured at the corresponding hours.

A comparative look at the four tables revealed that:

1. Ambient air temperatures observed during the tests were almost the same at the corresponding hours for each chimney tested.

2. Temperatures recorded inside the drying bin at corresponding hours were almost equal in values.

3. Exit air temperatures were almost equal for tests A, B, C and D.

4. Despite the above conditions the moisture removal rate and the moisture content observed for each chimney were markedly different. The cassava chips in the drying bin dried faster and attained lower moisture content when chimney A (of height 1200mm) was used than when the shorter chimneys were used.

The most likely reason for this could be that the taller chimney had a higher suction (drag) effect on the air flowing into the dryer than the shorter chimneys. The taller chimney enhanced the air flow rate through the drying bin thus increasing the drying rate.

Furthermore, it could be recalled that the mechanism of drying involves:

1. Mobilization of the internal moisture of the crop material by some heating process,
2. Continuous discharge or evacuation of the moisture hitherto liberated.

Other conditions being constant, drying rate could increase if either the heat or the cross flow of dry air through the crop material is increased, or both of them increased.

In the above case however, temperatures were fairly within the same range inside the drying bin for all the chimneys tested. Thus one could attribute the increased drying observed with chimney A, 1200mm high, to increased volume flow rate of dry air across the crop material.

Table 10: Averages of the Temperatures observed at the particular hours of the day for the tests using chimneys A, B, C and D (derived from tables 6, 7, 8 and 9)

Hours of the day	Average ambient air temperature Ta (°C)				Average drying chamber temperature Td (°C)				Average exit air temperature Te (°C)			
	A	B	C	D	A	B	C	D	A	B	C	D
8.00	26.67	26.27	26.30	26.70	27.43	26.87	26.97	27.13	26.70	26.43	26.37	26.8
9.00	27.70	27.63	27.67	27.97	34.70	34.80	35.50	34.87	30.17	30.17	29.70	29.5
10.00	30.47	31.37	30.57	30.10	40.57	40.23	39.97	40.10	35.57	36.13	35.83	36.2
11.00	31.97	32.47	32.33	31.93	43.90	44.43	44.20	44.03	38.63	38.33	39.27	40.7
12.00	33.03	33.30	33.73	33.17	47.63	47.87	47.33	48.00	40.53	41.40	41.60	42.9
13.00	35.40	34.57	35.60	35.87	53.53	52.30	53.07	53.83	42.00	42.73	43.17	43.8
14.00	36.40	36.30	36.90	36.20	58.03	58.20	58.17	57.70	43.00	44.07	45.37	44.8
15.00	34.87	34.93	34.17	34.50	55.00	54.80	55.00	54.83	42.47	43.07	44.33	43.8
16.00	32.43	32.97	31.83	32.77	52.36	51.80	52.13	52.60	40.60	41.03	42.80	42.5
17.00	30.83	30.70	30.17	29.93	49.73	48.57	49.07	50.00	38.53	39.10	40.23	39.5
18.00	28.50	28.47	28.27	28.17	44.50	44.50	44.23	44.67	34.50	35.03	36.17	35.0

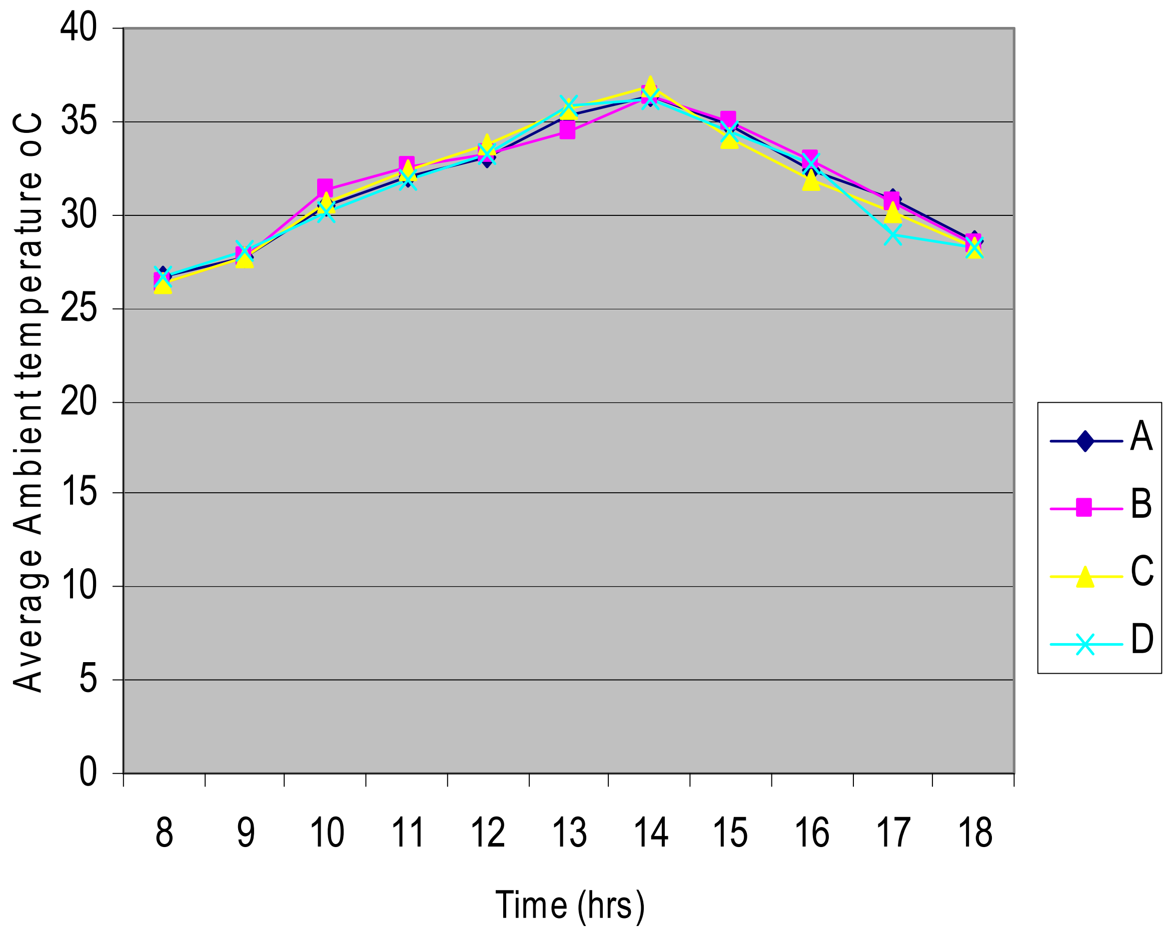


Fig.11: Plot of average Ambient temperature Vs time-hrs (table 10)

The plots of ambient temperature against time for the four chimneys (figure 11) gave curves of similar contours, with many coinciding points. That means there were minor or negligible differences in the atmospheric temperatures throughout the period of the experiments. Hence the daily weather temperatures were assumed fairly constant for the three days the tests were conducted.

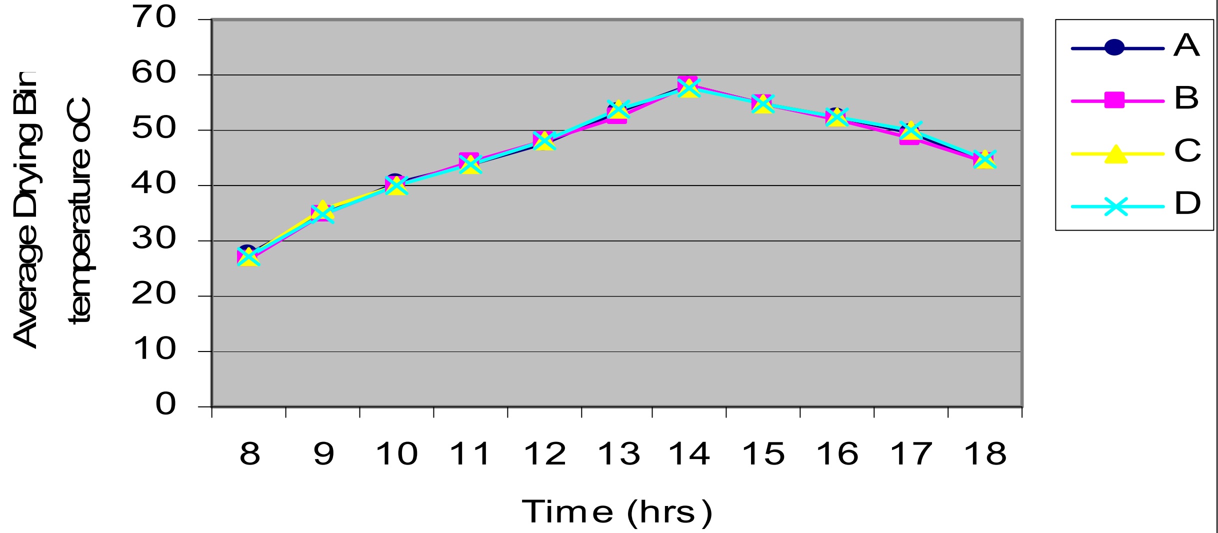


Fig.12: Plot of average Drying Bin temperature Vs time-hrs (table 10)

In figure 12 there were some coincident points. For simplicity and clarity reasons, the four curves – A, B, C and D were approximated.

The curves of exit air temperatures for chimneys A, B, C and D (figure 13) were similar and closely fitted, showing that the exit Air temperatures only varied slightly.

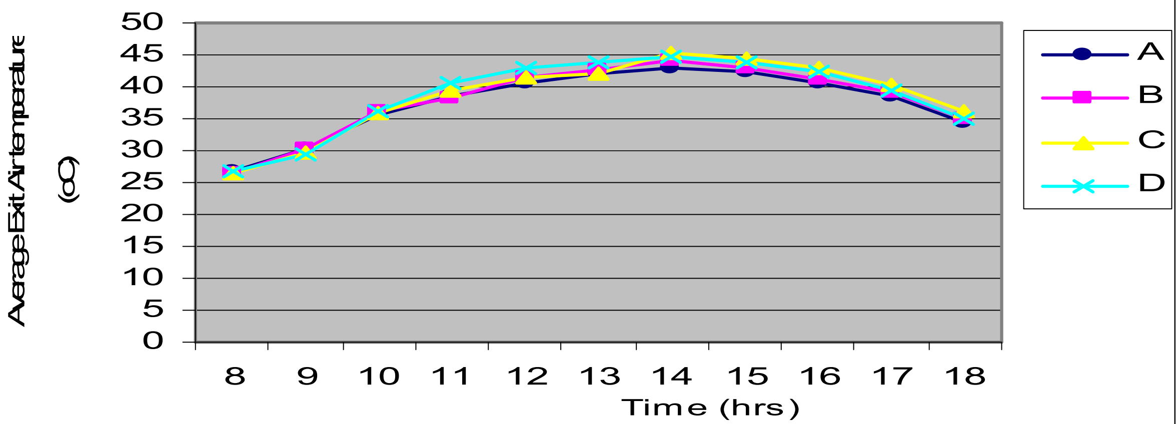


Fig.13: Plot of average Exit Air temperature Vs time-hrs (table 10)

4.3.1 Moisture Content Calculations

The solar dryer was evaluated using fresh cassava roots at initial moisture content of 62%(wb) Lurkey, (1984). Table 12 shows the moisture contents (percentage wet basis) of the drying samples of the cassava chips, as calculated from the hourly weights of the samples. Moisture contents of the drying samples were estimated using the relation:

$$M_c(wb) = (W_{wr} \div W_t)\, 100 \qquad (35)$$

Where $M_c(wb)$ = moisture content of the sample at any time t ,

W_t = Weight of sample at time t ,

W_{wr} = Weight of water retained in the sample, = $(W_t - D_m)$

Where D_m = dry matter content of sample, = $\{W_i - (M_{ci} \times W_i) \div 100\}$ as earlier given in equation (23),

$$D_m = W_i - \{(M_{ci} \times W_i) \div 100\}.$$

Where, W_i = Initial weight of sample

M_{ci} = Initial moisture content (% wb) of the sample

M_{ci} = 62% for any freshly harvested cassava. (Lurkey, 1984).

Table 11: Moisture Contents (% wb) attained by the samples during the drying tests.

Time of day	Moisture Content % (wb)									
	Preliminary test		Chimney A		Chimney B		Chimney C		Chimney D	
	Open air	Drying chamber	Open air	Drying chamber	Open air	Drying chamber	Open air	Drying chamber	Open air	Drying chamber
Day1										
8.00	62%	62%	62%	62%	62%	62%	62%	62%	62%	62%
9.00	61.7	61.6	61.3	61.6	61.3	61.5	61.3	61.6	61.3	61.7
10.00	61.2	60.9	60.9	60.4	61.2	60.6	61.1	60.5	61.2	60.5
11.00	60.5	59.8	60.7	58.4	60.7	58.9	60.6	59.1	60.6	59.0
12.00	59.7	58.2	59.6	55.8	59.6	57.4	59.5	57.5	59.6	57.3
13.00	58.6	56.5	58.1	52.4	58.1	55.1	57.9	55.2	58.0	55.1
14.00	57.4	54.2	56.0	47.7	55.9	51.1	55.5	49.6	55.6	49.6
15.00	56.1	51.6	53.9	43.9	54.0	47.5	53.6	46.3	53.8	45.9
16.00	54.9	49.4	52.5	40.2	52.8	44.2	52.5	43.6	52.5	43.1
17.00	54.2	47.9	51.7	38.5	51.6	42.3	51.5	41.7	51.5	41.2
18.00	53.7	46.9	51.0	37.9	51.0	40.9	51.0	40.2	51.0	39.7
Day2										
8.00	52.9	45.2	49.7	36.5	49.9	40.1	49.6	39.5	49.6	39.0
9.00	52.9	45.2	49.5	36.3	49.7	39.9	49.4	39.3	49.4	38.9
10.00	52.2	44.1	48.8	35.5	48.9	38.9	48.8	38.3	48.9	37.8
11.00	51.3	42.3	46.9	33.5	47.0	37.6	46.9	36.9	46.9	36.4
12.00	50.1	40.2	44.6	31.5	44.7	35.8	44.4	35.1	44.7	34.6
13.00	48.7	37.5	42.1	28.3	42.4	32.7	42.3	31.9	42.3	31.7
14.00	46.9	34.4	39.5	24.0	39.6	27.8	41.5	27.3	41.3	27.1
15.00	45.2	31.0	37.2	20.1	37.4	24.2	37.3	24.1	37.4	23.9
16.00	43.7	28.0	35.8	18.3	35.7	21.6	35.6	21.7	35.7	21.9
17.00	42.8	26.1	34.5	16.4	34.5	19.1	34.2	19.8	34.3	20.0
18.00	42.3	25.0	33.8	15.6	34.0	17.9	33.4	18.7	33.6	19.1

Table 11 continued.

Time of day	Prelim. test		Chimney A		Chimney B		Chimney C		Chimney D	
	Open air	Drying chamber	Open air	Drying chamber	Open air	Drying chamber	Open air	Drying chamber	Open air	Drying chamber
Day3										
8.00	41.8	23.8	32.2	15.0	32.4	16.5	32.4	17.4	32.5	17.7
9.00	41.8	23.8	32.2	15.0	32.4	16.5	32.4	17.4	32.5	17.7
10.00	41.4	23.4	31.1	14.3	31.2	15.7	31.3	16.8	31.2	17.4
11.00	41.0	22.6	30.1	13.6	30.2	15.4	30.2	16.6	30.3	16.8
12.00	40.4	21.0	29.2	13.0	29.2	14.5	29.2	15.7	29.2	16.0
13.00	39.8	19.0	27.9	12.1	27.8	13.5	28.0	14.7	27.7	15.0
14.00	39.0	16.8	26.0	10.8	26.1	12.3	26.2	14.0	25.9	14.3
15.00	38.4	14.6	24.2	10.1	24.3	11.7	24.5	13.3	24.5	13.6
16.00	37.8	13.4	23.9	9.7	23.9	11.5	24.0	12.9	23.9	13.4
17.00	37.7	12.8	23.8	9.7	23.7	11.4	23.8	12.5	23.7	13.1
18.00	37.5	12.6	23.8	9.7	23.7	11.4	23.8	12.4	23.6	13.0

In table 11 the moisture contents (% wb) calculated for the cassava chips during the drying tests using the chimneys – A, B, C and D, are shown. It could be seen that the cassava chips used for the control experiments (i.e. dried in the open air) during each drying test attained almost the same moisture levels within the same periods. Because of the closeness of these values, only one of the results was plotted as a representative of the rest, in figure 14.

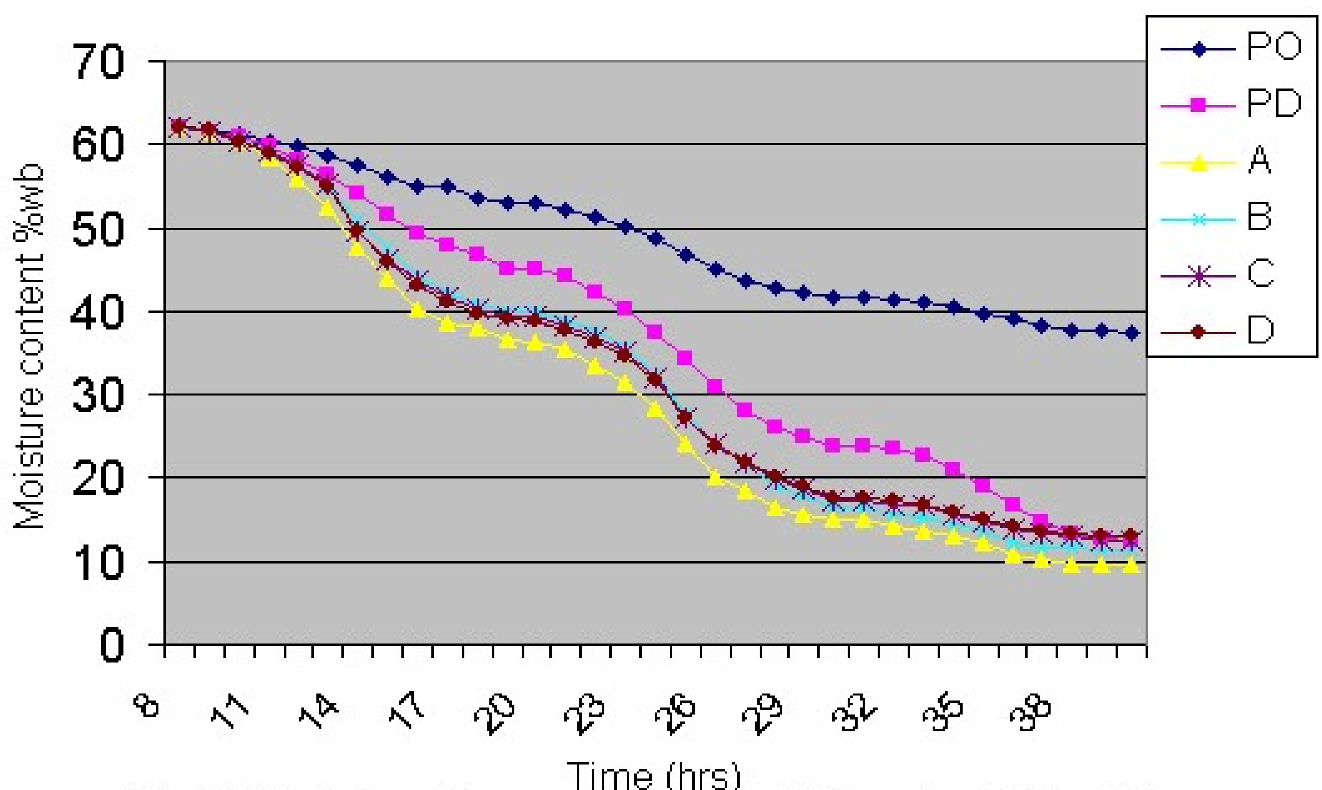


Fig.14: Plot of moisture content %wb Vs time-hrs (table 12)

Legend: **PO = Preliminary test done in open air, PD= Preliminary test on dryer; A,B,C and D refer to tests conducted on the integral solar dryer using chimneys of height 1200mm, 800mm, 400mm, and without chimney respectively.**

Thus if the drying rate, d_r is calculated as

d_r = (moisture loss %) / (time)hr ,

Then the overall drying rate for each of the chimneys A, B, C, and D is as given in the table below.

Table 12: Chimney height versus Drying Rate.

Chimney height (mm)	Drying rate (M_c% / hr)
A 1200	1.74
B 800	1.72
C 400	1.65
D 0	1.63
Open-air	1.28 (average)

Table 13: Calculated Hourly Weight Loses of the Samples.

Time of the Day	Weight Loses (g)							
	ChimneyA1200 mm		Chimney B 800mm		Chimney C 400mm		Chimney D 0mm	
	Open Air	Drying Bin	Open Air	Drying Bin	Open Air	Drying Bin	Open Air	Drying Bin
8.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
9.00	0.70	4.30	7.00	4.70	7.20	3.80	6.80	3.20
10.00	1.40	11.80	1.60	9.90	1.90	11.20	1.60	11.90
11.00	4.80	18.10	5.10	15.40	4.90	13.40	5.80	14.50
12.00	10.40	21.70	10.40	12.90	10.90	14.30	9.70	14.40
13.00	13.40	24.90	13.20	18.90	14.30	18.30	14.60	17.60
14.00	17.40	28.40	17.70	36.40	19.60	36.50	19.00	36.80
15.00	15.40	16.50	14.90	12.50	13.40	19.50	13.70	20.80
16.00	9.60	16.50	8.30	16.80	8.10	13.40	9.00	13.80
17.00	5.80	7.30	7.50	8.90	6.60	9.10	6.20	8.30
18.00	4.40	2,10	4.30	6.60	3.20	6.30	3.30	6.50
Day 2								
8.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
9.00	1.30	0.70	0.80	0.80	1.50	0.70	1.00	0.30
10.00	3.90	4.10	5.00	4.70	3.40	4.30	3.40	4.40
11.00	10.70	6.00	10.50	4.90	10.60	5.30	11.20	5.30
12.00	11.90	6.80	11.70	6.80	11.30	6.80	10.90	6.80
13.00	12.20	9.90	11.20	10.90	11.60	10.90	11.70	9.70
14.00	11.50	11.90	12,30	15.20	3.70	14.20	4.60	14.20
15.00	8.80	9.80	8.90	10.20	17.40	8.70	15.80	8.70
16.00	5.30	4.30	6.30	6.60	6.10	6.20	6.50	5.20
17.00	4.80	4.10	4.40	5.80	5.30	4.60	5.30	4.40
18.00	2.40	1.90	1.70	2.80	2.60	2.50	2.40	2.30
Day 3								
8.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
9.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
10.00	3.50	1.50	3.80	1.60	3.70	1.20	4.40	0.70
11.00	3.30	1.30	3.10	0.70	3.40	0.60	2.70	1.20
12.00	3.80	1.30	3.30	1.90	3.10	1.80	3.50	1.80
13.00	3.80	1.80	4.10	2.10	3.80	2.20	4.30	2.10
14.00	5.40	2.50	4.70	0.40	5.10	1.50	5.30	1.50
15.00	4.80	1.40	4.80	1.20	4.70	1.30	3.60	1.40
16.00	0.90	0.60	1.20	0.30	1.30	0.90	1.60	0.40
17.00	0.20	0.10	0.50	0.20	0.50	0.70	0.60	0.60
18.00	0.00	0.00	0.00	0.00	0.00	0.00	0.30	0.20

Table 14: Calculated Hourly Moisture Loses (%).

Time Of the Day	Moisture Loses (%)							
	ChimneyA1200mm		Chimney B 800mm		Chimney C 400mm		Chimney D 0mm	
	Open Air	Drying Bin	Open Air	Drying Bin	Open Air	Drying Bin	Open Air	Drying Bin
8.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
9.00	0.70	0.40	0.70	0.50	0.70	0.40	0.70	0.30
10.00	0.40	1.20	0.10	0.90	0.20	1.10	0.10	1.20
11.00	0.20	2.00	0.50	1.70	0.50	1.40	0.60	1.50
12.00	1.10	2.60	1.10	1.50	1.10	0.60	1.00	1.70
13.00	1.50	3.40	1.50	2.30	1.60	2.30	1.60	2.20
14.00	2.10	4.70	2.20	4.00	2.40	5.20	2.40	5.50
15.00	2.10	3.80	1.90	3.60	1.90	3.30	1.80	3.70
16.00	1.40	3.70	1.20	3.30	1.10	2.70	1.30	2.80
17.00	0.80	1.70	1.20	1.90	1.00	1.90	1.00	1.90
18.00	0.70	0.60	0.60	1.40	0.50	1.50	0.50	1.50
Day 2								
8.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
9.00	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.10
10.00	0.70	0.80	0.80	1.00	0.60	1.00	0.50	1.10
11.00	1.90	2.00	1.90	1.30	1.90	1.40	2.00	1.40
12.00	2.30	2.00	2.30	1.80	2.50	1.80	2.20	1.80
13.00	2.50	3.20	2.30	3.10	2.10	3.20	2.40	2.90
14.00	2.60	4.30	2.80	4.90	3.80	3.60	1.00	4.60
15.00	2.10	4.40	2.20	3.60	4.20	3.20	3.90	3.20
16.00	1.40	1.80	1.70	3.60	1.70	2.40	1.70	2.00
17.00	1.30	1.90	1.20	2.50	1.40	1.90	1.40	0.90
18.00	0.70	0.80	0.50	1.20	0.80	1.10	0.70	0.90
Day 3								
8.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
9.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
10.00	1.10	0.70	1.20	0.80	1.10	0.60	1.30	0.30
11.00	1.00	0.70	1.20	0.30	1.10	0.20	0.90	0.60
12.00	0.90	0.60	1.00	0.90	1.00	0.90	1.10	0.80
13.00	1.30	0.90	1.40	1.00	1.20	1.00	1.15	1.00
14.00	1.90	1.30	1.70	1.20	1.80	0.70	2.20	0.70
15.00	1.80	0.70	1.80	0.60	1.70	0.70	1.40	0.70
16.00	0.30	0.40	0.40	0.20	0.50	0.40	0.60	0.20
17.00	0.10	0.00	0.20	0.10	0.20	0.40	0.20	0.30
18.00	0.00	0.00	0.00	0.00	0.00	0.10	0.10	0.10

4.4 STATISTICAL ANALYSIS.

4.4.1 Preliminary Test.

Table 15: Effect of Drying Duration and Drying Media on Drying Rate.

Drying Duration (Day)	Mean Drying Rate (g/hr)	
	Open Air	Drying Bin
1	16.28 a	26.70 a
2	14.64 b	18.73 b
3	4.44 c	6.49 c

- NOTE: Means with different letters are significantly different at both levels of probability using the Duncan's Multiple Range Test (DNMRT).

From the statistical table above it can be seen that the effect of drying media – (open air and drying bin) – are significant at 5% level of probability; but the drying bin was highly significant at both probability levels, showing that it had a significant effect on the moisture removal and drying time of the cassava chips. Thus the Least Significant Difference or the Critical Difference and the Duncan's Multiple Range Test were employed to estimate or determine the level of significance of drying duration (in hours) and drying medium that contributes to the integral solar drying of the cassava chips.

4.4.2 Effect of Daily Ambient Temperature and Drying Media on Weight of Cassava Chips.

The experiment was analysed statistically as a 2 X 4 factorial experiment in a Randomized Complete Block Design (RCBD) with :

Factor A = Chimney Heights – H1200mm, H800mm, H400mm, and H0mm; and

Factor B = Weight of drying sample in open air - W_A, and weight of drying samples in drying bin - W_B;

Blocks = Days - 1, 2, and 3. The calculations are summarized in tables 16, 17 and 18 below.

Table 16: Treatment Totals for Factors A and B.

Factor B (Drying Media)	Levels	Factor A (Chimney Heights)				
		H1200mm	H800mm	H400mm	H0mm	Total
	W_A	19.37	19.47	19.56	19.17	77.57
	W_B	22.61	22.47	32.67	31.01	108.76
	Total	41.98	41.94	52.23	50.18	186.33

Table 17: Treatment Means for Chimney Heights and Drying Media.

	Levels	H1200mm	H800mm	H400mm	H0mm	Mean
Factor B	W_A	6.42 d	6.49 b	6.52 a	6.39 e	6.47 c
	W_B	7.54 d	7.49 e	10.89 a	10.34 b	9.07 c
	Mean	7.00	6.99	8.71	8.37	7.77

Table 18: Analysis of Variance for the Randomized Complete Block Design (RCBD) Experiment.

Source of Variation	Degree of Freedom	Sum of Square	Mean Square	F-Calculated	F- Tabulated (5%)	(1%)
Days	2	219.71	109.86	14.27	3.74	6.51
Chimney interaction	3	14.59	4.86	0.63N.S	3.34	5.56
Treatment combination	5	69.85	13.97	1.81N.S	2.96	4.69
Drying media	1	40.53	40.53	5.26	4.60	8.86
Chimney X Drying media	3	14.73	4.91	0.64 N.S	3.34	5.56
Error	14	107.84	7.70	-	-	-

From the table of analysis of variance, it can be seen that there is a significant day effect on the weight loss of the drying samples in the two drying media. This suggests that at least one of the Days means is not equal to the others. Also, the chimney height has no significant effect on the daily weight loss of the sample in the solar dryer. This statistically connotes that all the levels of factor A (chimney Heights) behaved the same in their various combination and thus did not contribute so much to the drying kinetics as when compared to the ambient daily / hourly temperature.

However, there is a significant effect at 5% level of probability of the drying media on weight loss. This is necessitated by the combined effect of the chimney heights and ambient air temperatures (for the integral solar dryer). The experimental results even showed that the sample placed in the dryer of chimney height 1200mm lost more weight than the samples placed in the same dryer of lower chimney heights; as well as the samples placed in open air. Tables 6,7,8 and 9 corroborate this. No significant drying interaction between the drying media and chimney heights on the cassava chips. This behavior as shown in the ANOVA statistically accounts for the equal level of one of the factors.

In general, therefore, the drying media (Factor B) with a mean square of 40.53 could be interpreted as being more effective than chimney heights (Factor A) with a mean square of 4.86 in effecting weight loss on the cassava chips.

4.4.3 Effect of Chimney Height and Drying Air Temperature on the Rate of Drying of the Cassava Chips.

The experiment was factorially Randomized in a Complete Block Design with:

Factor A = Chimney Heights – C_{1200mm}, C_{800mm}, C_{400mm} and C_{0mm};

Factor B = Drying Air Temperatures - T_a, T_d and T_e

Blocks / Replications = Days - 1, 2, and 3.

This gave a 3 X 4 factorial experiment in RCBD, i.e. 12 treatment combinations, t = 12;

The replications are the 3 days - i.e. r = 3

That resulted to 12 X 3 = 36 Observation Units.

Table 19: ANOVA for the Effect of Chimney Height and Drying Air Temperature on the Drying Rate of the Cassava Chips. (Derived from Tables 6,7,8,9,11,13,14).

Source of Variation	Degree of freedom	Sum of Squares	Mean Square	F-Calculated	F - Tabulated (5%)	(1%)
Days	2	21.37	10.685	11.05	-	-
Chimney combination	11	1250.96	113.68	117.56	-	-
Chimney heights	3	0.838	0.279	0.29 NS	3.05	4.82
Drying Air temperature	2	1247.17	623.59	644.87 **	3.44	5.72
Chimney vs air temperature Interaction	6	2.452	0.409	0.42 NS	2.55	3.76
Error	22	21.27	0.967	-	-	-
Total	35	2543.56	-	-	-	-

- NOTE: NS = Non significant effect; (**) = Significant effect.

Decision Rule: Since F- calculated is greater than F- tabulated (F-cal. > F-tab.) at both levels of probability, the Null Hypothesis is accepted, therefore the means are equal for chimney heights and also for chimney – air temperature interaction.

The ANOVA, table 19 shows that chimney heights have no significant effect on the drying kinetics of the cassava chips as compared to the drying air temperature. This statistically means that its significance will only depend on high drying air temperature. Factor A (chimney heights) means are statistically the same; and the interaction means are not significantly different. However, from the size of the mean square of factor B (drying air temperature) with a mean square of 623.59, it statistically implies that factor B has more effect on the drying rate of the sample than factor A (with a mean square of 0.279).

It can thus be stated or concluded that chimney height effect is less significant than the drying air temperature effect at different points of the integral solar dryer. Also, it is only the factor with a higher mean square value that can elicit the activity in the cassava chips.

4.4.4 Analysis of the Effect of Chimney Heights on Moisture Removal from the samples.

A Randomized Complete Block Design was used to analyse the effect of only the chimney heights on the moisture removal in the cassava chips. The treatments are:

Chimney Heights - H1200mm, H800mm, H400mm and H0mm;

The Blocks / Replications - Days : 1, 2 and 3;

Treatment combination = 3 X 4 = 12 Units.

Table 20: ANOVA Chart for the RCBD.

Source of variation	Degree of freedom	Sum of squares	Mean square	F-calculated	F - tabulated (5%)	(1%)
Days	2	5.80	2.90	878.97 **	5.14	10.92
Chimney heights	3	0.17	0.057	17.27 **	4.76	9.78
Error	6	0.02	0.0033	-	-	-
Total	11	5.99	-	-	-	-

The above table shows that there is a highly significant effect of chimney heights on moisture removal from the cassava chips and a significant effect due to blocking or days at both probability levels. This behavior resulted from the fact that f-calculated is greater than f-tabulated (F-cal > F-tab) which implies that at least one of the treatment means is greater than the other.

Using the Critical Difference or Least Significance Difference to determine the difference between the chimney (treatment) means as well as the Minimum Value between 2 separate means, we obtain the table of mean differences for the chimney heights as shown below:

Table 21: Table of Mean Differences.

	C1	C2	C3	C4
C4	0.22 *	0.03 NS	0.05 NS	-
C3	0.27 *	0.08 NS	-	-
C2	0.19 *	-	-	-
C1	-	-	-	-

❖ NOTE: (*) = Significant at both levels of probability.
NS = Non significant at both levels of probability.

The above table shows that chimneys C4 and C2, C3 and C2 are not significantly different but chimney C1 is significantly different from chimneys C4, C3 and C2; which means that chimney C1 performed better than others. Tables 20 and 21 above shows that there is a significant chimney effect on the moisture removal from the cassava chips. Whereas chimney C1 has a significant effect on moisture removal from the sample, chimneys C2 and C3 have no significant moisture removal effect, while chimney C4 has no effect.

This experimental design in Randomized Complete Block Design (RCBD) is justified since there is a significant days effect. It is, therefore, an indication that the RCBD contributed to the precision in detecting the effect of chimney heights differences, hence its adoption in preference to Complete Randomized Design (CRD) is advantageous.

4.5 Determination of Percentage Average Volume Shrinkage of Dried Chips.

In this exercise three dried cassava chips were picked at random from each batch of the product dried using each of the chimneys and, another three chips randomly picked from the corresponding control test. The diameter and thickness of each chip were measured and the volume calculated. Table 22 shows the data obtained.

Table 22: Volume Shrinkage of the Dried Cassava Chips.

Chimney	Drying Bin			Open air		
	Diameter(mm)	Thickness(mm)	Volume(mm^3)	Dia.(mm)	Thick(mm)	Vol.(mm^3)
	36.0	8	8143	38.1	8.6	9805
A	36.4	7.2	7492	38.8	8.0	9459
	36.1	7.5	7677	38.5	8.8	10244
B	37.5	8.0	8836	38.9	8.4	9983
	37.8	7.9	8865	38.9	8.7	10340
	36.7	7.6	8040	38.2	8.6	9856
C	37.0	8.2	8817	39.0	8.8	10512
	37.4	7.8	8569	38.6	8.3	9713
	37.7	7.4	8260	39.1	8.5	10206
D	37.8	7.7	8641	38.3	8.8	10138
	37.5	8.0	8836	38.5	8.9	10361
	37.1	8.0	8648	38.7	8.4	9881
Total Volume			100,824mm^3			120,498mm^3

Average Volume = (100,824 mm^3 ÷ 12) and (120,498 mm^3 ÷ 12)

= 8402 mm^3 and 10,041 mm^3

Percentage Volume Shrinkage = 33% and 20%

Note: Initial volume of each fresh cassava chip was obtained by the calculation:

Volume of cassava Chip = Thickness x $(\text{radius})^2$ x Л (40)

= 10mm x $(40\text{mm})^2$ x 1.342 = 12,566 mm^3

Table 22 shows that the cassava chips which were dried inside the drying bin experienced greater dimensional and volume shrinkage (33%) than the chips dried in open air (20%). This effect was attributed to the high thermal stress exerted on the cassava chips inside the drying chamber as a result of the high temperature developed inside the solar dryer, which made the chips to loose much water within a short time.

Table 23: Analyses of the Characteristics of the Dried Products.

Characteristics	*Prod. Dried in open air*	*Prod. Dried inside Dryer*
Colour of product 8 weeks after drying	Dark green/brownish-white with greenish patches.	Whitish or milk-white
Volume Shrinkage(mm3)	20%	33%
Final moisture content $\%_{(wb)}$	37.5%	12.6%
Odour	Repulsive odour	Sweet appetizing flavour

4.6 Organoleptic Assessment of the Dried Products

The dried cassava chips were closely examined assessed on the basis of such properties as aroma /odour, taste , colour and acceptability. Samples of the chips dried in open sun and the chips dried inside the solar dryer were packaged separately. The samples were given in pairs to 15 randomly selected persons to closely examine, assess and compare. They were simply asked to state their preference for the aforementioned properties of both packages on a scale of zero to three (0-3) as defined below:

3 = Very good

2 = Good

1 = Fair

0 = Poor.

Table24: Results of the Organoleptic Assessment Carried Out.

Properties	Score	
	Open air	Drying Bin
Aroma	1.2	3.0
Colour	1.0	3.0
Taste	1.3	2.6
Acceptability	0.9	3.0

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

Solar energy has been identified as one of nature's cheapest and commonest energy source. It has also been shown that the origin of almost every other source of energy known to mankind can be traced directly or indirectly to the sun. However, in the remote past little effort was made to harness the radiant energy of the sun. Emphasis had been on fossil fuels, especially coal and petroleum. In recent times sustained efforts are being made by scientists and engineers all over the world to develop suitable technologies for efficient tapping and utilization of this superabundant, non-diminishable energy of the sun. A situation probably necessitated by the fear of possible and imminent depletion of the fossil fuels. Solar energy crop dryer is among the offshoots of the recent breakthrough in solar energy researches.

The target of this work was to make a simple solar dryer which would be handy, efficient, less expensive and easy to run/ manage. In this way the dryer would serve domestic needs of the rural populace. The solar dryer thus fabricated and evaluated certified all these conditions: the construction materials are readily available in our local markets, construction process fairly simple. The dryer was test-run with absolute zero expense on fuel. Its portable nature notwithstanding, the dryer would not require relocation to improve its performance if it were mounted.

5.1 Summary of Findings.

. Perspex material boosts radiant solar energy incident on or passing through it, (section 3.4): Water which received radiant solar energy that passed the Perspex gained more heat than the water which received direct solar radiation (tables 2 & 3, figure 7).

. From 0 to 1200mm height of suction chimney attached to the solar dryer had little or no significant effect on the temperature dynamics (temperature rise or fall) within the solar dryer; and drying kinetics of the drying samples placed in the integral dryer. Graph of the average drying bin temperature versus time (figure 12) plotted for chimneys A,B, C and D showed the same pattern of temperature for each of the four cases. Also, graph of average exit air temperature against time, (figure 13) plotted for the four chimney conditions and the ANOVA tables (tables 16, 17, 18 and 19) equally corroborated this fact.

. The drying material showed similar moisture reduction pattern when chimneys of the height 0mm, 400mm, and 800mm were used (figure 14). However, the result obtained was slightly different with a chimney height of 1200mm; and the least moisture content was obtained.

. Solar dryer overall drying ability is highly affected by the daily ambient air temperature. Though, naturally, it would be expected that tall chimneys should exert stronger suction force on the atmospheric (drying) air than the short ones, thus increasing air flow into the dryer, between 0 to 1200mm, chimney height tended to exhibit little or no significant effect on the drying kinetics of the integral solar dryer.

5.2 Recommendations.

The integral solar dryer is good for use by households because of its numerous good qualities. Its size cannot be a hindrance to those who might wish to use it on a fairly large scale since there is no strict limitation to the nominal size of the integral solar dryer. Even large households can maintain more than one unit of the small dryer if so desired.

5.3 Suggestions for Further Researches.

As a follow up to this work, it is recommended that further researches be done on:

1. Effects of variation in diameter of the chimney on the performance of the dryer.
2. How the shape (pyramidal, conic, cylindrical, prismatic), of the chimney affects the performance of the solar dryer.
3. Improving performance of the solar dryer through the incorporation of wind-driven impeller/ suction fan.
4. Relation of chimney height and the solar dryer performance.

Appendix 1

Solar Dryer Efficiency Ŋ

Solar dryer efficiency Ŋ, as described in section 3.1 was estimated using the relations:

$Ŋ = \{(Q_d) \div E_i\} = \{q_l \div E_i\}$, as given in equation (21).

Where, $Q_d = q_l = P_s$ = heat energy absorbed in drying = 0.158kW

E_i = total incident solar energy on the solar dryer

$E_i = I_c.A_d.R$ (equation 18),

Where, I_c = average insolation or solar power per unit area (kJ/m^2) or (kW/m^2)

I_c = ($0.5kW/m^2$) as shown in section 3.1

A_d = area of solar dryer exposed to solar radiation = $0.32m^2$

R = solar energy transmittance of the solar dryer cover plate

R = 1.034 (as calculated from figure 8).

$\therefore$ Ŋ = (0.158) ÷ (0.5 x 0.32 x 1.034)

= 0.955

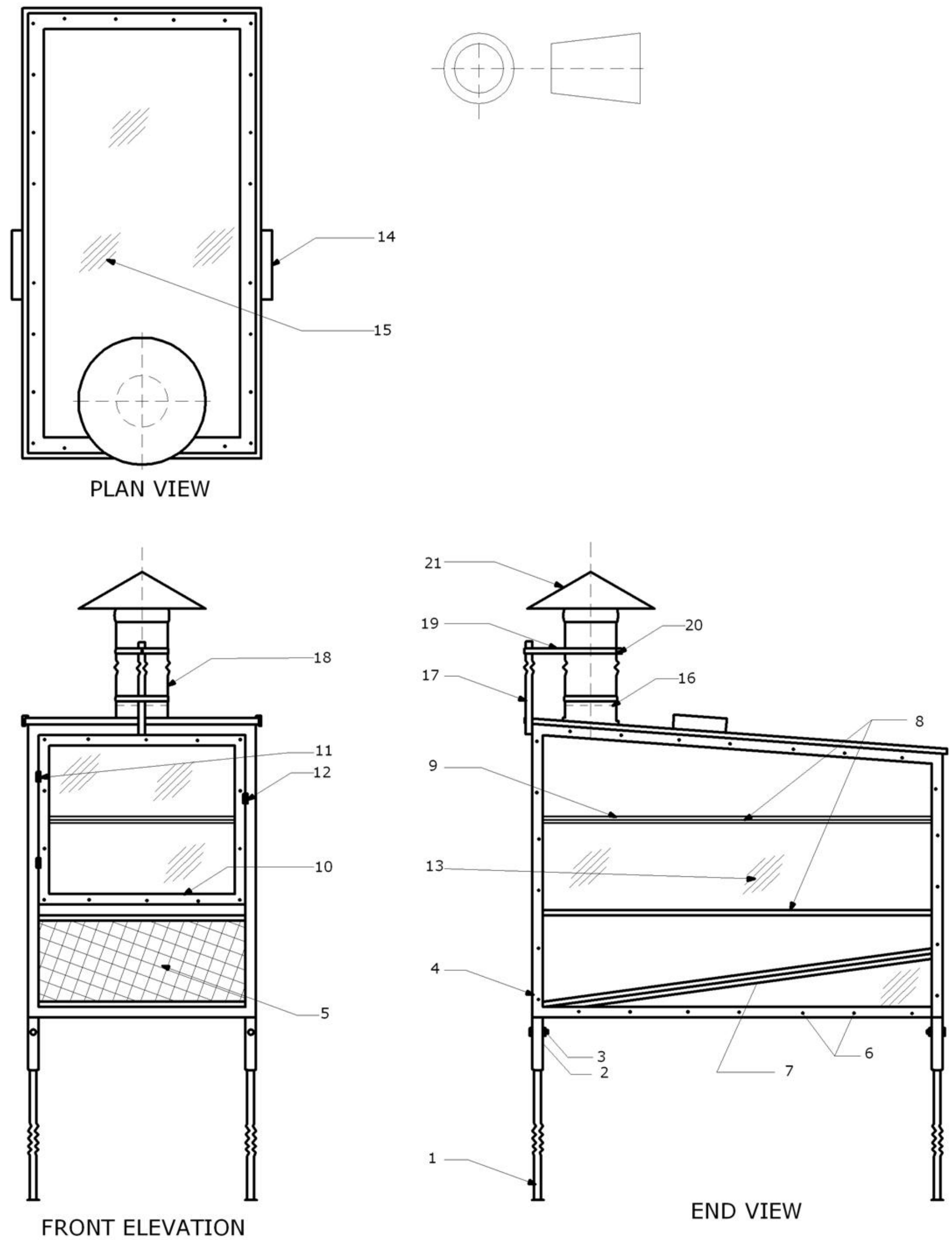
= 95.5%.

Appendix 2 Analysis of Cost

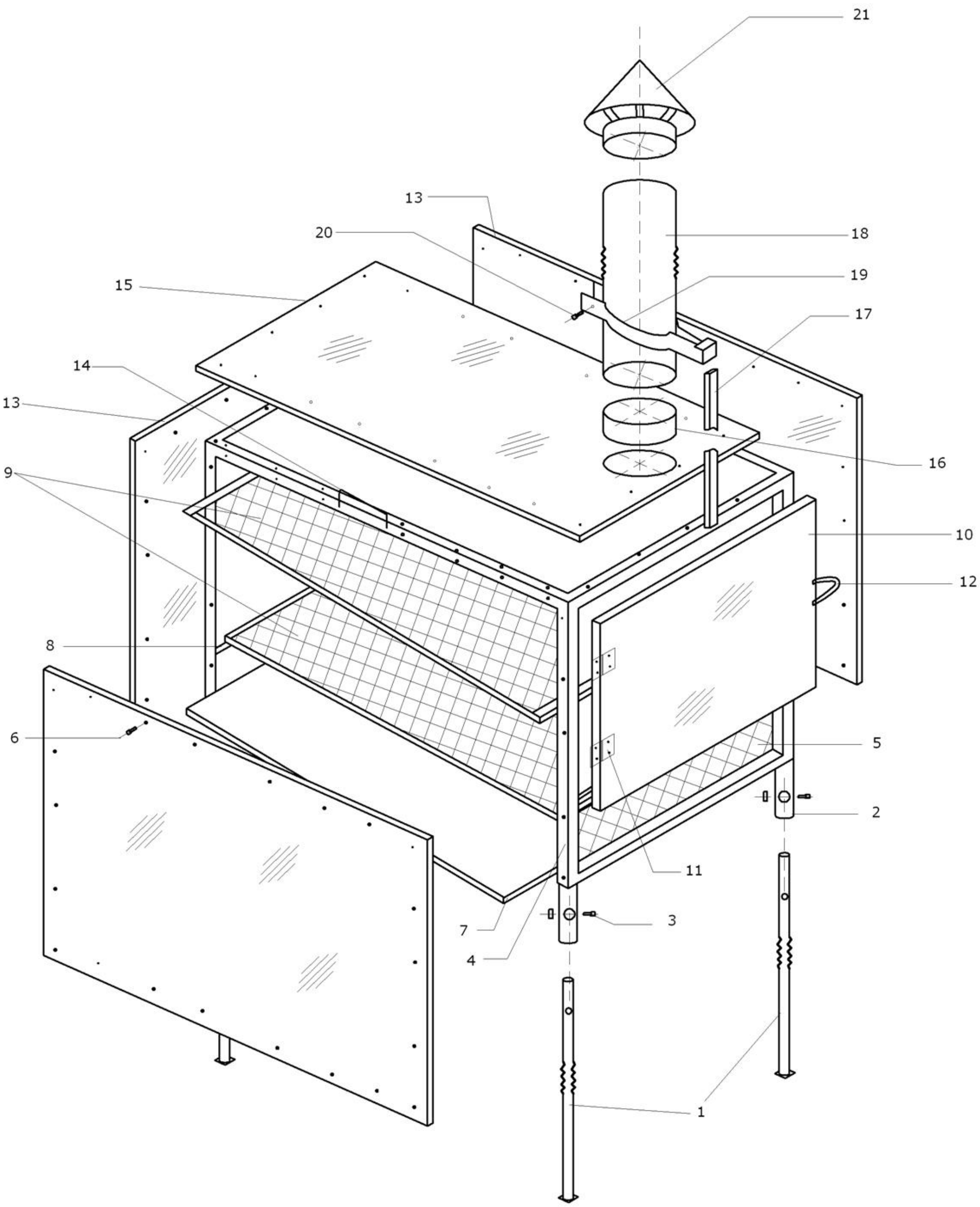
S/No	Item / Material	Specification	Quantity needed	Cost (₦.)
1.	Ø25mm(1 inch)Square Pipe	Mild steel	2½ lengths	3,350
2.	Ø20mm pipe	Galvanized	1 length	1,680
3.	Ø27mm pipe, 40mm long	Galvanized	1 length	840
4.	Aluminum sheet	(2400 x 1200)	1 sheet	3,300
5.	Wire mesh	(1200 x 900)	1 yard	1,400
6.	Perspex sheet	(2400 x 1200)	1 sheet	8,650
7.	Ply-wood /ceiling board	(2400 x 1200)	½ sheet	740
8.	Screw & nut pair	-	1 packet	1,260
9.	Hinges	2-inches, mild steel	2 pairs	80
10.	Electrode	Mild steel	½ packet	850
11.	Paint	Black oil paint	2 litres	1,300
12.	TOTAL MATERIAL COST	…………………………………….		23,450
13.	Workmanship was put at 8% total material cost, i.e. ……………			1,876
14.	Contingency / miscellaneous was put at 4% total material cost …...			938
15.	Total construction cost	……………………………………..		26,264

16. Maintenance cost is essentially the cost of replacing the perspex, which lasts more than six years under continuous exposure.

17. Projected service life is 27 to 34 years, and could be prolonged if the metal frame work is well protected.



FEDERAL UNIVERSITY OF TECHNOLOGY OWERRI (FUTO)
ORTHOGRAPHIC PROJECTION OF THE INTEGRAL SOLAR-ENERGY CROP DRYER
DRAWN BY: OKORONDU, MARCEL C. -20024364738
CHECKED BY ENGR. DR. G. I. NWANDKOM - PROJECT SURPERVISOR
SCALE: 1:100/ DATE........................ ALL DIMENTIONS IN mm

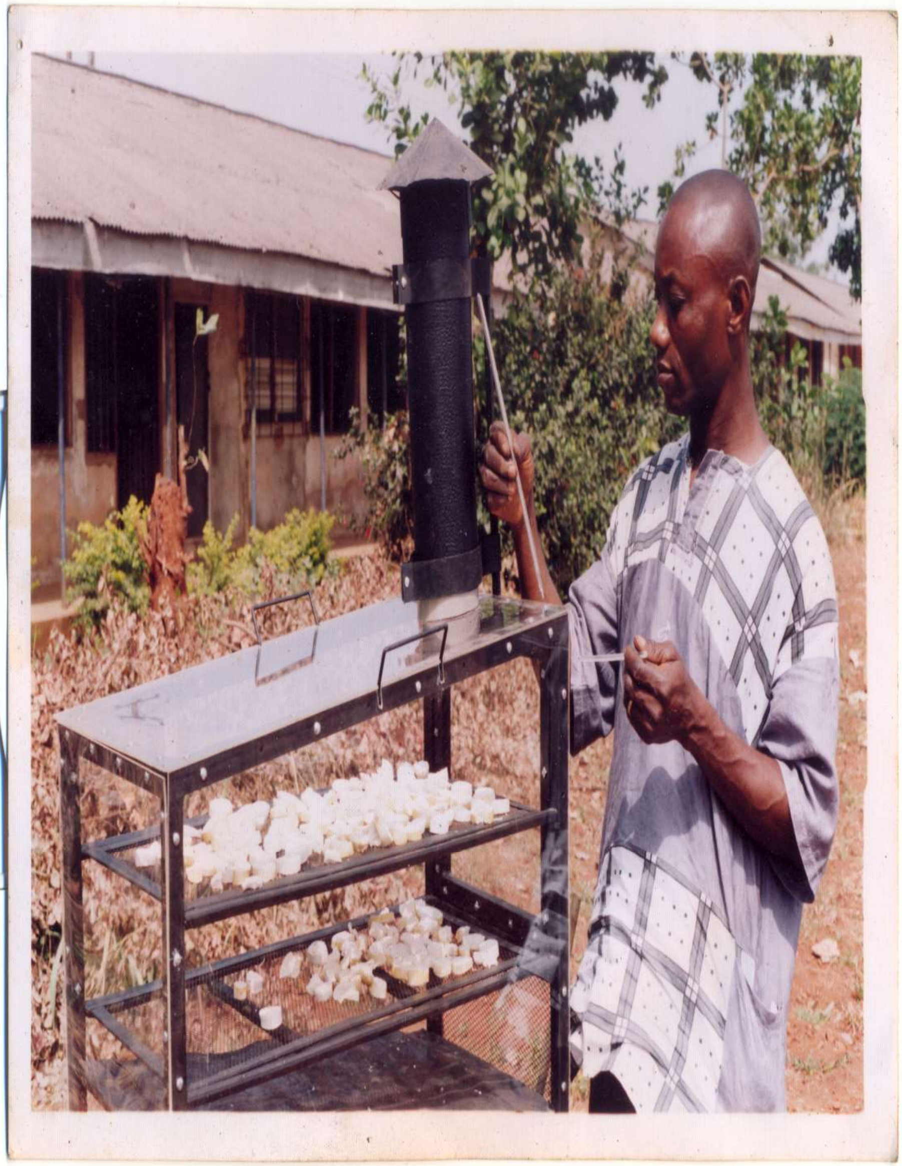


EXPLODED VIEW OF THE SOLAR DRYER
SCALE: 1:100

S/N	DESCRIPTION	No OFF 99	CONSTRUCTION MATERIAL

21	1	Aluminum sheet
20	1	Mild steel
19	2	Mild steel sheet
18	1	Aluminum sheet
17	1	Mild steel sheet
16	1	5” PVC pipe
15	1	Perspex
14	2	Mild steel rod
13	4	Perspex
12	1	Mild steel rod
11	2	Mild steel sheet
10	1	25mm square pipe
9	2	Mild steel wire gauze
8	2	Mild steel sheet
7	1	Double floor(particle board /aluminum)
6	110	Mild steel
5	1	Mild steel gauze
4	1	25mm square pipe
3	4	Mild steel rod
2	4	Ø27mm galvanized pipe
1	4	Ø20mm galvanized pipe

PARTS LIST



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