LONG TERM PERFORMANCE OF SMALL SCALE INDIRECT SOLAR DRYER

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LONG TERM PERFORMANCE OF SMALL SCALE INDIRECT SOLAR DRYER

Major Project Report

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This is certify that the Major Project entitled "**Long Term Performance of Small Scale Indirect Solar Dryer**" submitted by **Mr. Vivek P. Kalariya** (Roll no :11MMET06), towards the partial fulfillment of the requirements for semester-III of Master of Technology in mechanical engineering (Thermal Engineering) of Institute of Technology, Nirma University, Ahmedabad is the record of work carried out by his under our supervision and guidance.In our opinion, the submitted work has reached a level required for being accepted for examination. The result embodied in this major project, to the best of my knowledge, haven't been submitted to any other university or institution for award of any degree.

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Abbreviation

T_{amb}	=	Ambient temperature
A_c	=	Area of collector
w_s	=	Wind speed
C_p	=	Specific heat
ρ	=	Density
T_{co}	=	Collector outlet temperature
T_{do}	=	Dryer outlet temperature
h_{fg}	=	Latent heat of vaporisation
k	=	Thermal conductivity
η_d	=	Dryer efficiency
η_c	=	Collector efficiency
F_R	=	Heat removal factor
U_L	=	Heat loss coefficient
α	=	absorptance
τ	=	Transmittance
ρ_d	=	Diffuse reflectance
A_v	=	Area of vent
A_d	=	Area of dryer

Abstract

Strictly speaking, all forms of energy on the earth are derived from the sun. However, the more conventional forms of energy, the fossil fuels received their solar energy input eons ago and possesses the energy in a greatly concentrated form. These highly concentrated solar energy sources are being used as such at a rapid rate that they will be depleted in not-too distant future.

Drying is a part of many conventional food preparations. It also helps to impart special taste and store food items for longer periods. Solar dryer technology is simple and therefore easily adoptable by households and small communities. A solar dryer is an enclosed unit which allows the solar isolation to pass through a glazing and get absorbed. The heated surface, in turn, heats up a draft of air which then flows across/through food items and leads to their drying. Drying is dependent on two fundamental processes: mass and heat transfer. In the indirect type solar dryer, heat has to be first transferred from the heated absorber plate in the collector to the air draft. Heat has to then transfer from the flowing hot air to the moist material in the drying chamber which is then followed by moisture removal to attain the desired moisture level of the product. The effectiveness of drying depends both on the rate of drying and the extent of drying.

Hence, various food materials (aamla, methi, ginger, garlic, onion, potato chips and grapes) were efficiently dried using specially designed indirect solar dryer and its rate of drying and extent of drying were calculated. Also, a nutritional values for the dried grapes were analysed.

For mathematically designed dryer, the drying capacity was 12 kg food product per day and area of collector was $3.088m^2$. Specially designed V-trough were arranged for an enhancement of collectors efficiency which was estimated to be$\eta_c = 51.2\%$. Aluminium painted with black nickel as a absorber plate was used and thermocole as a insulating material with tempered glass for cover plate.

Performance analysis of solar dryer is carried out for no load condition in open loop as well as in closed loop. The steady state mathematical model based on heat balance concept of solar dryer without load is applied to identify the dimensionless parameter called no-load performance index (NLPI). For load condition in open loop, different food materials are dried in dryer as well as in open sun drying.

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Chapter 1

INTRODUCTION

1.1 Sun: as a Source of Energy

From many centuries, sun has been the primary source of energy for the globe. Technically, solar energy can be defined as Electromagnetic energy transmitted from the sun (solar radiation). The amount of energy that reaches the earth is equal to one billionth of total solar energy generated. The amount of energy which strikes the surface of earth in one day exceeds daily consumption by 10,000 to 15,000 times. In other words, the amount of solar energy intercepted by the earth every minute is greater than the amount of energy the world uses in fossil fuels each year.

Solar energy can be a major source of power.Its potential is 178 billion MW. But so far it could not be developed on a large scale. Sun's energy can be utilised as thermal and photovoltaics. The former is currently being used for steam and hot water production.

Sun's energy has been used by both nature and man throughout the time to grow food, to see by, to dry clothes, it has also been deliberately harnessed to performed a number of other 'chores'. Solar energy is used to heat and cool buildings, to heat water and swimming pools, to power refrigerator; and to operate engines, pumps and sewage treatment plants. It powers cars, ovens, water stills, furnaces, distillation equipments, crop dryers, and sludge dryers powered by solar energy. Stoves and cars run on solar-made methane gas, power plants operate on organic trash and sewage plants produce methane gas. The sun powered evaporation, in combination with gravity, powers machines and electric turbines. Solar electrolysers convert water to clean hydrogen gas (a fuel).[1]

1.2 Application of Solar Energy

- Heating and cooling of buildings.
- Solar water heating and solar air heating.
- Salt production by evaporation of sea water or inland brines.

- Solar distillation on a small community scale.
- Solar drying or agricultural products.
- Solar cookers.
- Solar engines for water-pumping.
- Food refrigeration.
- Photo-voltaic conversion.
- Solar furnaces.
- Solar thermal power generation.
- Industrial process heat.
- Indirect source of solar energy conversion, i.e. in the form of wind, through bio-conversion tides.

1.3 Drying

Drying (or dewatering) is a simple process of excess water (moisture) removal from a natural or industrial product due to simultaneous heat and mass transfer in order to reach the standard specification moisture content. It is an energy intensive operation.[2]

1.3.1 Need for drying

At the time of harvesting, most of the agricultural crops have higher moisture content. Crops with higher moisture content after harvesting deteriorate from several causes such as growth of micro-flora, particularly, the aerobic species of molds. The respiration of the micro-flora as well as increased respiration of agricultural produce due to the higher moisture content, produces heat and more moisture to cause further damage to crops. Such self-heating of forage crops stored at too high a moisture content can result in uncontrolled temperature rise to point of ignition and spontaneous combustion.

For safe long-term storage of agricultural produce, maximum moisture contents have been determined-known as safe storage moisture content-below which, produce can be stored for definite durations without chances of spoilage at ambient temperatures. Crops can be stored even at high moisture contents at temperatures in the range of freezing point of water or below. However, it is very expensive to maintain such temperatures for large scale storage.

Drying of the agricultural products to safe storage moisture content is the most practical way to preserve it for a period of about a year. Depending upon the type of the crop, the rates of drying and temperatures used for drying are different crops.

The early harvesting and subsequent drying are desirable for various crops to reduce field losses from weather, insects, birds, as well as to permit earlier use of harvested land for replanting of other crops.[2]

1.3.2 Drying principle

Drying is a heat and a mass transfer process involving the vaporisation of water from liquid state, mixing the vapour with the drying air and removal of the vapours by carrying away the mixture. Considerable heat is needed for vaporisation of the moisture. Heat must be supplied by reducing the sensible heat of drying air or by applying heat directly to the product. The moist material loses moisture whenever its water vapour pressure exceeds the partial pressure of water vapours in the drying air. In the initial stages the moisture removal rate is quite rapid since moisture on the surface of the product presents a wet surface to the drying air. Drying thus can be accelerated by increasing the flow rates of drying air. This state is known as surface drying. When the surface moisture has been removed further drying depends upon the rate at which the moisture within the product moves to the outer surface by diffusion process. This may be a slow or a rapid process depending upon the types of material being dried. The raising of the temperature of the product rather than large flow rates of drying air is likely to improve the moisture removal process at this stage.

Under direct radiation, part of the radiation may penetrate the material and be absorbed, thus generating heat within the material as well as the surface. This process raises the temperature of the product above that of the surrounding air, thus raises its vapour pressure.

The rate of drying of food products is normally controlled on the basis of quality of dried product even though it may be desirable to dry the products at maximum drying rates. In the case of some material rapid drying may result in the formation of hard drying surfaces thus reducing considerably the flow of moisture from within the material to its surface. Thus it is necessary to provide controls for varying the rate of drying either by controlling heat supply or by controlling the relative humidity of the surrounding air or by both.

The drying of a product by aeration only and without any heat supply is known as adiabatic drying. The latent heat of vaporization of moisture is extracted from the air surrounding the product and thus lowering the temperature of surrounding air. The drying air progressively becomes cooler and more humid as it progress through the material being dried. Since latent heat of vaporization is quite high compared to heat capacity of air, relatively large volumes of air at low relative humidity must be used in this type of drying.

If the materials to be dried are soluble in water then for adiabatic drying such materials require air at still lower relative humidity than do the materials having no solutes in water. These solutes which contain generally salts and sugar cause lowering of vapour pressure of moisture as is the case with fruits and vegetables.[2]

1.4 Sun Drying or Direct Solar Drying

Food drying is a very simple, ancient skill. It is one of the most accessible and hence the most widespread processing technology. Sun drying of fruits and vegetables is still practiced largely unchanged from ancient times. Traditional sun drying takes place by storing the product under direct sunlight. It is a process used for millennia to preserve food, a natural convection drying procedure is due to density differences. It is divided into two categories:

- The outdoor direct incidence solar radiation onto the surface of the material and,
- Through a transparent cover which protects partly the foodstuff from rain and other natural phenomena i.e. a passive solar drying method.

Sun drying is only possible in areas where, in an average year, the weather allows foods to be dried immediately after harvest. The main advantages of sun drying are low capital and operating costs and the fact that little expertise is required. The main disadvantages of this method are as follows: contamination, theft or damage by birds, rats or insects; slow or intermittent drying and no protection from rain or dew that wets the product, encourages mould growth and may result in a relatively high final moisture content; low and variable quality of products due to over - or under-drying; large areas of land needed for the shallow layers of food; laborious since the crop must be turned, moved if it rains; direct exposure to sunlight reduces the quality (color and vitamin content) of some fruits and vegetables. Moreover, since sun drying depends on uncontrolled factors, production of uniform and standard products is not expected.

The quality of sun dried foods can be improved by reducing the size of pieces to achieve faster drying and by drying on raised platforms, covered with cloth or netting to protect against insects and animals.[3]

1.4.1 Advantages and disadvantages of direct solar drying

This technique changed very little from its early prehistoric uses. The sun's free energy for drying in open-air is counterbalanced by a multitude of disadvantages, which reduce not only the quantity but also the quality of the final product.

- There exist no scientific observations during the long period of drying. The whole procedure depends on experience of the unskilled personnel.
- It is not possible any scientific control of final quality and moisture content which depends only on observations by experience.
- It is a very slow rate operation. According to the nature of product and weather conditions, drying takes place from few days up to one month. Drying rate depends on solar intensity fluctuations but also on environmental air humidity of the site.

- The product is exposed directly to all kinds of weather changes, as rain, hail, and strong winds, etc., that can rot or destroy totally the material. These conditions are especially hazardous to sensitive agricultural products. Most drying threshing floors are provided with a transparent plastic cover but it is not always feasible, especially in sudden weather changes, to protect the material by quick covering. Bad weather conditions on the other hand facilitate growing of bacteria, molds, etc.
- They have very large qualitative and quantitative losses due to all weather and natural attack conditions closely related to the open-air procedure, as dusting, rotting when weather conditions are not favorable, attacks by insects, etc., fermentation of juice from broken crops, decrease of sugar from breathing and ecchymosis in the case of fruits, attacks by rodents, birds and other unpredictable conditions.

Against all these disadvantage direct solar drying is an economic drying procedure that needs very small initial capital and low, unskilled personnel salaries for operation. Despite all these disadvantages the selection of sunny days and continuous observation, by experience, of drying progress, especially for foodstuff that need short time drying, the final product can be very good.[3]

1.5 Indirect Solar Drying

Due to the current trends towards higher cost of fossil fuels and uncertainty regarding future cost and availability, use of solar energy in food processing will probably increase and become more economically feasible in the near future.

Solar dryers have some advantages over sun drying when correctly designed. They give faster drying rates by heating the air to 10-30 ^{o}C above ambient, which causes the air to move faster through the dryer, reduces its humidity and deters insects. The faster drying reduces the risk of spoilage, improves quality of the product and gives a higher throughput, so reducing the drying area that is needed. However care is needed when drying fruits to prevent too rapid drying; which will prevent complete drying and would result in case hardening and subsequent mould growth. Solar dryers also protect foods form dust, insects, birds and animals. They can be constructed from locally available materials at a relatively low capital cost and there are no fuel costs. Thus, they can be useful in areas where fuel or electricity are expensive, land for sun drying is in short supply or expensive, sunshine is plentiful but the air humidity is high. Moreover, they may be useful as a means of heating air for artificial dryers to reduce fuel costs.

Solar food drying can be used in most areas but how quickly the food dries is affected by many variables, especially the amount of sunlight and relative humidity. Typical drying times in solar dryers range from 1 to 3 days depending on sun, air movement, humidity and the type of food to be dried.

Indirect solar drying is a rather new technique, not yet standardized or widely commercialized, that involves some thermal energy collecting devices and dryers of special techniques. There exist several types of dryer size, the construction technique of which fulfill the special drying requirements of food products, many of which still operate.[3]

1.5.1 Advantages and disadvantages of indirect solar drying

Indirect solar drying technique has almost only advantages. Its only disadvantage is the high initial capital cost for the dryer, the collector field and all necessary auxiliary equipment, as ducts, pipes, blowers, control and measurement instruments, and more or less skilled personnel to operate drying process. The advantages are

- Drying rate is high. Agricultural products are dried within 15–30 h instead of e.g. few days.
- Drying can be controlled scientifically, ensuring the proper moisture content of the final product, according to the specifications. Thus the dried product can be stored for long times.
- No losses at all, as the product are not subject to any natural phenomena.
- For the same quantity of material they need smaller surface areas due to trays accommodation in stacks, one upon the other, inside the dryers.
- Increased productivity, as dryers can be loaded again within few hours.
- Flexibility of the dryer to accept similar seasonal crops, thus expanding operation of the system almost around the year.
- The high initial capital and operating cost counterbalance, partly, the direct sun's drying.[3]

1.6 Techniques of Solar Drying

It is of importance to take into consideration that, in order to establish the suitable drying conditions, e.g. temperature and pretreatment procedure in relation to the dryer in use, experimentation is necessary.[3]

1.6.1 The suitable temperature

Temperature is of importance for agricultural products in order to keep the nutrient values, i.e. vitamins sensitive to heat, and retain color, flavor, etc. The lower drying temperature starts from 30 ^{o}C (85 F), but around these temperatures drying rate is very slow and there is risk of spoilage or molding. In sun open-air drying, temperature variations are subject to the intensity of solar radiation and are not easily controlled. Temperature, range from 40 ^{o}C (140 F) to 70 ^{o}C (158 F) and in some special cases, up to 80 ^{o}C (176 F), without an intermediate heat storage unit, i.e. by using direct heating from the heat source. Thus temperature depends directly on solar radiation intensity. In cases of high radiation intensities temperature can be regulated by mixing hot air with the necessary amount of fresh air from the atmosphere.

In general, the majority of food can be dried at a mean temperature of 60 ºC (140 F). Some products need lower drying temperatures at the beginning, e.g., apricots, and after being semi-dried temperature can be raised up to a certain suitable point. This technique helps to keep the skin of the crop soft, as in many cases higher temperature hardens the skin.[3]

1.6.2 Pretreatment of crops for solar drying

Many crops, fruits and vegetables are grown near the soil and are susceptible to the activity of various microorganisms. They must, immediately after harvest if possible, to be treated and dried. This applies for both methods, direct and indirect drying. Pretreatment helps to slow down the activity of microorganisms, soften the skin, etc.

Following are the main steps for agricultural products to keep good quality:

- Selection of the best quality of crops after harvest. They must be ripe, firm and without scratches.
- Must be washed thoroughly to decrease microorganisms to a minimum. Microorganisms, when exposed again for long time to the atmosphere, grow up very fast. With respect to the type of product they must be shelled, peeled and/or sliced.
- Blanching is a procedure that treats many products. Consists in dipping the crops in boiling water solution or they are treated by steam. Blanching destroys enzymes and helps retain color.
- Sulfuring is an old method of treating the crops by sodium sulfite solution or solutions of sodium bisulfate or metabisulfite. Another, old method is by burning sulfur and uses the fumes for sulfuring. It helps preventing losses in color, flavor and nutrients, as vitamins, etc. acting also as a disinfectant.
- Treatment with ascorbic acid solution in order to prevent browning of fruit or fruit slices, e.g. apples, is used.[3]

In general every crop has its own optimum conditions of pretreatment when drying. Here are the useful guidelines for solar drying:

- Most of the resources recommend pretreatment of food such as blanching (boiling/steaming).
- Washing thoroughly the products.
- Effective drying is accomplished with a combination of heat and air movement.
- 80–90% of moisture content must be removed.
- Direct sunlight is not recommended.
- Drying process must not be interrupted, or allowed to freeze.

- Typical drying period ranges from 2 to 3 days depending on the sun, air movement, humidity, quantity and type of product.
- For uniform drying the trays must be rotate 180 º daily. Dried product must move to bottom of the drying unit.
- Before storing the product must be cooled completely.
- Recommended material of the trays: stainless steel rack, wood slats with cheesecloth cover, Teflon, Teflon coated fiberglass, nylon, food grade plastics.[3]

1.7 Classification of Solar Dryers

It is not an easy task to classify, reliably, solar drying equipment as there as there are a lot of configurations many of which are empirical constructions. They can be classified by various modes, as according to the type of dryer, to the operation temperature or the material to be dried, to type of operation, e.g., batch or continuous, etc. In this classification a new mode of solar dryers may be added, the hybrid solar dryer one, that combines solar energy with an auxiliary energy source, mainly a gas, as propane, conventional fuels or biomass.[3]

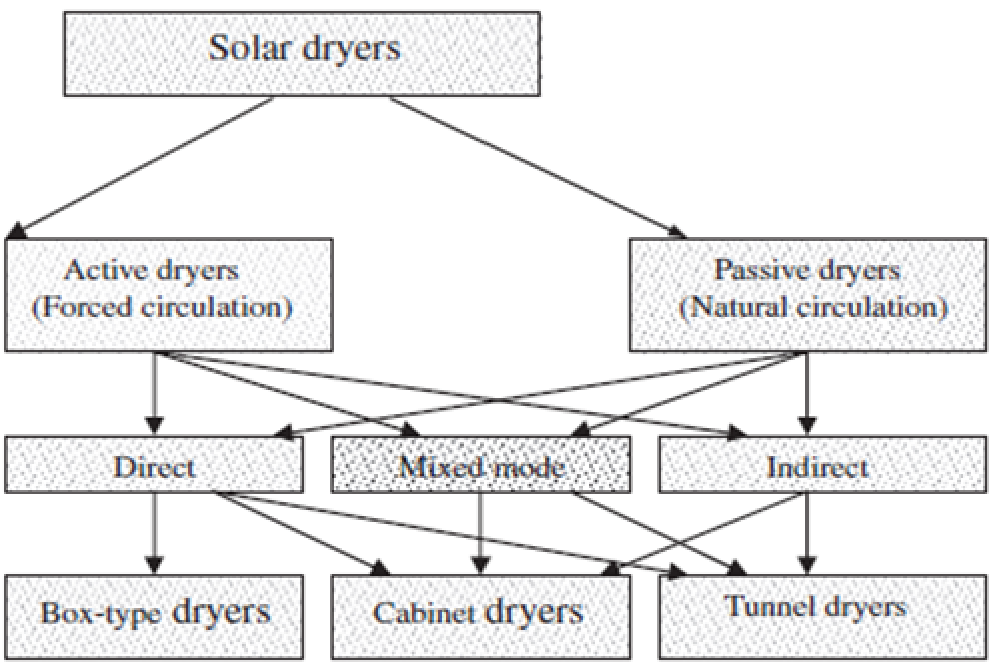

Figure 1.1: Classification of dryers and solar heating modes[3]

According to the drying process, e.g. direct or indirect, solar dryers may be classified as passive and active ones

- Passive dryers are heated directly from the sun's radiation with or without natural air circulation.
- Active (or forced convection) solar dryers, where hot drying air circulates by means of a ventilator.

1.7.1 Passive solar dryers

Passive solar dryers are "hot box" units where the product in the hot box is exposed to the solar radiation through a transparent cover. Heating takes place by natural convection, through the dryer transparent cover or in a solar air heater.

The passive type solar dryers are primitive, inexpensive constructions, easy to install and to operate especially at sites where not electrical grid exists.[3]

1.7.1.1 *Cabinet and green house type dryers*

The simplest passive solar dryers are of the chamber (or cabinet) greenhouse type. In Fig.1.2 two types of very simple solar passive dryers are presented. In A: a tent dryer covered with transparent plastic material at the southern side (a) and black poly-ethylene cover at the northern side (bp). The other sides (os) are uncovered for easy air circulation. The product is spread on the plate (mp), or it lies in a thin layer onto a tray. Fig. 1.2B is a similar type dryer covered with transparent glass covers (a) and shelters (sh) for the air flow. Humid air is exhausted from the top of the cover (ao).

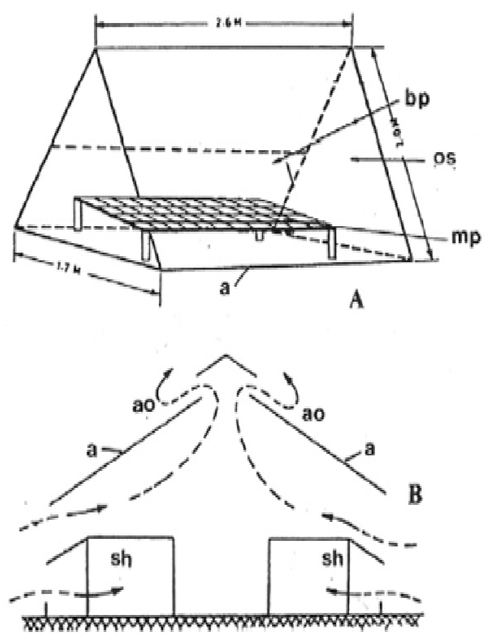

Figure 1.2: The tent dryers. (A) Passive dryer covered by transparent plastic material only in two sides. (B) Passive solar dryer glass covered[3]

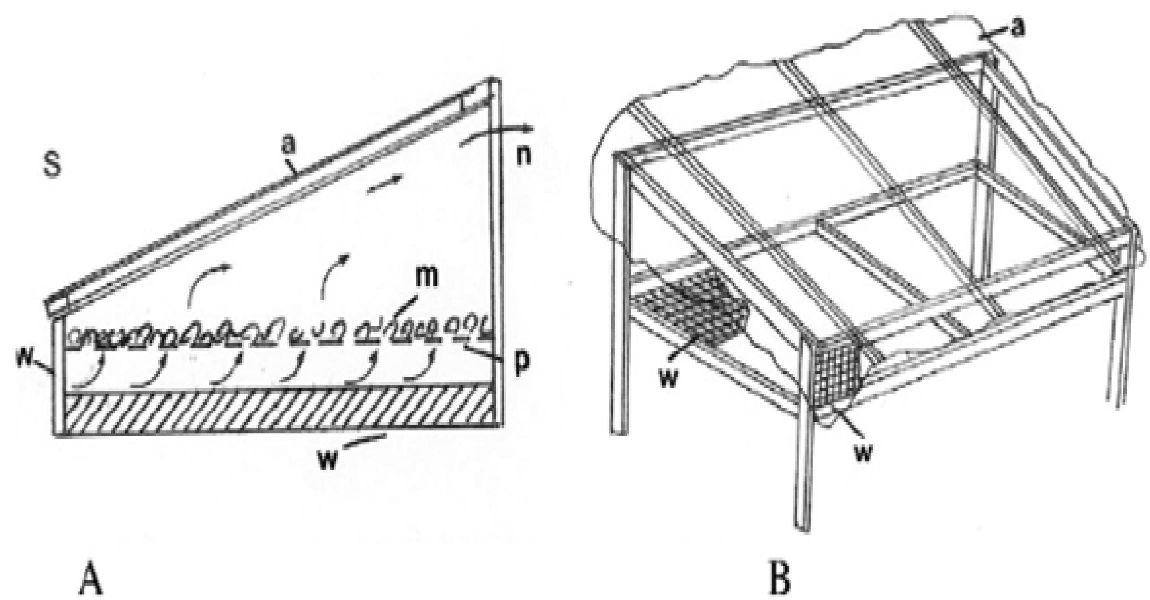

Figure 1.3: (A) Cross section of a greenhouse type dryer.(B) The wire basket type solar dryer[3]

A variation of the above chamber dryers of Fig. 1.2, presented in Fig. 1.3A, is the cabin dryer. It resembles an asymmetric solar still unit oriented north–south. The cover (a) is made from glass or transparent plastic material.

The material to be dried (m) is spread on perforated plates, through which the air circulates by natural convection and finally leaving the drying chamber from the upper north side (n). Bottom and side walls (w) are opaque and well insulated. Fig. 1.3B presents a similar, greenhouse type dryer, made of wooden frames and covered at the bottom with a chicken wire (w) to allow free air flow. The transparent cover (a) is removable to permit operation with direct solar radiation, but even when covered drying temperature is about 5 ^{o}C higher than the one of the ambient temperature. Cabinet dryers are simple and inexpensive. They are suitable for drying agricultural products, spices, herbs, etc.

Another type of chamber greenhouse type dryer is given in Fig. 1.4A. It is a dual purpose tool, used as a fruit dryer at summer and beginning of autumn, while in winter and spring acts as a greenhouse for vegetable growing and seedlings. The transparent surface faces southward, and consists of a single layer of glass during drying period.

In winter it is covered with a second layer of poly-ethylene on the side, to reduce heat loss. The forward part of the drying chamber, in order to achieve additional heating a blackened surface is employed. The drying regime is created under the action of solar energy passing through the transparent surface. The highest incident solar radiation penetrates inside the incline transparent surface (39 ^{o}C) when the sun is low in the sky.[3]

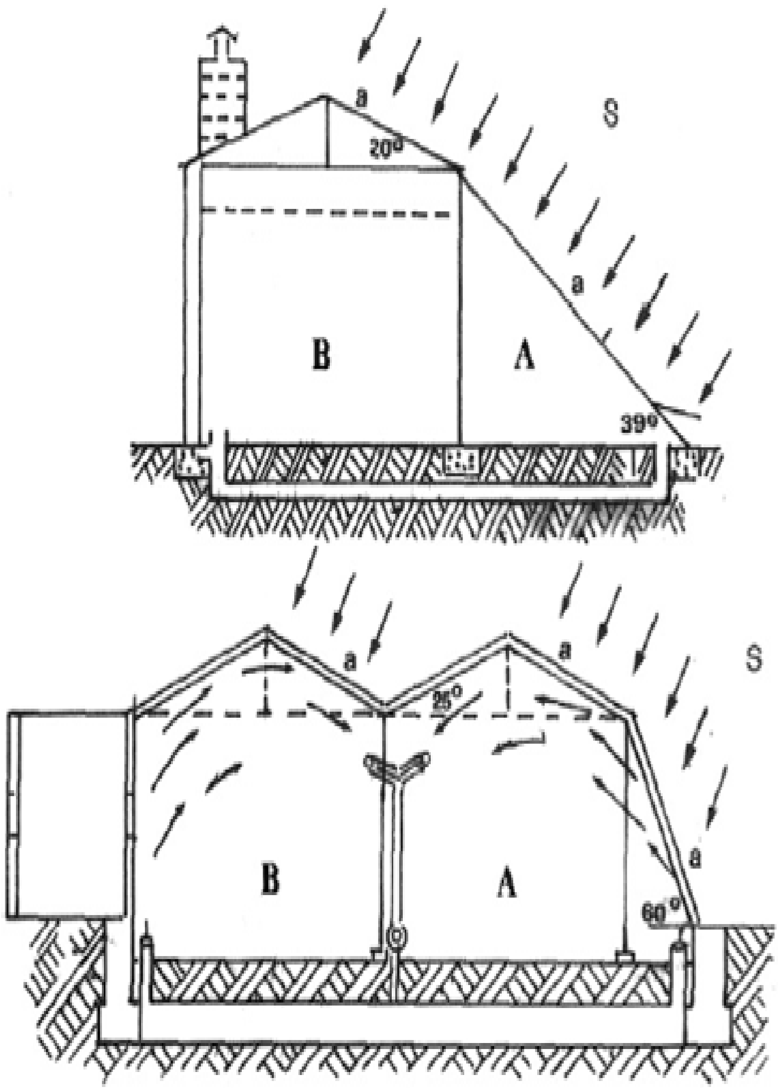

Figure 1.4: (A and B) Solar dryers of greenhouse type[3]

1.7.1.2 *Passive solar dryers with natural convection*

The previously described dryers are of low capacities because they can only handle one layer of product. To increase capacity, keeping constant the available area, the trays containing the material must be accommodated in more than one independent layer, one upon the other. This results in creating an additional resistance to the movement of air by natural convection through the multi-layer bed of products. Thus the vertical flow of air must be increased without the use of a ventilator. To achieve this, the so-called "chimney effect" may be used.

Fig. 1.5 present a multi-layer dryer which is called "shelf-type solar dryer". It is oriented southwards having the top and south wall covered with a transparent material (a). The thermal effect is increased by the use of an air heater (c), which helps the chimney effect to be developed. Humid air is exhausted from the northern wall (n), of the dryer. North wall (w) is well insulated. The material is spread on the trays inside the dryer (d). The authors give also a detail "quasi steady state" analysis and a performance evaluation for shelf-type solar dryers.

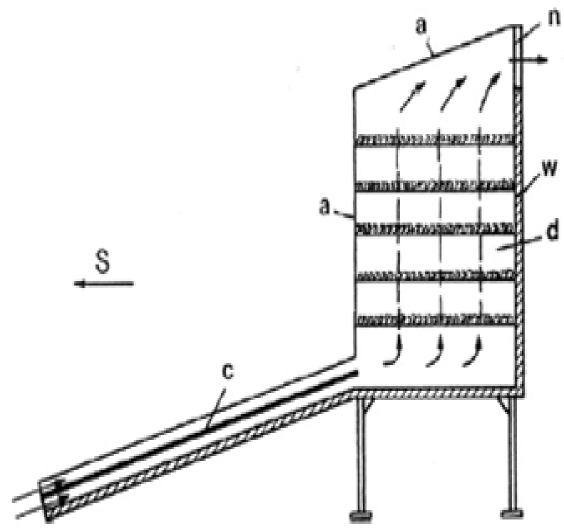

Figure 1.5: A shelf-type solar dryer[3]

For large amounts of material to be dried, up to 1000 kg, chimney has to be taller for proper air circulation. Fig. 1.6 presents a typical chimney solar dryer.

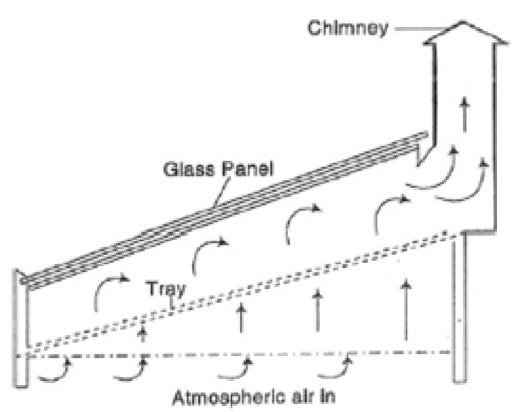

Figure 1.6: A typical cabinet solar dryer with chimney[3]

Chimney dryers are suitable for remote and/or small agricultural communities for in site drying immediately after harvest. They have the advantage to operate on natural convection basis having no need of any auxiliary energy, as electricity, use. They are inexpensive constructions and easy to operate. Usually they do not need foundations. Their disadvantage is the height restriction of the chimney, especially in places with strong winds. Smaller chimneys affect the air flow rate and thus the drying rate of the material.[3]

1.7.2 Forced convection solar dryers

Forced convection solar dryers (or active solar dryers) are suitable for larger amounts of material. They use either a direct absorption system through transparent covers or a system connected to solar collectors using indirect solar heat. Many times they are hybrid systems by using auxiliary sources of energy as conventional fuels, biomass, gas, etc., when available, avoiding some disadvantages of the passive solar dryers, therefore. Forced convection solar drying systems are more complicated and more expensive than passive systems as they need fans, ventilators for air circulation and piping loops.[3]

1.7.2.1 *Chamber greenhouse type forced convection dryers*

Fig. 1.7A presents a typical forced convection dryer similar to the passive type one of Fig 1.5. Drying air is heated passively, by penetration of solar radiation through the transparent cover (a) facing southwards.

The air is circulated flowing through the bed of the product (m) and exhausted from the northern, well insulated, wall at its bottom (b). Northern wall is well insulated as well.

The dryer in Fig. 1.7B is similar to that in Fig. 1.6. Inside the chamber plates (p), to support the trays with the material, are built.

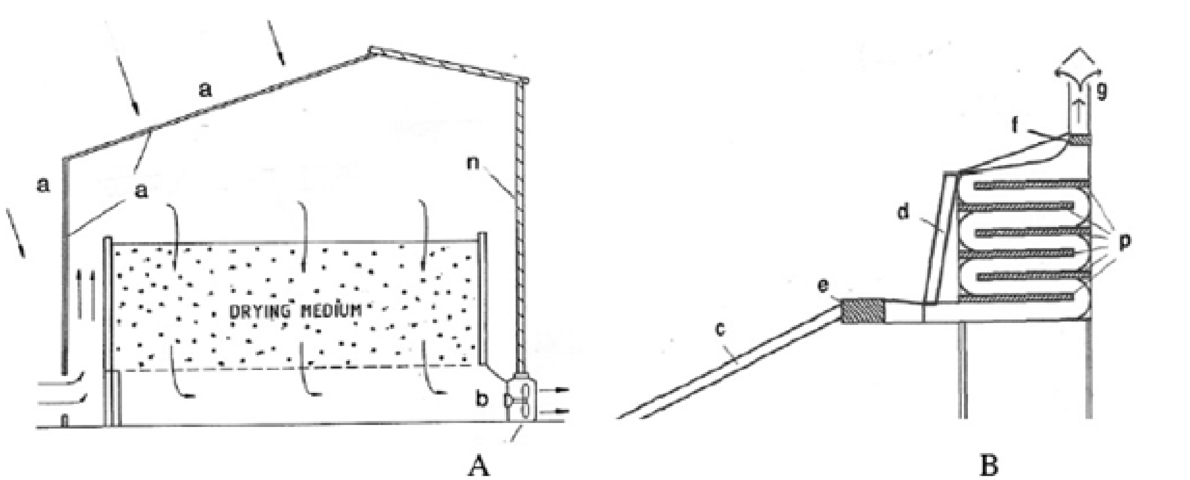

Figure 1.7: (A) Forced circulation air solar dryer with passive heating system. (B) Forced circulation solar dryer with a solar heater and chimney[3]

Air circulation is achieved by an electrically driven ventilator (e) operated by a photovoltaic module (d). The air is exhausted on the top of the dryer (f) through a short chimney (g). It is suitable to support drying of various agricultural products produced in small farms, e.g. fruits, herbs, seeds, mushrooms, etc.[3]

1.7.2.2 *Solar dryers with greenhouse type collectors*

These types of solar dryers use long transparent plastic tunnels as air heaters. They are of the mixed-mode solar heaters combining passive air heating with forced air circulation.

A German solar drying chamber, which consists of a long tunnel type plastic collector, is presented in the photograph of Fig. 1.8A. In Fig. 1.8B the cross section of the system is presented.

The dryer (d) is a 1.8 m high chamber having nine tray layers with 1.5 m2 surface each and are situated at the top of the plastic tunnel (d). The solar heater consists of a transparent poly-ethylene sheet (a) supported by stainless steel bows (Fig 1.9). The tunnel has 78 m length, 4 m width and 2.1 m height. Its inclination is 18º, facing southwards. The bottom of the tunnel is covered with a black absorbing plastic sheet (b). A ventilator (v) circulates the heated air up to the dryer. The system is used for drying fruits, vegetables, aromatic herbs, e.g. dill, laurel, etc. The photograph of Fig. 1.9 gives a view of the tunnels inside and the place of the various steel bows.[3]

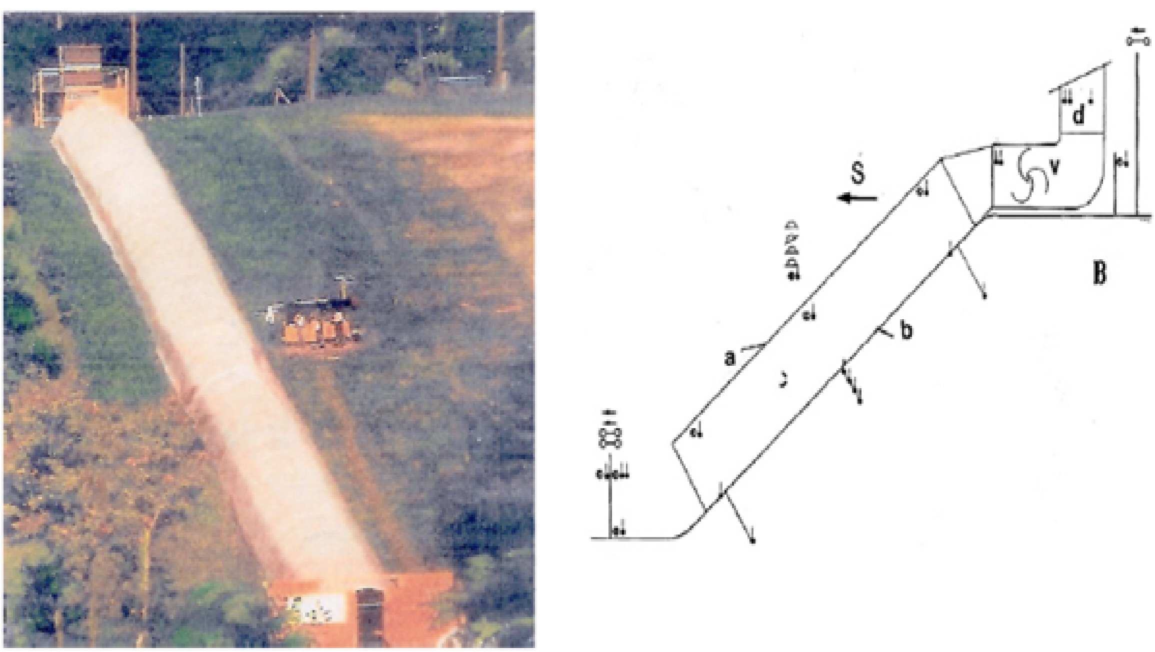

Figure 1.8: (A) Photograph of the solar heating tunnel with the dryer on the top. (B) Schematic of the drying system[3]

Figure 1.9: The inside of the collector tunnel with the stainless steel bows the poly-ethylene cover hemi-spherical and the black plastic sheet in the bottom[3]

1.7.2.3 *Tunnel dryers*

Tunnel solar dryers are used for larger amounts of material and are almost near to be commercialized. They consist of a transparent roof and transparent side walls, mainly in hemi-spherical mode. Inside the tunnel chariots with several stacked trays containing the material to be dried, are moving. Hot air flows though the trays containing the material. The chariots are either stable during the drying cycle or they can be moved manually. They operate similarly as the conventional batch chamber dryers.

Fig. 1.10 shows a typical tunnel dryer with chariots. Solar radiation is collected in long tubes (c) made of clear transparent poly-ethylene tube. The collector tubes are situated on the top of the tunnel dryer because of their light-weight construction. A ventilator (v) circulates the heated air through the chariots containing the trays with the material (h). The system is provided with auxiliary heat.[3]

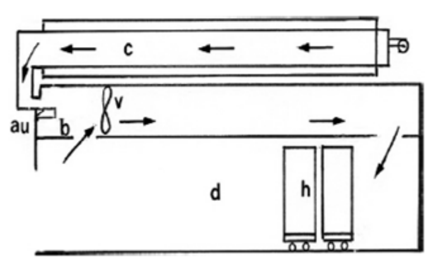

Figure 1.10: Tunnel dryer for fruits. h, chariots with trays and the material; c, poly-ethylene tubes; v, ventilator; b, auxiliary heat gas generator[3]

When choosing solar dryers the most important characteristics to be considered are:

- Low capital and operation cost.
- High load ratio.
- Use of commercially available technology.
- Achievement of uniform material drying.
- Have a high throughput of fruit or other crops.
- Have simple mechanical material handling system.

1.7.3 Hybrid solar dryers

Hybrid solar dryers combine solar radiation energy with an auxiliary conventional source of energy.

They can be operated either only by solar energy, only by conventional energy sources or by both. In most of the cases hybrid solar drying systems are medium to large capacity installations and operate by a solar ratio in the range of 50–60%.

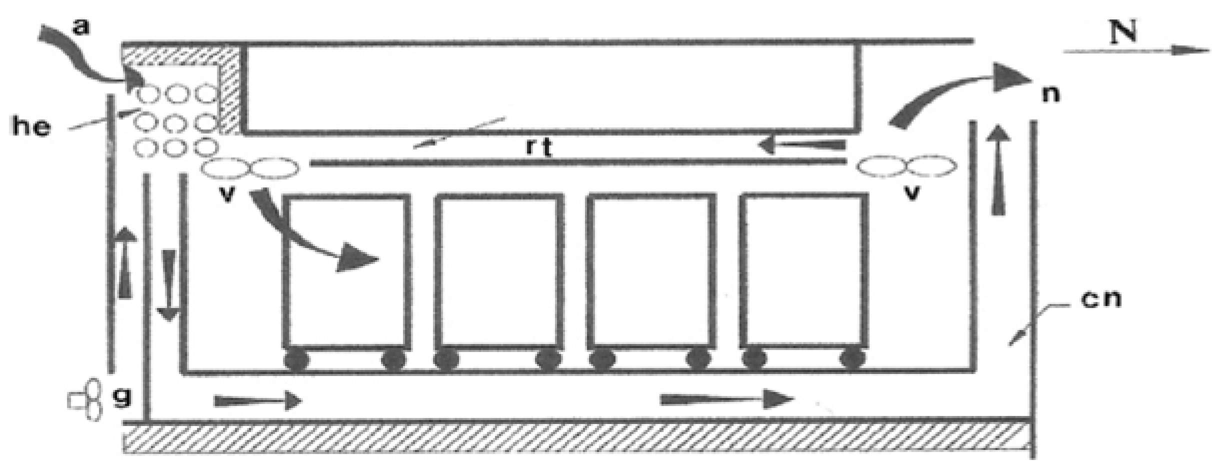

Figure 1.11: Solar tunnel with an additional auxiliary heat source

Fig.1.11 presents a hybrid solar dryer with auxiliary source of heating. Ambient air (a) flows through a heat exchanger (he) where is heated up to the necessary drying temperature, by combustion gas (g). Part of the used air is exhausted from the north wall (n) of the dryer and the rest is recycled through the recycling tube (rt). Cooled gas exits through the chimney (cn) to the ambient.

Hybrid solar dryers were developed the recent years, due to significant increase of agricultural production. Thus the operation, especially for large amount of material was swift from open-air drying to larger active solar drying systems, especially to hybrid systems, in order to overcome energy demand.

On the other hand the increased agricultural production needs immediate drying for preservation. There are a lot of advantages in favor of active solar drying. When drying in active systems, solar or hybrid, the characteristics and especially the drying behavior of the agricultural products, need to be exactly known.[3]

Chapter 2

LITERATURE REVIEW

V. Belessiotis and E.Delyannis [3] presented a review of solar drying and its applications. Solar radiation use for drying is one of the oldest applications of solar energy. It was used since the dawn of mankind mainly for food preservation but also for drying other useful materials as cloths, construction materials, etc. Solar drying has not yet widely commercialized. Solar dryers are equipment, generally of small capacity and based rather on empirical and semi-empirical data than in theoretical designs. The majority of the numerous solar dryer designs, which are available, are used mainly for drying of various crops either for family use or for small-scale industrial production. Also various direct and indirect solar drying applications and some of the numerous solar dryers are described. A very short historical description of solar drying through the centuries is also given. Some drying phenomena, independently of the type of energy used, and the general laws that govern drying methods by convection are shortly analyzed in order the reader to easily follow the details of the solar drying procedure. Special solar collectors used in drying and methods of coupling to the various solar dryers are described as an indirect solar thermal energy source.

A. Sreekumar et al. [4] presented the development and testing of a new type of efficient solar dryer, particularly meant for drying vegetables and fruit, is described. The dryer has two compartments: one for collecting solar radiation and producing thermal energy and the other for spreading the product to be dried. This arrangement was made to absorb maximum solar radiation by the absorber plate. In this dryer, the product was loaded beneath the absorber plate, which prevented the problem of discoloration due to irradiation by direct sunlight. Two axial flow fans, provided in the air inlet, can accelerate the drying rate. After using this dryer the conclusion is the product was loaded beneath the absorber plate to protect it from direct exposure to solar radiation. The drying duration of the product was reduced considerably in comparison with traditional sun drying. Moreover, the product could retain its original color after the drying process, which is an important parameter to determine the quality of the product. The quality of the product dried in the solar dryer was competitive with the branded products available in the market.

Teslime Mahmutoglu et al [5] described the effects of pretreatment solutions and drier types (solar VS sun) were investigated for grapes (var. sultanas). Pretreatment solutions containing 5% K_2CO_3 plus 1.5% olive oil and 4% K_2CO_3 plus 2% ethyl oleate accelerated dying rates nearly to the same extent, as compared to untreated grapes. Dying rates were classified for the tested dying methods: solar dying > sun dying on concrete ground > sun dying on wooden racks, or on polypropylene canvas sheets. Increasing K_2CO_3 concentration from 4 to 7% in ethyl oleate (2%) solution increased dying rates on concrete ground. Treatment with SO, gas (645 mg/kg) in addition to ethyl oleate, further increased the dying rates but the color of the product was rated to be too light and unacceptable to the market. The moisture content and color intensities of the sun-dried grapes were found to be non-uniform. Storage stability of treated, dried grapes was investigated in (I) modified atmosphere (1% O_2 plus 13% CO,), (2) vacuum packed and (3) ordinary. Plastic pouch packed storage at 6°C. Untreated grapes had the lowest Hunter L (lightness), a (redness) and b (yellowness) values compared to treated grapes. Storage caused color parameters to decline, but this reduction was less pronounced for SO_2 gas treated products. In conclusion, solar drying reduced drying times of grapes to about half of that of the sun drying on concrete ground. Color of the treated grapes was lighter than that of the untreated grapes. Drying on polypropylene canvas sheets or on wooden racks or by solar drying gave a relatively lighter product compared to drying on concrete ground.

C. Ratti ans A. S. Mujumdar [6] discussed on simulation code was developed to predict the batch drying performance of a packed bed of particles, e.g. cylinders or slices of carrot, apples, etc., subjected to time-varying air conditions. This model allows for shrinkage of the particles. The time-dependent inlet drying air conditions permit the simulation of the case of a solar dryer in which the inlet air temperature is necessarily a function of the hour of the day. All the parameters involved in the model were obtained independently from experimental solar dryer data. The results compared well with published experimental data for solar drying of diced carrot. Artificial drying of foodstuffs is an important method of preservation and production of a wide variety of products. Such materials are generally characterized by the following features: (1) High initial moisture content. (2) High temperature-sensitivity (i.e. color, flavor, texture and nutritional value subject to thermal deterioration). (3) High susceptibility to microbial attack. (4) Presence of a "skin" (e.g. fruits like grapes or blueberries) which has poor permeability for water or moisture. It concludes that the solar drying of shrinking particles was simulated with a model with no adjustable parameters. The comparison between experimental and simulated values during solar drying of carrots (water content and temperature of the solids as a function of time) was favorable.

V. T. Karathanos and V. G. Belessiotis [7] stated drying of agricultural products took place by traditional means using solar energy. Drying experiments for various products, such as Sultana grapes, currants, figs, plums and apricots, were conducted and the drying rates were found for both solar and industrial drying operations. Air and product temperatures were measured for the whole industrial drying process. It was proved that most materials were dried in the falling rate period, while currants, plums, apricots and jigs exhibited two drying rate periods, a first slowly decreasing (almost constant) and a second fast decreasing (falling) drying rate period. Based on the findings of preliminary runs the drying cycle of this fully automated industrial dryer was designed to give maximum quality of dried products with reasonable energy costs. A high air velocity and medium temperature were utilized for the beginning of the process, while for the second falling drying rate period a medium air velocity, a high air temperature and a partial recirculation of the air stream were used. The industrial drying operation resulted in a product of superior quality compared to products dried by solar dehydration. Also the comparison of sun drying and solar drying is carrying out and discussed its characteristics. Drying of agricultural products under direct sunlight is the traditional way of preservation of a large number of fruits and vegetables. Traditional sun drying takes place by storing the product under direct sunlight or in indirect sunlight under transparent plastic films, glass or non-transparent covers. In the last method the sun heating is indirect through heating of convective air. Drying with the various forms of solar drying has the advantage of small or negligible installation and energy costs.

Babagana Gutti et al. [8] presented that the solar is one of the renewable and sustainable sources of power that attracted a large community of researchers from all over the world. Solar dryers are available in a range of size and design and are used for drying various agricultural products. It is found that various types of dryers are available to suit the needs of farmers. Therefore, selection of dryers for a particular application is largely a decision based on what is available and the types of dryers currently used widely. The use of solar dryers in the drying of agricultural products can significantly reduce or eliminate product wastage, food poisoning and at the sometime enhance productivity of the farmers towards better revenue derived. Drying of agricultural products is an essential process in their preservation which normally provides longer shelf-lighter weight for easy transportation and small space for storage. It is a process of moisture removal due to simultaneous heat and mass transfer. Agricultural products, especially fruits and vegetables require hot air in the temperature range of 45–60 °C for safe drying. The drying systems are usually classified according to their operating temperature ranges; into low and high temperature dryers. Agricultural products are dried for the purpose of removing moisture as quickly as possible at a suitable temperature to prevent decay and spoilage. Depending on the agricultural product, water content of properly dried product (food) varies from 5%-25% with successful drying. The utilization of solar energy for drying agricultural products can drastically reduce agricultural products lost due to poor storage facilities and contamination as a result of common practice of open-air drying. Solar drying processing helps in preserving the quality of agricultural food products and provides opportunities for farmers to add value for local, regional and international markets.

N. A. Vlachos et al. [9] described that a novel low cost tray dryer equipped with a solar air collector, a heat storage cabinet and a solar chimney is designed and tested. The design is based on energy balances and on an hourly-averaged radiation data reduction procedure for tilted surfaces. Measurements of total solar radiation on a horizontal plane, ambient temperature and humidity, air speed, temperature and relative humidity inside the dryer as well as solids moisture loss-in-weight data are employed as a means to study the performance of the dryer. First, detailed diagnostic experiments are carried out with no drying material on the trays. Next, a number of experiments is conducted using a controlled reference material whose reproducible dehydration pattern allows comparisons among runs. Drying is also tested during night operation and under adverse weather conditions. For all the employed conditions, the material gets completely dehydrated at a satisfactory rate and with an encouraging system's efficiency. For many agricultural products an abrupt drying process is completely undesirable, since it demotes the product's quality and the final drying result seems to be uncontrollable. This is due to the fact that quite often an external over-dried layer is formed which prohibits the process of drying at the material's inner layers. On the other hand, the rather slow process of direct sun drying, a traditional drying technique in Mediterranean climates where high solar irradiation occurs, can have a negative impact on dried products' quality mainly due to contamination, e.g. by windborne dirt and dust, insects etc. The resulting decrease in quality renders the product less marketable. Several types of indirect solar dryers were realized and built in the past, aiming to products of higher quality in terms of color, texture or taste, reduced drying times and greater efficiencies compared to the traditional open sun drying. When designing such dryers, the cost of construction and the range of applicability are two additional factors that pose an even greater challenge in developing an economically viable drying system. The performance of the dryer is tested also under adverse weather conditions (i.e. cloudy and rainy) and during night operation.

Lyes Bennamoun and Azeddine Belhamri [10] presented study the drying kinetic behavior with respect to the variation of the external conditions. Diffusion model based on Fick's law is used. The heated air thermo-physical properties variation and shrinking effect are taken into consideration. The coefficient of diffusion is calculated based on experimental data and presented as a function of temperature and velocity. The numerical resolution of the mass transfer equation allows the calculation of the distribution of moisture inside the product, at any time. Sudden and progressive augmentation of temperature and velocity are simulated; the drying kinetic answers by changing its behavior with a non-instant response. Solar drying was investigated through the study of a flat air collector. The ambient air velocity considerably influenced the outlet temperature of the collector air which reverberates on the drying kinetic. Sun natural drying is one of the most common traditional preservation methods used, in particular in non industrialized countries. It was found that the quality of the products solar dried was superior to ones naturally dried. Solar drying was performed using an air flat collector. In this way, it is necessary to present the equations governing its behavior, based on heat transfer. Many characteristics of foodstuffs change during drying, with the appearance of shrinkage. This latter is an important parameter to take into consideration; whereby false results can occur. The diffusion model can detect the variations in the drying kinetics during external condition changes. Therefore, it can be used to study solar drying. During solar drying, the ambient air velocity is an influential parameter.

I. Montero et al. [11] which a solar dryer prototype is designed, constructed, and performance tested for the analysis of the drying kinetics of these by-products and their possible power valuation. The characteristics of the prototype are presented, together with the variations of the properties of temperature, relative humidity, air mass flow, and efficiency for indirect, mixed, passive, active, and hybrid operation modes. The most efficient operation mode will be the forced-hybrid one, followed by the passive and active modes. The analysis of the drying kinetics of the olive pomace shows the better performance of the hybrid and mixed modes, obtaining reductions of the drying time of a 50% in both cases. In general, the main objectives that are usually aimed in the operations of drying are: to facilitate a later industrial process, to obtain a satisfactory use of a certain product, to make the conservation, storage and transport of a material possible, to improve the performance of an installation or equipment, to reduce costs (storage, transport, conservation, reduction in fuel consumption, etc.), to allow the later use of the by-product and to obtain direct or indirect environmental improvements. In this work a solar dryer prototype has been designed and constructed for the drying of humid agro industrial by-products in different operation modes (active, passive, indirect, mixed and hybrid modes). Previous to the valuation of the drying kinetics, the experimental analysis carried out has been shown to establish the most suitable operation strategies. The solar dryer developed in this work will allow to research and improve the solar drying process of other agro industrial waste.

Sobhana Singh and Subodh Kumar [12] stated A generalized methodology is developed for thermal testing of various solar dryer designs operated for natural and forced air flow conditions. The steady state mathematical model based on heat balance concept of solar dryer without load is applied to identify the dimensionless parameter called no-load performance index (NLPI). Laboratory models of direct (cabinet), indirect and mixed mode solar dryer are designed and constructed to perform steady state thermal tests for natural and forced air circulation. The present study reveals that the forced convection operated dryer provides higher NLPI in contrast to that of natural convection. The comparative performance analysis of dryers indicates that the mixed mode dryer exhibits maximum value of NLPI followed by indirect and cabinet ones for both natural band forced air circulation. It is also found that for any dryer operating at given air flow condition, almost invariable NLPI values have been obtained for a wide range of absorbed energy and ambient air temperature data, thus facilitating performance comparison between different dryer designs on equitable basis. The dimensionless parameter referred as no-load performance index, NLPI is identified for performance evaluation of a given dryer. Based on experimental investigation, it is concluded that the proposed parameter, NLPI of any solar dryer operating for given air flow condition is more or less independent of absorbed thermal energy and ambient air temperature data (climatic variables) and thus, can be used as an index for performance comparison between different solar dryer designs on equitable basis.

Dilip R. Pangavhane [13] presented the Mechanical drying of agricultural products is an energy consuming operation in the post-harvesting technology. Greater emphasis is given to using solar energy sources in this process due to the high prices and shortages of fossil fuels. For these purposes, a new natural convection solar dryer consisting of a solar air heater and a drying chamber was developed. This system can be used for drying various agricultural products like fruits and vegetables. In this study, grapes were successfully dried in the developed solar dryer. The qualitative analysis showed that the traditional drying, i.e. shade drying and open sun drying, dried the grapes in 15 and 7 days respectively, while the solar dryer took only 4 days and produced better quality raisins. The developed natural convection solar dryer is capable of producing the average temperature between 50 and 55 °C, which was optimum for dehydration of the grapes as well as for most of the fruits and vegetables. This system is capable of generating an adequate flow of hot air to enhance the drying rate. The drying air flow rate increases with increase in ambient temperature by the thermal buoyancy in the collector. The collector efficiencies of this natural convection solar dryer were ranged between 0.26 for 0.0126 kg/s and 0.65 for 0.0246 kg/s; which were sufficient for heating the drying air. The drying time of the grapes is also reduced by 43% compared to the open sun drying.

E. Kavak Akpinar [14] carried out the study was investigated the thin-layer drying characteristics in solar dryer with forced convection and under open sun with natural convection of mint leaves, and, performed energy analysis and exergy analysis of solar drying process of mint leaves. An indirect forced convection solar dryer consisting of a solar air collector and drying cabinet was used in the experiments. The drying data were fitted to ten the different mathematical models. Among the models, Wang and Singh model for the forced solar drying and the natural sun drying were found to best explain thin-layer drying behavior of mint leaves. Using the first law of thermodynamics, the energy analysis throughout solar drying process was estimated. However, exergy analysis during solar drying process was determined by applying the second law of thermodynamics. Energy utilization ratio (EUR) values of drying cabinet varied in the ranges between 7.826 and 46.285%. The values of exergetic efficiency were found to be in the range of 34.760–87.717%. The values of improvement potential varied between 0 and 0.017 kJ/s. Energy utilization ratio and improvement potential decreased with increasing drying time and ambient temperature while exergetic efficiency increased. The values of EUR and improvement potential of the cabinet decreased with the increase of ambient temperature, while the exergetic efficiency values of the cabinet increased with the increase of ambient temperature. It is expected that this study will be beneficial to everyone involved or interested in the performance improvement of drying systems.

O. V. Ekechukwu and B. Norton [15] presented a comprehensive review of the various designs, details of construction and operational principles of the wide variety of practically-realized designs of solar-energy drying systems reported previously is presented. A systematic approach for the classification of solar-energy dryers has been evolved. Two generic groups of solar-energy dryers can be identified, viz passive or natural-circulation solar-energy dryers and active or forced-convection solar-energy dryers (often referred to as hybrid solar dryers). Three sub-groups of these can also be identified, viz integral-type (direct mode), distributed-type (indirect mode) and the mixed-mode type. The appropriateness of each design type for application by rural farmers in developing countries is discussed. Some very recent developments in solar drying technology are highlighted. They presented a comprehensive review of the various designs, details of construction and operational principles of the wide variety of practically-realized designs of solar-energy drying system. They also evolved a systematic classification of solar-energy dryers. This classification illustrates clearly how these solar dryer designs can be grouped systematically according to their operating temperature ranges, heating sources and heating modes, operational modes or structural modes. Two broad groups of solar-energy dryers can be identified, viz, passive or natural-circulation solar-energy dryers and active or forced-convection solar-energy dryers (often called hybrid solar dryers). Three sub-groups of these, which differ mainly on their structural arrangement, can also be identified, viz integral or direct mode solar dryers, distributed or indirect-modes and the mixed-modes. Though properly designed forced-convection (active) solar dryers are agreed generally to be more effective and more controllable than the natural-circulation (passive) types, the requirement of electricity or fossil-fuel driven fans and/or the use of auxiliary heating sources, however, renders the former clearly inappropriate for remote rural village farm application in most developing countries and makes both their capital, maintenance and operational costs prohibitive for small scale farming operations. For large scale applications in rural locations, the "ventilated greenhouse dryer" has the advantage of low cost and simplicity in both on-the-site construction and operation.

Cigdem Tiris et al. [16] stated a new solar dryer, which consisted of a solar air heater and drying chamber, was developed for drying food products. The present drying system was successfully tested using sultana grapes, green beans, sweet peppers and chili peppers. The traditional sun-drying experiments were employed and compared with the solar-drying experiments. It was shown that the use of this type of dryer reduced the drying time significantly and essentially provided better product quality. An experimental investigation was conducted to test a new solar dryer consisting of a solar air-heater and a drying chamber. Sultana grapes, green beans, sweet and chili peppers were selected as test samples and dried in the present system. The drying times varied between 2 and 5 days. The drying results obtained were compared with the results obtained for natural sun drying of products. Therefore, the present solar dryer provided better quality and a shorter drying period, etc. Further research is required to determine the overall thermal efficiency of the drying system and the technical and economical aspects, and to optimize the solar air-heater.

Subarna Maiti et al. [17] reports the design and development of an indirect, natural convection batch-type solar dryer fitted with North–South reflectors. With the help of the reflectors the collector efficiency without load was enhanced from 40.0% to 58.5% under peak solar irradiation conditions during a typical day in January in Bhavnagar, Gujarat, India. The corresponding computed values based on heat transfer equations were 36.5% and 50.3%. The desired extent of drying (ca. 12%, wet basis) of 'papad' – a popular Indian wafer – could be achieved within 5 h in this static dryer having 1.8 m^2 area of the collector and computed loading capacity of 3.46 kg. The initial and average values of the drying efficiency were 16.3% and 4.1%, respectively. The drying performance data could be fitted to the diffusivity equation with effective diffusivity value of 3.9×10^{-9} m^2/s. Despite the high collector efficiency achieved, the average drying efficiency was low on account of under-loading of the dryer, as evident from the increase in drying efficiency to 13% in a smaller dryer loaded with the same amount of wet papad. An improvement was brought about in the design of the natural convection indirect solar dryer by fitting the collector with N–S reflectors in a V-trough alignment. The high values of collector outlet temperature did not have any adverse effect on the quality of the dried papad, it may cause case hardening of certain food items. In such cases, the design of operation with reflectors may need to be suitably modified.

Stamatios J. Babalis and Vassilios G. Belessiotis [18] is presented the influence of the drying air characteristics on the drying performance of figs (ficus carica) several drying tests have been carried out in a laboratory scale tunnel-dryer. The dryer using ambient heated air and working in closed loop was equipped with a continuous monitoring system. The investigation of the drying characteristics has been conducted in the temperature range of 55–85 °C and the airflow in the range of 0.5–3 m/s. An Arrhenius-type equation was used to interpret the influence of the drying air parameters on the effective diffusivity, calculated with the method of slopes in terms of energy of activation, and this was found to be insensitive to air velocity values higher than 2 m/s. The effect of the air temperature and velocity on the drying constants was determined by fitting the experimental data using regression analysis techniques. The influence of the air temperature on the drying kinetics of figs has been shown to follow the Arrhenius relationship. The strong influence of air temperature and velocity at the early stages of drying was evident, as well as the relative insensitivity of the drying process at the later stages. A value beyond which the increase of the airflow velocity has no significant effect on the drying rate was encountered and was determined to be 2 m/s, indicating the predominance of the internal mass transfer resistance over the external one. The investigation revealed that the drying kinetics is most significantly affected by temperature, with the airflow velocity having a limited influence on the drying process.

2.1 Conclusion from literature review

Many people completed work on different types of solar dryers with different techniques. They also compare difference between direct sun drying and indirect sun drying and get best results in indirect solar drying with good efficiency and good quality of drying product. Someone also developed generalized methodology for thermal testing for various solar dryer designs operated for natural and forced air flow condition and also evaluate no load performance index for natural circulation and forced circulation. The no load performance index is higher in case of forced circulation.

2.2 Objective of present work

The problem under consideration is to carry out the long term performance of small scale indirect dryer. Following are the objectives of the present study:

- The main objective of the project is to utilize the solar energy efficiently in drying application as it is an important and viable alternative as it decreases the consumption of conventional energy.

- To study no load performance index of dryer in open loop and closed loop system which would help in the further drying application of various food materials

- To study about quality of dried food products. To achieve the required quality of dried food product by forcing an external source in form of air efficiently by using two collector with V-trough reflectors.

- To maximize the efficiency of drying by performing various experimental runs and maintain its nutritional values.

Chapter 3

EXPERIMENTAL SETUP

3.1 Construction of dryer

With respect to objective revised in the earliest chapter, the experimental setup was designed and fabricated at CSMCRI, Bhavnagar. The details of which are discussed in following section.

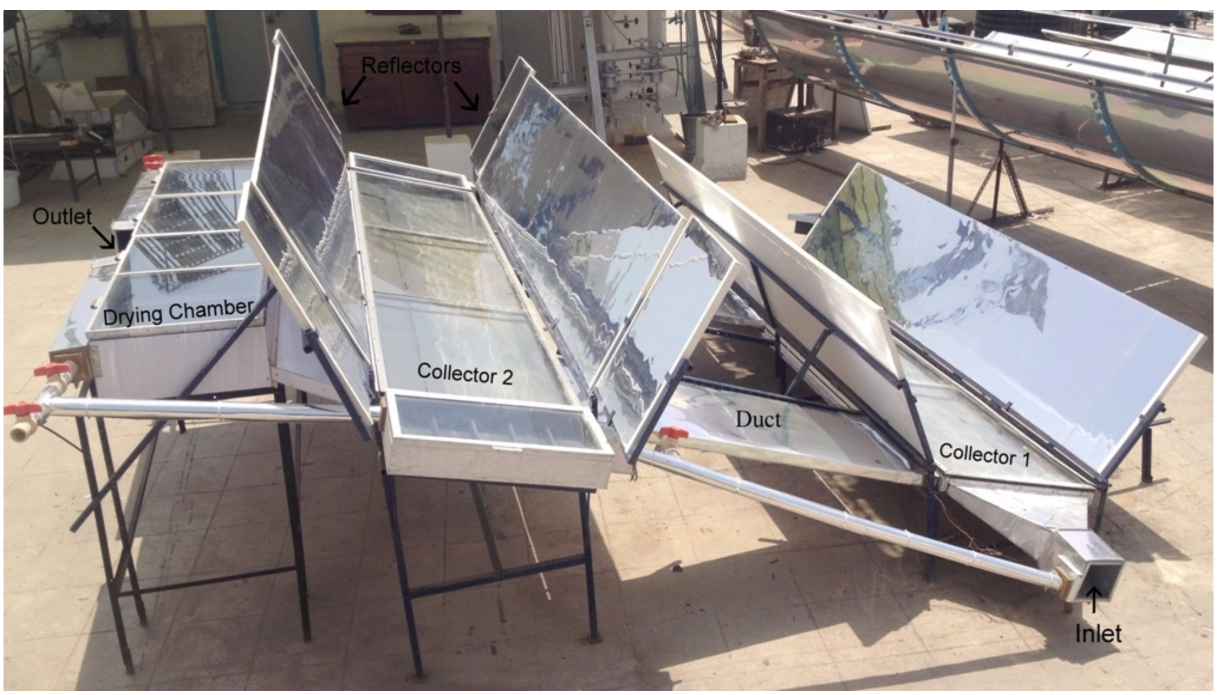

Figure 3.1: Construction of dryer

Fig. 3.1 shows main components of dryer which includes Collector 1 and 2 connected through two parallaly arranged rectangular ducts. The collector 2 is connected to a drying chamber where drying of a food material takes place.

Air at an ambient temperature is forced into both the side of collector 1 using fan as shown in Fig. 3.1. Here, air is heated through the solar radiation which falls on collector 1 efficiently due to V-trought reflectors. Heated air at heigher velocity is passed through ducts with minimum heat loss. Similarly heated air is reheated once it passes through the collector 2 through ducts. Both the collectors have similar construction except collector 2 is completely closed. The heated air enters drying chamber via ducts due to pressure gradiant. Drying chamber and collectors are painted with black nickel paint for higher absorptivity. Four exaust fans are arranged at an equal distance at an end of drying chamber.

Solar intensity was measured using pyranometer at regular interval of time where as temperature was accurately measured using digital thermometer(HTC-DT305) which has a range of -50ºC to 1300ºC. Humidity was measured using hygrometer. All the instruments are shown in the below Fig. 3.2 and a detailed figure of drying chamber is shown in Fig. 3.3

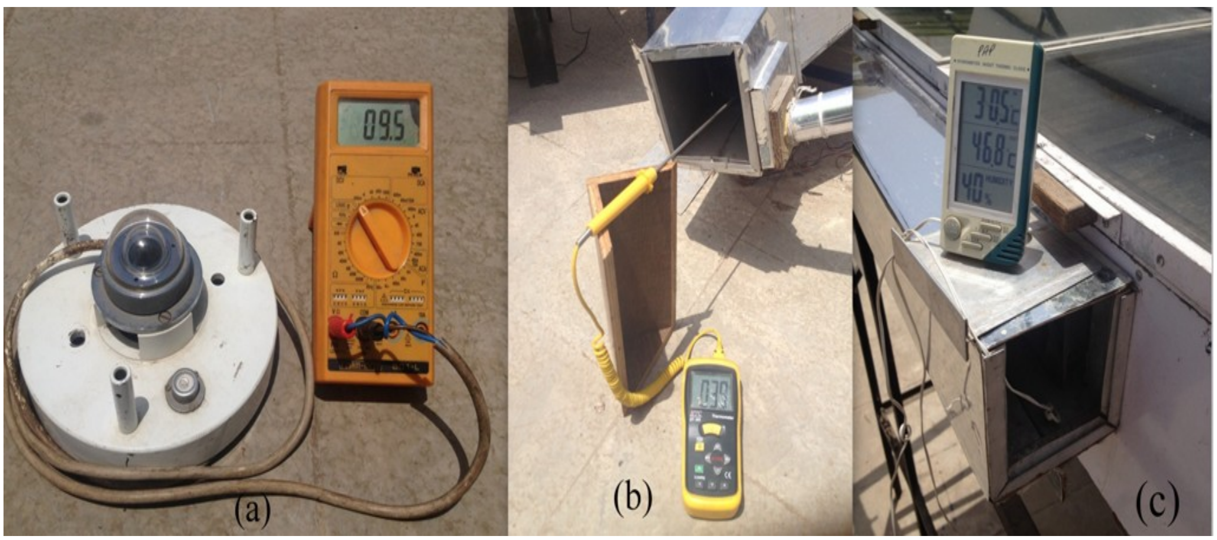

Figure 3.2: Mesuring instruments,(a)Pyranometer,(b)Digital thermometer,(c)Hygrometer

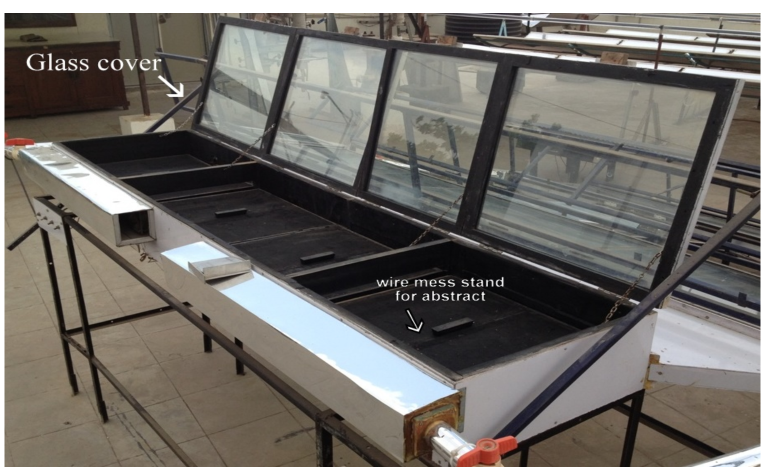

Figure 3.3: Drying chamber

3.2 Design procedure

The area of the collector is determined for drying area required for 12 kg of moist material (80% wet basis) to be dried within duration of 10:00 am-5:00 pm. The moisture level of the dried material is taken as 10%. The conditions/assumptions for design of dryer are provided in Table 3.1.

Table 3.1: Conditions/Assumptions for design of dryer

Location	Central Salt & Marine Chemicals Research Institute, Bhavnagar, Gujarat (21º46'N, 72º11'E)
Material	Different fruits and vegetables
Drying Period	January-March 2013
Ambient air temperature, T_{amb}	30 ^oC
Ambient relative humidity, RH_{amb}	50%
Load, M_p	12 kg
Initial moisture content, M_i	80%
Final moisture content, M_f	10%
Drying time, td (10:00 am -5:00 pm)	7 h
Average solar radiation on the collector over a period of td = 7 h, I_T	4.11 MJ/m^2hr or 28.81MJ/m^2 or 1143.55 W/m^2
Latent heat of vaporization, h_{fg}	2257 kJ/kg
Specific heat, C_p	1.005 kJ/kgK
Collector outlet air temperature,T_{co}	70 ^oC
Fan speed at the mouth of the collector, w_s	1.5 m/s
Dryer outlet air temperature, T_{do}	50 ^oC
Average air inlet temperature, T_{fi}	36 ^oC

3.3 Material for flat plate collectors

To design and construct solar collectors for heating and cooling purposes and to knowledge of the properties of the materials and characteristics of the various components is necessary to predict the performance and durability of the collector. Property data can generally be classified into three categories: thermophysical, physical and environmental properties. Thermophysical properties include thermal conductivity, heat capacity and radiant heat transfer characteristics. Physical properties include density, tensile strength, melting point and modulus of elasticity. Environmental properties include resistance to UV degradation, moisture penetration, corrosion resistance and degradation due to pollutants in the atmosphere. Durability is the criterion most often overlooked by the novice in constructing collectors.

3.3.1 Absorber plate

The absorber plate material should have high thermal conductivity, adequate tensile and compressive strength, and good corrosion resistance. Suitable materials for absorber plate are copper, aluminium, steel and various thermoplastics. Aluminium and steel require a corrosion-inhibited heat transfer fluid.

In our case, we take aluminium as a absorber plate material.

Table 3.2: Properties of aluminium used for absorber plate[19]

Material	Density (kg/m^2)	Specific heat (kJ/kg^oC)	Thermal conductivity (W/m^oC)
Aluminium	2707	0.996	204

3.3.2 Insulation

Several thermal insulating materials which can be used to reduce heat losses from the absorbing plates are commonly available. The desired characteristic of an insulating material are: low thermal conductivity, stability at high temperature (up to 200 ºC), no degassing upto around 200 ºC, self-supporting feature without tendency to settle, ease of application, no contribution in corrosion.

We use thermocole as a insulating material.

Table 3.3: Properties of thermocole used for insulation[19]

Material	Thermal conductivity at 200 ºC (W/m^oC)	Density (kg/m^3)	Out gassing	Saging	Colour change
Thermocole	0.035	16	yes	no	yes

3.3.3 Cover plate

The characteristics of the cover plates through which the solar energy is transmitted are extremely important in the functioning of a collector. The functions of cover plates are:

1. to transmit maximum solar energy to the absorber plate;
2. to minimize upward heat loss from the absorber plate to the environment; and

3. to shield the absorber plate from direct exposure to weathering. The most critical factors for the cover plate materials are the strength, durability, non-degradability and solar energy transmittance.

In collector, we use tempered glass, which is the most common cover material for collectors because of its proven durability and stability when exposed to UV radiation. Tempered glass cover, if properly mounted, is highly resistant to breakage both from thermal cycling and natural events. Glass cover also reduces radiation loss from the absorber plate because it is opaque to the longer wavelength IR radiation emitted by the hot absorber plate.

Table 3.4: Properties of glass used for cover plate material[19]

Material	Index of refraction(n)	Thickness (m)	Density (kg/m^3)	Specific heat (J/kg^oK)
Glass	1.518	3.175×10^{-3}	2.489×10^3	0.754×10^3

Table 3.5: Solar collector performance parameters[19]

Manufacturer and remarks	NASA/Honeywell
Absorber material	Aluminium
Absorber surface coating	Black nickel
Transparent covers	1 glass cover
Density of air, ρ	1.077 kg/m^2
Kinematic viscosity, μ	$19.85 \times 10^{-6} Ns/m^2$
Thermal conductivity, k	0.0287 W/mK
Absorptance of black absorber surface (α)	0.97
Tranmittance of cover plate(τ)	0.92
Emissivity of absorber plate	0.9
Emissivity of glass cover	0.9
Average glass cover temperature,T_g	65 ^oC
Average absorber plate temperatureT_p	75 ^oC
Mean fluid temperature, T_{fm}	55 ^oC
Length of collector, L_1	2.75m
Width of collector, L_2	1.28m
Spacing between glass cover & absorber plate,L_3	0.05m
Diffuse reflectance of cover at 60^o angle of incidenceρ_d	= 0.16 for single glass cover = 0.24 for two glass cover = 0.29 for three glass cover

3.4 Design of various components

Top loss coefficient (U_t)

$$U_t = \left[\frac{M}{\left(\frac{C}{T_p}\right)\left(\frac{T_p - T_a}{M+f}\right)^{0.252}} + \frac{1}{h_w}\right]^{-1} + \left[\frac{\sigma(T_p^2 + T_a^2)(T_p + T_a)}{\frac{1}{\varepsilon_p + 0.0425M(1-\varepsilon_p)} + \frac{2M+f-1}{\varepsilon_g} - M}\right]$$

where,

Convective heat transfer coefficient at the top cover(h_w)

$h_w = 8.55 + 2.56V_\infty$

$h_w = 8.55 + 2.56 \times 1.5$, here $V_\infty =$Average wind speed

$h_w = 12.39W/m^2K$

Friction factor(f)

$f = \left(\frac{9}{h_w} - \frac{30}{h_w^2}\right)\left(\frac{T_a}{316.9}\right)(1 + 0.091M)$

$f = \left(\frac{9}{12.39} - \frac{30}{12.39^2}\right)\left(\frac{30}{316.9}\right)(1 + 0.091 \times 1)$, here $M =$number of glass cover

$f = 0.0548$

Concentration ratio(C)

$C = 204.429(cos\beta)^{0.252}/L^{0.24}$

where,

$\beta =$collector tilt

$\beta = 0.9 \times latitude$

$\beta = 0.9 \times 21.77$

$\beta = 19.59^{\circ}$

$L =$Length of concentrator $= 2.75m$

$C = \frac{204.429 \times (cos19.59^{\circ})^{0.252}}{2.75^{0.24}}$

$C = 148.55$

$$U_t = \left[\frac{1}{\left(\frac{148.55}{75+273}\right)\left(\frac{75-30}{1+0.0584}\right)^{0.252}} + \frac{1}{12.39}\right]^{-1} + \left[\frac{5.67 \times 10^{-8}(348^2 + 303^2)(348 + 303)}{\frac{1}{0.9+0.0425\times1\times(1-0.9)} + \frac{2\times1+0.0548-1}{0.9} - 1}\right]$$

$$U_t = 1.0096 + \frac{7.85}{1.27}$$

$$U_t = 7.190W/m^2K$$

Bottom loss coefficient(U_b)

$$U_b = \frac{k_i}{\delta_b}$$

where,

k_i= thermal conductivity of insulation

δ_b=thickness of insulation

$$U_b = \frac{0.035}{0.025}$$

$$U_b = 1.4 W/m^2K$$

Side loss coefficient(U_s)

$$U_s = \frac{(L_1+L_2)L_3 \times k_i}{L_1 L_2 \delta_s}$$

$$U_s = \frac{(2.75 + 1.28) \times 0.05 \times 0.035}{2.75 \times 1.28 \times 0.025}$$

$$U_s = 0.08014 W/m^2K$$

Overall loss coefficient(U_l)

$$U_l = U_t + U_b + U_s$$

$$U_l = 7.190 + 1.4 + 0.08014$$

$$U_l = 8.67 W/m^2K$$

,

Equivalent diameter(d_e)

$$d_e = 4 \times \frac{1.28 \times 0.05}{2\,(1.28 + 0.05)}$$

$$d_e = 0.0962m$$

therefore, $\frac{L_1}{d_e} = \frac{2.75}{0.0962} = 28.57$

Air flowrate$(\dot{m})$

$\dot{m}$ =Average air velocity×3600×density×C.S. area

$$\dot{m} = 3 \times 3600 \times 1.077 \times 1.28 \times 0.05$$

$$\dot{m} = 744.42 kg/hr$$

Reynold's number(R_e)

$$R_e = \frac{\rho V d_e}{\mu}$$

$$R_e = \frac{1.077 \times 3 \times 0.0962}{19.85 \times 10^{-6}}$$

$$R_e = 15658.54$$

Hence, flow is turbulent and fully developed.

$N_u = 0.0158 \times R_e^{0.8}$

$N_u = 0.0158 \times 15658.54^{0.8}$

$N_u = 35.84$

Therefore,

$h_{fp} = h_{fc} = 35.84 \times \frac{k}{l}$

$h_{fp} = h_{fc} = 35.84 \times \frac{0.0287}{0.0962}$

$h_{fp} = h_{fc} = 10.69 W/m^2K$

where,

h_{fp} =Heat transfer coefficient between absorber plate and air stream.

h_{fc} =Heat transfer coefficient between cover plate and air stream.

Radiative heat transfer coefficient(h_r)

$$h_r = \frac{\sigma}{\left(\frac{1}{\varepsilon_p} + \frac{1}{\varepsilon_c} - 1\right)} \times \frac{(T_p^4 - T_g^4)}{(T_p - T_g)}$$

$$h_r = \frac{5.67 \times 10^{-8}}{\left(\frac{1}{0.9} + \frac{1}{0.9} - 1\right)} \times \frac{\left[(75 + 273)^4 - (65 + 273)^4\right]}{(75 - 65)}$$

$$h_r = 7.50 W/m^2K$$

Effective heat transfer coefficient between absorber plate and air stream(h_e)

$$h_e = \left[h_{fp} + \frac{h_r \cdot h_{fc}}{h_r + h_{fc}}\right]$$

$$h_e = \left[10.69 + \tfrac{7.50 \times 10.69}{7.50 + 10.69}\right]$$

$$h_e = 15.09 W/m^2K$$

Collector efficiency factor(F')

$$F' = \left(1 + \frac{U_l}{h_e}\right)^{-1}$$

$$F' = \left(1 + \frac{8.67}{15.09}\right)^{-1}$$

$$F' = 0.6351$$

Collector heat removal factor(F_R)

$$F_R = \tfrac{\dot{m}C_p}{U_l \cdot A_p}\left[1 - exp\left\{-\tfrac{F'U_lA_p}{\dot{m}C_p}\right\}\right]$$

$$F_R = \tfrac{744.42}{3600} \times \tfrac{1.005 \times 1000}{8.67 \times 2.75 \times 1.28}\left[1 - e^{-\frac{F'U_lA_p}{\dot{m}C_p}}\right]$$

$$F_R = 7.26 \times \left(1 - e^{-\frac{0.6351}{7.26}}\right)$$

$$F_R = 0.6018$$

Useful heat gain rate(q_u)

$$q_u = F_R A_p \left[S - U_l(T_{fi} - T_a)\right]$$

$$q_u = 0.6018 \times 1.28 \times 2.75 \times [1143.55 \times 0.8967 - 8.67(36 - 30)]$$

$$q_u = 2061.99W$$

where,

$S = I_T \times (\tau \cdot \alpha)_e$

$(\tau \cdot \alpha)_e$ =effective transmittance absorptance product

$(\tau \cdot \alpha)_e = \frac{\tau \cdot \alpha}{1-(1-\alpha)\rho_d}$

$(\tau \cdot \alpha)_e = \frac{0.92 \times 0.97}{1-(1-\alpha)\rho_d}$

$(\tau \cdot \alpha)_e = 0.8967$

Instantaneous efficiency of collector(η_{ic})

$$\eta_{ic} = \frac{q_u}{I_T \times A_p}$$

$$\eta_{ic} = \frac{2061.99}{1143.55 \times 2.75 \times 1.28} \times 100$$

$$\eta_{ic} = 51.2\%$$

Amount of moisture to be removed(M_w)

$$M_w = \frac{M_p\left(M_i - M_f\right)}{100 - M_f}$$

$$M_w = \frac{12(80-10)}{100-10}$$

$$M_w = 9.33kg$$

Drying rate(D)

$$D = \frac{M_w}{t_d}$$

$$D = 9.33/7$$

$$D = 1.33kg/hr$$

Drying efficiency(η_d)

$$\eta_d = \frac{10^{-3} \times D \times h_{fg}}{A_c \times I_T} \times 100$$

$$\eta_d = \frac{10^{-3} \times 1.33 \times 2257 \times 100}{3.52 \times 4.11}$$

$$\eta_d = 20.74\%$$

Quantity of heat required to evaporate the moisture(Q)

$$Q = \frac{M_w h_{fg} \eta_d}{\eta_{ic}}$$

$$Q = \frac{9.33 \times 2257 \times 0.2074}{0.512}$$

$$Q = 8530.05kJ$$

Mass flowrate of air required for drying(M_a)

$$M_a = \frac{\eta_c \times A_p \times I_T}{10^{-6} \times (T_{CO} - T_{amb}) C_p \times 100}$$

$$M_a = \frac{0.512 \times 3.52 \times 28.81}{10^{-6} \times (70 - 30) \times 1000}$$

$$M_a = 1298.06kg/hr$$

Volumetric air flowrate inside collector(V_a)

$$V_a = M_a/\rho_i$$

$$V_a = 1298.06/1.029$$

where,

ρ_i =Density of air at 70ºC

$$V_a = 1261.47m^3/hr$$

Area of vent(A_v)

$$A_v = \frac{V_a}{3600 \times \rho_0 \times w_s}$$

$$A_v = \frac{1261.47}{3600 \times 1.165 \times 1.5}$$

$$A_v = 0.2005m^2$$

Chapter 4

RESULTS AND DISCUSSION

4.1 No load performance of dryer

Performance of dryer without any load was performed to find maximum temperature. No load performance of the dryer was done using open loop and a closed loop. These experimental runs were majorly performed to know about the food materials which could be dried at an achieved temperature. Accordingly food materials(Aamla, Methi, Grapes, Potato chips, Garlic, Onion, Ginger) were selected based on their moisture content.

4.1.1 Open loop

In an open loop air was forced through the collector 1 to collector 2. From collector 2 it entered into drying chamber which has the vents for the exit of heated air. Hence, air once entered the system was not recirculated back into the system. Such system is known as an open loop drying system.

The maximum temperature achieved with an open loop system was measured to be 67.5ºC which was sufficient enough to dry the selected food material. All the detailed results for an open loop system are given in Appendix A(Table A.1. to A.7.)

4.1.2 Closed loop

Air once entered in a drying system from collector 1 was recirculated back to it from the drying chamber. Such a system in which there is no heat loss from the air and is recirculated within the system is known as a closed loop drying system.

With closed loop system, the maximum temperature achieved was measured to be 76ºC which was higher than open loop system. The main drawback of this system was an remove of moisture from the system. Hence, for the further experiments of drying of the food materials, open loop system was preffered over closed loop system. All the detailed results for a closed loop system are given in Appendix A(Table A.8. to A.14.)

4.2 No load performance index(NLPI)

No load performance index describes the performance characteristic of a given dryer. It is defined as "the ratio of heat capacity rate of working fluid,$\dot{m}C_p$ to remove energy from the absorber surface of solar dryer system to convective heat transfer coefficient h_{cpf}". Precisely, it is a measure of effectiveness of a solar dryer to transfer heat. Higher values of NLPI are always desirable.

The sample calculation of one particular set of experimental run for the NLPI is shown below. The detailed results for all the calulated experimental runs is summarised in Appendix B.(Table B.1-Table B.6)

Rayleigh number(R_a)

$$R_a = \frac{g \cdot \beta}{\nu \cdot \alpha} (T_s - T_a) \, x^3$$

where,

$g =$Acceleration due to gravity$= 9.8 m/s$

$\beta =$Thermal expansion coefficient$= 3 \times 10^{-3}/K$

$\nu =$Kinematic viscosity$= 18.90 \times 10^{-6} m^2/s$

$\alpha =$Thermal diffusivity$= \dfrac{k}{\rho C_p}$

$k =$thermal conductivity of air$= 0.0285 w/mK$

$\rho =$Density of air$= 1.067 kg/m^3$

$C_p =$Specific heat of air$= 1.009 kJ/kgK$

$x =$characteristic length of dryer

$T_s =$Surface temperature of plate

$T_a =$Air temperature far from surface

$T_f =$Collector outlet temperature

$T_p \& T_g =$Average plate and glass temperature respectively

$T_{fi} \& T_{fo} =$Inlet and outlet temperature of air respectively

$\sigma =$Stefan–Boltzmann's constant$= 5.67 \times 10^{-8} W/m^2K^4$

This calculation is for closed loop condition dated 4^{th}december, 2012 at 12:00PM. At that time $T_s = 112.2^oC$, $T_a = 107^oC$,$T_g = 78^oC$,$T_p = 112.2^oC$

$$R_a = \frac{9.8 \times 3 \times 10^{-3} \times 1.067 \times 1.009}{18.90 \times 10^{-6} \times 0.0285} \times (112.2 - 107) \times 3^3$$

$$R_a = 8250179$$

Radiative heat transfer coefficient between absorber plate & glass cover(h_{rpg})

$$h_{rpg} = \frac{\sigma\left[(T_p+273)^2+(T_g+273)^2\right]\left[(T_p+273)+(T_g+273)\right]}{\left[\frac{1}{\varepsilon_p}+\frac{1}{\varepsilon_g}-1\right]}$$

$$h_{rpg} = \frac{5.67\times10^{-8}\times\left[(112.2+273)^2+(78+273)^2\right]\left[(112.2+273)+(78+273)\right]}{\frac{1}{0.9}+\frac{1}{0.9}-1}$$

$$h_{rpg} = 9.2921 W/m^2K$$

Bottom heat transfer coefficient(U_b)

$$U_b = \frac{k_b}{L_b}$$

where,

k_b =thermal conductivity of insulation= $0.035W/mK$

L_b =thickness of insulation= $0.025m$

$$U_b = \frac{0.035}{0.025} = 1.4W/m^2K$$

Radiative heat transfer coefficient between glass cover and ambient air(h_{rga})

$$h_{rga} = \frac{\sigma\cdot\varepsilon_g\left[(T_g+273)^4-(T_{am}+273)^4\right]}{T_g-T_{am}}$$

$$h_{rga} = \frac{5.67\times10^{-8}\times0.9\times\left[(78+273)^4-(29.9+273)^4\right]}{78-29.9}$$

$$h_{rga} = 7.17W/m^2K$$

Convective heat transfer coefficient between glass cover and ambient air(h_{cga})

$$Nu = h_{cga}\cdot\frac{K}{L} = 0.54(R_a)^{0.25}$$

$$h_{cga} = 0.54 \times (R_a)^{0.25} \times \frac{k}{L}$$

$$h_{cga} = 0.54 \times (8250179)^{0.25} \times \frac{0.0285}{3}$$

$$h_{cga} = 0.274W/m^2K$$

Total heat loss coefficient(U_t)

$$U_t = h_{rga} + h_{cga}$$

$$U_t = 7.17 + 0.274$$

$$U_t = 7.44W/m^2K$$

No load performance index$(NLPI)$

$$\frac{\dot{m}C_p}{Ah_{cpf}} = NLPI = \frac{T_p - T_f}{T_{fo} - T_{fi}}\left[\frac{S - U_b\left(T_p - T_{am}\right) - U_t\left(T_g - T_{am}\right)}{S - U_b\left(T_p - T_{am}\right) - h_{rpg}\left(T_p - T_g\right)}\right]$$

$$NLPI = \frac{(112.2 - 62.5)}{(71.4 - 37.6)}\left[\frac{1336.73 - 1.4\,(112.2 - 29.9) - 7.44\,(78 - 29.9)}{1336.73 - 1.4\,(112.2 - 29.9) - 9.29\,(112.2 - 78)}\right]$$

$$NLPI = 1.4046$$

The NLPI may range from zero to large value depending on the relative values of heat capacity rate through dryer, collector area and heat transfer coefficient. For a large value of $\dot{m}C_p$, the thermal resistance between moving hot air and absorber plate becomes very small, resulting in significant overall larger NLPI values. On the other hand, very low heat capacity rate ($\dot{m}C_p$ tends to zero, near stagnation conditions) enables the maximum air temperature attained, at which point, the heat transfer will come to halt and NLPI would be nearly zero. In these extreme situations, the quality of dried food product in terms of colour, nutrients, etc., would deteriorate resulting in poor acceptability by consumers. Thus, NLPI and hot air temperature are the critical parameters for a dryer to operate satisfactorily with a reasonably shorter drying period.[12]

In the various experimental runs for open and closed loop, NLPI was estimated. For the open loop system, the minimun value of NLPI estimated was 0.4068 and the maximum value was 1.9915. Whereas for the closed loop the minimum value of NLPI estimated was 1.2784 and maximum value was 5.0826.

4.3 Performance of dryer with various food materials

Dryer was loaded with various food materials and its performance was compared with an open atmospheric drying of the same food material. The deviations in the results of both was the effect of experimental condition. Drying in an open atmospheric condition took almost more than the double period than that of the indirect solar dryer. The detailed results for different food materials are discussed below.

4.3.1 Drying of aamla

Aamla is a fruit which is used as a major constituent in several ayurvedic preparation. It is one of the richest source of Vitamin C and is potent antioxident. The moisture content of aamla is about 70-80%. Aamla was equally cut into pieces and placed in a drying chamber of an open loop system above the wire mess stand beneth which and hot air was circulated.

822gms of aamla were placed in each drying chamber and in an open atmospheric condition. Indirect solar dryer took 20hrs to get the product in form of dried aamla weighing 159.84gms. Whereas, in an open atmospheric condition same aamla took 35hrs to get same quality of product which weighted 156 gms. The colour difference can be easily distinguished from the image as shown below in Fig. 4.1. A detailed result which included collector efficiency, drying efficiency, drying rate etc. are given in Table 4.1.[24]

Figure 4.1: Drying of aamla(a) pieces of aamla before drying(b)dried aamla in solar dryer(c)dried aamla in open drying

The collector efficiency, drying efficiency and drying rate were calculated for aamla and results are tabulated in Table 4.1.

Results for the drying of aamla : Experiments were performed on $7^{th} Jan, 2013$, Time: 11:00AM

For oven

Initial weight of sample in oven= $3.39gms$

Final weight of sample in oven= $0.55gms$

Moisture removed in oven=(Initial weight of sample in oven-Final weight of sample in oven) / Initial weight of sample in oven

$$\text{Moisture removed in oven}= \frac{3.39-0.55}{3.39} \times 100 = 83.77\%$$

For solar dryer

Initial weight of sample in dryer at$(t = 0) = 3.49gms$

Weight of sample in dryer at$(t = t_1) = 3.19gms$

Moisture removed in dryer=Initial weight of sample in dryer at$(t = 0)-$Weight of sample in dryer at$(t = t_1)$ / Initial weight of sample in dryer at$(t = 0)$

$$\text{Moisture removed in dryer(for an hour)}= \frac{3.49-3.19}{3.49} \times 100 = 8.595\%$$

Dry weight=Initial weight of sample in dryer at$(t = 0)$-[Initial weight of sample in dryer at$(t = 0)\times$Moisture removed in oven]

$$\text{Dry weight}= 3.49 - (3.49 \times 0.8377) = 0.5662gms$$

Intensity on inclined collector$(I_c) = 1569.89W/m^2$

Temperature at dryer outlet$(T_{do}) = 39.1^{\circ}C$

Temperature at collector inlet$(T_{in}) = 21.6^{\circ}C$

Temperature at collector outlet$(T_{co}) = 53.4^{\circ}C$

Area of dryer$(A_d) = 0.9954m^2$

Area of vent$(A_v) = 0.0512m^2$

Average velocity in collector$(V_{avg}) = 1m/s$

$$\text{Mean temperature}= \frac{T_{co}+T_{in}}{2} = \frac{53.4+21.6}{2}$$

$$\text{Mean temperature}= 37.5^{\circ}C$$

The values of prandtl number, kinemativ viscosity, conductivity of air, density of air, specific heat of air at mean temperature were estimated as below.[25]

Prandtl number$(P_r) = 2.48 \times 10^{-5} \times (T_{mean})^2 - (1.3 \times 0.001 \times T_{mean}) + 0.732$

$P_r = 2.48 \times 10^{-5} \times (37.5)^2 - (1.3 \times 0.001 \times 37.5) + 0.732$

$P_r = 0.718125$

Kinematic viscosity$(\nu) = (8.1 \times 10^{-8} \times T_{mean}) + (1.35 \times 10^{-5})$

$\nu = (8.1 \times 10^{-8} \times 37.5) + (1.35 \times 10^{-5})$

$\nu = 1.65375 \times 10^{-5} m^2/s$

Conductivity of air$(k) = (0.0001 \times T_{mean}) + 0.0245$

$k = (0.0001 \times 37.5) + 0.0245$

$k = 0.02825 W/mK$

Density of air$(\rho) = \dfrac{353}{T_{mean} + 273}$

$\rho = \dfrac{353}{37.5 + 273}$

$\rho = 1.136876 kg/m^3$

Specific heat of air$C_p = \dfrac{P_r \times k_{air}}{\rho \times \nu}$

$C_p = \dfrac{0.718125 \times 0.02825}{1.136876 \times 1.65375 \times 10^{-5}}$

$C_p = 1079.035 J/kgK$

$$\text{Mass flowrate} = \rho \times A_v \times V_{avg.}$$

$$\text{Mass flowrate} = 1.136 \times 0.0512 \times 1 = 0.058208 kg/s$$

$$\text{Collector efficiency}(\eta_{collecor}) = \frac{C_p \times \dot{m} \times (T_{co} - T_{in}) \times 100}{A_c \times I_c}$$

$$\eta_{collector} = \frac{1079.035 \times 0.058208 \times (53.4 - 21.6)}{3.55 \times 1569.892} \times 100$$

$$\eta_{collector} = 35.83\%$$

Drying rate=moisture removed in dryer / Area of dryer×time

$$\text{Drying rate}= \frac{0.08595}{0.9954 \times 3600} = 2.396 \times 10^{-8} kg/s$$

Drying efficiency(η_{drying}) =(moisture removed in dryer×h_{fg} × 1000) / ($A_c \times I_c$)

$$\eta_{drying} = \frac{8.595 \times 2257 \times 1000}{1000 \times 3.55 \times 1569.89}$$

$$\eta_{drying} = 3.58\%$$

Table 4.1: Results for the drying of aamla

time	Ic-inclined (W/m^2)	Mean temp. (T_{co}&T_{in})	Mass flow rate (kg/s)	$\eta_{coll.}$	Weight (gms)	Moisture removed (%)	Drying rate(kg/s)	η_{drying}
11:00[1]	1569.89	37.5	0.0582	35.83	3.49	8.84	2.46709E-06	3.58
12:00	1763.44	40.1	0.0577	35.07	3.19	11.50	3.20722E-06	4.14
13:00	1892.47	42.225	0.0573	35.46	2.8	10.02	2.79604E-06	3.36
14:00	1451.61	41.15	0.0575	38.08	2.46	6.48	1.8092E-06	2.84
15:00	1225.80	39.425	0.0578	40.01	2.24	3.53	9.86837E-07	1.83
16:00	817.20	32.75	0.0591	41.06	2.12	2.65	7.40128E-07	2.06
17:00	301.07	24.175	0.0608	32.50	2.03	10.32	2.87827E-06	21.80
10:00[2]	1225.80	29.95	0.0596	28.04	1.68	3.53	9.86837E-07	1.83
11:00	1483.87	34.975	0.0586	33.97	1.56	3.24	9.046E-07	1.39
12:00	1731.18	39.725	0.0577	36.49	1.45	1.76	4.93418E-07	0.64
13:00	1763.44	41.525	0.0574	39.21	1.39	3.24	9.046E-07	1.16
14:00	1559.13	41.475	0.0574	41.74	1.28	2.06	5.75655E-07	0.84
15:00	1322.58	39.3	0.0578	41.16	1.21	1.47	4.11182E-07	0.70
16:00	849.46	33.075	0.0590	38.97	1.16	2.06	5.75655E-07	1.54
17:00	387.09	25.675	0.0605	27.99	1.09	2.35	6.57891E-07	3.87
10:00[3]	1118.27	32.05	0.0592	35.75	1.01	0.88	2.46709E-07	0.50
11:00	1397.84	38	0.0581	37.45	0.98	1.17	3.28946E-07	0.53
12:00	1623.65	42.5	0.0572	39.80	0.94	1.47	4.11182E-07	0.57
13:00	1634.40	45.35	0.0567	43.74	0.89	0.88	2.46709E-07	0.34
14:00	1483.87	45.075	0.0568	45.74	0.86	0.29	8.22364E-08	0.12
15:00	1354.83	42.8	0.0571	42.22	0.85	-	-	-
16:00	913.97	38.425	0.0580	46.33	0.85	-	-	-
17:00	365.59	30.575	0.0595	46.97	0.85	-	-	-

Note:[1] for day 1(7/1/2013), [2] for day 2(8/1/2013), [3] for day 3(9/1/2013)

For more details refer to Appendix C(Table C.1-Table C.4)

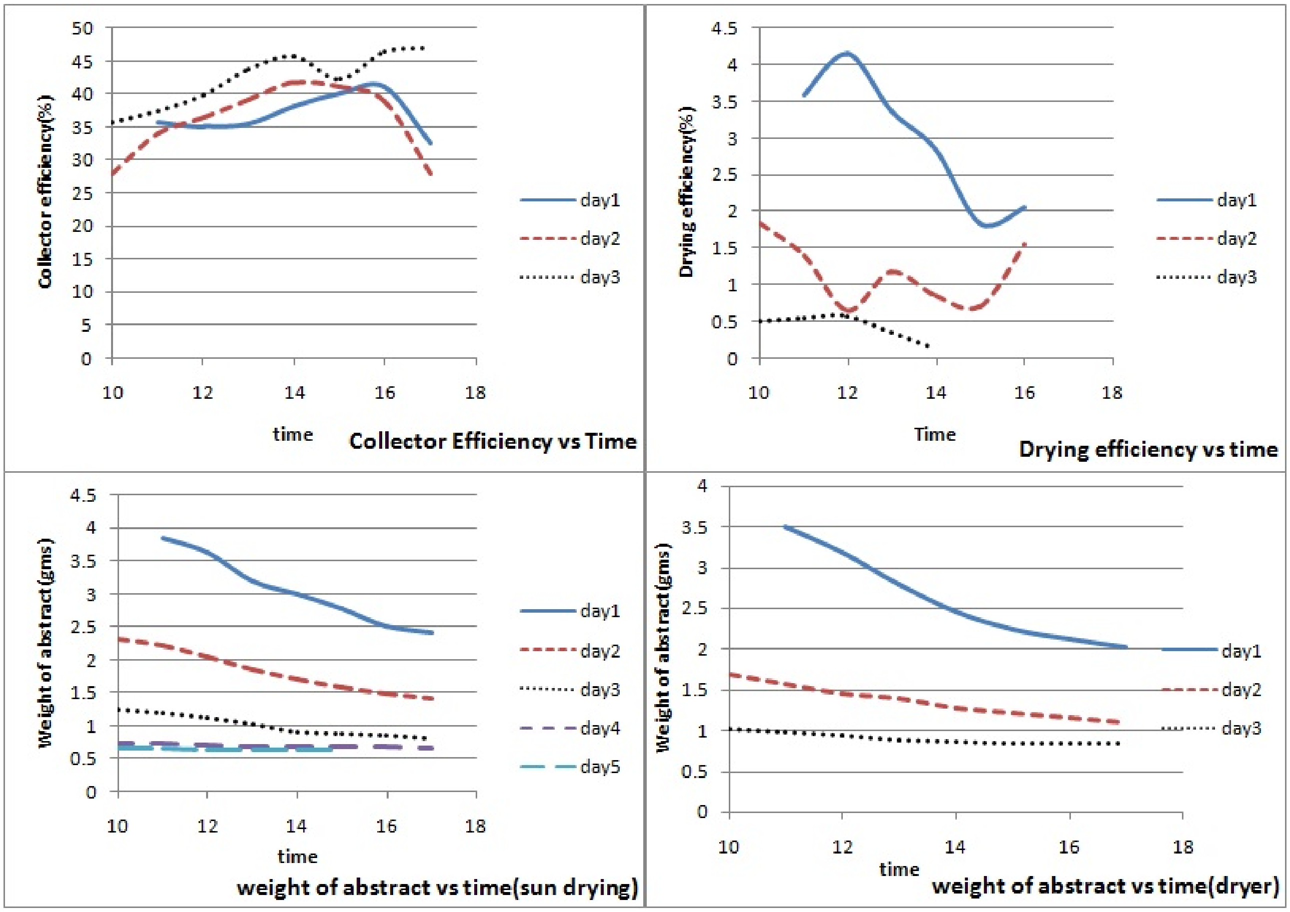

Figure 4.2: Differents graphs for drying of aamla(a)Collector efficiency vs time(b)Drying efficiency vs time(c)Moisture w.b. vs time(open sun drying)(d)Moisture w.b. vs time(solar dryer)

Fig. 4.2(a) shows the change in collector efficiency with time for three different days on which experiment was carried out. The collector efficiency is found to be maximum at about 2PM to 3PM for all the three experiments. After 4PM collector efficiency significantly decrease due to lower solar insolation. Fig. 4.2(b) indicates the drying efficiency at different time for aamla food material. However there is no strong relation between drying efficiency and time. It is observe from the graph that drying efficiency is higher on first day and than decresed day by day. Fig. 4.2(c) and (d) indicates the weight of food materials in gram at different time intervals on a given day. Fig. 4.2(c) is a weight of a food material during sun drying whereas 4.2(d) indicates same the food material dried in the dryer. For sun drying the food material was kept open under the sun. The initial weight was measured and subsequent weight were taken at different time interval on given day. The same food material was again kept open under sun on day 2 and weight were taken as discussed earlier. This procedure was repeated for five days. From Fig. 4.2(c) it can be seen that there is progressive loss of weight from day 1 to day 5 due to removal of moisture.

Fig. 4.2(d) indicates the weight of the object at different time intervals for three consecutive days. The weights were taken at different time on different days as discussed in preceding paragraph. It is observe that the removal of the moisture in solar dryer is much faster as compare to the same in open drying. The total moisture removal in three days in solar dryer is equivalent to same in five days in open drying.

4.3.2 Drying of methi

The second food material selected was Fenugreek(methi) which is a legume, originally from southeastern Europe and western Asia, but grown now mainly in India. Fenugreek seeds are traditionally used for the treatment of many diseases. The seeds of fenugreek have an antioxidant properties.The moisture content in methi is almost about 70%.[26]

884gms of methi were placed in each drying chamber and in an open atmospheric condition. Indirect solar dryer took 7hrs to get the product in form of dried methi weighing 115.70gms (with sticks) and 50.96gms (without stick). Whereas, in an open atmospheric condition same methi took 14hrs to get same quality of product which weighted 119.83 gms (with sticks) and 52.51gms (without sticks). The colour difference can be easily distinguished from the image as shown below in Fig. 4.3. A detailed result which included collector efficiency, drying efficiency, drying rate etc. are shown in Table 4.2.

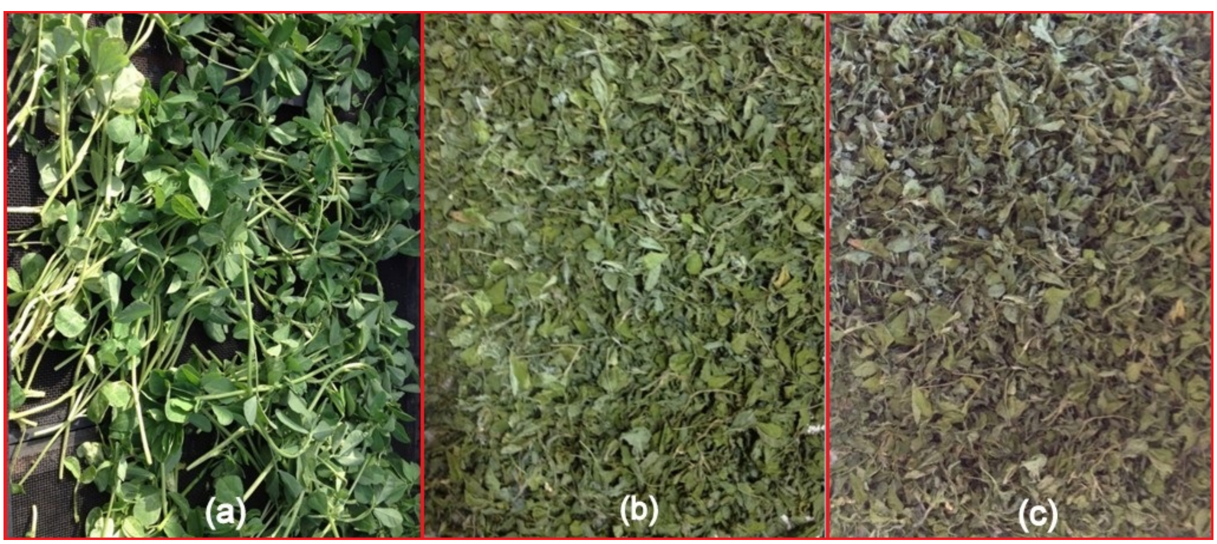

Figure 4.3: Drying of methi(a) Methi before drying(b)Dried methi in solar dryer(c)Dried methi in open drying

The calculation were done in the similar fashion as shown in section 4.3.1. The initial weight of sample in the oven was weighted to be 2.36gms and the final weight of sample in the oven was found to be 0.22gms. The moisture removed in oven was estimated to be 90.67%.

Table 4.2: Results for drying of methi (5/2/2013)

Time	Ic-inclined (W/m^2)	Mean temp. (T_{co}&T_{in})	Mass flow rate (kg/s)	$\eta_{coll.}$	Weight (gms)	Moisture removed (%)	Drying rate(kg/s)	η_{drying}
10:00	827.95	35.325	0.0586	36.70	2.24	23.21	6.47171E-06	17.82
11:00	1440.86	40	0.0577	31.64	1.72	30.35	8.46301E-06	13.39
12:00	1623.6	48.025	0.0562	39.976	1.04	30.80	8.58746E-06	12.06
13:00	1924.73	53.825	0.0553	40.43	0.35	4.91	1.36902E-06	1.62
14:00	1989.24	51.8	0.0556	32.18	0.24	0.89	2.48912E-07	0.28
15:00	1419.35	49.325	0.0560	41.764	0.22	1.78	4.97824E-07	0.79
16:00	1139.78	36.275	0.0584	22.75	0.18	-	-	-
17:00	494.62	33.7	0.0589	45.91	0.18	-	-	-

For more details refer to Appendix C(Table C.5-Table C.6)

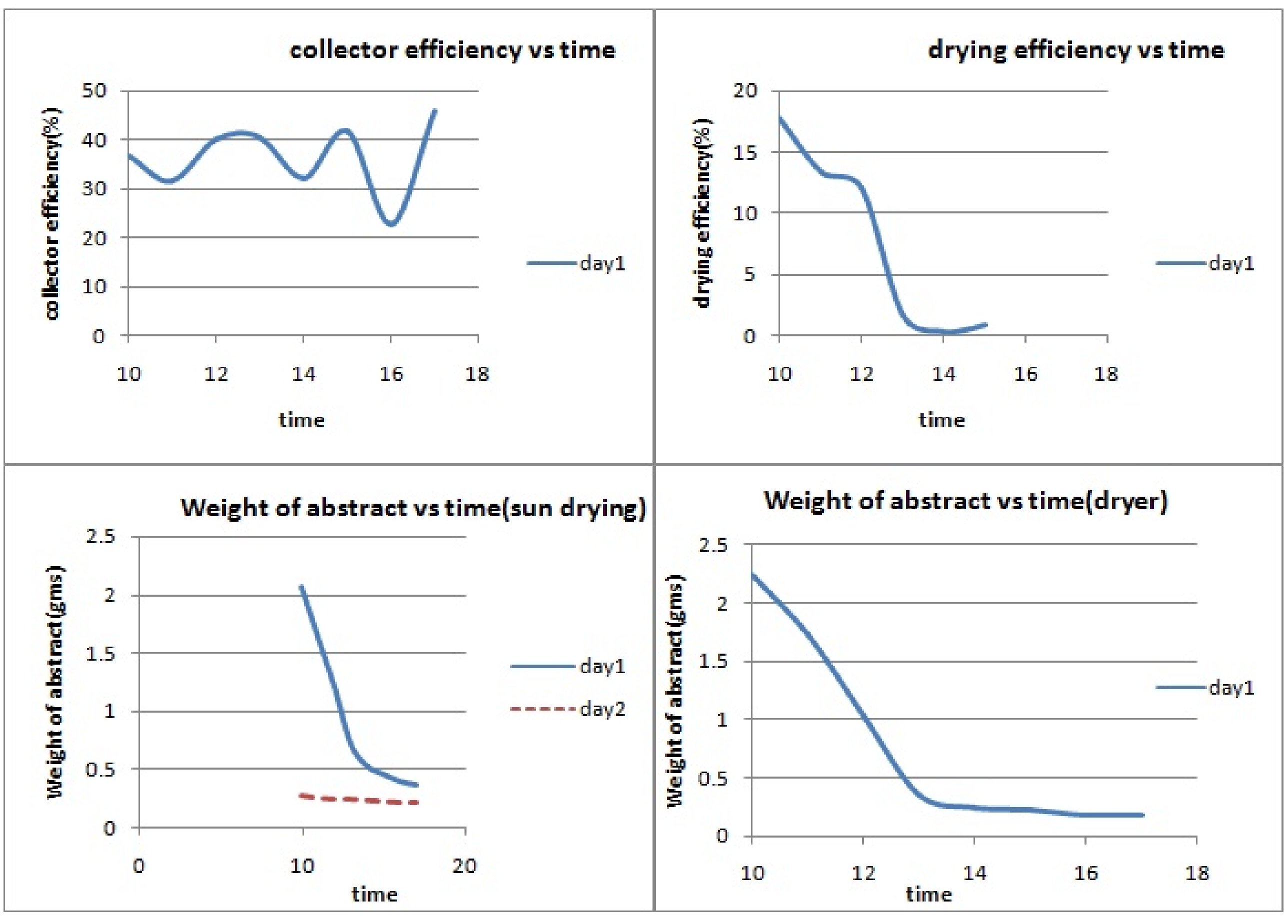

Figure 4.4: Different graphs for drying of methi(a)Collector efficiency vs time(b)Drying efficiency vs time(c)Moisture w.b. vs time(open sun drying)(d)Moisture w.b. vs time(solar dryer)

Fig. 4.4(a) shows the change in collector efficiency with time for the day on which experiment was carried out. The collector efficiency is found to be maximum at about 2PM to 3PM for the experiment. After 3PM collector efficiency significantly decrease due to lower solar insolation. Fig. 4.4(b) indicates the drying efficiency at different time for methi food material. It is observe from the graph that drying efficiency is high at 10AM and decresing continuously. Fig. 4.4(c) and (d) indicates the weight of food materials in gram at different time intervals on a given day. Fig. 4.4(c) is a weight of a food material during sun drying whereas 4.4(d) indicates same the food material dried in the dryer. For sun drying the food material was kept open under the sun. The initial weight was measured and subsequent weight were taken at different time interval on given day. The same food material was again kept open under sun on day 2 and weight were taken as discussed earlier. From Fig. 4.4(c) it can be seen that there is progressive loss of weight from day 1 to day 2 due to removal of moisture.

Fig. 4.4(d) indicates the weight of the object at different time intervals for the day. The weights were taken at different time as discussed in preceding paragraph. It is observe that the removal of the moisture in solar dryer is much faster as compare to the same in open drying. The total moisture removal in a day in solar dryer is equivalent to same in two days in open drying.

4.3.3 Drying of garlic

Garlic (Allium sativum L.) has been cultivated for centuries all over the world on account of its culinary and medicinal properties. Clinical trials have shown that garlic has important health benefits. The most encouraging results have occurred in the area of cholesterol reduction. The compound responsible for these benefits is allicin, which gives garlic's characteristic flavour and odour. More recently, it has found uses as a raw material in the pharmaceutical industry and, in its dried form, as an ingredient of precooked and instant convenience foods, which has led to a sharp increase in the demand for dried garlic.The content of moisture in the garlic is almost 80% and its desire level of moisture for dried garlic is 4%.[27]

770gms of garlic were placed in each drying chamber and in an open atmospheric condition. Indirect solar dryer took 21hrs to get the product in form of dried garlic weighing 312gms. Whereas, in an open atmospheric condition same garlic took 40hrs to get same quality of product which weighted 307gms. The colour difference can be easily distinguished from the image as shown below in Fig. 4.5. A detailed result which included collector efficiency, drying efficiency, drying rate etc. are shown in Table 4.3.

The calculation were done in the similar fashion as shown in section 4.3.1. The initial weight of sample in the oven was weighted to be 1.3gms and the final weight of sample in the oven was found to be 0.6gms. The moisture removed in oven was estimated to be 53.8462%.

Figure 4.5: Drying of garlic(a) Garlic before drying(b)Dried garlic in solar dryer(c)Dried garlic in open drying

Table 4.3: Results for drying of garlic

time	Ic-inclined (W/m^2)	Mean temp. (T_{co}&T_{in})	Mass flow rate (kg/s)	$\eta_{coll.}$	Weight (gms)	Moisture removed (%)	Drying rate (kg/s)	η_{drying}
10:00[1]	1365.59	37.1	0.0582	29.80	1.27	0.78	2.19513E-07	0.36
11:00	1559.13	43.95	0.0570	39.97	1.26	0.78	2.19513E-07	0.32
12:00	1903.22	50.45	0.0558	39.28	1.25	2.36	6.58539E-07	0.78
13:00	1946.23	51.3	0.0557	38.16	1.22	2.36	6.58539E-07	0.77
14:00	1817.20	52.9	0.0554	42.26	1.19	3.93	1.09756E-06	1.37
15:00	1494.62	49.75	0.0559	38.66	1.14	1.57	4.39026E-07	0.66
16:00	1000	43.25	0.0571	38.66	1.12	6.29	1.7561E-06	4.00
10:00[2]	1225.80	38.85	0.0579	33.02	1.04	3.14	8.78052E-07	1.63
11:00	1473.11	44.775	0.0568	35.77	1	3.14	8.78052E-07	1.35
12:00	1892.47	51.475	0.0557	34.80	0.96	7.87	2.19513E-06	2.64
13:00	1967.74	53.65	0.0553	36.085	0.86	7.08	1.97562E-06	2.28
14:00	1763.44	55.725	0.0549	40.37	0.77	6.29	1.7561E-06	2.27
15:00	1569.89	53.625	0.0553	40.32	0.69	2.36	6.58539E-07	0.95
16:00	1053.76	47.15	0.0564	40.05	0.66	1.57	4.39026E-07	0.95
10:00[3]	1333.33	38	0.0581	34.22	0.64	0.78	2.19513E-07	0.37
11:00	1741.93	42.575	0.0572	32.89	0.63	0.78	2.19513E-07	0.28
12:00	2075.26	48.825	0.0561	34.68	0.62	0.78	2.19513E-07	0.24
13:00	2129.03	51.45	0.0557	36.46	0.61	1.57	4.39026E-07	0.47
14:00	2096.77	51.825	0.0556	37.58	0.59	-	-	-
15:00	1731.18	50.175	0.0555	42.11	0.59	-	-	-
16:00	1268.81	45.8	0.0566	44.80	0.59	-	-	-

Note:[1] for day 1(25/2/2013), [2] for day 2(26/2/2013), [3] for day 3(27/2/2013)

For more details refer to Appendix C(Table C.7-Table C.10)

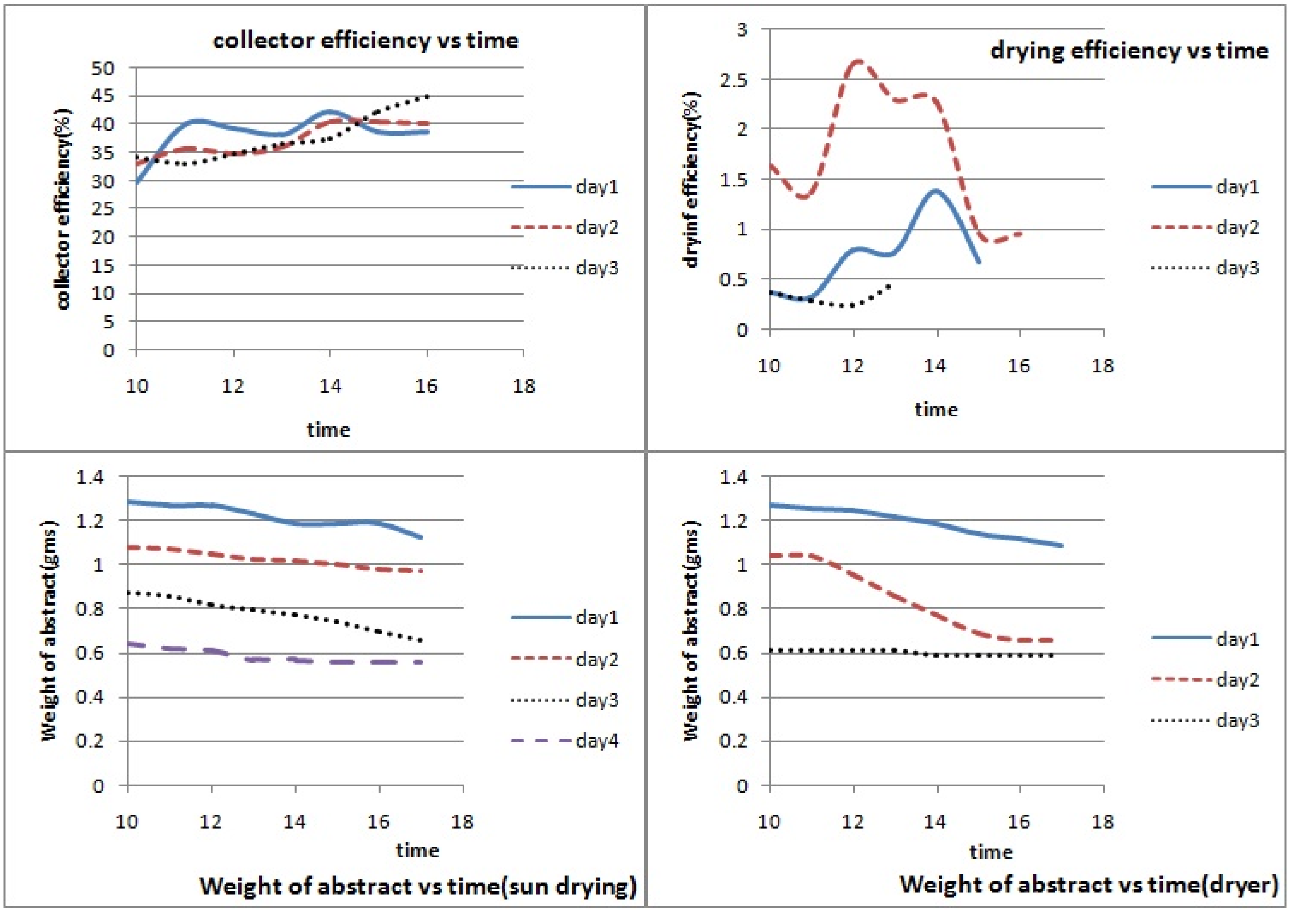

Figure 4.6: Different graphs for drying of garlic(a)Collector efficiency vs time(b)Drying efficiency vs time(c)Moisture w.b. vs time(open sun drying)(d)Moisture w.b. vs time(solar dryer)

Fig. 4.6(a) shows the change in collector efficiency with time for three different days on which experiment was carried out. The collector efficiency is found to be maximum at about 2PM to 3PM for all the three experiments. After 4PM collector efficiency significantly decrease due to lower solar insolation. Fig. 4.6(b) indicates the drying efficiency at different time for garlic food material. It is observe from the graph that drying efficiency is high during peak hours for all the three days. Drying efficiency was decreasing continuously day by day. Fig. 4.6(c) and (d) indicates the weight of food materials in gram at different time intervals on a given day. Fig. 4.6(c) is a weight of a food material during sun drying whereas 4.6(d) indicates same the food material dried in the dryer. For sun drying the food material was kept open under the sun. The initial weight was measured and subsequent weight were taken at different time interval on given day. The same food material was again kept open under sun on day 2 and weight were taken as discussed earlier. This procedure was repeated for four days. From Fig. 4.6(c) it can be seen that there is progressive loss of weight from day 1 to day 4 due to removal of moisture.

Fig. 4.6(d) indicates the weight of the object at different time intervals for three consecutive days. The weights were taken at different time on different days as discussed in preceding paragraph. It is observe that the removal of the moisture in solar dryer is much faster as compare to the same in open drying. The total moisture removal in three days in solar dryer is equivalent to same in four days in open drying.

4.3.4 Drying of ginger

Ginger is the rhizome of Zingiber officinale Roscoe (Zingiberaceae). Although ginger is technically a rhizome rather than a root (which means it is a tuber that grows horizontally under the ground), its name comes from the Sanskrit word for "horned root." Ancient Greek, Roman, Indian, Persian, and Chinese cultures had a fondness for its culinary and medicinal properties. They have used it to add flavor, tenderize meat, stimulate the appetite, and to calm the stomach. Recently, clinical trials showed that ginger rhizome could relieve appetite loss, motion sickness, and prevent vomiting, and even to boost the pumping action of heart.In the drying of ginger, the water is evaporated from the freshly harvested ginger rhizome to moisture content close to that of its storage environment.The moisture content in the garlic is about 65%.[28]

794gms of ginger were placed in each drying chamber and in an open atmospheric condition. Indirect solar dryer took 9hrs to get the product in form of dried ginger weighing 125.84gms. Whereas, in an open atmospheric condition same ginger took 17hrs to get same quality of product which weighted 124.55gms. The colour difference can be easily distinguished from the image as shown below in Fig. 4.7. A detailed result which included collector efficiency, drying efficiency, drying rate etc. are shown in Table 4.4.

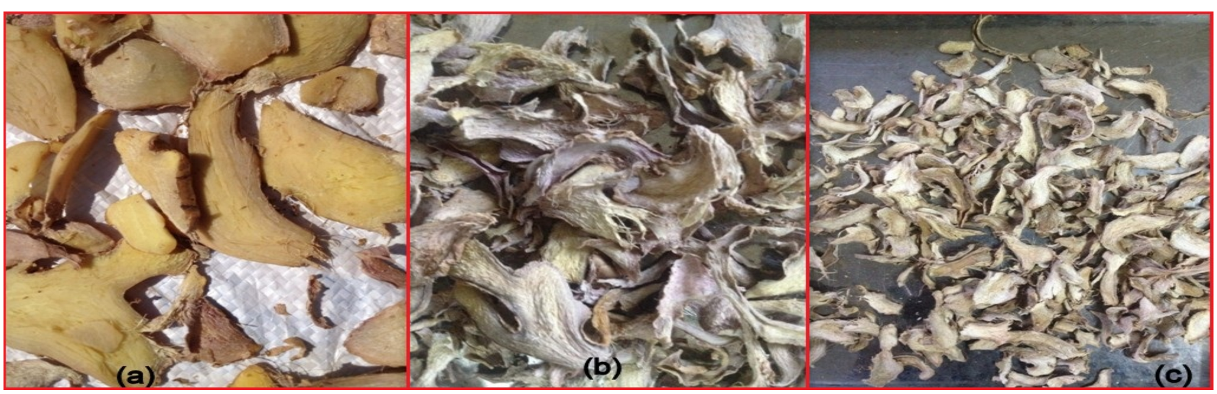

Figure 4.7: Drying of ginger(a) Ginger before drying(b)Dried ginger in solar dryer(c)Dried ginger in open drying

The calculation were done in the similar fashion as shown in section 4.3.1. The initial weight of sample in the oven was weighted to be 6.7gms and the final weight of sample in the oven was found to be 0.98gms. The moisture removed in oven was estimated to be 85.3731%.

Table 4.4: Results for drying of ginger

time	Ic-inclined (W/m^2)	Mean temp. $(T_{co}\&T_{in})$	Mass flow rate (kg/s)	$\eta_{coll.}$	Weight (gms)	Moisture removed (%)	Drying rate (kg/s)	η_{drying}
12:00[1]	1870.96	43.975	0.0570	33.64	6.79	36.67	1.02234E-05	12.46
13:00	2032.25	45.375	0.0567	33.05	4.3	21.64	6.03547E-06	6.77
14:00	1967.74	48.2	0.0562	36.62	2.83	13.84	3.85942E-06	4.47
15:00	1752.68	47.2	0.0564	37.6	1.89	5.74	1.60125E-06	2.08
16:00	1268.8	42.95	0.0572	39.94	1.5	1.91	5.33749E-07	0.95
17:00	602.15	35.575	0.0585	42.5	1.37	0.44	1.23173E-07	0.46
10:00[2]	1215.05	33.525	0.0589	26.5	1.34	0.88	2.46346E-07	0.46
11:00	1473.11	41.975	0.0573	36.02	1.28	0.14	4.10576E-08	0.06
12:00	1849.46	44.125	0.0569	31.8	1.27	0	0	0
13:00	1924.73	49.85	0.0559	38.65	1.27	-	-	-
14:00	1817.20	52.4	0.0555	42.25	1.27	-	-	-

Note:[1] for day 1(18/2/2013), [2] for day 2(19/2/2013)

For more details refer to Appendix C(Table C.11-Table C.13)

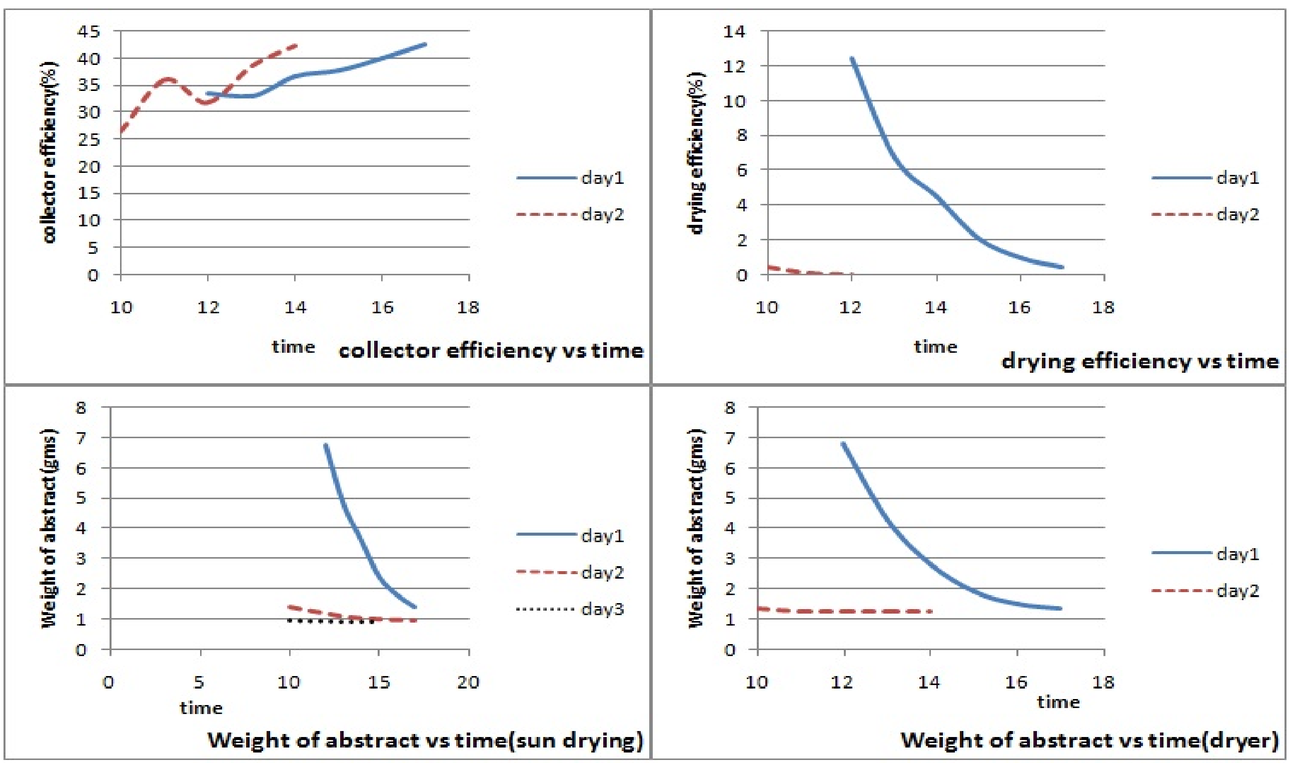

Figure 4.8: Different graphs for drying of ginger(a)Collector efficiency vs time(b)Drying efficiency vs time(c)Moisture w.b. vs time(open sun drying)(d)Moisture w.b. vs time(solar dryer)

Fig. 4.8(a) shows the change in collector efficiency with time for two different days on which experiment was carried out. The collector efficiency is found to be maximum at about 3PM to 4PM for both experiments. Collector efficiency was almost constant after 2PM. Fig. 4.8(b) indicates the drying efficiency at different time for ginger food material. It is observe from the graph that drying efficiency is decresing constantly after 12PM. It seems from graph that the drying efficiency is higher at the starting of the day. Fig. 4.8(c) and (d) indicates the weight of food materials in gram at different time intervals on a given day. Fig. 4.8(c) is a weight of a food material during sun drying whereas 4.8(d) indicates same the food material dried in the dryer. For sun drying the food material was kept open under the sun. The initial weight was measured and subsequent weight were taken at different time interval on given day. The same food material was again kept open under sun on day 2 and weight were taken as discussed earlier. This procedure was repeated for three days. From Fig. 4.8(c) it can be seen that there is progressive loss of weight from day 1 to day 3 due to removal of moisture.

Fig. 4.8(d) indicates the weight of the object at different time intervals for two consecutive days. The weights were taken at different time on different days as discussed in preceding paragraph. It is observe that the removal of the moisture in solar dryer is much faster as compare to the same in open drying. The total moisture removal in two days in solar dryer is equivalent to same in three days in open drying.

4.3.5 Drying of onion

Onion, Allium cepa L., is considered as one of the most important crops in all countries. Onion ranks third highest in production in the world among seven major vegetables, namely onion, garlic, cauliflower, green peas, cabbage, tomato and green beans. The four major onion producing countries in the world are China with largest production of 3.93 million tones, followed by India with 3.35 million tones, USA 2.45 million tones and Turkey 1.55 million tones. In India, deterioration of considerable quantities of onion takes place during storage operation. Various preservative methods have been employed to minimize this loss. The most primitive method employed in preserving onion deterioration is that onion flakes are spread on the ground such as wheat, raisins, fig or apricot, exposed to the sun in order to be dried. This method is commonly known as open sun drying. The dried crop can be stored for a considerable period without the fear of its deterioration.The onion contains around 83% moisture.[29]

871gms of onion slices were placed in each drying chamber and in an open atmospheric condition. Indirect solar dryer took 13hrs to get the product in form of dried onion slices weighing 152.39gms. Whereas, in an open atmospheric condition same onion slices took 33hrs to get same quality of product which weighted 149.56gms. The colour difference can be easily distinguished from the image as shown below in Fig. 4.9. A detailed result which included collector efficiency, drying efficiency, drying rate etc. are shown in Table 4.5.

Figure 4.9: Drying of onion(a) Onion before drying(b)Dried onion in solar dryer(c)Dried onion in open drying

The calculation were done in the similar fashion as shown in section 4.3.1. The initial weight of sample in the oven was weighted to be 9.83gms and the final weight of sample in the oven was found to be 1.78gms. The moisture removed in oven was estimated to be 81.8922%.

Table 4.5: Results for drying of onion

time	Ic-inclined (W/m^2)	Mean temp. (T_{co}&T_{in})	Mass flow rate (kg/s)	$\eta_{coll.}$	Weight (gms)	Moisture removed (%)	Drying rate (kg/s)	η_{drying}
11:00[1]	1279.56	42.825	0.0572	40.77	10.6	26.79	7.46924E-06	13.31
12:00	1731.18	47.175	0.0564	35.95	7.76	21.98	6.12793E-06	8.07
13:00	1978.49	52.15	0.0555	36.57	5.43	14.90	4.15542E-06	4.78
14:00	1688.17	54.575	0.0551	44.55	3.85	10.84	3.02452E-06	4.08
15:00	1516.12	53.6	0.0553	45.08	2.7	3.30	9.20505E-07	1.38
16:00	1064.51	49.675	0.0560	47.55	2.35	1.69	4.73402E-07	1.01
17:00	505.37	40.95	0.0575	45.79	2.17	0.56	1.57801E-07	0.7
10:00[2]	1010.75	38.175	0.0580	41.03	2.11	0.37	1.05201E-07	0.23
11:00	1440.86	45.425	0.056	39.14	2.07	0.09	2.63001E-08	0.04
12:00	1580.64	50.375	0.0558	41.43	2.06	0.37	1.05201E-07	0.12
13:00	1913.97	53.425	0.0553	39.72	2.02	1.88	5.26003E-07	0.62
14:00	1978.49	53.325	0.0553	36.82	1.82	0.18	5.26003E-08	0.06
15:00	1774.19	53.675	0.0553	39.37	1.8	-	-	-
16:00	1225.80	49.325	0.0560	44.03	1.8	-	-	-

Note:[1] for day 1(21/2/2013), [2] for day 2(22/2/2013)

For more details refer to Appendix C(Table C.14-Table C.16)

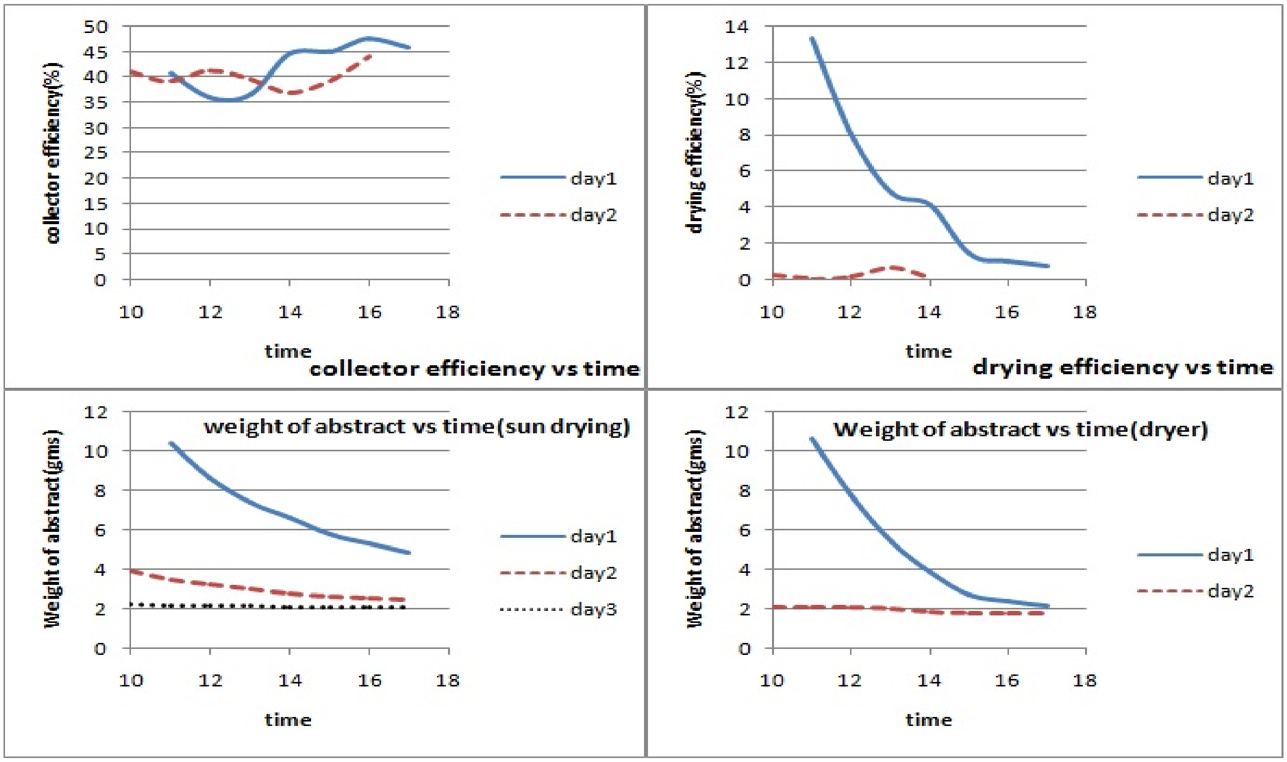

Figure 4.10: Different graphs for drying of onion(a)Collector efficiency vs time(b)Drying efficiency vs time(c)Moisture w.b. vs time(open sun drying)(d)Moisture w.b. vs time(solar dryer)

Fig. 4.10(a) shows the change in collector efficiency with time for two different days on which experiment was carried out. The collector efficiency is found to be maximum at about 2PM to 4PM for both experiments. After 4PM collector efficiency significantly decrease due to lower solar insolation. Fig. 4.10(b) indicates the drying efficiency at different time for onion food material. It is observe from the graph that drying efficiency is very high at 11AM on day1 and after that it continuously decresing. Fig. 4.10(c) and (d) indicates the weight of food materials in gram at different time intervals on a given day. Fig. 4.10(c) is a weight of a food material during sun drying whereas 4.10(d) indicates same the food material dried in the dryer. For sun drying the food material was kept open under the sun. The initial weight was measured and subsequent weight were taken at different time interval on given day. The same food material was again kept open under sun on day 2 and weight were taken as discussed earlier. This procedure was repeated for three days. From Fig. 4.10(c) it can be seen that there is progressive loss of weight from day 1 to day 3 due to removal of moisture.

Fig. 4.10(d) indicates the weight of the object at different time intervals for two consecutive days. The weights were taken at different time on different days as discussed in preceding paragraph. It is observe that the removal of the moisture in solar dryer is much faster as compare to the same in open drying. The total moisture removal in two days in solar dryer is equivalent to same in three days in open drying.

4.3.6 Drying of potato chips

Potatoes are the fourth most important vegetable crop for human nutrition in the world and approximately 12% are dehydrated products. Potatoes are often dried by sun-light. However, there are many problems in sun drying such as the slowness of the process, the exposure to environmental contamination. Hence, an efforts were made to dry the potatoes using indirect solar dryer utilising solar energy efficiently to enhence the drying of potato. Moisture content in the potato is around 80%.[30]

Fresh potatoes weighing 930gms were sliced equally with the thickness of 2-3mm. They were placed in a drying chamber on a wiremess stand beneath which the concentrated hot air passes. Same quantity of sliced fresh potatoes were placed in an open atmospheric condition for drying it naturally. Indirect solar dryer took 6hrs to get the product in form of dried potato slices weighing 169.06gms. Whereas, in an open atmospheric condition same potato slices took 16hrs to get same quality of product which weighted 119.83gms. The colour difference can be easily distinguished from the image as shown below in Fig. 4.11. A detailed result which included collector efficiency, drying efficiency, drying rate etc. are shown in Table 4.6.

Figure 4.11: Drying of potato chips(a) Potato chips before drying(b)Dried potato chips in solar dryer(c)Dried potato chips in open drying

The calculation were done in the similar fashion as shown in section 4.3.1. The initial weight of sample in the oven was weighted to be 7.85gms and the final weight of sample in the oven was found to be 1.51gms. The moisture removed in oven was estimated to be 80.7643%.

Table 4.6: Results for drying of potato chips(12/2/2013)

time	Ic-inclined (W/m^2)	Mean temp. (T_{co}&T_{in})	Mass flow rate (kg/s)	$\eta_{coll.}$	Weight (gms)	Moisture removed (%)	Drying rate (kg/s)	η_{drying}
11:30	1634.40	44.75	0.0568	30.57	8.09	51.54	1.43698E-05	20.05
12:30	1688.17	50.325	0.0558	36.59	3.92	22.00	6.13388E-06	8.28
13:30	1806.45	53.475	0.0553	39.2	2.14	3.83	1.06826E-06	1.34
14:30	1666.66	54.65	0.0551	44.54	1.83	1.85	5.169E-07	0.70
15:30	1225.80	47.5	0.0563	38.32	1.68	0.37	1.0338E-07	0.19
16:30	741.93	41.8	0.0574	38.56	1.65	0	0	0
17:30	387.09	36.275	0.0584	35.90	1.65	-	-	-

For more details refer Appendix C(Table C.17-Table C.18)

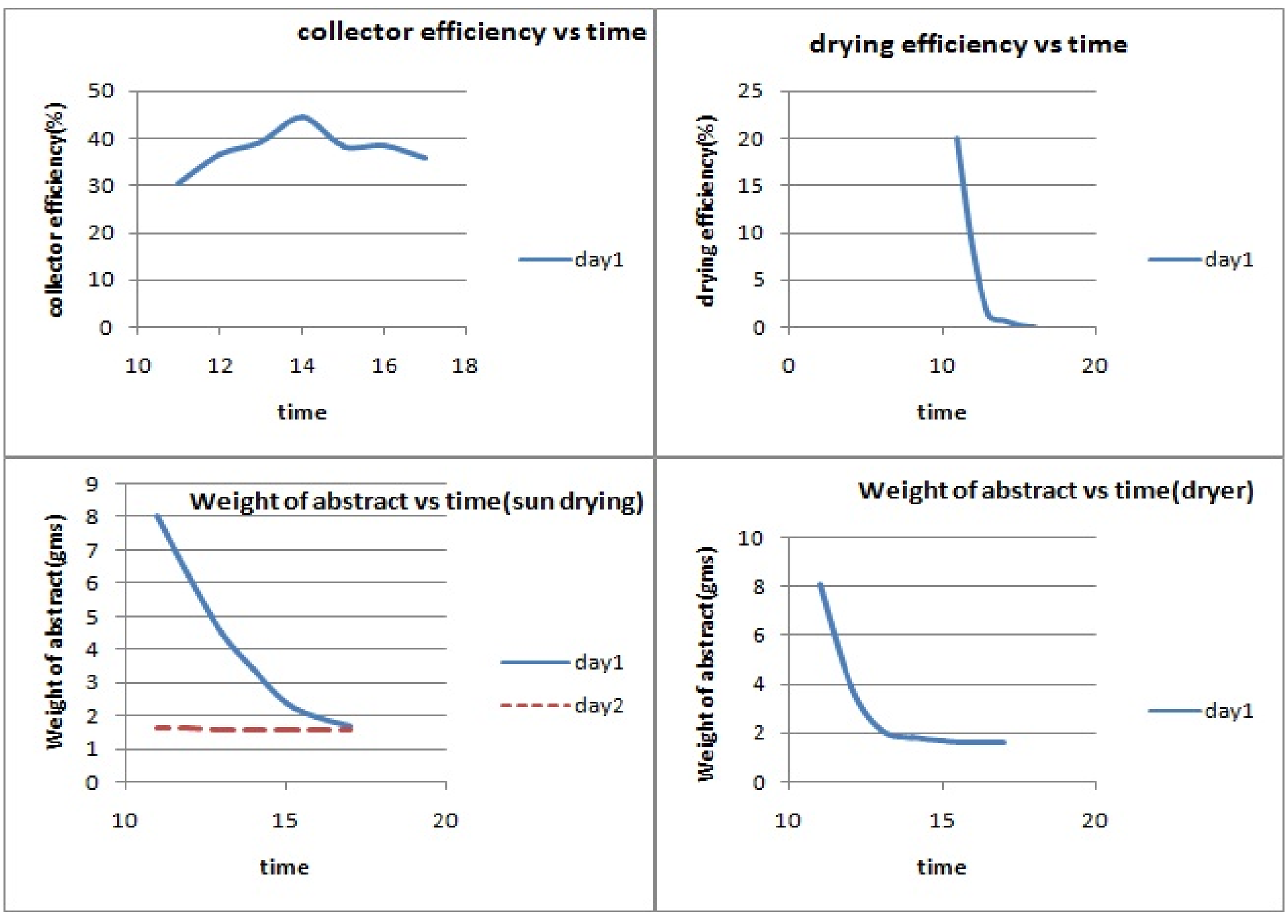

Figure 4.12: Different graphs for drying of potato chips(a)Collector efficiency vs time(b)Drying efficiency vs time(c)Moisture w.b. vs time(open sun drying)(d)Moisture w.b. vs time(solar dryer)

Fig. 4.12(a) shows the change in collector efficiency with time for a day on which experiment was carried out. The collector efficiency is found to be maximum at about 1PM to 2PM for an experiments. After 2PM collector efficiency significantly decrease due to lower solar insolation. Fig. 4.12(b) indicates the drying efficiency at different time for potato chips food material. It is observe from the graph that drying efficiency is high at the starting of experiment at 11PM and than it decresing continuously. Fig. 4.12(c) and (d) indicates the weight of food materials in gram at different time intervals on a given day. Fig. 4.12(c) is a weight of a food material during sun drying whereas 4.12(d) indicates same the food material dried in the dryer. For sun drying the food material was kept open under the sun. The initial weight was measured and subsequent weight were taken at different time interval on given day. The same food material was again kept open under sun on day 2 and weight were taken as discussed earlier. From Fig. 4.12(c) it can be seen that there is progressive loss of weight from day 1 to day 2 due to removal of moisture.

Fig. 4.12(d) indicates the weight of the object at different time intervals for a day on which experiment was carried out. The weights were taken at different time through the day as discussed in preceding paragraph. It is observe that the removal of the moisture in solar dryer is much faster as compare to the same in open drying. The total moisture removal in a day in solar dryer is equivalent to same in two days in open drying.

4.3.7 Drying of grapes

In practice, dried grapes are commonly known as raisins and make up a large quantity of the dried fruits produced today. All over the world the annual average production of raisins is about 500 000 tons. In the production, the most imponant raisin is Sultana grape. Turkey is one of the main raisin producing countries. Harvesting time is an important factor in selecting a grape cultivar because the primary production of raisins is by sun drying.[31]

2400gms of grapes were placed in each drying chamber and in an open atmospheric condition. Indirect solar dryer took 20hrs to get the product in form of dried grapes weighing 645gms. Whereas, in an open atmospheric condition same grapes took 40hrs to get same quality of product which weighted 638gms. The colour difference can be easily distinguished from the image as shown below in Fig. 4.13. A detailed result which included collector efficiency, drying efficiency, drying rate etc. are shown in Table 4.7.

The calculation were done in the similar fashion as shown in section 4.3.1. The initial weight of sample in the oven was weighted to be 3.18gms and the final weight of sample in the oven was found to be 0.85gms. The moisture removed in oven was estimated to be 73.2707%.

Figure 4.13: Drying of grapes(a) Grapes before drying(b)Dried grapes in solar dryer(c)Dried grapes in open drying

Table 4.7: Results for drying of grapes

time	Ic-inclined (W/m^2)	Mean temp. (T_{co}&T_{in})	Mass flow rate (kg/s)	$\eta_{coll.}$	Weight (gms)	Moisture removed (%)	Drying rate (kg/s)	η_{drying}
11:00	1655.91	47.85	0.0563	30.82	3.28	0.60	1.69989E-07	0.23
12:00	1913.97	51.45	0.0557	31.32	3.26	2.43	6.79955E-07	0.81
13:00	2000	54.45	0.0551	35.16	3.18	0.91	2.54983E-07	0.29
14:00	1935.48	53.65	0.0553	33.57	3.15	3.35	9.34938E-07	1.10
15:00	1709.67	53.45	0.0553	34.69	3.04	1.82	5.09966E-07	0.68
16:00	1118.27	48.5	0.0562	37.59	2.98	1.21	3.39977E-07	0.69
17:00	634.40	43	0.0571	40.63	2.94	4.57	1.27491E-06	4.58
10:00	1387.09	45	0.0568	34.11	2.79	0.30	8.49943E-08	0.13
11:00	1795.69	50.05	0.0559	32.77	2.78	2.74	7.64949E-07	0.97
12:00	1989.24	55.1	0.0550	34.57	2.69	3.35	9.34938E-07	1.07
13:00	2043.01	56.5	0.0548	35.96	2.58	5.18	1.4449E-06	1.61
14:00	1806.45	55.25	0.0550	35.62	2.41	3.35	9.34938E-07	1.18
15:00	1720.43	52.65	0.0555	32.40	2.3	2.13	5.9496E-07	0.78
16:00	1311.82	50.15	0.0559	35.97	2.23	2.43	6.79955E-07	1.18
17:00	688.17	45.6	0.0567	47.20	2.15	4.57	1.27491E-06	4.22
10:00	1451.61	41.75	0.0574	33.21	2	1.52	4.24972E-07	0.66
11:00	1935.48	50.3	0.0559	30.1	1.95	3.65	1.01993E-06	1.20
12:00	2043.01	55.4	0.0550	34.71	1.83	8.84	2.46484E-06	2.75
13:00	2139.78	57.45	0.0546	34.61	1.54	10.36	2.88981E-06	3.07
14:00	1978.49	56.85	0.0547	35.79	1.2	5.79	1.61489E-06	1.86
15:00	1688.17	54.5	0.0551	35.68	1.01	-	-	-
16:00	1161.29	52.15	0.0555	44.02	0.92	-	-	-
17:00	698.92	46.3	0.0566	55.07	0.92	-	-	-

Note:[1] for day 1(18/3/2013), [2] for day 2(19/3/2013), [3] for day 3(20/3/2013)
For more details refer to Appendix C(Table C.19-Table C.22)

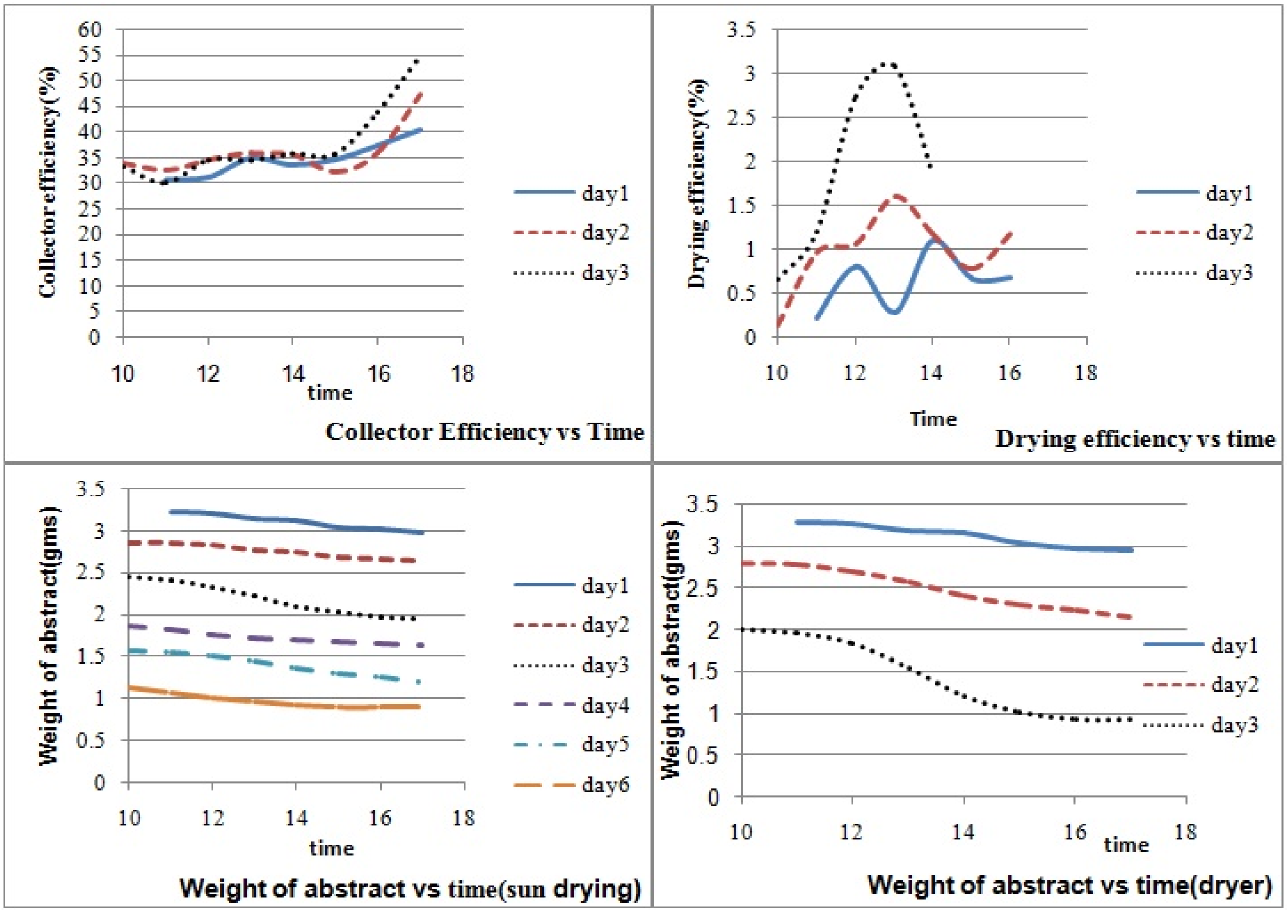

Figure 4.14: Different graphs for drying of grapes(a)Collector efficiency vs time(b)Drying efficiency vs time(c)Moisture w.b. vs time(open sun drying)(d)Moisture w.b. vs time(solar dryer)

Fig. 4.14(a) shows the change in collector efficiency with time for three different days on which experiment was carried out. The collector efficiency is found to be maximum at about 3PM to 4PM for all the three experiments. After 4PM collector efficiency significantly decrease due to lower solar insolation. Fig. 4.14(b) indicates the drying efficiency at different time for grapes food material. It is observe from the graph that drying efficiency is higher during pick hours for all the three days. Fig. 4.14(c) and (d) indicates the weight of food materials in gram at different time intervals on a given day. Fig. 4.14(c) is a weight of a food material during sun drying whereas 4.14(d) indicates same the food material dried in the dryer. For sun drying the food material was kept open under the sun. The initial weight was measured and subsequent weight were taken at different time interval on given day. The same food material was again kept open under sun on day 2 and weight were taken as discussed earlier. This procedure was repeated for five days. From Fig. 4.14(c) it can be seen that there is progressive loss of weight from day 1 to day 5 due to removal of moisture.

Fig. 4.14(d) indicates the weight of the object at different time intervals for three consecutive days. The weights were taken at different time on different days as discussed in preceding paragraph. It is observe that the removal of the moisture in solar dryer is much faster as compare to the same in open drying. The total moisture removal in three days in solar dryer is equivalent to same in five days in open drying.

Table 4.8: Nutritional analysis of dried grapes(100gms)

Constituents	Indirect solar dryer	Open sun drying
Moisture(%)	4.15	0
Energy(Kcal)	372	380
Total fat	0	0
Total carbohydrate(gms)	90	91
Sugar(gms)	42	40
Protein(gms)	3	4
Vitamin A	0IU	0IU
Vitamin C(mg/100gms)	2.34	2.56
Iron(mg/100gms)	1.85	1.95
Calcium(mg/100gms)	56	56

The results for the nutritional analysis of dried grapes shows a negligible difference. Hence, it can be observed that in an indirect solar dryer there isn't greater loss of essential nutrient. Indirect solar dryer can perform drying in less than half the duration taken by an open atmospheric drying.

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Chapter 5

CONCLUSIONS

Use of solar radiation for drying is one of the oldest applications of solar energy. Initially a complete experimental set was designed including solar collector with V-trough reflectors and drying chamber. The construction was made in such a way that it enhanced the outlet of drying. Once the setup was ready, no load performances were carried in an open and closed loop. With an open loop, sufficient temperature was achieved. In a closed loop, the upper limit of temperature achieved was higher than that of open loop but the disadvantage of it was the removal of the moisture which could lower down efficiency of drying. Hence, open loop construction was preferred for drying purpose.

No load performance index were estimated which is a measure of effectiveness of a solar dryer to transfer heat. It should usually be more than zero. NLPI were estimated and the values for all the experimental were greater than zero in both cases i.e. open loop and closed loop. Further experiments of drying with an open loop for different food materials were performed.

Based on the maximum temperature achieved, moisture content and the maximum usage, different food materials were chosen. Aamla, methi, garlic, ginger, onion, potato chips and grapes were selected as a food materials. All the food materials were efficiently dried with less than half the duration taken by an open atmospheric drying. Collector efficiency, drying efficiency and drying rate were measured at an equal interval of time during drying of it. Collector efficiency, drying efficiency and drying rate showed a comparative results and also showed an enhancement in terms of drying duration.

Finally nutritional analysis for the grapes after drying was performed. It can be concluded that there was a marginal difference in the nutritional contents of both the cases i.e. indirect solar dryer and open atmospheric drying. Moreover, a food material was not over burned. Solar drying which is yet not commercially used widely can be used for small scale indirect solar dryer which has showed comprehensive performance.

FUTURE SCOPE OF WORK

Similar experiments can be performed in a closed loop for the food material having higher moisture content. The main drawback of the closed loop was the removal of heated moisture which could be compensated by using silica gel which would absorb the moisture without affecting temperature. The other problem would be the life period of the silica gel used to absorb the heated moisture. Hence, a future scope would also include a research on the alternative of silica gel for the closed loop indirect solar dryer.

Other food materials having higher moisture content can be dried and nutritionally analyzed. Also, collector with different reflector can be designed for the enhancement of dried product output by efficiently utilizing solar radiations. A detailed energy balance may be carried out for the clear idea of the heat dissipation, heat absorbed and heat accumulated.

APPENDIX A

Data Collection Sheet for No Load Performance

Table A.1 (Open loop condition,10/10/2012)

Time	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00
Horizontal Solar Intensity I(t)	7.2	8.2	9.1	9	8.1	6.6	4.7	2
Solar intensity of collector I(t)	9.2	11.8	13.3	13.1	10.9	9	5.9	2.6
Ambient wind speed Wamb	1	0.8	0.3	0.4	1.2	2.6	1.3	0.8
Temperature at inlet 1	36.1	36.6	38	37.9	39	38.1	37.9	37.3
Temperature at inlet 2	33.1	34.8	36.6	37.1	38.3	38.9	39.4	38.6
Ambient temperature	33	34	36	37	37	37	36	35
Wind speed out 1	3.2	2.8	2.9	3.1	2.7	2.5	2.9	1.9
Wind speed out 2	3.9	3.5	3.7	3.8	3.5	3.4	3.8	2.4
Temperature at collector end	58.8	63.5	67.4	68	65.5	60.4	53.7	45.4
Temperature at dryer end	59.1	62.9	66.6	65.9	63.5	57.3	50.7	43.8
Ambient relative humidity	35	30	34	32	27	25	24	27
Relative humidity at dryer end	25	20	20	less	than	20%		

Table A.2 (Open loop condition,11/10/2012)

Time	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00
Horizontal Solar Intensity I(t)	7.3	8.2	9.3	9	8.4	6.8	4.7	2.1
Solar intensity of collector I(t)	10.4	11.1	13.2	12.4	11.8	9	5.9	2.7
Ambient wind speed Wamb	0.6	0.7	0.2	1.3	1.1	2.3	1.5	2
Temperature at inlet 1	35.6	37.8	36.8	38.8	38.7	38.6	38.1	36.6
Temperature at inlet 2	32	34.1	35.7	37.9	37.1	37.9	38.8	36.7
Ambient temperature	34	34	35	37	36	36	36	35
Wind speed out 1	2.9	2.7	2.9	2.4	2.3	2.5	2.5	1.7
Wind speed out 2	3.8	3.6	3.7	3	2.9	3	3	2.2
Temperature at collector end	57.6	63.3	66.6	65.1	65.9	60.6	53.9	44.7
Temperature at dryer end	59.1	63.9	67.5	65.4	63.3	58.3	50.6	43
Ambient relative humidity	34	31	30	25	27	27	24	25
Relative humidity at dryer end	25	21	less	than	20%			

Table A.3 (Open loop condition,12/10/2012)

Time	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00
Horizontal Solar Intensity I(t)	6.8	8.2	9	8.8	7.5	6.3	3.8	2
Solar intensity of collector I(t)	9.3	11.7	12.6	12.1	10.5	8.4	6	2.6
Ambient wind speed Wamb	1.3	0.2	2.1	0.5	3.2	0.8	0.3	1.2
Temperature at inlet 1	35	36.9	37	38.4	39.6	38.3	38.8	36.7
Temperature at inlet 2	33	33.6	34.7	36.1	37.2	37.4	38.4	35.7
Ambient temperature	32	33	34	35	36	36	36	34
Wind speed out 1	2.6	2.6	2.6	2.5	2.4	2.5	2.1	1.9
Wind speed out 2	3	2.9	3.1	3	2.9	3	2.5	2.2
Temperature at collector end	55.6	60.9	63.9	65.6	64.5	60.3	53.6	46.1
Temperature at dryer end	57.1	58.3	64.2	65.7	62.6	58	50.8	43.8
Ambient relative humidity	46	37	38	34	30	32	30	34
Relative humidity at dryer end	32	24	23	20	less than 20%			

Table A.4 (Open loop condition,15/10/2012)

Time	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00
Horizontal Solar Intensity I(t)	6.7	8	8.5	8.4	7.5	6.5	0.9	1.2
Solar intensity of collector I(t)	9.8	11.8	10.2	13.7	12.4	11	1.4	1.6
Ambient wind speed Wamb	1.1	0.8	0.2	0.4	1	0.6	0.4	1.5
Temperature at inlet 1	36.4	37.8	38.3	39.3	40.2	40.2	38.4	38.4
Temperature at inlet 2	33.7	35.2	37	38.3	39.5	38.6	36.6	36.1
Ambient temperature	34	35	35	34	35	35	34	34
Wind speed out 1	2.6	2.6	2.8	2.7	2.5	2.5	0.3	1
Wind speed out 2	3.3	3.4	3	2.9	2.8	2.9	0.5	1.6
Temperature at collector end	56	64	69.5	69.6	66.7	59.1	43	41.5
Temperature at dryer end	54.4	60.9	65.3	63.2	60.8	56.5	43	39.8
Ambient relative humidity	54	50	50	49	48	48	45	41
Relative humidity at dryer end	50	42	40	35	32	31	28	23

Table A.5 (Open loop condition,16/10/2012)

Time	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00
Horizontal Solar Intensity I(t)	6.4	7.7	8.3	7.9	7.4	5.3	3.8	1.5
Solar intensity of collector I(t)	12	13.3	14.2	12.7	11.8	8.3	6	2.4
Ambient wind speed Wamb	1.4	0.2	1.8	3.2	0.6	0.6	0.4	0.2
Temperature at inlet 1	35.5	37.6	38.1	38.6	40	39.3	38.7	38.2
Temperature at inlet 2	33.9	36	37	37.7	38.4	38.3	37.9	36.9
Ambient temperature	30	34	35	35	35	34	34	34
Wind speed out 1	1.2	2.6	2.3	2.5	2.4	2.2	2.1	0.9
Wind speed out 2	1.7	2.9	2.9	3	2.9	2.9	2.5	1.3
Temperature at collector end	47.5	57.3	59.5	59.9	65.1	58.5	51.5	43.3
Temperature at dryer end	55.5	56.7	60.5	60.7	58.2	53.5	50.4	40.9
Ambient relative humidity	45	39	40	42	42	37	34	35
Relative humidity at dryer end	36	26	23	25	23	21	20	20

Table A.6 (Open loop condition,17/10/2012)

Time	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00
Horizontal Solar Intensity I(t)	6.3	8	8.3	8.2	7.5	6.2	3.8	1.4
Solar intensity of collector I(t)	10.9	15.8	15.2	14	12.5	10	5.7	2
Ambient wind speed Wamb	0.6	1.3	1.2	2.5	2.5	1.3	1.1	0.8
Temperature at inlet 1	37.7	32.9	33.6	36.3	35.5	36	35.8	35
Temperature at inlet 2	35.4	31.7	32.6	34.7	34.6	35.3	34.7	34.4
Ambient temperature	30	32	33	33	33	34	34	33
Wind speed out 1	0.1	2.6	2.7	2.6	2.2	2.1	2	0.8
Wind speed out 2	0.1	3.4	3.1	3	2.9	2.9	2.6	1.1
Temperature at collector end	53.3	56	56.6	56.6	54.2	51.1	46.3	40.3
Temperature at dryer end	53.9	56.7	58.6	59.3	57.7	53.8	47.3	39.8
Ambient relative humidity	59	55	56	51	41	42	42	38
Relative humidity at dryer end	55	49	42	35	24	26	24	20

Table A.7 (Open loop condition,18/10/2012)

Time	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00
Horizontal Solar Intensity I(t)	6.3	8	8.3	8.2	7.5	6.2	3.8	1.4
Solar intensity of collector I(t)	10.9	15.8	15.2	14	12.5	10	5.7	2
Ambient wind speed Wamb	0.6	1.3	1.2	2.5	2.5	1.3	1.1	0.8
Temperature at inlet 1	37.7	32.9	33.6	36.3	35.5	36	35.8	35
Temperature at inlet 2	35.4	31.7	32.6	34.7	34.6	35.3	34.7	34.4
Ambient temperature	30	32	33	33	33	34	34	33
Wind speed out 1	0.1	2.6	2.7	2.6	2.2	2.1	2	0.8
Wind speed out 2	0.1	3.4	3.1	3	2.9	2.9	2.6	1.1
Temperature at collector end	53.3	56	56.6	56.6	54.2	51.1	46.3	40.3
Temperature at dryer end	53.9	56.7	58.6	59.3	57.7	53.8	47.3	39.8
Ambient relative humidity	59	55	56	51	41	42	42	38
Relative humidity at dryer end	55	49	42	35	24	26	24	20

Table A.8 (Closed loop condition,29/10/2012)

Time	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00
Horizontal Solar Intensity I(t)	7	8.2	8.7	7.9	6.8	5	2.5	0.4
Solar intensity of collector I(t)	12.7	13.5	14.1	15.5	11.2	7.1	3.6	0.6
Ambient wind speed Wamb	1	1.6	1.8	1.9	1	0.9	0.5	0.3
Temperature at inlet 1	36.7	39.2	41.2	40.9	40.2	38.2	35.6	32.1
Temperature at inlet 2	38.9	42.3	44.3	45.1	43.9	41.2	38.8	34
Ambient temperature	31	32	35	35	35	35	34	34
Wind speed out 1	1.2	1.4	1.1	1.2	1.2	1.1	0.4	0.2
Wind speed out 2	1.3	1.5	1.3	1.4	1.3	1.2	0.6	0.3
Temperature at collector end	53.5	62.2	62.9	62.5	58.8	50.7	43.6	37.6
Temperature at dryer end	63	higher	than	70C	67.8	56.1	44.3	37.3
Ambient relative humidity	39	38	26	25	24	24	26	26
Relative humidity at dryer end	25	20	Less	than	20%			

Table A.9 (Closed loop condition,30/10/2012)

Time	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00
Horizontal Solar Intensity I(t)	6.7	7.7	8.4	8.5	7.4	5.2	2.4	0.3
Solar intensity of collector I(t)	11.3	14.1	16.3	14.6	12	8.3	5.5	0.5
Ambient wind speed Wamb	1.3	1.6	1.1	1.9	1.4	2.2	1.3	1
Temperature at inlet 1	30.8	35.1	38.7	39.7	38.9	37.5	34.7	31.2
Temperature at inlet 2	34.3	38.5	42.5	44.1	43.6	41.1	37.9	35.3
Ambient temperature	30	31	33	33	34	34	34	33
Wind speed out 1	1.1	1.2	1.3	1.2	1.2	1.2	1.1	0.7
Wind speed out 2	1.4	1.4	1.6	1.5	1.5	1.4	1.3	0.9
Temperature at collector end	53	57	64.8	63.2	56.9	49	40.8	38.6
Temperature at dryer end	58	66	75.8	76	64.2	57.6	44.2	42.1
Ambient relative humidity	46	42	37	32	27	26	25	26
Relative humidity at dryer end	38	26	22	less than 20%				

Table A.10 (Closed loop condition,31/10/2012)

Time	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00
Horizontal Solar Intensity I(t)	6.3	7.4	7.7	7.4	6.8	5.7	4.2	0.6
Solar intensity of collector I(t)	10.6	12.5	14.1	12.6	11.1	7.3	6.6	1
Ambient wind speed Wamb	1.6	1.1	1.3	1.2	1	2.3	0.9	1.3
Temperature at inlet 1	32.1	38.2	40.5	42.5	42.6	40.3	39.9	34.3
Temperature at inlet 2	35.8	39.7	42	43.8	43.9	41.6	40.9	34.6
Ambient temperature	30	31	31	32	33	33	32	31
Wind speed out 1	1.1	1.2	1.1	1.2	1.2	1	0.8	0.1
Wind speed out 2	1.4	1.5	1.4	1.4	1.5	1.2	1	0.1
Temperature at collector end	42	57	59.3	66.2	57.4	47.2	45.9	36.8
Temperature at dryer end	50.3	64.1	66.2	70	65.2	55.1	49.9	39.5
Ambient relative humidity	47	45	42	39	36	34	30	41
Relative humidity at dryer end	36	30	25	20	less than 20%			

Table A.11 (Closed loop condition,2/11/2012)

Time	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00
Horizontal Solar Intensity I(t)	6.4	7.1	8.3	8.3	7.3	6.1	2.9	1.8
Solar intensity of collector I(t)	10.9	13.8	13.8	13.9	12.2	9.4	4.2	2.9
Ambient wind speed Wamb	1.5	1	2.3	1.8	1.6	1.9	1	2.4
Temperature at inlet 1	34.2	36.6	39.3	38.6	38.1	37.7	33.2	31.7
Temperature at inlet 2	36	39.1	41.3	41.8	41	40	35.6	33
Ambient temperature	30	31	31	32	32	32	32	31
Wind speed out 1	1.1	1.2	1.2	1.3	1.3	1.2	0.8	0.2
Wind speed out 2	1.3	1.5	1.4	1.5	1.5	1.4	1	0.3
Temperature at collector end	46.4	50.9	58.2	59.9	53.9	47.9	36.7	35.2
Temperature at dryer end	55.8	62.6	69.1	70.3	64.5	56.7	36.8	36.5
Ambient relative humidity	51	46	44	42	40	40	39	43
Relative humidity at dryer end	42	37	29	25	23	23	22	24

Table A.12 (Closed loop condition,5/11/2012)

Time	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00
Horizontal Solar Intensity I(t)	6.4	7.1	8.3	8.3	7.3	6.1	2.9	1.8
Solar intensity of collector I(t)	10.9	13.8	13.8	13.9	12.2	9.4	4.2	2.9
Ambient wind speed Wamb	1.5	1	2.3	1.8	1.6	1.9	1	2.4
Temperature at inlet 1	34.2	36.6	39.3	38.6	38.1	37.7	33.2	31.7
Temperature at inlet 2	36	39.1	41.3	41.8	41	40	35.6	33
Ambient temperature	30	31	31	32	32	32	32	31
Wind speed out 1	1.1	1.2	1.2	1.3	1.3	1.2	0.8	0.2
Wind speed out 2	1.3	1.5	1.4	1.5	1.5	1.4	1	0.3
Temperature at collector end	46.4	50.9	58.2	59.9	53.9	47.9	36.7	35.2
Temperature at dryer end	55.8	62.6	69.1	70.3	64.5	56.7	36.8	36.5
Ambient relative humidity	51	46	44	42	40	40	39	43
Relative humidity at dryer end	42	37	29	25	23	23	22	24

Table A.13 (Closed loop condition,6/11/2012)

Time	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00
Horizontal Solar Intensity I(t)	5.1	6.2	6.8	6.9	6.4	5	3.2	0.5
Solar intensity of collector I(t)	8.2	11.4	11.7	12.1	10.3	7.6	4.7	0.8
Ambient wind speed Wamb	1.6	1.1	1.9	1.4	0.9	1.1	2.3	1.3
Temperature at inlet 1	29.1	33	34.8	36.6	36.3	35.3	33.7	30.6
Temperature at inlet 2	31.2	35.6	37.3	39.2	39.1	37.7	34.9	31.4
Ambient temperature	27	29	30	31	32	32	31	30
Wind speed out 1	0.9	1.1	1	1.1	1.2	1.1	0.6	0.2
Wind speed out 2	1.1	1.3	1.2	1.4	1.5	1.3	0.8	0.3
Temperature at collector end	40.9	49.9	51.2	54.2	49.6	46.6	40.6	34.9
Temperature at dryer end	45.3	55.8	61.3	63.9	59.9	54.1	41.8	35.3
Ambient relative humidity	41	38	37	38	33	29	27	30
Relative humidity at dryer end	30	28	21	21	less than 20%			

Table A.14 (Closed loop condition,7/11/2012)

Time	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00
Horizontal Solar Intensity I(t)	5.1	6.2	6.8	6.9	6.4	5	3.2	0.5
Solar intensity of collector I(t)	8.2	11.4	11.7	12.1	10.3	7.6	4.7	0.8
Ambient wind speed Wamb	1.6	1.1	1.9	1.4	0.9	1.1	2.3	1.3
Temperature at inlet 1	29.1	33	34.8	36.6	36.3	35.3	33.7	30.6
Temperature at inlet 2	31.2	35.6	37.3	39.2	39.1	37.7	34.9	31.4
Ambient temperature	27	29	30	31	32	32	31	30
Wind speed out 1	0.9	1.1	1	1.1	1.2	1.1	0.6	0.2
Wind speed out 2	1.1	1.3	1.2	1.4	1.5	1.3	0.8	0.3
Temperature at collector end	40.9	49.9	51.2	54.2	49.6	46.6	40.6	34.9
Temperature at dryer end	45.3	55.8	61.3	63.9	59.9	54.1	41.8	35.3
Ambient relative humidity	41	38	37	38	33	29	27	30
Relative humidity at dryer end	30	28	21	21	less than 20%			

APPENDIX B

Calculation of No load performance index

Table B.1 (Open loop condition,5/12/2012)

Time	10:00	11:00	12:00	13:00	14:00	15:00	16:00
I(t) horizontal	5.2	6.6	7.5	7.6	6.3	5	3.2
I(t) inclined	10.8	12.7	13.4	14.7	12.8	10.2	7.2
Tp Avg. Plate temp	61.6	81.1	90.4	94.7	90.8	83.3	76.2
Tg Avg. Glass temp.	47.3	58.4	72.5	73.7	66.5	55.2	47.6
Ti Avg. inlet temp.	27.4	28.8	30.4	30.6	30.7	31.1	31.4
To Dryer outlet temp.	45.2	55.9	62.7	65.1	62.4	55.7	47.2
Tam Ambient temp	25.1	27.5	29.1	29.4	30.2	30.5	30.2
Tf Coll. outlet temp	47.3	58.5	63.6	66.6	65.2	59.1	49.6
Ta,coll. air temp.	56.9	67.2	73.5	73.8	70.5	67.9	61.7
Ts. Avg wall temp.	61.6	81.1	90.4	94.7	90.8	83.3	76.2
I(t) inclined, w/m2	1102.04	1295.91	1367.34	1500	1306.12	1040.81	734.69
hrpg	6.53	7.49	8.28	8.47	8.09	7.46	6.99
hrga	6.04	6.45	6.96	7.01	6.79	6.44	6.19
rayleigh number	7.4E06	2.20E07	2.68E07	3.3E07	3.22E07	2.44E07	2.30E07
hcga	0.2680	0.3515	0.3691	0.3892	0.3861	0.3606	0.3552
H.L.Coefficient,Ut	6.30	6.80	7.33	7.39	7.18	6.80	6.55
NLPI	0.7641	0.8020	0.7053	0.7153	0.7571	1.0379	1.9915

Table B.2 (Open loop condition,6/12/2012)

Time	10:00	11:00	12:00	13:00	14:00	15:00	16:00
I(t) horizontal	3.7	5.8	5.2	5.3	5.5	4.5	3.5
I(t) inclined	6.8	11.3	9.4	10.6	10.1	8.9	6.6
Tp Avg. Plate temp	55.2	68.2	73.3	82.1	71.2	69.4	63.2
Tg Avg. Glass temp.	42.1	49.7	55.1	61.8	50.1	49.6	46.2
Ti Avg. inlet temp.	28.5	28.7	29.4	32	33.1	33.5	33.2
To Dryer outlet temp.	44.5	50.8	57.4	60.4	56	53.6	48.1
Tam Ambient temp	26.4	27.1	31	31.1	31.4	32.3	31.4
Tf Coll. outlet temp	47.1	53.9	61.1	61.7	59.7	57.6	48.5
Ta,coll. air temp.	50.3	59.4	65.1	67.6	64.1	60.6	53.9
Ts. Avg wall temp.	55.2	68.2	73.3	82.1	71.2	69.4	63.2
I(t) inclined, w/m2	693.87	1153.06	959.18	1081.63	1030.61	908.16	673.46
hrpg	6.18	6.80	7.13	7.63	6.91	6.83	6.54
hrga	5.92	6.17	6.45	6.66	6.30	6.32	6.19
rayleigh number	7.77E06	1.39E07	1.30E07	2.30E07	1.12E07	1.39E07	1.47E07
hcga	0.2708	0.3135	0.3080	0.3552	0.2971	0.3135	0.3179
H.L.Coefficient,Ut	6.19	6.48	6.76	7.02	6.6	6.63	6.50
NLPI	0.4919	0.6332	0.4169	0.6673	0.5156	0.6038	1.0150

Table B.3 (Open loop condition,7/12/2012)

Time	10:00	11:00	12:00	13:00	14:00	15:00	16:00
I(t) horizontal	4.7	5.6	6.5	6.5	5.8	4.5	2.8
I(t) inclined	9.3	11.2	12.1	12.8	10.7	9.4	5.6
Tp Avg. Plate temp	63.6	74.1	86.4	91.7	88.4	78.1	66.5
Tg Avg. Glass temp.	49.9	56.1	64.7	71.6	67.2	58.7	57.1
Ti Avg. inlet temp.	27.7	30.2	31.7	32.6	33.3	33.2	35.4
To Dryer outlet temp.	50.2	56.1	62.8	65.7	63.2	57	50.9
Tam Ambient temp	26.1	28	30.1	32.3	33.1	32.9	32.9
Tf Coll. outlet temp	53.7	59.5	65.6	68.5	66.9	61.1	52.4
Ta,coll. air temp.	60.6	63.4	69.9	72.7	72.4	65.5	64.5
Ts. Avg wall temp.	63.6	74.1	86.4	91.7	88.4	78.1	66.5
I(t) inclined, w/m2	948.97	1142.85	1234.69	1306.12	1091.83	959.18	571.42
hrpg	6.66	7.18	7.8	8.29	8.03	7.40	6.97
hrga	6.14	6.39	6.73	7.02	6.90	6.62	6.57
rayleigh number	4.75E06	1.69E07	2.61E07	3.01E07	2.53E07	1.99E07	3.17E06
hcga	0.2396	0.3292	0.3669	0.3801	0.3641	0.3430	0.2165
H.L.Coefficient,Ut	6.38	6.72	7.10	7.40	7.27	6.96	6.78
NLPI	0.4068	0.5289	0.6180	0.6183	0.6529	0.6799	0.7139

Table B.4 (Closed loop condition,30/11/2012)

Time	10:00	11:00	12:00	13:00	14:00	15:00	16:00
I(t) horizontal	5.6	6.7	7.4	7.6	6.6	5.7	2.8
I(t) inclined	11.2	12.8	14.1	14.8	11.7	11.4	6.7
Tp Avg. Plate temp	78.9	97.6	110	113	107	104	70.2
Tg Avg. Glass temp.	53.2	68.4	77	81.3	76.2	71.4	47
Ti Avg. inlet temp.	31.5	34.3	37.6	37.3	37.1	36.5	34.9
To Dryer outlet temp.	46.9	59.9	68.6	70.3	67.2	57.2	41.3
Tam Ambient temp	24.7	26.1	27.5	28.8	28.5	28.5	27.3
Tf Coll. outlet temp	40.5	51.5	59.3	60.4	58.9	51.4	39.6
Ta,coll. air temp.	77.2	92.2	102	103	96	85	64
Ts. Avg wall temp.	78.9	97.6	110	113	107	104	70.2
I(t) inclined, w/m2	1204.30	1376.34	1516.12	1591.39	1258.06	1225.80	720.43
hrpg	7.25	8.40	9.17	9.44	9.02	8.74	6.78
hrga	6.20	6.73	7.06	7.25	7.06	6.90	6.09
rayleigh number	2.69E06	8.56E06	1.26E07	1.58E07	1.74E07	3.01E07	9.83E06
hcga	0.2078	0.2775	0.3061	0.3237	0.3315	0.3801	0.2872
H.L.Coefficient,Ut	6.41	7.0	7.37	7.57	7.39	7.28	6.38
NLPI	2.5030	1.7112	1.5428	1.4604	1.4604	2.4571	5.0826

Table B.5 (Closed loop condition,3/12/2012)

Time	10:00	11:00	12:00	13:00	14:00	15:00	16:00
I(t) horizontal	4.1	5.2	6	5.9	5.1	3.8	2.4
I(t) inclined	7.9	9.6	11.6	10.8	9.4	7.6	4.6
Tp Avg. Plate temp	65.3	83.4	98.3	101.2	95.2	84.7	71.8
Tg Avg. Glass temp.	42.3	59.7	66.3	71.3	65.2	58.4	48.1
Ti Avg. inlet temp.	29.3	33.7	34.9	39	38.6	37.6	37.2
To Dryer outlet temp.	43.6	54.9	65.2	67.9	64.9	58.8	48.7
Tam Ambient temp	23.6	26.6	29.4	31	32	31.7	31.3
Tf Coll. outlet temp	38.1	49.5	58.7	60.8	59.2	54.8	47.3
Ta,coll. air temp.	62.1	79.6	94.7	95.1	87.2	77.5	65.1
Ts. Avg wall temp.	65.3	83.4	98.3	101.2	95.2	84.7	71.8
I(t) inclined, w/m2	849.46	1032.25	1247.31	1161.29	1010.75	817.20	494.62
hrpg	6.49	7.61	8.35	8.63	8.20	7.61	6.87
hrga	6.50	7.18	7.51	7.75	7.56	7.30	6.93
rayleigh number	5.07E06	6.02E06	5.71E06	9.67E06	1.26E07	1.14E07	1.06E07
hcga	0.2435	0.2542	0.2507	0.2861	0.3061	0.2982	0.2929
H.L.Coefficient,Ut	6.74	7.44	7.76	8.04	7.87	7.60	7.23
NLPI	1.9711	1.4627	1.2784	1.2835	1.3382	1.4029	2.4503

Table B.6 (Closed loop condition,4/12/2012)

Time	10:00	11:00	12:00	13:00	14:00	15:00	16:00
I(t) horizontal	4.7	6.3	6.8	6.8	6.1	4.9	2.5
I(t) inclined	8.3	10.5	13.1	13.4	12.6	9.3	4.9
Tp Avg. Plate temp	76.7	98.9	112.2	114.3	106	92.3	76
Tg Avg. Glass temp.	52.3	68.2	78	82	75.3	66.4	59.2
Ti Avg. inlet temp.	32.4	35.1	37.6	38.3	41.1	37.9	35.4
To Dryer outlet temp.	47.5	62.7	71.4	69.9	66.4	56.2	49.5
Tam Ambient temp	26.6	28.8	29.9	31.1	32	32	30.6
Tf Coll. outlet temp	41.7	55.8	62.5	61.7	59.9	52	44.4
Ta,coll. air temp.	74.1	93.1	107	108.1	96.2	80.9	69.3
Ts. Avg wall temp.	76.7	98.9	112.2	114.3	106	92.3	76
I(t) inclined, w/m2	846.93	1071.42	1336.73	1367.34	1285.71	948.97	500
hrpg	7.1	8.44	9.29	9.52	8.95	8.14	7.349
hrga	6.23	6.80	7.17	7.34	7.14	6.84	6.57
rayleigh number	4.12E06	9.20E06	8.25E06	9.83E06	1.55E06	1.80E07	1.06E07
hcga	0.2311	0.2825	0.2749	0.2872	0.3221	0.3345	0.2929
H.L.Coefficient,Ut	6.46	7.09	7.44	7.63	7.46	7.18	6.86
NLPI	2.3501	1.5178	1.4046	1.5214	1.7249	2.0804	1.719

APPENDIX C

Load performance data and Open drying data

Table C.1 Load performance(AAMLA),7/1/2013

Time	11:00	12:00	13:00	14:00	15:00	16:00	17:00
Horizontal Solar Intensity I(t)	7.2	7.7	8	7.2	5.5	3.6	0.4
Solar intensity of collector I(t)	14.6	16.4	17.6	13.5	11.4	7.6	2.8
Ambient wind speed Wamb	1.9	1.8	1.5	1.6	1.8	1.7	1.6
Temperature at inlet 1	21.5	22.7	23.4	25.2	25.3	23.1	21.4
Temperature at inlet 2	21.7	22.5	23.1	25.5	25.7	23.5	21.5
Ambient temperature	20	21	22	24	24	22	21
Wind speed out 1	2.6	2.7	2.6	2.2	2.3	2.1	-
Wind speed out 2	3.2	3.3	3.1	2.8	2.8	2.4	-
Temperature at collector end	53.4	57.6	61.2	56.8	53.3	42.2	26.9
Temperature at dryer end	39.1	43.6	46.6	46.7	43.4	35.4	23.9
Ambient relative humidity(%)	42	40	39	34	33	33	34
Relative humidity at dryer end(%)	33	29	25	24	24	22	23
Material one piece weight(gms)	3.49	3.19	2.8	2.46	2.24	2.12	2.03

Table C.2 Load performance(AAMLA),8/1/2013

Time	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00
Horizontal Solar Intensity I(t)	5.2	6.7	7.7	7.9	7.3	5.9	3.8	0.5
Solar intensity of collector I(t)	11.4	13.8	16.1	16.4	14.5	12.3	7.9	3.6
Ambient wind speed Wamb	0.8	1.4	1.6	1.8	1.7	1.3	1.6	1.8
Temperature at inlet 1	21	21.3	22.1	21.5	22.8	23.7	23.6	22.5
Temperature at inlet 2	19.6	20.2	21.6	22.4	23.3	24.1	23.9	22.8
Ambient temperature	16	18	20	21	22	23	23	22
Wind speed out 1	1.8	2.2	2.5	2.7	2.6	2.5	2.2	-
Wind speed out 2	2.4	2.8	3.1	3.3	3.1	2.9	2.5	-
Temperature at collector end	39.6	49.2	57.6	61.1	59.9	54.7	42.4	28.7
Temperature at dryer end	31.8	39.9	46.3	49	49.2	45.9	33.3	25.3
Ambient relative humidity(%)	52	48	45	44	41	38	38	39
Relative humidity at dryer end(%)	48	45	34	32	30	26	26	26
Material one piece weight(gms)	1.68	1.56	1.45	1.39	1.28	1.21	1.16	1.09

Table C.3 Load performance(AAMLA),9/1/2013

Time	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00
Horizontal Solar Intensity I(t)	5.1	6.6	7.6	7.7	6.8	5.4	3.7	0.5
Solar intensity of collector I(t)	10.4	13	15.1	15.2	13.8	12.6	8.5	3.4
Ambient wind speed Wamb	1.4	1.3	1.8	1.6	1.5	1.2	1.3	1.1
Temperature at inlet 1	21.9	23.3	24.4	24.9	25.3	26.4	26.2	25.6
Temperature at inlet 2	19.7	23.1	24	25.3	26.4	26.8	26.7	25.9
Ambient temperature	16	22	23	24	25	26	26	25
Wind speed out 1	2	2.2	2.6	2.6	2.6	2.5	2.2	-
Wind speed out 2	2.3	2.7	2.9	3.1	3.2	2.9	2.8	-
Temperature at collector end	43.3	52.8	60.8	65.6	64.3	59	50.4	35.4
Temperature at dryer end	33.6	42	48.1	51.5	51.3	48	41.5	32.3
Ambient relative humidity(%)	43	44	38	36	35	35	38	38
Relative humidity at dryer end(%)	40	39	30	26	23	23	23	23
Material one piece weight(gms)	1.01	0.98	0.94	0.89	0.86	0.85	0.85	0.85

Table C.4 Open drying data(AAMLA),

time	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00
Sample weight(7/1/2013)	-	3.84	3.63	3.2	3	2.78	2.52	2.41
Sample weight(8/1/2012)	2.31	2.22	2.04	1.86	1.7	1.58	1.49	1.4
Sample weight(9/1/2013)	1.24	1.19	1.13	1.02	0.91	0.87	0.84	0.81
Sample weight(10/1/2013)	0.73	0.72	0.7	0.69	0.68	0.68	0.67	0.66
Sample weight(11/1/2013)	0.66	0.65	0.64	0.64	0.64	0.64	-	-

Table C.5 Load performance(METHI),5/2/2013

Time	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00
Horizontal Solar Intensity I(t)	2.7	7.7	8.2	9.1	9	6.9	5.9	2.7
Solar intensity of collector I(t)	3.4	13.4	15.1	17.9	18.5	13.2	10.6	4.6
Ambient wind speed Wamb	0.6	0.5	0.8	1.3	1.4	1.7	1.1	1
Temperature at inlet 1	26.8	27.2	29.7	31.8	33.6	32.4	28.7	27.2
Temperature at inlet 2	26.7	27	29.6	31.9	33.8	32.7	29.2	27.4
Ambient temperature	26	26	28	30	32	30.5	27	26.5
Wind speed out 1	0.9	2.7	2.7	2.8	2.7	2.6	2.5	0.8
Wind speed out 2	1	3.1	3	3.1	3.1	2.9	2.8	1
Temperature at collector end	43.9	52.9	66.4	75.8	69.9	66.1	43.6	40.1
Temperature at dryer end	35.9	40	54.5	64.8	62.6	58.8	40.3	35.8
Ambient relative humidity(%)	48	51	45	41	41	40	55	54
Relative humidity at dryer end(%)	34	40	33	25	20	20	40	38
Material one piece weight(gms)	2.24	1.72	1.04	0.35	0.24	0.22	0.18	0.18

Table C.6 Open drying data(METHI)

Time	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00
Sample weight(5/2/2013)	2.06	1.63	1.21	0.72	0.53	0.46	0.4	0.37
Sample weight(6/2/2012)	0.28	0.26	0.25	0.25	0.24	0.23	0.22	0.22

Table C.7 Load performance(GARLIC),25/2/2013

Time	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00
Horizontal Solar Intensity I(t)	6.9	8.5	9.2	9.3	8.5	6.5	4.2	0.7
Solar intensity of collector I(t)	12.7	14.5	17.7	18.1	16.9	13.9	9.3	2.4
Ambient wind speed Wamb	1.4	3.2	1.8	3.1	2.4	0.8	2.9	2.2
Temperature at inlet 1	25.6	26.7	29.5	30.4	31.4	33.9	32.5	30.6
Temperature at inlet 2	25.6	26.5	29.6	30.6	31.4	33.8	32.6	30.8
Ambient temperature	25	26	29	30	31	33	32	30.5
Wind speed out 1	2.7	2.7	2.8	2.6	2.7	2.8	2.5	1
Wind speed out 2	3.1	3	3.2	3	3	3.1	2.6	1.3
Temperature at collector end	48.6	61.6	71.6	72.3	74.6	66.1	54.2	42.6
Temperature at dryer end	40.6	52.4	60.6	56	58.1	52.3	46.9	39.3
Ambient relative humidity(%)	43	41	40	38	33	30	28	27
Relative humidity at dryer end(%)	33	29	24	20	less than 20			
Material one piece weight(gms)	1.27	1.26	1.25	1.22	1.19	1.14	1.12	1.09

Table C.8 Load performance(GARLIC),26/2/2013

Time	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00
Horizontal Solar Intensity I(t)	6.2	7.8	8.9	9.1	8.5	7.2	5.2	1.7
Solar intensity of collector I(t)	11.4	13.7	17.6	18.3	16.4	14.6	9.8	3.8
Ambient wind speed Wamb	1.5	1	1.8	1.9	0.4	0.7	0.9	2.1
Temperature at inlet 1	27.5	29.9	32.8	33.6	35.6	35.7	35.2	33.6
Temperature at inlet 2	27.3	29.8	32.9	33.6	35.7	35.8	35.4	33.7
Ambient temperature	27	29.5	32.5	33.5	35	35.5	35	33.5
Wind speed out 1	2.3	2.5	2.7	2.7	2.8	2.7	2.6	1.4
Wind speed out 2	2.8	2.9	3.1	3.2	3.2	3	2.9	1.9
Temperature at collector end	50.3	59.7	70.1	73.7	75.8	71.5	59.1	46.8
Temperature at dryer end	43.1	51.1	58.3	62	63.8	60.7	54.5	44.9
Ambient relative humidity(%)	36	32	33	24	24	21	31	31
Relative humidity at dryer end(%)	26	21	less than 20					
Material one piece weight(gms)	1.04	1.04	0.96	0.86	0.77	0.69	0.66	0.66

Table C.9 Load performance(GARLIC),27/2/2013

Time	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00
Horizontal Solar Intensity I(t)	6.8	8.4	9.5	10	9.5	8	6	1.4
Solar intensity of collector I(t)	12.4	16.2	19.3	19.8	19.5	16.1	11.8	3.4
Ambient wind speed Wamb	2.1	1.8	2.6	1.9	1.1	2.9	3.3	1.7
Temperature at inlet 1	25.4	26.4	28.5	29.4	29.4	29.5	29.7	29.3
Temperature at inlet 2	25.2	26.3	28.4	29.6	29.7	29.6	29.7	29.4
Ambient temperature	25	26	28	29	29	29	29.5	29
Wind speed out 1	2.5	2.7	2.7	2.7	2.7	2.6	2.6	1.1
Wind speed out 2	2.9	3	3.1	3	3.2	3.1	3	1.4
Temperature at collector end	50.9	58.8	69.2	73.4	74.1	70.8	61.9	48.3
Temperature at dryer end	42.1	47.3	54.6	58.4	57.1	55.5	50.7	43.4
Ambient relative humidity(%)	43	39	33	36	46	44	42	39
Relative humidity at dryer end(%)	30	28	22	23	28	25	23	24
Material one piece weight(gms)	0.61	0.61	0.61	0.61	0.59	0.59	0.59	0.59

Table C.10 Open drying data(GARLIC)

Time	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00
Sample weight(25/2/2013)	1.29	1.27	1.27	1.23	1.19	1.19	1.19	1.13
Sample weight(26/2/2012)	1.08	1.07	1.05	1.03	1.02	1	0.98	0.97
Sample weight(27/2/2013)	0.87	0.86	0.82	0.8	0.77	0.74	0.7	0.66
Sample weight(28/2/2012)	0.64	0.62	0.61	0.57	0.57	0.56	0.56	0.56

Table C.11 Load performance(GINGER),18/2/2013

Time	12:00	13:00	14:00	15:00	16:00	17:00
Horizontal Solar Intensity I(t)	8.8	9.3	9	7.7	5.7	2.3
Solar intensity of collector I(t)	17.4	18.9	18.3	16.3	11.8	5.6
Ambient wind speed Wamb	1.8	2.7	3.2	3.1	2.5	1.7
Temperature at inlet 1	26.2	26.4	27.7	28.4	28.7	28.4
Temperature at inlet 2	26.1	26.3	27.9	28.6	28.9	28.3
Ambient temperature	26	26	27.5	28	28.5	28
Wind speed out 1	2.7	2.6	2.7	2.6	2.5	0.8
Wind speed out 2	2.9	2.9	3.1	3	2.8	0.9
Temperature at collector end	61.8	64.4	68.6	65.9	57.3	42.8
Temperature at dryer end	51.1	49.3	53.1	53.2	49.1	39
Ambient relative humidity(%)	42	39	37	31	30	30
Relative humidity at dryer end(%)	26	23	21	20	20	21
Material one piece weight(gms)	6.79	4.3	2.83	1.89	1.5	1.37

Table C.12 Load performance(GINGER),19/2/2013

Time	10:00	11:00	12:00	13:00	14:00
Horizontal Solar Intensity I(t)	6.2	8	8.7	9.3	8.9
Solar intensity of collector I(t)	11.3	13.7	17.2	17.9	16.9
Ambient wind speed Wamb	1.4	1.7	0.7	0.6	0.3
Temperature at inlet 1	24.5	27	27.6	28.7	30.5
Temperature at inlet 2	24.4	26.9	27.3	28.9	30.9
Ambient temperature	24	26.5	27	28.5	30
Wind speed out 1	2.3	2.5	2.6	2.6	2.7
Wind speed out 2	2.7	2.9	3.1	3	3.1
Temperature at collector end	42.6	57	60.8	70.9	74.1
Temperature at dryer end	33.1	47.3	52.9	58.1	61
Ambient relative humidity(%)	47	35	33	33	32
Relative humidity at dryer end(%)	46	26	24	24	20
Material one piece weight(gms)	1.34	1.28	1.27	1.27	1.27

Table C.13 Open drying data(GINGER)

Time	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00
Sample weight(18/2/2013)	-	-	6.74	4.81	3.61	2.42	1.82	1.42
Sample weight(19/2/2012)	1.4	1.28	1.18	1.07	1.01	0.98	0.95	0.93
Sample weight(20/2/2013)	0.93	0.92	0.92	0.91	0.91	0.91	-	-

Table C.14 Load performance(ONION),21/2/2013

Time	11:00	12:00	13:00	14:00	15:00	16:00	17:00
Horizontal Solar Intensity I(t)	7.5	8.8	9	8.4	6.7	5.2	2.6
Solar intensity of collector I(t)	11.9	16.1	18.4	15.7	14.1	9.9	4.7
Ambient wind speed Wamb	2.4	2.8	1.1	1.5	1.7	0.3	1.3
Temperature at inlet 1	28.1	29.5	31.6	33.3	34.2	35.3	34.4
Temperature at inlet 2	28	29.6	31.8	33.4	34.4	35.4	34.4
Ambient temperature	27.5	29	31	33	34	35	34
Wind speed out 1	2.6	2.7	2.7	2.6	2.5	2.5	1.3
Wind speed out 2	2.9	3.1	3	3	2.9	2.8	1.7
Temperature at collector end	57.6	64.8	72.6	75.8	72.9	64	47.5
Temperature at dryer end	48.4	52.9	57.6	59.4	59.1	54.1	43.3
Ambient relative humidity(%)	43	41	36	32	24	23	26
Relative humidity at dryer end(%)	26	24	20	less	than	20	
Material one piece weight(gms)	10.6	7.76	5.43	3.85	2.7	2.35	2.17

Table C.15 Load performance(ONION),22/2/2013

Time	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00
Horizontal Solar Intensity I(t)	6.1	8	8.6	9	8.9	7.5	5.6	2.7
Solar intensity of collector I(t)	9.4	13.4	14.7	17.8	18.4	16.5	11.4	5.3
Ambient wind speed Wamb	1.5	1.8	2.7	2.1	2.4	1.5	2.5	2.5
Temperature at inlet 1	26.5	29.4	31.8	32	32.7	33.9	34	33.8
Temperature at inlet 2	26.4	29.5	31.9	31.9	32.8	34	34.1	33.9
Ambient temperature	26	29	31.5	31.5	32.5	33.5	33.5	33.5
Wind speed out 1	2.4	2.8	2.7	2.7	2.6	2.7	2.5	1.4
Wind speed out 2	2.8	3.2	3.1	3.1	3	3.2	2.7	1.8
Temperature at collector end	49.9	61.4	68.9	74.9	73.9	73.4	64.6	63.6
Temperature at dryer end	40.8	50.7	57	60.7	61.1	61.2	54.8	57.4
Ambient relative humidity(%)	35	32	31	31	30	28	27	28
Relative humidity at dryer end(%)	24	22	less	than	20			
Material one piece weight(gms)	2.11	2.07	2.06	2.02	1.82	1.8	1.8	1.8

Table C.16 Open drying data(ONION)

Time	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00
Sample weight(21/2/2013)	-	10.37	8.64	7.38	6.64	5.75	5.32	4.87
Sample weight(22/2/2012)	3.9	3.47	3.23	2.98	2.74	2.64	2.54	2.46
Sample weight(23/2/2013)	2.25	2.17	2.15	2.13	2.09	2.09	2.09	2.09

Table C.17 Load performance(POTATO CHIPS),12/2/2013

Time	11:30	12:30	13:30	14:30	15:30	16:30	17:30
Horizontal Solar Intensity I(t)	7.6	8.1	8.5	7.7	5.5	3.5	1.8
Solar intensity of collector I(t)	15.2	15.7	16.8	15.5	11.4	6.9	3.6
Ambient wind speed Wamb	1.3	1.3	1.2	1.3	1.1	1.6	1.4
Temperature at inlet 1	30.7	32.9	33.4	33.6	34.1	33.6	33.3
Temperature at inlet 2	30.5	32.8	33.5	33.8	34.3	33.8	32.7
Ambient temperature	28.5	31	32	32	33	33	32
Wind speed out 1	2.8	2.7	2.6	2.7	2.5	2	0.5
Wind speed out 2	2.6	3	3	3.1	2.9	2.5	0.6
Temperature at collector end	58.9	67.8	73.5	75.6	60.8	49.9	40.2
Temperature at dryer end	49.9	55.2	58.5	60.5	52.4	45.7	39.4
Ambient relative humidity(%)	48	36	34	33	30	28	29
Relative humidity at dryer end(%)	40	27	23	21	20	20	20
Material one piece weight(gms)	8.09	3.92	2.14	1.83	1.68	1.65	1.65

Table C.18 Open drying data(POTATO CHIPS)

Time	11:30	12:30	13:30	14:30	15:30	16:30	17:30
Sample weight(12/2/2013)	8.04	6.22	4.49	3.41	2.37	1.95	1.7
Sample weight(13/2/2012)	1.65	1.62	1.59	1.57	1.56	1.55	1.55

Table C.19 Load performance(GRAPES),18/3/2013

Time	11:00	12:00	13:00	14:00	15:00	16:00	17:00
Horizontal Solar Intensity I(t)	8.6	9.5	9.8	9.3	7.9	5.7	3.4
Solar intensity of collector I(t)	15.4	17.8	18.6	18	15.9	10.4	5.9
Ambient wind speed Wamb	0.9	1.1	1.7	1.6	1.4	1.3	1
Temperature at inlet avg.	33.4	34.5	34.6	35.3	36.7	36.6	35.7
Ambient temperature	32.5	34	34	35	36	36	35
Wind speed out 1	2.5	2.7	2.7	2.8	2.7	2.7	2.1
Wind speed out 2	2.9	3.1	3	3.2	3.1	3.2	2.4
Temperature at collector end	62.3	68.4	74.3	72	70.2	60.4	50.3
Temperature at dryer end	54.1	60.2	68.9	64.3	68.6	59.3	49.1
Ambient relative humidity(%)	39	39	38	33	28	27	30
Relative humidity at dryer end(%)	25	21	20	less	than	20	
Material one piece weight(gms)	3.28	3.26	3.18	3.15	3.04	2.98	2.94

Table C.20 Load performance(GRAPES),19/3/2013

Time	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00
Horizontal Solar Intensity I(t)	7	8.8	9.4	9.6	8.6	8.2	5.9	3.7
Solar intensity of collector I(t)	12.9	16.7	18.5	19	16.8	16	12.2	6.4
Ambient wind speed Wamb	0.8	1.1	1.3	1.9	1.8	2.4	2	1.3
Temperature at inlet avg.	31.6	33.4	35.7	35.8	37.1	36.9	36.8	36.4
Ambient temperature	31	33	35	35.5	36.5	36.5	36.5	36
Wind speed out 1	2.4	2.7	2.8	2.7	2.7	2.6	2.6	2.3
Wind speed out 2	2.8	3	3.2	3.1	3.2	3.1	3	2.7
Temperature at collector end	58.4	66.7	74.5	77.2	73.4	68.4	63.5	54.8
Temperature at dryer end	54.3	63.2	69.5	71.6	70.2	64.3	58.1	51.9
Ambient relative humidity(%)	29	28	27	29	31	30	29	24
Relative humidity at dryer end(%)	less	than	20					
Material one piece weight(gms)	2.79	2.78	2.69	2.58	2.41	2.3	2.23	2.15

Table C.21 Load performance(GRAPES),20/3/2013

Time	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00
Horizontal Solar Intensity I(t)	7.8	9.2	9.9	10.1	9.6	7.8	5.8	3.5
Solar intensity of collector I(t)	13.5	18	19	19.9	18.4	15.7	10.8	6.5
Ambient wind speed Wamb	1.1	1.3	2.1	2.7	2.3	0.7	1.3	1.2
Temperature at inlet avg.	28.1	33.8	35.4	36.6	36.9	37.5	37.7	35.4
Ambient temperature	27.5	33.5	35	36	36.5	37	37.5	35
Wind speed out 1	2.6	2.8	2.7	2.8	2.7	2.7	2.6	2.4
Wind speed out 2	3	3.2	3.1	3.1	3.1	3	3	2.8
Temperature at collector end	55.4	66.8	75.4	78.3	76.8	71.5	66.6	57.2
Temperature at dryer end	54.2	64.7	71.2	72.6	72	70	65.2	53.4
Ambient relative humidity(%)	22	20	18	18	17	17	15	23
Relative humidity at dryer end(%)	21	less	than	20				
Material one piece weight(gms)	2	1.95	1.83	1.54	1.2	1.01	0.92	0.92

Table C.22 Open drying data(GRAPES)

Time	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00
Sample weight(18/3/2013)		3.22	3.21	3.15	3.13	3.05	3.03	2.99
Sample weight(19/3/2012)	2.86	2.86	2.83	2.78	2.74	2.69	2.66	2.64
Sample weight(20/3/2013)	2.46	2.42	2.34	2.22	2.1	2.03	1.98	1.95
Sample weight(21/3/2013)	1.86	1.82	1.77	1.73	1.7	1.68	1.66	1.64
Sample weight(22/3/2012)	1.58	1.56	1.52	1.46	1.37	1.31	1.26	1.2
Sample weight(23/3/2013)	1.14	1.08	1.02	0.97	0.93	0.9	0.9	0.9

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