DESIGN, CONSTRUCTION AND PERFORMANCE STUDY OF AN INDIRECT TYPE SOLAR DRYER FOR FOOD PRESERVATION

A THESIS SUBMITTED TO THE DEPERTMENT OF "MECHANICAL ENGINEERING" IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE OF BACHALOR OF SCIENCE IN MECHANICAL ENGINEERING

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STUDENT DECLARATION

This is to certify that the thesis entitled, **"DESIGN, CONSTRUCTION AND PERFORMANCE STUDY OF AN INDIRECT TYPE SOLAR DRYER FOR FOOD PRESERVATION"** is an outcome of the investigation carried out by the author under the supervision of **Dr. A. K. M. Monjur Morshed,** Associate Professor, Department of Mechanical Engineering, BUET. This thesis or any part of it has not been submitted to elsewhere for the award of any other degree or diploma or other similar title or prize.

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SUPERVISOR CERTIFICATION

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I wish them every success in life.

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ABSTRACT

Utilizing the most abundant and free of cost energy of the sun to heat up the air and to use that heated air to dry foods is the main goal of this thesis. In order to do this an indirect type forced convection solar dryer is fabricated with components like screen absorber solar collector, drying chamber, fan, etc. The performance of the designed solar dryer is evaluated by carrying drying experiments with potatoes. The temperature inside the drying chamber ranges from 49^0C to 58^0C while the ambient temperature ranges from 33^0C to 35^0C. Initial moisture content in potatoes ranges from 77-79% and the final moisture content obtained about 15.44% in 7 hours. Solar drying of potatoes is carried for forced convection and is compared with open solar drying. The drying rate was 0.1223 kg/hr and 0.1173 kg/hr in solar dryer and open sun drying method respectively. It is seen that applying indirect solar drying not only reduce the drying time, but also higher quality of dried products can be obtained.

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CHAPTER 1

INTRODUCTION

Sun drying is considered as the most common, economical and environmentally friendly method of preservation of agricultural products. Open sun drying is widely used by farmers. It has some disadvantages which are bad weather conditions like rain, wind, moist and dust. Others include infestation by insects and other animals as well as degradation by bacteria. That's why the dried product are not so much hygienic and international standards. Lack of effective technology is a major obstacle for small scale farmers because of inadequate electricity. So the closest solution for the farmers is to use solar dryer. This study aims to build a low cost indirect type active solar dryer for the unprivileged farmers of our country which has better control of temperature along with better quality of foods.

1.1 MOTIVATION

Many of our villages are detached from the national grid. Villages which are connected to the grid don't get sufficient electricity. One of the important economic sectors in Bangladesh is agriculture. 80% people of our country are related to agriculture. From these we can earn a lot of foreign currency. Our country is agricultural based because we have fertile soil and sufficient water supply. Farmers work hard in the field to produce agricultural products in rural areas. Farmers also produce fruits and vegetables more than the actual demand, thus flooding the markets. This increases the chance of food spoilage at market level. The lack of appropriate food preservation is also responsible for the spoilage of food. Cold storages require power to run and if the power supply fails a lot of food is spoilt. In Munshiganj, 2008, five thousand tonnes of potato, stored in cold storage were rotten due to collapse of its cooling system [1]. Solar dryer does not depend on the supply of electricity from the national grid. It uses the energy of sun to preserve foods. So in rural areas, the use of solar dryer can eliminate the wastage of food due to lack of electricity supply.

In 2008, the farmers of Bangladesh produced 8 million tons of potatoes on 500,000 hectares of land. It was a bumper production of our country. But there are only 300 cold storages in our country with a capacity of 2-2.2 million tons [2]. Lack of cold storage facilities, potato is shriveled, rotten or sprouted causing huge loss of potato under normal temperature and humidity. Solar dryer can eliminate these problems.

The transportation methods of our country used in transporting the agricultural products to markets and warehouses are not very effective. Some of them are very slow and cause physical damage to the products. Traffic jam that delays the delivery of food to the customer is also responsible for spoilage of food. Preservation of foods before transportation can eradicate this problem. Here solar dryer can be an effective solution.

Some of the food preservation methods are very expensive for the farmers to bear, such as refrigeration and freezing, canning, irradiation, dehydration, freeze-drying, pickling, pasteurizing, fermentation. Technologies like canning and compressed gas refrigeration require much energy input. But solar dryer which requires only the energy of the sun, which is free of cost.

There are many food reservation methods that are very complex and difficult. Such as canning requires heating of products at a specified temperature for a specific length of time and then vacuum sealing the pasteurized food in a special glass jar designed for this purpose [3]. But solar drying is very simple and consists of some easy process.

Food spoilage is a major problem. Causes of spoilage include the growth of microorganism such as yeasts, molds and bacteria. The presence of water is a key factor in all this process. Microorganisms need water to support their life. Very few chemical reactions can occur without the presence of water. The dissolved sugars serve as a source of nutrients for microorganisms. This creates an ideal environment for microbial growth and chemical reactions. Removal of water basically shuts down the growth of microorganisms and prevents chemical reactions from taking place. The important thing to note that there is an incredible amount of water we eat. In order to prolong the storage life, water from foods have to be removed.

Removing the water to increase its storage life also reduces the weight of final product significantly. This might be viewed as a bonus for those drying foods for export or shipping to other locations. Looking at the various constituents of fresh fruits and vegetables, water is usually, the one that is most abundant on a weight basis. It may also have an impact on the load capacity of small vehicles to move material. Weight reduction is also a big advantage to hikers and campers, as well as for military rations etc.

This may not be obvious at first glance, but there is often a reduction in volume when moisture is removed from a product. Sometimes the structure of the material is such that its volume doesn't change appreciably. Volume reduction may be on a case by case basis. It may also have an impact on the volume or spatial capacity of small vehicles to move material.

Anyone who has ever eaten fresh fruits and dried fruits will have noticed the obvious differences in texture. Dried fruits tend to become leathery but still remain pliable. Dried fruits tend to be chewy. Along with textural changes, there are also dramatic taste changes due to drying especially for fruits. Most pronounced among these taste changes is sweetness. Adjustments in water intake must be made to accommodate the consumption of dried fruits.

Drying can be used to change the form of various fruits and vegetables. Raisins can be produced by removing moisture from the grapes. The concentration of sugars in raisins permits them to have a somewhat higher moisture content than other dried fruits. Form changes expand the potential uses of the products.

There are occasions when dried fruits and vegetables offer the advantage of easy handling versus their fresh counterparts. This reduces the messiness of consuming fresh juicy fruits by hand.

Variation is a major advantage of dried products. Many products offer the just add water and stir approach to preparation.

1.2 OBJECTIVE

The main objectives of the study are as follows:

- To design an indirect solar dryer with forced circulation of air that can dry and preserve foods within the least period of time.
- To construct the solar dryer.
- To determine the performance of the solar dryer and compare it with the traditional sun drying method.
- To design a solar dryer which solar collector can be separated from the system and can be used as a solar air heater to heat up the air in winter season
- To design a solar dryer for the unprivileged village farmers and also for the food industries which will be very economical and efficient.

CHAPTER-2

LITERATURE REVIEW

This chapter describes the related literature about different types of drying technologies along with solar drying technologies which are conducted by many researchers around the world and also describes the scope of work in solar drying technology in Bangladesh.

2.1 DRYING TECHNOLOGY

The dryer can be divided into two groups based on the methods in which heat is delivered to the material being dried. There are also ways of removing moisture without the application heat. With the direct application of heat, the material is usually dried directly over the heat source. With the indirect application of heat, the material is dried using air that has been previously heated by contact with heat source. Most dryers use the indirect heating method. The indirect application of heat offers better control over the drying process than can be achieved by direct heating. There are also many different methods for drying such as:

Convection drying, bed drying, drum drying, freeze drying, microwave-vacuum drying, shelf drying, spray drying, infrared radiation drying, combined thermal hybrid drying, sunlight, commercial food dehydrators, household oven [4].

Different Types of Drying Methods

- Convection air drying
  In this method, a flow of heated air is passed through the agricultural products. This heated air removes the water from products by vaporization as long as the saturation vapor pressure of the moisture is less than the operating pressure. Here the temperature is between 40-80^{0}C [5].

- Vacuum drying
  This is a one type of conduction dryer. The vacuum oven consists of a jacketed vessel to withstand vacuum within the oven. The oven is connected through a condenser and liquid receiver to a vacuum pump. Operating pressure can be as low as 0.03 bar at which pressure water boils at 25-35^{0}C [6].

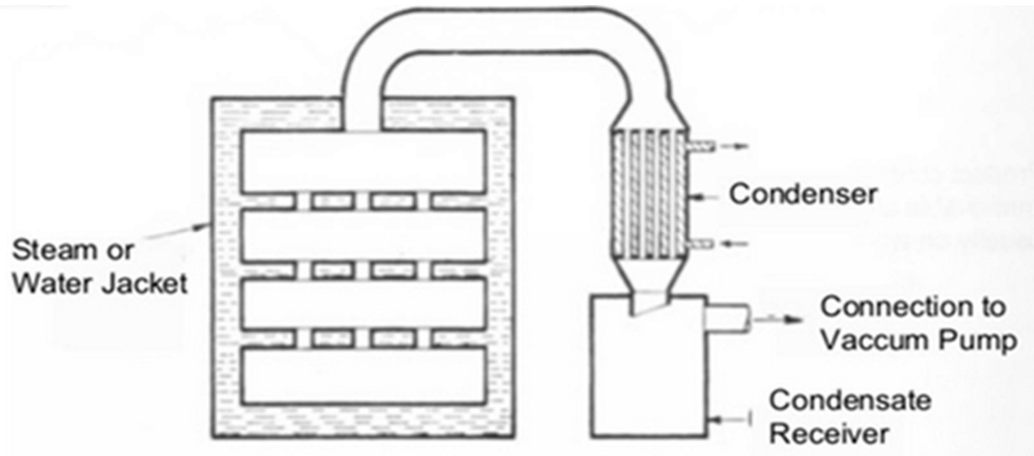


Figure 2-1 Vacuum Dryer

- Drum Dryer
  It consists of drums of about 0.75-1.5 m in diameter and 2-4 m in length, heated internally, usually by steam and rotated on its longitudinal axis [6]. Two counter rotating drums pinch the material which then sticks to the heated surfaces. A doctor blade scraps the dried material off the heated drums. One or both drums may be heated. Used to produce dried potato flakes etc.

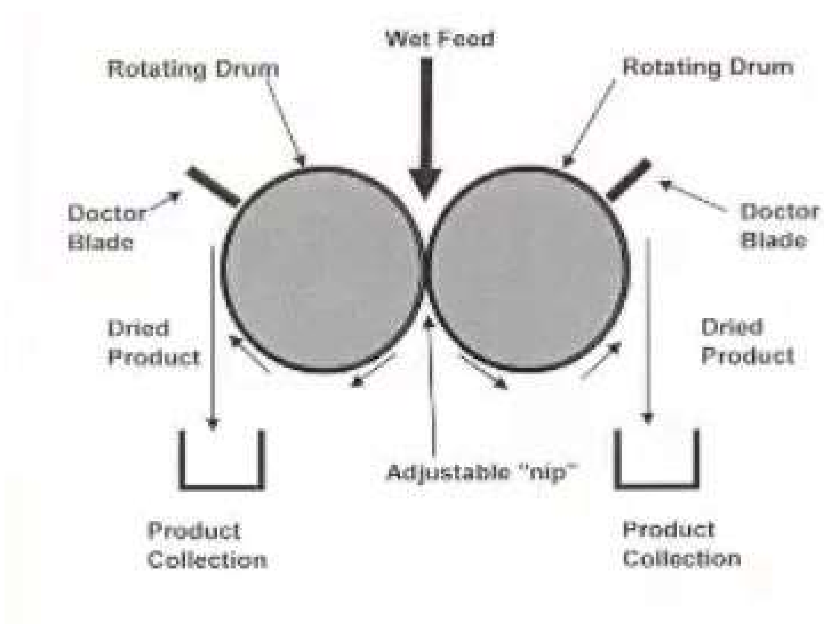


Figure 2-2 Drum dryer

- Spray dryer

  Spray dryer allows particles in solutions to be dried to form powders. These are very useful for spray dried powders in the dairy industry and pharmaceutical industry. The liquid is sprayed through an atomizing nozzle to create small droplets. The small droplets then enter a chamber where hot air is flowing. As the droplets fall, they lose moisture and form a powder. The powder is then collected.

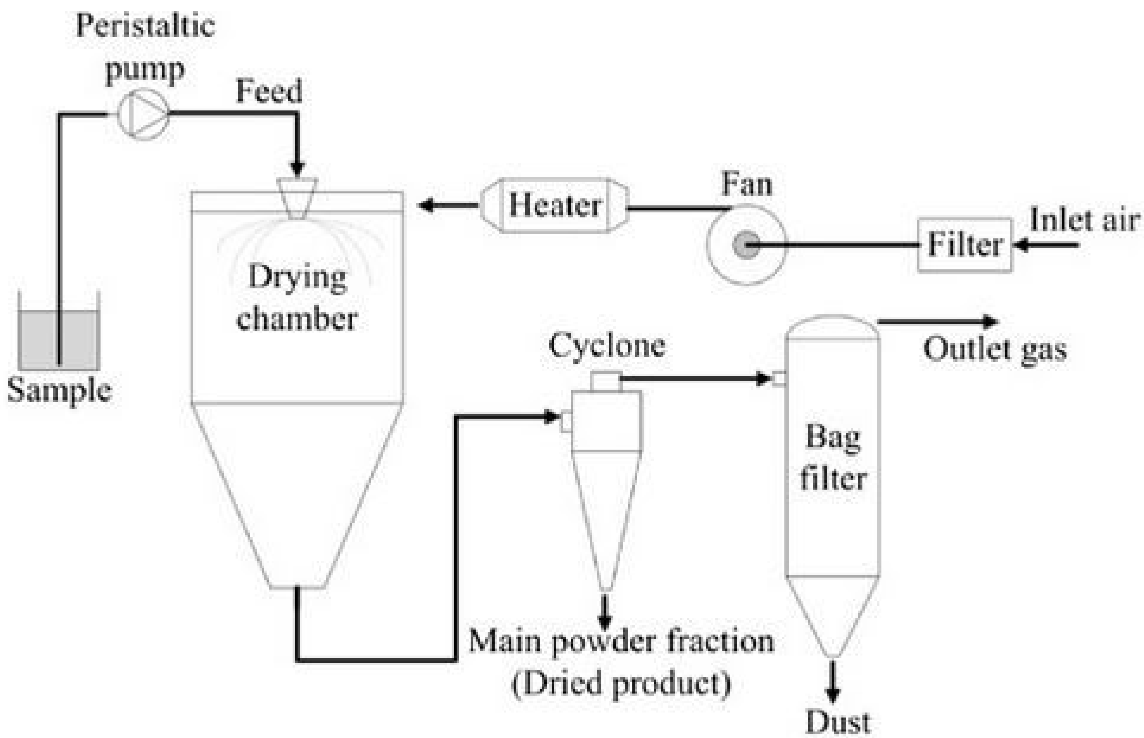


Figure 2-3 Spray Dryer

- Freeze dryer

  Heat sensitive materials are dried by this process. It allows the drying, without excessive damage of proteins, blood products and even microorganisms which retain a small but significant viability. In this process, the initial liquid solution or suspension is frozen, the pressure above the frozen state is reduced and the water is removed by sublimation. This a liquid to vapor transition takes place, but here three states of matter involved: liquid to solid, then solid to vapor [6].

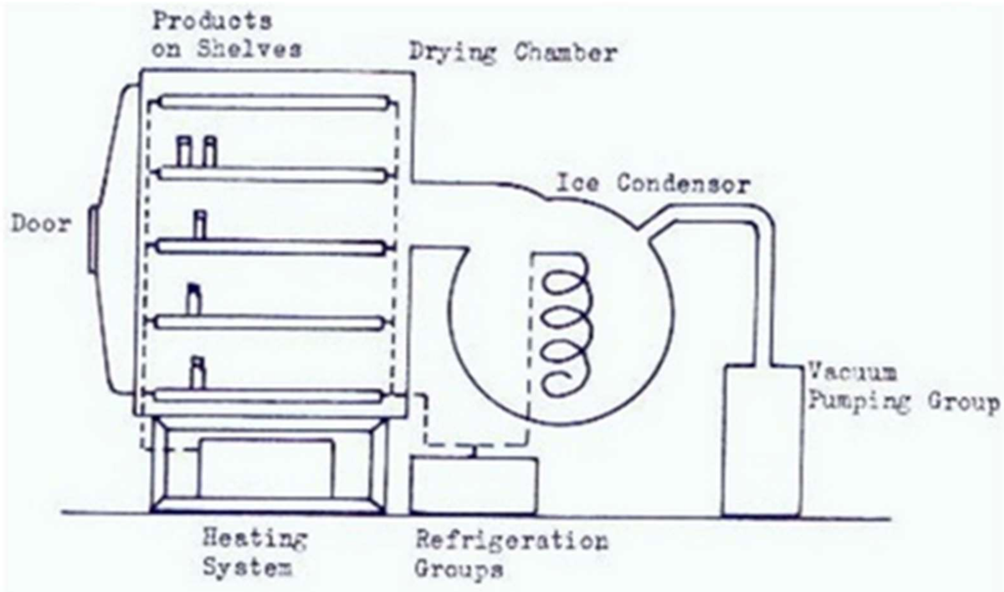


Figure 2-4 Freeze Dryer

- Fluidized bed dryer
  Fluidized means something that behaves like liquid. In the fluidized bed dryer, the mixture of solids and gas behaves like a liquid and solid are called fluidized. It provides better contact between hot air and particles to obtain efficient drying. The hot air passes through a mesh, which supports the conical vessel with a porous base. This vessel is filled with powder to be dried. It has wheels and can be clipped to the central plate by means of a rapid acting ring closure [6].

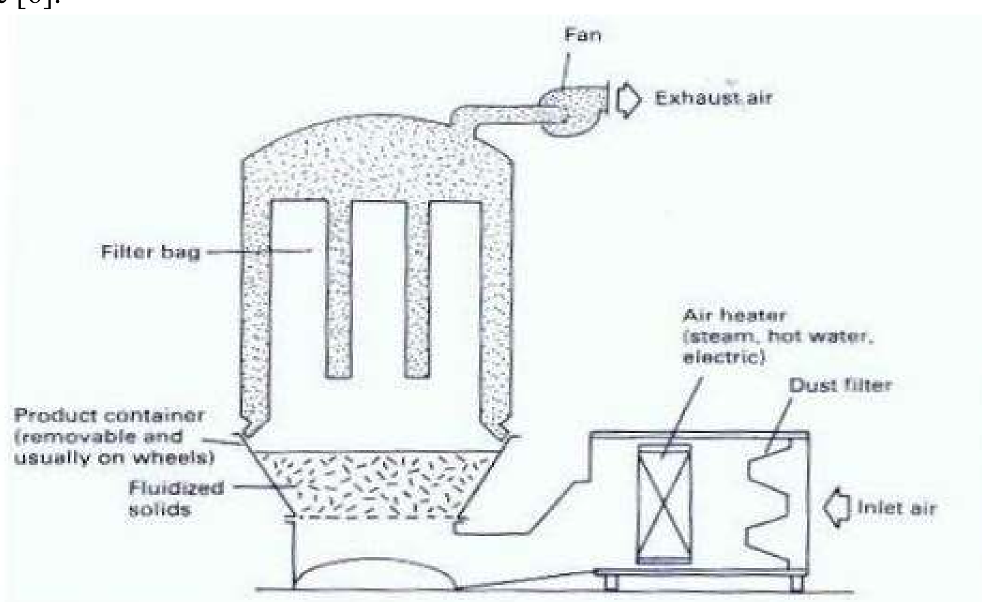


Figure 2-5 Fluidized bed dryer

Different Drying Technologies Conducted by Many Researchers

- Effects of far-infrared radiation on the freeze-drying of sweet potato (Yeu-PyngLin, Jen-HorngTsen, V.An-ErlKing)
  In this paper an experimental dryer was developed to determine the drying characteristics of sweet potato during freeze-drying with far-infrared radiation. The experimental drying time of sweet potato cubes dehydrated by three drying methods, i.e., air-drying, freeze-drying, and freeze-drying with far-infrared radiation, were compared, and freeze-drying with far-infrared radiation was found to be able to reduce the drying time of sweet potato. Application of far-infrared radiation in freeze-drying could reduce drying time in freeze-drying [7].

- Performance evaluation and process optimization of potato drying using a hot air oven (Shahzad Faisal, Ruhi Tabassum and Vishal Kumar)
  The effect of various process parameters on the drying behavior of Potato (Solanum tuberosum) was studied, and the optimization of process parameters based on quality was investigated. In the very first phase of preliminary experiments the oven was tested at experimental temperatures 60, 70 and 80°C and the time taken from the oven to attain the set temperature was noted. It was found in all the experimental temperatures that oven is taking approximately one hour to equilibrate to the required temperature. The oven attained the set temperature with a deviation of ± 1°C. The central tray was found to be satisfactory for the drying purpose as there was almost a uniform air flow pattern measured through anemometer. After selection of tray, temperature distribution over the surface was determined by placing digital temperature meters at the perimeter and center of the tray. The result of which shows that there is only a variation of ± 0.5°C [8].

- Vacuum microwave drying of fresh mango and/or pineapple fruit pieces to produce an improved dried product (Durance, Wang and Meyer)
  The invention used microwave technology to raise the temperature of the raw material in the vacuum state. The less vacuum, the longer the drying time and the higher the temperature required for drying. The higher the temperature to which the fruit pieces are subjected, the more likely the pieces lose their fresh flavor. It is therefore preferred to use the highest achievable vacuum and minimize the temperature required to dry the fruit pieces to thereby minimize the loss of flavor. The testing of the vacuum microwave shows that the mango and pineapple products of this invention had a significant different density compared to conventional air dried product, i.e. the pineapple of the invention has a density of about 60% of that the conventional air dried product. It is significantly better because it is less tough to chew and more chew and more crunchy [9].

- Osmotic dehydration in fruit and vegetable processing (Danila Torreggiani)
  The basic principles which control osmotic dehydration of fruit and vegetables are reported together with the most important parameters and their influence on the process. The effects of osmosis as a pre-treatment, mainly related to the improvement of nutritional, sensorial and functional properties of the products, are analyzed. The distinctive aspect of this process,

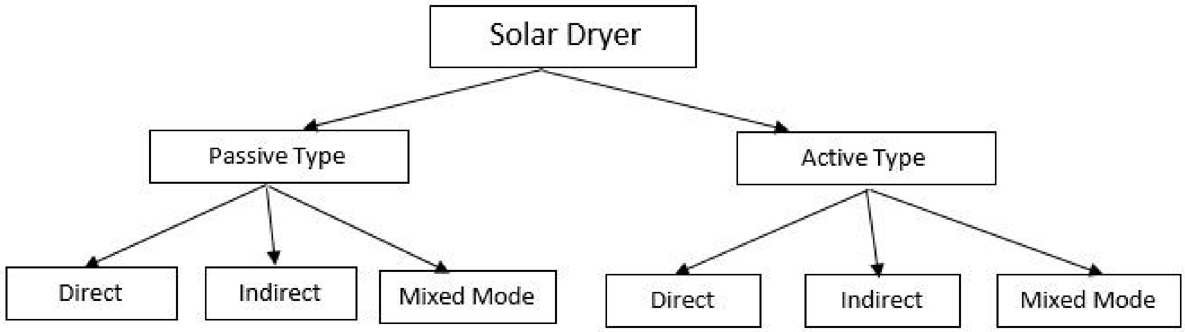
when compared to other dehydration methods, is the ‘direct formulation’ achievable through the selective incorporation of solutes, without modifying the food integrity. By balancing the two main osmotic effects, water loss and soluble solids uptake, the functional properties of fruit and vegetables could be adapted to many different food systems [10].

- Tray dryer system for agricultural products (S. Misha S.Mat, M.H. Ruslan, K. Sopian and E. Salleh)
  Application of tray dryer is widely used in agricultural drying because of its simple design and capability to dry products at high volume. However, the greatest drawback of the tray dryer is uneven drying because of poor air flow distribution in the drying chamber. This paper discussed several designs of tray dryer system for drying agricultural products and its performance [11].

- Study on drying kinetics of summer onion in Bangladesh (Md. Masud Alam, Md. Nurul Islam and Md. Nazrul Islam)
  This study was concerned with the kinetics of drying of summer onion. Drying was done in a mechanical dryer at constant air flow using blanched and unblanched onion with variable temperature (52, 60 and 680C) and thickness (3,5 and 7 mm). Drying rate was increased with increase of temperature and decreased with the increase in thickness in blanched and unblanched onion. Blanched onion showed higher drying rate than unbalanced onion. The activation energy (Ea) for the diffusion of water was found 5.781 Kcal/g-mole for unbalanced and 2.46 Kcal/g-mole for blanched onion when onions were dried in a mechanical dryer [12].

2.2 SOLAR DRYER TECHNOLOGY

The major component of a solar dryer system is a solar collector and a drying chamber. Solar collector absorbs the energy of the sun and heats up the air, which passes through the absorption of the collector. The high temperature and low humidity air, then enter the drying chamber, remove the moisture content from the food to be dried and exits the chamber. There are many types of solar dryer.



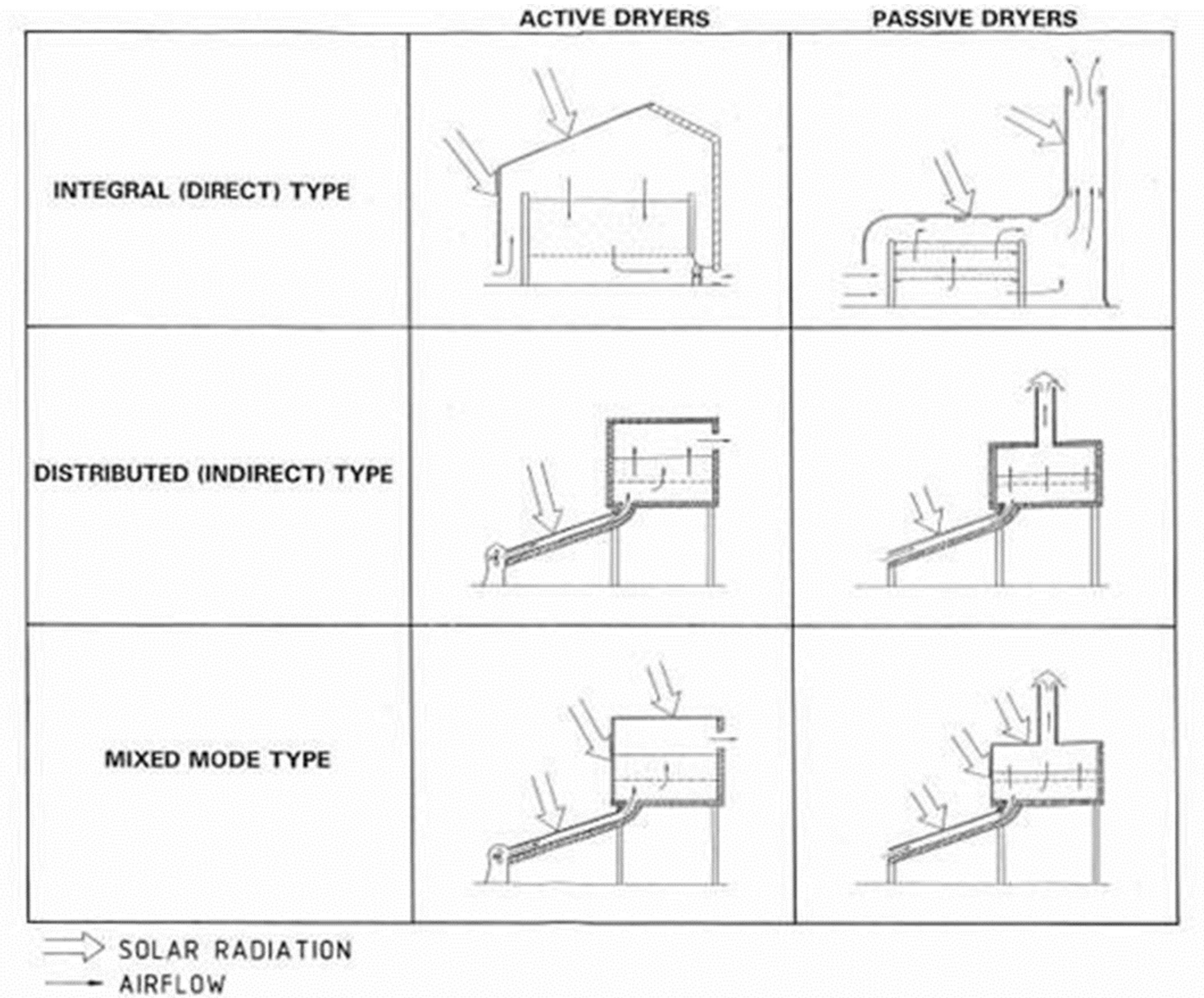


Figure 2-6 Classification of solar dryer

Open Sun Drying

It is the conventional method of food drying, still widely used around the world. It is a method where various crops such as fruits, vegetables, grains, tobacco, etc. are spread on the ground, mat, cement floor and dried for a period of time. But there are many problems associated with the open sun drying method. The problems have been discussed below:

- It requires a large amount of space and a long period of time.
- There is greater risk of spoilage due to bad weather conditions like rain, wind, moist and dust
- Longer wavelength radiation loss of air
- Convective loss due to blowing air
- Conductive loss
- Exposure to direct sunlight, which is undesirable for some foodstuffs
- Infestation by insects
- Attack by animals
- Depending on good weather
- Very slow drying rate

To eradicate the problems of open sun drying problems two drying technologies are developed such as passive type and active type solar dryer.

Passive Solar Drying System

In this system air is heated and circulated naturally by buoyancy force or by wind pressure or by both. Example: Normal and reverse absorber cabinet dryer, green house dryer.
Advantages of this system is it is primitive, inexpensive and easy to install and generate heat.
This system is not suited for drying small batches of food.
Three types of passive types solar drying system are:

1) Indirect type passive solar dryer
   Foods are enclosed in an opaque chamber and hot air is passed into the drying chamber due to natural buoyancy forces. Capacity can be increased by adding more layer of trays. Trays are generally placed vertically in racks with some space between trays. Additional resistance generated for air movement due to this arrangement of trays is achieved.

2) Direct type passive solar dryer
   Foods are in direct exposure to the sun. Color ripening of foods can be enhanced.
   There are two types of direct type passive drying system: Solar cabinet dryer, green house dryer.

   a) Solar cabinet dryer

In this dryer heat transmitted through glass cover which is absorbed in a black surface. Air circulation-warm, moist air leaving via upper vent, under the action of buoyancy forces, generating suction of fresh air from the inlet. Here long plywood chimney is used to enhance natural circulation.

Some of the advantages of this system are, it is very cheap and easy to construct, although it has a poor moist removal rate, overheating of the product.

b) Natural circulation greenhouse dryer

It is one kind of tent dryer. Also, it has extensive glazing by transparent cover of polyethylene sheet. The alignment of this system is length wise north-south. Its internal is black coated or black polyethylene. It has plastic nets to protect foods from insects.

3) Mixed mode, type passive solar dryer

Solar collector and drying chamber have glass cover. Pile of granite as absorber and heat storage.

Active Solar Drying System

Air is circulated through the fan. The heat source is solar energy. Solar energy in the form of heated air has moved from the solar collector area for drying bed. Higher moisture content food can be dried in this system.

Three types of active solar dryer system are:

1) Indirect type active solar drying system

The four components of this system are-solar air heater, drying chamber, fan-for air circulation. Higher temperatures can be obtained here by controlling air flow rate. Efficiency of collector is decreased with a high operating temperature. Optimum temperature and airflow for cost efficiency. Solar collector material are-wood, metal. Recirculation of drying air-ensures low exhaust air temperature. In this dryer efficiency depends on location of the farm.

2) Direct type active solar drying system

Different types of this system are absorption type, storage type and greenhouse dryers. Foods absorb the solar radiation directly.

3) Mixed mode active solar drying system

The mixed mode solar dryer assemblies the features of a solar energy with a conventional source of energy. These dryers are normally medium to large installations operating in the range of 50-60% and compensate the temperature fluctuations induced by the climatic uncertainties.

Different Solar Drying Technology Conducted by Many Researchers

- Development of solar dryer incorporated with evacuated tube collector (T.Rajagopal, S.Sivakumar, R.Manivel)
  In this paper an indirect type forced convection solar dryer is fabricated with the components like evacuated tube collector, drying chamber and blower. The performance of the designed drier is evaluated by carrying drying experiments with copra at Coimbatore district Tamilnadu, India. A short survey of these showed that applying the forced convection solar dryer not only significantly reduced the drying time, but also resulted in many improvements in the quality of the dried products. Solar drying of copra is carried for forced convection and is compared with natural convection solar drying. The temperature of the drying chamber ranges from 49ºC to 78ºC for natural and forced convection while the ambient temperature ranges from 28ºC to 32ºC. Initial moisture content of copra ranges from 51.7% to 52.3% and the final moisture content obtained about 7 to 8%. The forced convection solar dryer takes less time than the natural convection solar dryer to attain the equilibrium moisture content [14].

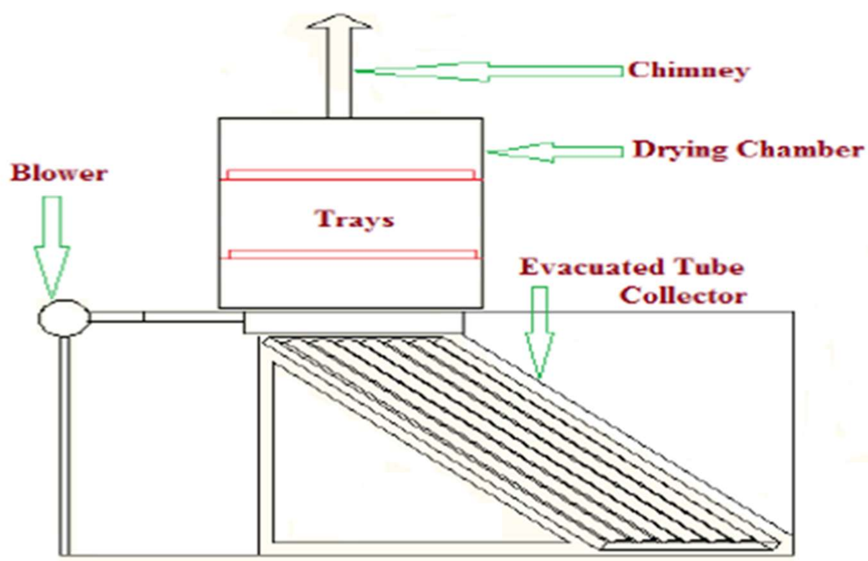


Figure 2-1 Solar dryer with evacuated tube collector

- Design, construction and performance study of a low cost solar dryer for food preservation in Bangladesh (Biswas, Pias Kumar)
  The objective of the thesis is to design, develop and evaluate performance of an indirect solar dryer using thermal energy storage for the drying of vegetables and other foods. Later the future prospects in Bangladesh have been discussed in details. This design was employed by measuring various features such as cost, efficiency, durability and has compared with the performance testing through parameters such as temperature, air velocity, collector efficiency and weight loss [15].

- Solar tunnel fish dryer for seasonal application in the perspective of Bangladesh (M. A. Wazed, M. T. Islam and N. Uddin)
  The main objectives of this research are: i) to design and to fabricate a model type solar tunnel dryer like a solar air heater; ii) to analyze the effectiveness of the dryer; and iii) finally a comparison is performed with traditional method of sun drying. The authors have constructed a simple solar tunnel using local available low cost materials. The collector surface temperature, duct temperature and ambient temperature, as well as relative humidity with definite time interval are measured. The maximum obtained surface and duct temperatures are 52-530C and 37-380C, respectively. The use of solar tunnel dryer leads to a considerable reduction of drying time in comparison to the drying in direct sunlight. The fishes dried in the solar tunnel dryer are completely protected from rain, insects and dust [16].

Figure 2-7 Solar tunnel fish dryer

- The construction and testing of a combined solar and mechanical cabinet dryer (MHR Bhuiyan, MM Alam, MN Islam)
  The combined solar and mechanical dryer was constructed to use solar energy and electrical energy either separately or in combination to conduct air drying. There were various arrangements of drying conditions for mechanical drying system. While for solar drying either no fan or one fan or two fans were used. Different drying conditions were applied by changing the heating source and flow of air. During drying it was observed that 3 mm thick potato slices become wrinkled. On the other hand, 7 and 5mm thick potato slices were selected as the best dried product [17].

- Solar Vacuum Fruit Dryer (Asis, Jay Marvin H, Dacullo, John Jame O, Manalo, Lendl Mark H, Salvador, John Patrick J)
  Here The solar energy is being collected by a solar panel and stores it in a battery. The battery is the electricity source of the vacuum pump. The product will be confined and air is to be evacuated to attain a partial vacuum condition. This will make the products free from dust, insects, and other contaminants. Solar vacuum fruit dryer which can dry 1kg of ripe mango within 10 hours. Drying chamber with at least (12x12x12) in3 [18].

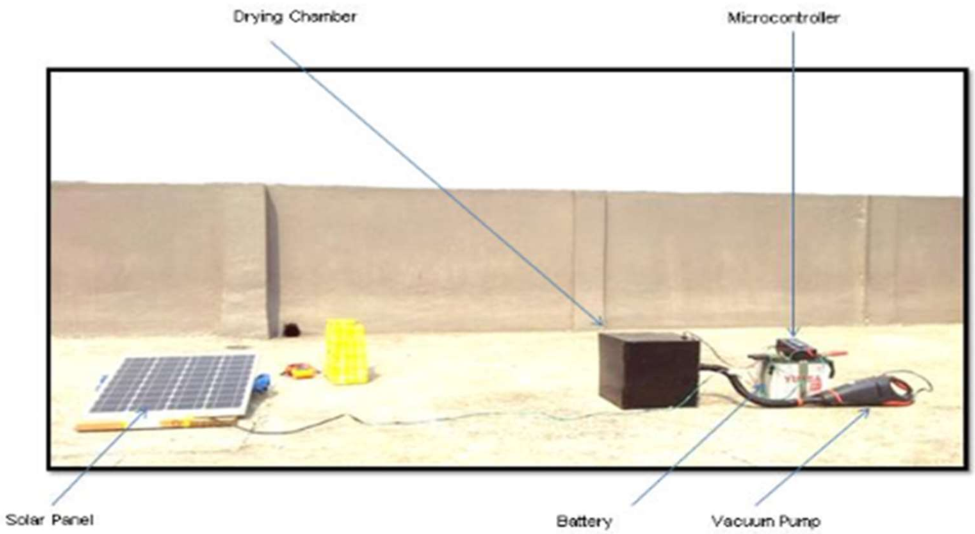


Figure 2-8 Solar vacuum fruit dryer

- Design of mixed-mode natural convection solar crop dryers: Application of principles and rules of thumb (F.K.Forson, M.A.A.Nazha, F.O.Akuffo, H.Rajakaruna)
  In this paper a mixed-mode natural convection solar crop dryer designed and used for drying cassava and other crops in an enclosed structure are presented. A batch of cassava 160 kg of mass, having an initial moisture content of 67% wet basis from which 100 kg of water is required to be removed to have it dried to a desired moisture content of 17% wet basis, is used as the drying load in designing the dryer. A drying time of 30–36 h is assumed for the anticipated test location (Kumasi; 6.7°N,1.6°W) with an expected average solar irradiance of 400 W/m2 and ambient conditions of 25 °C and 77.8% relative humidity. A minimum of 42.4 m2 of solar collection area, according to the design, is required for an expected drying efficiency of 12.5%. Under average ambient conditions of 28.2 °C and 72.1% relative humidity with solar irradiance of 340.4 W/m2, a drying time of 35.5 h was realized and the drying efficiency was evaluated as 12.3% [19].

2.3 SCOPE OF WORK

Lack of effective preservation technology is a major barrier for farmers in our country, as electricity is either inadequate or unaffordable to the small-scale farmers, thus discouraging refrigeration of the farm produce. This has left most farmers, particularly those engaged in small- and medium-scale farming, with no other option than to depend on one of the most abundant and free primary energy resources, the sun. Faced with the challenges of inadequate supply of electricity and to make the farm produce competitive in the international market, the closest solution is the use of solar dryer. This drying technique is not a new concept. But in our country, there are many scopes of work in solar drying technologies. The main target of this thesis is to build a cheap, easy to install/operate, high drying rate, controlled flow rate, zero fuel requirement and environment friendly solar dryer for the farmers and for the food industries of our country.

CHAPTER-3

DESIGN AND CONSTRUCTION OF THE SOLAR DRYER

In this chapter design consideration, conceptual design along with the design and construction of solar dryer components are discussed.

3.1 DESIGN CONSIDERATION

- Location: Dhaka,(Longitude $90°25'E$, Latitude$23°45'N$)
- Drying period: October-November
- Solar intensity: $463\ W/m^2$(Average value during experiment)
- Tilt angle: Tilt angle of solar collector should be such that maximum solar energy is incident on the absorber surface. The choice of tilt angle for solar collector is guided by the angle of altitude of location e.g. for Dhaka ($23°45'N$) the preferred tilt angle would be $23°45'$ facing south. So the tilt of the solar collector was taken $23°45'$.
- Temperature: The minimum and maximum temperature for drying food are 30^0 C and 60^0C. So the temperature inside the solar drying chamber was maintained 55-60^0C.
- Food products: Potato
- Initial moisture content of potato: 78.58% [20].
- Mode of heating: Indirect heating of air
- Number of trays in drying chamber: 4
- Plywood thickness: 15 mm.
- Drying capacity: 1-1.5 kg
- Thickness of the potato slices: 2-4 mm
- Glazing materials: Glass
- Number of glazing: 1
- Thickness of glass: The glazing material should be 4-5 mm thick. Here 4 mm thick transparent glass was used.
- Loading provision: Door at the back side of chamber.
- Air outlet provision: Two hole at each side of the drying chamber (extractor hole) which can be open or close as desired.
- Insulation used: Solar collector and drying chamber was insulated with polyethylene (PE) foam and the air duct was insulated with glass wool.
- Insulation thickness: 20 mm of PE foam.
- Air circulation mode: Forced convection.
- Dimension of collector: (0.94×.73) m^2

- Air velocity: 0.9125 m/s (Average value)
- Emissivity of the absorber: 0.97 [21].
- Transmittance of glass: 0.88 [21].
- Construction materials: Plywood, glass, aluminum wire net.

3.2 CONCEPTUAL DESIGN OF THE DRYER

The laws of electromagnetic radiation absorption and emission play an important part in collector performance. Before these laws can be properly considered some definitions are needed.
The absorptivity, α of a surface can be defined as the fraction of incident radiation, which is absorbed by the surface. Values of absorptivity range from zero for a perfectly reflecting surface, to unity for a blackbody.

A blackbody is a theoretical body which has the following properties:

- It absorbs all radiation incident upon it,
- The level of radiation emitted from a blackbody is a function of temperature only.

For a blackbody exposed to a constant level of radiation, R the amount of energy absorbed per unit of the blackbody, R_a is given by:
$R_a= a_b \times R$
Where, a_b=absorptivity of a blackbody
The absorption of energy will cause the temperature of the body to rise, until at equilibrium the amount of radiation emitted, R_e equals the amount of radiation absorbed
$R_e=Ra=R$
The emissivity, $\varepsilon$of a body as a ratio of the radiation emitted by the body to the radiation which would be emitted by a blackbody at the same temperature. As for absorptivity values of emissivity range from zero to unity for a blackbody.
The rate at which energy is radiated from a black body is proportional to the fourth power of its absolute temperature T,
$R_e = \sigma T^4$
Where,
σ=Stefan-Boltzman constant.
Consideration must be given to a further optical property of materials important in performance of flat plate collectors, this is the transmissivity,τ of clear material used for the collector cover. This is defined as the fraction of the radiation incident upon a clear cover which is permitted to pass through the cover. The ideal cover will permit the passage of sunlight but not the longer infrared wavelengths which are emitted by the absorber surface.

There are two stages in which the energy of sun's radiation is transformed into the thermal energy in the drying air. Firstly, the radiation must be absorbed on the absorber surface, thus heating the absorber plate. The heat is then transferred to the air by contact between air and absorber plate. By viewing the solar collector in this way its design and performance in relation to ambient conditions can be appreciated.

The sun's radiation passes through the glass cover (glazing material) of the solar collector to the fine mesh screen (screen absorber). The screen absorber is made of aluminum. The air is heated mostly as it makes contact on its way through the small holes in the screen, going from the front of the collector to the back and to the drying chamber. Six layers of aluminum wire mesh screen were used to increase total heat transfer to air.

There are several factors affecting the amount of energy absorbed by the absorber plate.

- The level of insolation clearly the higher the insolation, the greater the energy absorbed.
- The angle between incident insolation and the absorber plate surface. The absorber plate should be perpendicular to the insolation.
- The greater the absorptivity of the absorber surface the higher the proportion of incident radiation that will be absorbed.
- The transmissivity of the cover material.

The rate at which the energy absorbed by the transferred to the air is controlled by the pattern of air flow over, below or around the absorber plate. At low velocities, as in natural convection collectors, the airflow pattern will be laminar resulting in poor heat transfer between the absorber plate and the air. As velocity increases the air flow becomes more turbulent and heat transfer improves. Therefore, for a high collection efficiency, high volumetric flow rates in narrow ducts are best. Volumetric flow rates and duct depth are limited by two factors. Firstly, high volumetric flow rates, although giving good collection efficiency will also lead to low temperature increases, and secondly, high volume flow rates in narrow ducts will result in high pressure drops.

The insolation on any collector, no matter what its slope or orientation, will vary over the period during which it is used. Consequently, the heat output of the collector will also vary.
Gluing aluminum foil (reflectors) to the bottom interior of the collector will increase the temperature gained by the air.

In solar drying the rate and distribution of air flow, both through the solar collector and through or across the drying chamber, is of vital importance. The result of insufficient air flow is undesirable long drying times, and with irregular air flow distribution unevenly dried product can result. When a high air flow is required fans are used. There are mainly two types of fan. Axial and centrifugal. Here axial fan is used.

The pressure drop produced by the flow of air through a solar dryer can be usually considered in two parts:

- That encountered in the drying chamber.
- That produced in the solar collector and connecting air ducts.

The pressure drop through the drying chamber, particularly for air flow through a deep bed, will usually be much greater than that through the collector and ducts, indeed the latter can be relatively insignificant. However, if the fan is to be positioned between the collector and the drying chamber, the pressure drop through the former, although much less can be of equal importance as the latter [23].

The drying of materials involves migration of water from the interior of the material to its surface, followed by removal of water from the surface, which requires an amount of heat equals to the latent heat of evaporation of water. This heat is supplied to the drying chamber to dry the food by the solar collector [24].

Temperature, airflow, humidity and food density will all affect a solar dryer's performance. Ideally, high temperatures and heavy airflow, but because changes in one factor also affect all the others, the best food dryers must achieve a balance among these variables. The temperature and humidity inside the drying chamber can also be controlled by opening or closing the two extractor hole at the top on each side of drying chamber. Fully opened holes cause the airflow to increase and the temperature to decrease. In general, more airflow (fully opened holes) is important during the early stages of food drying, while higher temperatures (partially closed holes) are more effective in the later stages of drying [25].

The insulators are used to minimize the heat losses. The thermal conductivity of polyethylene foam is 0.33 W/mK and glass wool is 0.04 W/mK. The air duct can be covered with glass wool to minimize heat losses. The solar collector and drying chamber can be covered with PE foam.

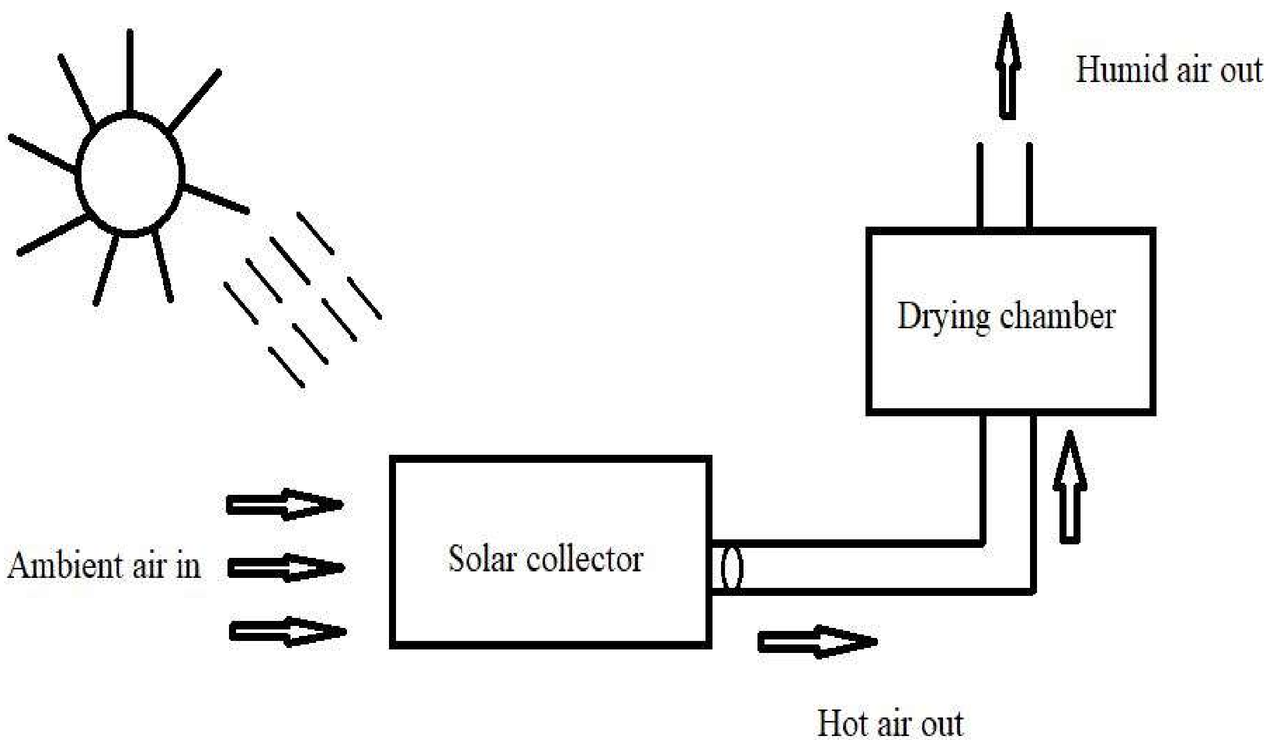


Figure 3-1 Conceptual drawing of solar dryer

3.3 DESIGN OF THE COMPONENT

The complete design of the solar dryer component such as solar collector, drying chamber

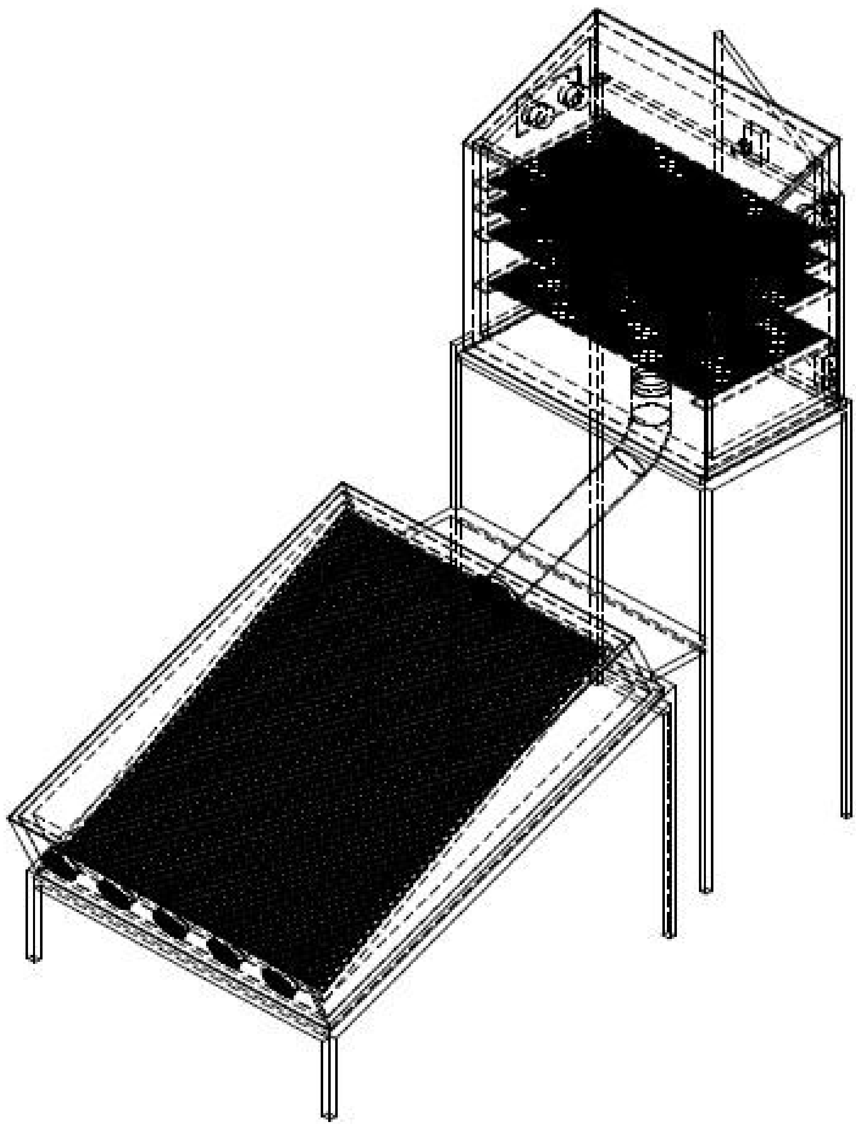


Figure 3-2 Indirect type active solar dryer

3.3.1 DESIGN OF SOLAR COLLECTOR

Solar collector consists of plywood box, glazing material, absorber, fan, air inlet and air outlet holes, reflector, insulator (polyethylene foam).

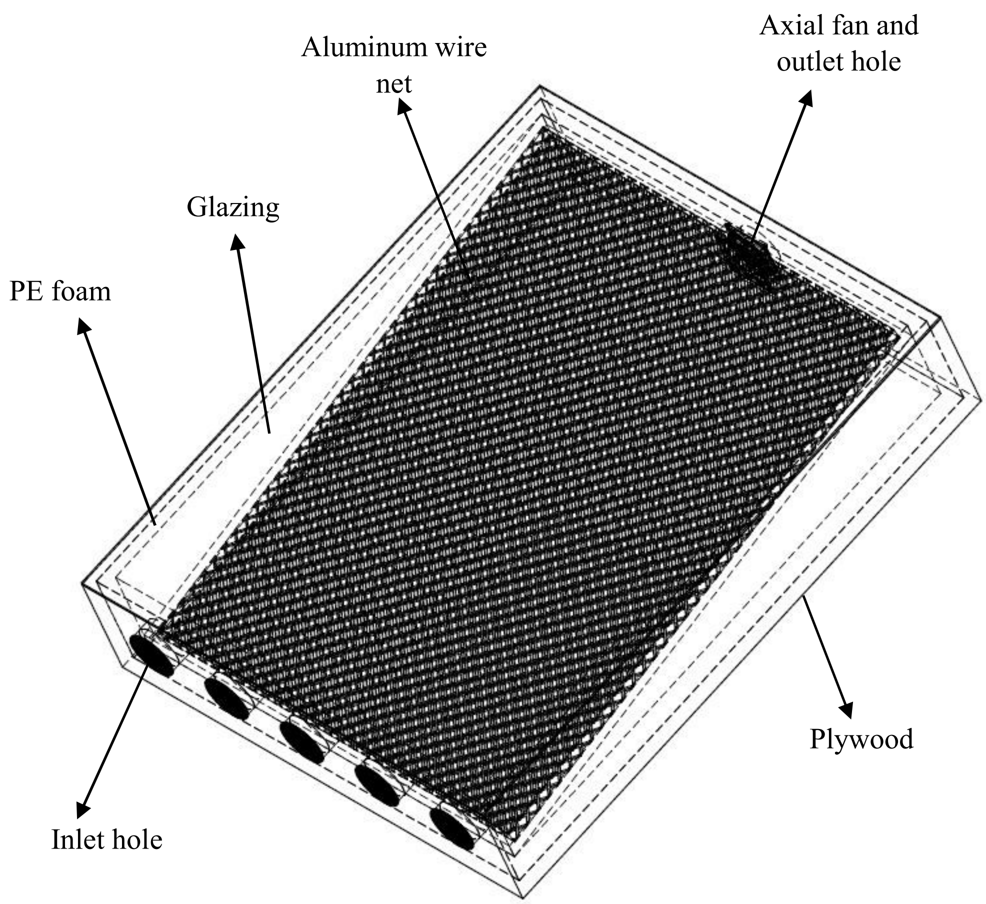


Figure 3-3 Solar collector with screen absorber

Desirable properties of glass cover are:

- High transmissivity in the visible range of the spectrum.
- Low transmissivity of infrared radiation.
- Stability of the operating temperature.
- Durability of weatherability.
- Strength and resistance to breakage.
- Low cost.
- Low weight.

Ramadhani Bakari, Rwaichi J. A. Minja [26] conducted a research to investigate the effect of the thickness of glazing material on the performance of solar collectors. They used low iron (extra clear) glass of thickness 3 mm, 4 mm, 5 mm, and 6 mm was used as glazing materials. They found that collector with 4 mm glass thick gave the best efficiency of 35.4% compared to 27.8% for 6 mm glass thickness.
So a single 4mm glass was selected as a glazing material.

Desirable properties for the absorber in solar collectors are:

- High absorptivity of incident radiation.
- Low emissivity.
- Good thermal conductivity in the case where air flow is below the absorber.
- Stability at the temperatures encountered during operation and under stagnation conditions.
- Durability.
- Low cost.
- Low weight per unit area.

Gary and Scott [27] built 4 by 8 feet prototypes of several different designs and test them side by side. The solar collector they used were backpass collector, empty box collector, aluminum soffit collector, screen absorber collector, downspout collector, pop can collector. Among them, they ranked screen absorber the best because it has a great combination of high performance, low cost, and is a very easy build. This collector also has a low pressure drop which means a smaller (maybe quieter and cheaper) fan can be used to drive it. Screen absorber was the best performer.
So Fine screen mesh was of aluminum wire was selected as an absorber of solar energy after it was painted flat black paint.

Axial fan of diameter 100 mm is selected to draw outside air through the inlet of the solar collector to the drying chamber. Axial fans are very compact, straight through flow, suitable for installing in any position in the run of ducting. They are used in low pressure atmospheric air application. So axial fan was selected. The outlet of the solar collector was designed next to axial fan.

PE foam with thermal conductivity of 0.33 *W/mK* of 20 mm thickness is selected as insulator at all sides of solar collector to minimize heat losses.

Reflectors increase the performance of the solar collector. Aluminum foil tape was attached at the bottom interior of the collector which acts as a reflector.

Five inlet hole is designed to draw more air through the solar collector and to increase the temperature of drying.

Air duct insulated with glass wool is designed to connect the solar collector and the drying chamber so that hot air from a solar collector can enter the drying chamber without any heat losses.

3.3.2 DESIGN OF DRYING CHAMBER

Drying chamber consists of a plywood box, chamber inlet and outlet, 4 trays to hold dried foods, loading door, PE foam.

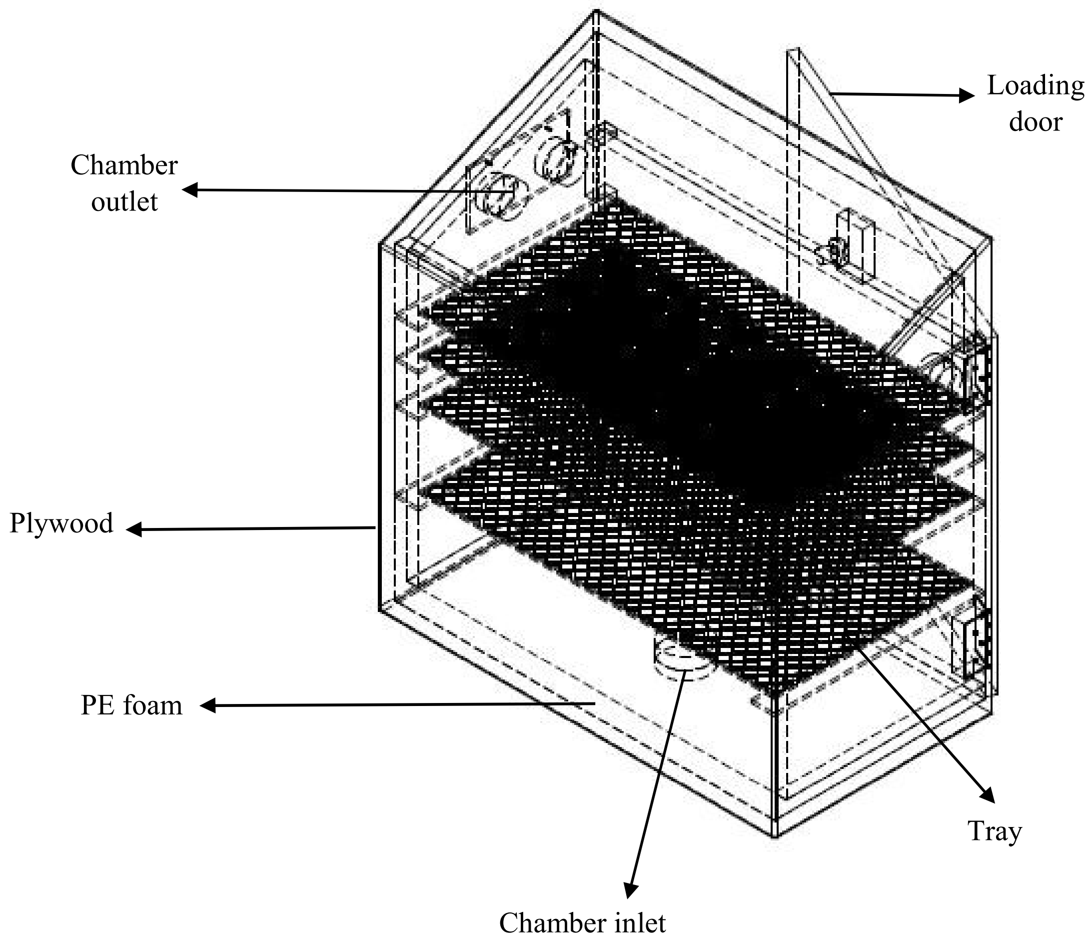


Figure 3-4 Drying chamber

The main structure of the drying chamber is designed to made of low cost plywood of thickness 15 mm. PE foam covered at all sides of the dryer to minimize the heat losses.

High temperature and low humidity air enter the drying chamber through the inlet of the chamber.

4 trays are designed to make of aluminum wire net and can be put in or out of the drying chamber.

The extractor hole at two opposite sides of the drying chamber are designed so that high moisture content air after taking water from the foods can exit easily.

The loading door at the back side of dryer is designed to check dried foods and to load or unload foods easily.

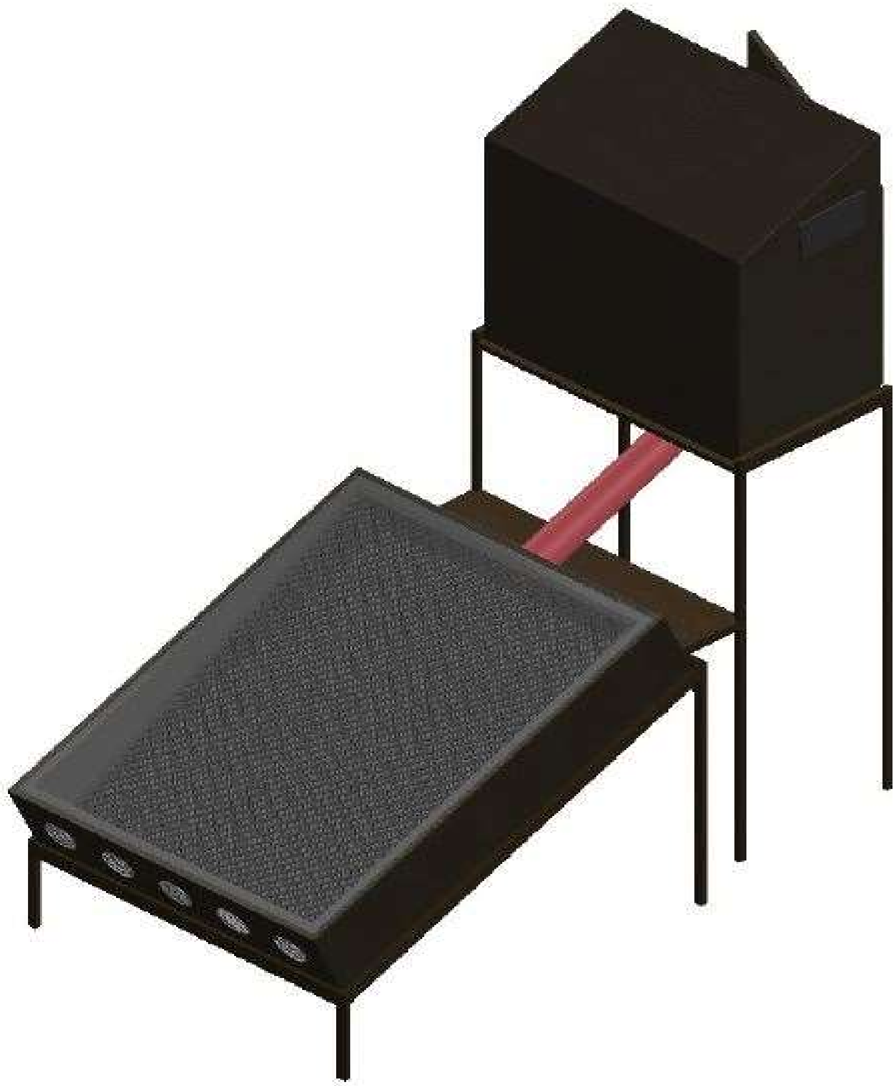


Figure 3-**Error! Unknown switch argument.** Isometric view of designed solar dryer

3.3.3 DESIGN OF CONTROL SYSTEM

Three DHT11 temperature and humidity sensor were used to measure temperature and relative humidity at three sections of the solar dryer such as a collector in (A), collector out (B) and chamber out (C).

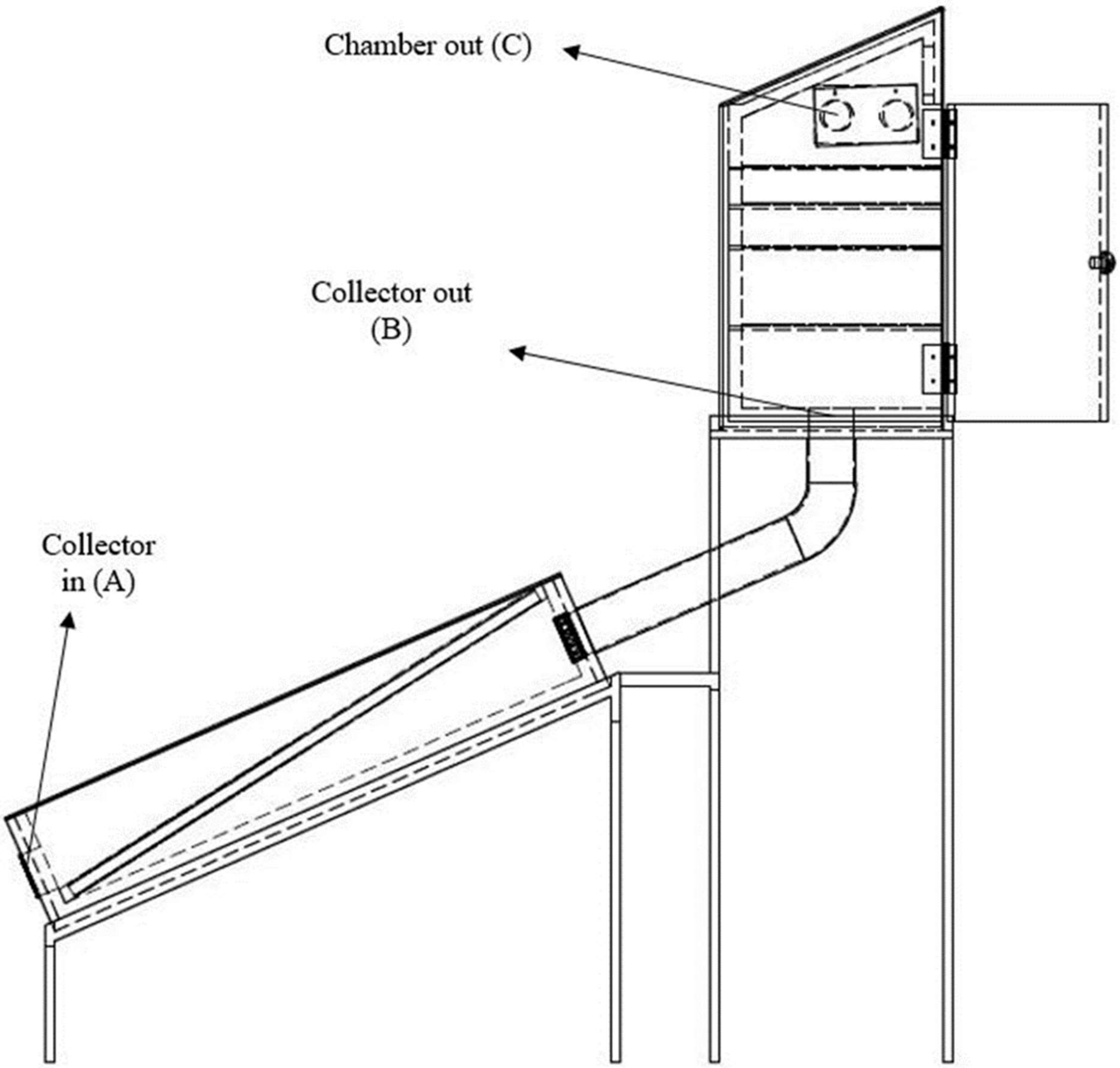


Figure 3-6 Position of three sensors

The circuit diagram for the three humidity sensor controlled by an Arduino is shown in the following figure:

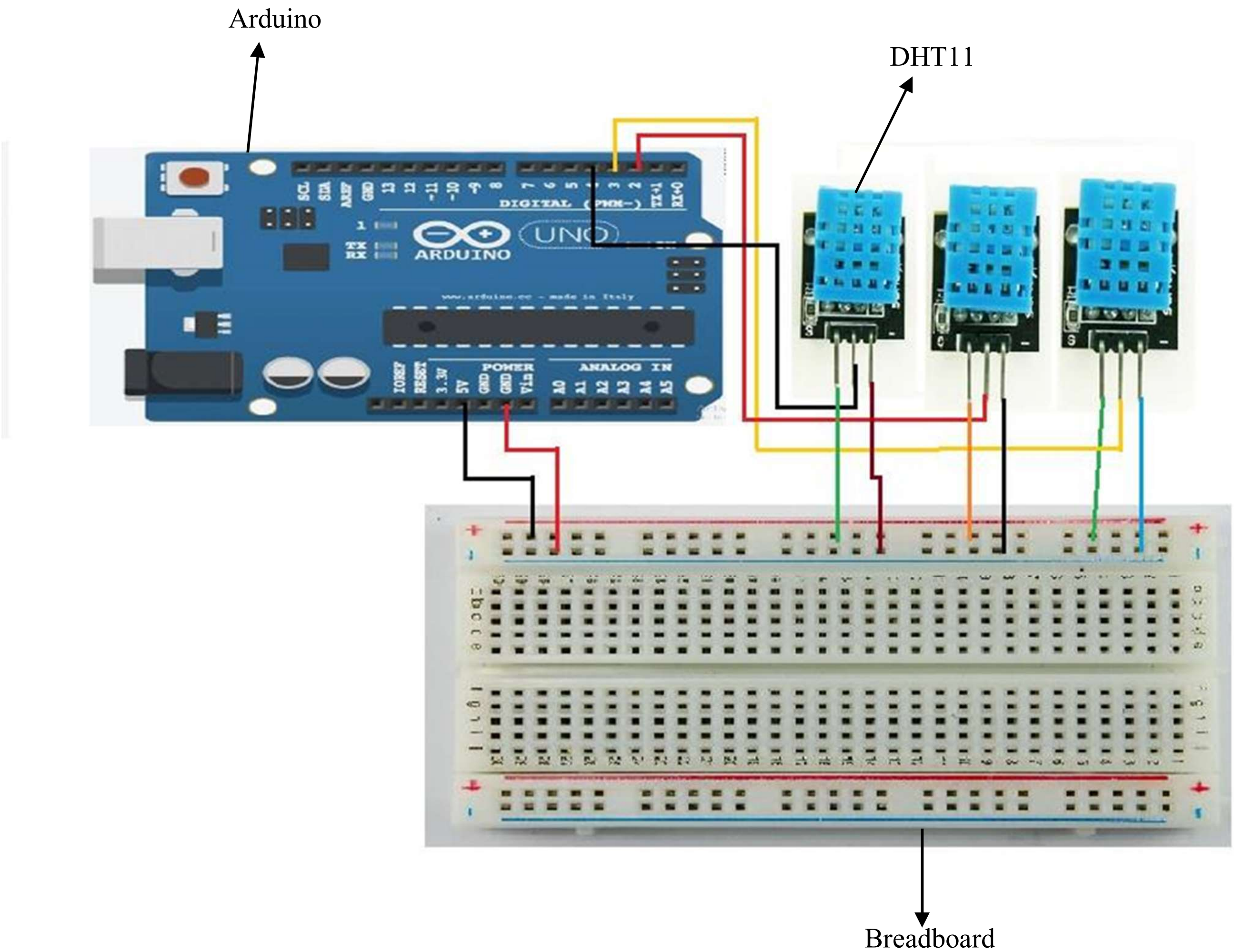


Figure 3-7 Humidity sensor circuit

The flow rate of the fan is controlled by a LM2596 DC-DC boost converter. The electrical energy produced by solar panels is stored in a 12V battery. An input section of LM2596 is connected to the battery and output section is connected to the fan. To reduce the fan speed LM2596 reduces the input voltage, thus supplies lower voltage at output and to increase the speed the output voltage is increased by regulating a screw in the module.

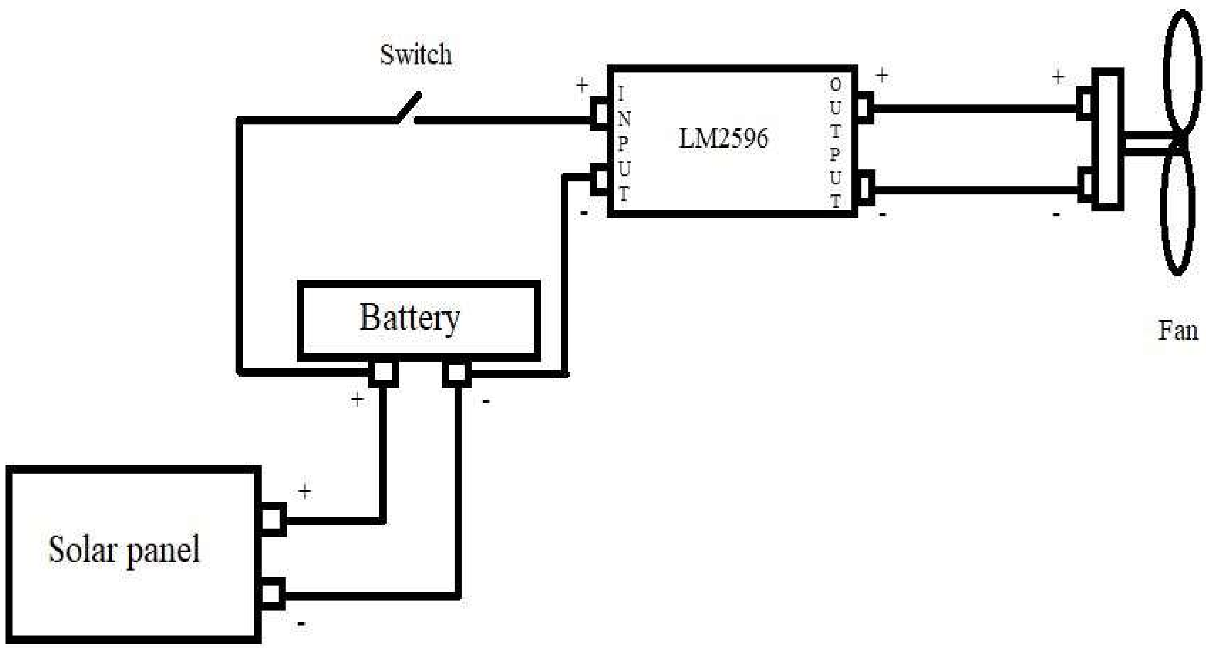


Figure 3-8 Flow control circuit

The whole design of solar dryer is represented in the Appendix D with detailed dimension.

3.4 CONSTRUCTION OF THE SOLAR DRYER

Construction of solar dryer includes construction of solar collector, drying chamber, insulated air duct and control system.

3.4.1 CONSTRUCTION OF SOLAR COLLECTOR

At first the main plywood structure of solar collector was constructed according to the design. The insulator polyethylene foam was cut and then stuck to the sides of the collector with the help of glue. Inlet hole and outlet hole were cut according to the design.

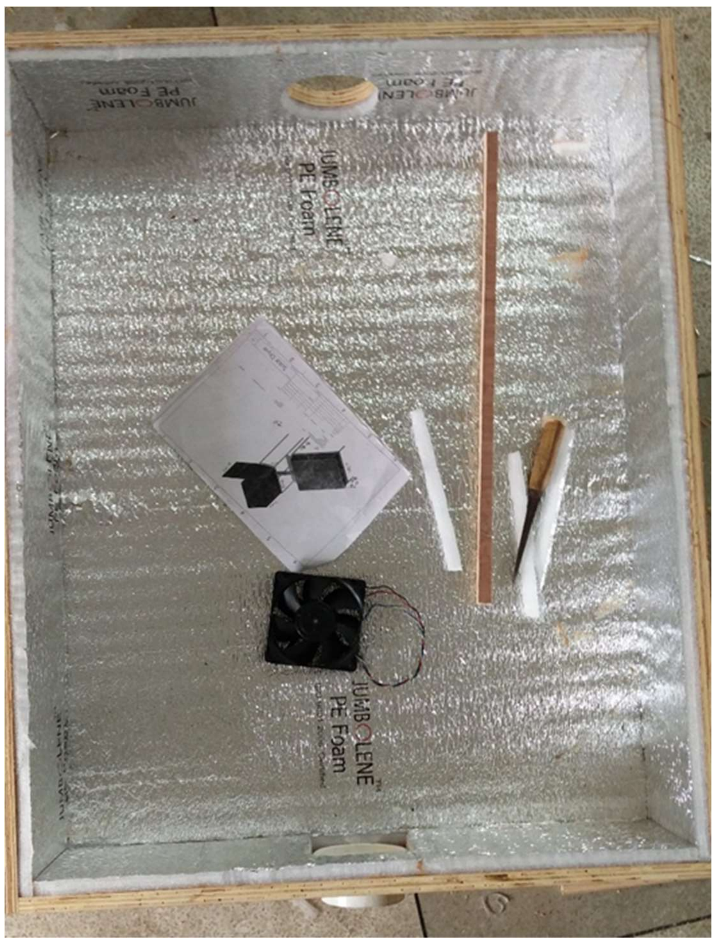


Figure 3-9 Collector covered with PE foam

Then the absorber frame was constructed and six layers of aluminum wire net were pinned to the frame with nail tools. Two layers at bottom, one layer at middle and three layers of aluminum net on top.

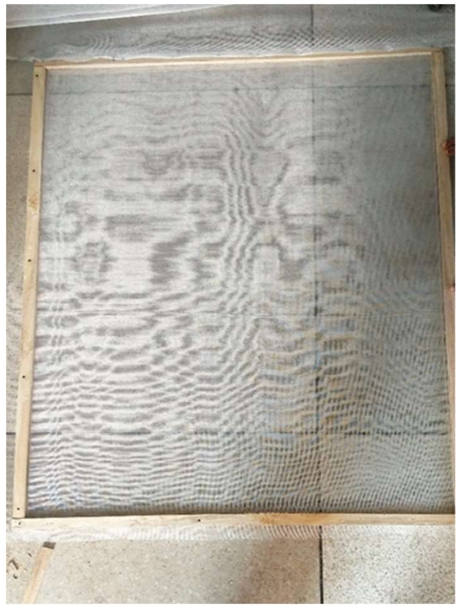


Figure 3-10 Absorber frame with aluminum net

After that screen the absorber was painted with matte black color to ensure maximum solar absorbance.

Figure 3-11 Absorber painted with matte black

The whole structure of solar collector was painted black (exterior and interior both) and wheels were attached at four sides for easy movement of the collector. Aluminum foil tape was attached at the bottom of the collector as a reflector.

Figure 3-12 Collector painted black and reflector attached at bottom

Axial fan was attached at the outlet of the collector with the help of screws.

Figure 3-13 Axial fan at collector outlet

Glazing material (glass, 4 mm thickness) was placed on top of the solar collector and silicon glue was used to fix the glass at the position.

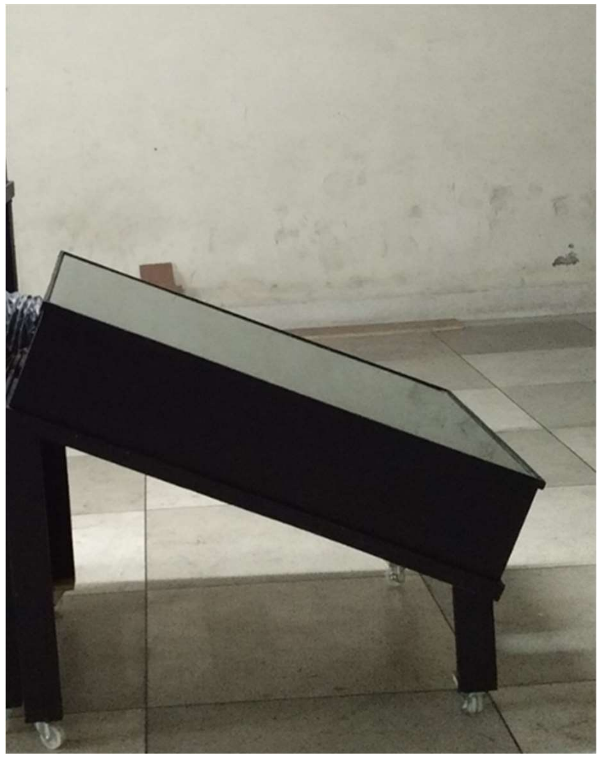


Figure 3-14 Whole collector assembly

3.4.2 CONSTRUCTION OF AIR DUCT

At first, 100 mm air duct was selected for the air duct. To minimize heat losses through air duct was covered with glass wool. After that aluminum foil tape also attached over the glass wool to minimize heat losses further. Then the air duct was tightened and fixed to the inlet of the drying chamber with the help of screws.

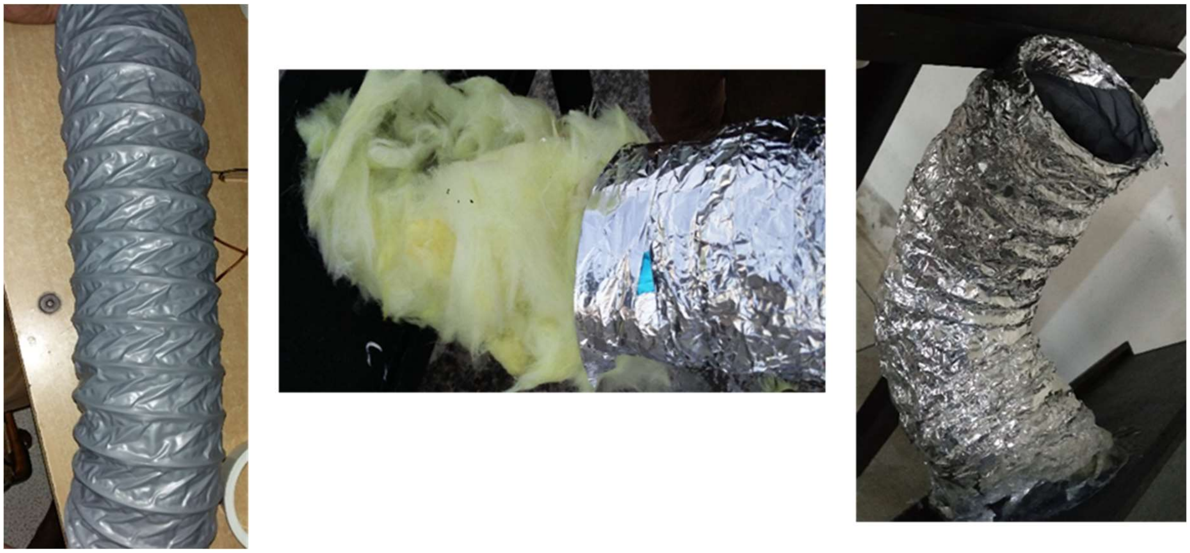


Figure 3-15 Three stages in construction of air duct

3.4.3 CONSTRUCTION OF DRYING CHAMBER

The structure of drying chamber was constructed according to the design and PE foam was attached to the inner surface of the drying chamber to minimize heat losses. At first, 3 shelf was used to hold the trays, then addition, one shelf was made to hold an extra tray. Trays were made of aluminum wire net.

Figure 3-1 Drying chamber with PE foam attached

After that the outer surface of the drying chamber was painted black and also the inlet of the chamber was cut. Four trays were put inside the drying chamber. The loading door was attached to the chamber with the help of a hinge and magnet.

Figure 3-17 Chamber painted black showing 4 trays

At the last outlet of the chamber was cut (2 holes on each opposite side). These extractor holes can be opened or closed. Small plywood piece (one at each side) was used cover the holes. It was fixed in that position with 2 screws. If one screw was unscrewed then this would open the holes partially, in order to open the extractor holes fully two screws was unscrewed.

Figure 3-**Error! Bookmark not defined.** Extractor holes at top which can be opened or closed

Figure 3-16 Solar dryer assembly with all setups

CHAPTER-4

PERFORMANCE STUDY OF THE SOLAR DRYER

This chapter describes the experimental procedures of the solar drying system. The performance of the system is also measured in terms of dryer efficiency, collector efficiency and drying rate. Data measurement, calculation and analysis of the drying system are also shown here.

4.1 METHODOLOGY OF THE ANALYSIS

At first potatoes were sliced. Each slice ranges from 2-4 mm. Then the initial weight of the potato was measured in digital weight machine. Then the trays were taken out of the drying chamber. Potatoes were spread on each tray. Before that weight of each tray was measured. After that the weight of potatoes spread on each tray were measured ([Tray + Potato] – Tray = Potato weight). The trays with potatoes were put in the drying chamber. The solar dryer was moved to a position directly facing south and the same thing for the solar panel. The fan was switched on. At 8.30 a.m. the dry bulb temperature and relative humidity at three sections were measured using three temperature and humidity sensor (DHT11). Also the air flow rate and solar intensity were measured using a digital anemometer and a solar power meter (SM206) respectively. The air flow rate was controlled using a LM2596 DC-DC adjustable step down module, it was adjusted depending on the solar intensity. After one hour, at 9.30 a.m. the weight of potatoes on each tray was measured individually, after the trays were taken out from the chamber. Air flow rate, solar intensity along with dry bulb temp and relative humidity were measured after that. Every hour parameters such as dry bulb temperature, relative humidity, air flow rate, solar intensity along with potato weight were measured. Six data were taken after 9.30 a.m. When the values of relative humidity in collector out and chamber out were coming close to each other the drying process was stopped because at that time evaporation were taken place can be neglected and the potatoes were mostly dry. The final weight of potatoes was taken gathering all the potatoes in a plastic bag. At last, all the circuits were disconnected and the drying process was completed at 3.30 a.m.

Figure 4-1 Potatoes at initial stage (8.30 a.m.)

Figure 4-2 Shrinkage of potatoes takes place

Figure 4-3 Final stage of dried potatoes

Another experiment was conducted to measure and compare the performance between indirect solar dryer designed and open sun drying method. For this equal amount of potatoes was cut. Potatoes were put in the dryer and in open place side by side and they were let to dry. Every 2 hour potatoes weight were taken using weight machine. The experiment was started at 10.00 a.m. and ended at 4.00 p.m. Four data were taken. After that drying rate was calculated separately for both solar dryer and open sun drying method and comparison was made.

(a) (b)

Figure 4-4 Initial stage of potatoes at 10.00 a.m. (a) Potatoes for solar dryer (b) Potatoes for open sun drying method

(a) (b)

Figure 4-5 Final stages of dried potatoesthe solar dryerm. (a) potatoes in solar dryer (b) potatoes in open sun drying method

4.2 INSTRUMENTATION

Different instrument used were weight machine, anemometer, solar power meter, solar panel, infrared thermometer, axial fan (DC), battery, Arduino, breadboard, DHT11, LM2596 etc.

- Weight machine
  Weight machine was used to measure the weight of potatoes. The capacity of weight machine was 5 kg and the accuracy was 1 gram.

- Anemometer
  An anemometer is a wind speed measuring device. It was used to measure the air velocity at the inlet of the drying chamber. It can display the air velocity mph, kph, knots, or metres/sec.

- Solar power meter
  Solar power meter (SM206) was used to measure solar intensity. It can display values in two units W/m^2 and Btu/ft^2-h. It has accuracy of $10W/m^2$. Maximum value it can display is 3999.

- Solar panel
  The solar panel was used to charge the battery. It was 10W, polycrystalline solar panel.

- Infrared thermometer
  Infrared thermometer was used to measure the additional temperatures. It is non-contact and with high accuracy of measurement. Units can be exchanged between ^0C and ^0F. Accuracy was 0.1^0C.

- Axial fan
  Axial fan was used to draw in ambient air to the solar collector. It is a small 12VDC, 1.92W fan with 120 mm diameter. It was connected to LM2596 module to adjust fan speed.

- Battery
  The battery was used to store solar energy and to use it to run the fan. It is 12V, 7.5AH lead acid battery.

- Arduino
  Arduino was used to take input from the humidity sensors and showing the output in the computer.

- DHT11
  Three DHT11 temperature and humidity sensor was used to measure dry bulb temperature and relative humidity was measured at 3 sections of solar dryer. It has high reliability and long term stability

- LM2596
  LM2596 DC-DC boost converter was used to adjust the output voltage at the fan, thus regulating the fan speed.

Figure 4-6 Weight machine

Figure 4-7 Solar panel

Figure 4-8 Solar power meter

Figure 4-9 Infrared Thermometer

Figure 4-10 Anemometer

Figure 4-11 LM2596

4.3 DATA MEASUREMENT

At first solar dryer performance was calculated separately. The initial weight of potatoes = 1.089 kg, Final weight = 0.214 kg. The data (Dry bulb temp, relative humidity of air) were taken from 8.30 a.m. to 3.30 p.m. at three sections of the solar dryer and the absolute humidity, enthalpy and specific volume were calculated from an online psychometric calculator [22]. The experiment was conducted on 12.10.2017.

Table 1 Air properties at three sections (A, B & C) of the solar dryer

Time	Collector in or ambient (A)					Collector out or chamber in (B)					Chamber out (C)				
	Dry bulb temp	Relative Humidity	Absolute Humidity	Enthalpy	Specific Volume	Dry bulb temp	Relative Humidity	Absolute Humidity	Enthalpy	Specific. Volume	Dry bulb Temp	Relative Humidity	Absolute Humidity	Enthalpy	Specific Volume
8:30	34	36	0.011	64.908	0.885	34	36	0.011	64.908	0.885	34	36	0.011	64.908	0.885
9:30	35	46	0.016	77.002	0.894	58	19	0.021	115.472	0.966	45	71	0.044	161.00	0.964
10:30	34	46	0.015	73.655	0.890	57	20	0.022	114.677	0.966	43	63	0.035	134.390	0.945
11:30	33	45	0.014	69.598	0.886	53	21	0.019	102.643	0.950	44	51	0.029	121.376	0.940
12:30	35	38	0.013	69.573	0.890	55	19	0.018	104.539	0.956	40	50	0.023	100.732	0.919
1:30	35	40	0.014	71.424	0.891	57	22	0.024	120.641	0.970	44	33	0.019	96.312	0.924
2:30	35	50	0.018	80.743	0.896	52	19	0.016	94.60	0.943	46	25	0.015	87.306	0.925
3:30	33	55	0.017	74.920	0.890	49	23	0.017	93.390	0.936	41	24	0.011	71.307	0.905

Table 2 Flow rate (m/s) and solar intensity (W/m^2)

Time	Flow Rate (m/s)	Solar Intensity (W/m^2)
8:30	.8	443
9:30	1	508
10:30	1.2	634
11:30	0.9	551
12:30	1	519
1:30	.9	498
2:30	.7	308
3:30	0.6	243

Table 3 Potatoes weight on each tray and total weight of potatoes (kg)

Time	Potato Weight (kg)					Moisture loss (kg)
	Tray 1	Tray 2	Tray 3	Tray 4	Total	
8:30	0.26	0.275	0.282	0.272	1.089	-
9:30	0.199	0.213	0.254	0.213	0.879	0.21
10:30	0.172	0.185	0.181	0.159	0.697	0.182
11:30	0.162	0.15	0.167	0.086	0.565	0.132
12:30	0.12	0.101	0.106	0.058	0.385	0.18
1:30	0.094	0.064	0.079	0.047	0.284	0.101
2:30	0.081	0.049	0.072	0.039	0.241	0.043
3:30	0.073	0.045	0.059	0.037	0.214	0.027

Table 4 Potato weight (kg) in solar dryer and open sun drying method (Experiment conducted on 12.12.2017, Ambient temperature and relative humidity was 290/210C and 50% respectively)

Time	Indirect solar dryer		Open sun drying	
	Potato weight (kg)	Moisture loss (kg)	Potato weight (kg)	Moisture loss (kg)
10:00	1.073	-	1.072	-
12:00	0.696	0.377	0.81	0.262
2:00	0.527	0.169	0.69	0.12
4:00	0.44	0.087	0.512	0.178

4.4 CALCULATION METHOD

The calculation method was carried out in the following order:

Percentage moisture removed from product, $\gamma\%$

$$\gamma\% = \frac{100(m_w - m_d)}{m_w} \quad wet\ basis$$

Final moisture content of product, m_f

$$m_f = m_i \frac{100 - \gamma}{100}\%$$

Amount of moisture removal, m

$$m = \frac{m_w(m_{i\_}m_f)}{100 - m_f}$$

Quantity of heat used in evaporating moisture, Q_e

$$Q_e = mh_{fg}$$

Average drying rate, m_{ave}

$$m_{ave} = \frac{m}{t_d}$$

Efficiency of dryer, η_d

$$\eta_d = \frac{Q_e}{A_c It}$$

Heat output from collector $Q_O = \dot{m}c_p\Delta T = \rho Q C_p \Delta T$

Now,

$$Q = AV = \frac{\pi}{4} \times D^2 \times V$$

Solar collector efficiency, η_c

$$\eta_c = \frac{heat\ energy\ out}{solar\ energy\ in} = \frac{\rho Q C_p \Delta T}{IA_C}$$

CHAPTER 5

RESULTS AND DISCUSSIONS

This chapter represents the results and discussions of the data obtained during an experiment. The performance of the solar dryer was compared with the traditional sun drying method. Graphs were drawn to visualize the data more easily.

Relative humidity vs time was plotted on the graph at three sections of the solar dryer at collector inlet (A), collector outlet (B) and chamber outlet (C) from 8.30 a.m. to 3.30 p.m. at one hour interval. It was seen at first, at all sections the relative humidity was same. When the air start heating in the solar collector the relative humidity began to decrease and on average it was around 20%. The hot air from the collector entered the drying chamber evaporate moisture from the products so the relative humidity at chamber outlet began to increase at 9.30 a.m. it is 71%. As the foods began to dry the relative humidity begins to decrease this indicate that evaporation rate was decreasing as the time passes. When the relative humidity at chamber outlet and collector outlet were close to each other drying was stopped because negligible moisture was evaporated from that point. At collector inlet relative humidity was highest 55% at 3.30 a.m.

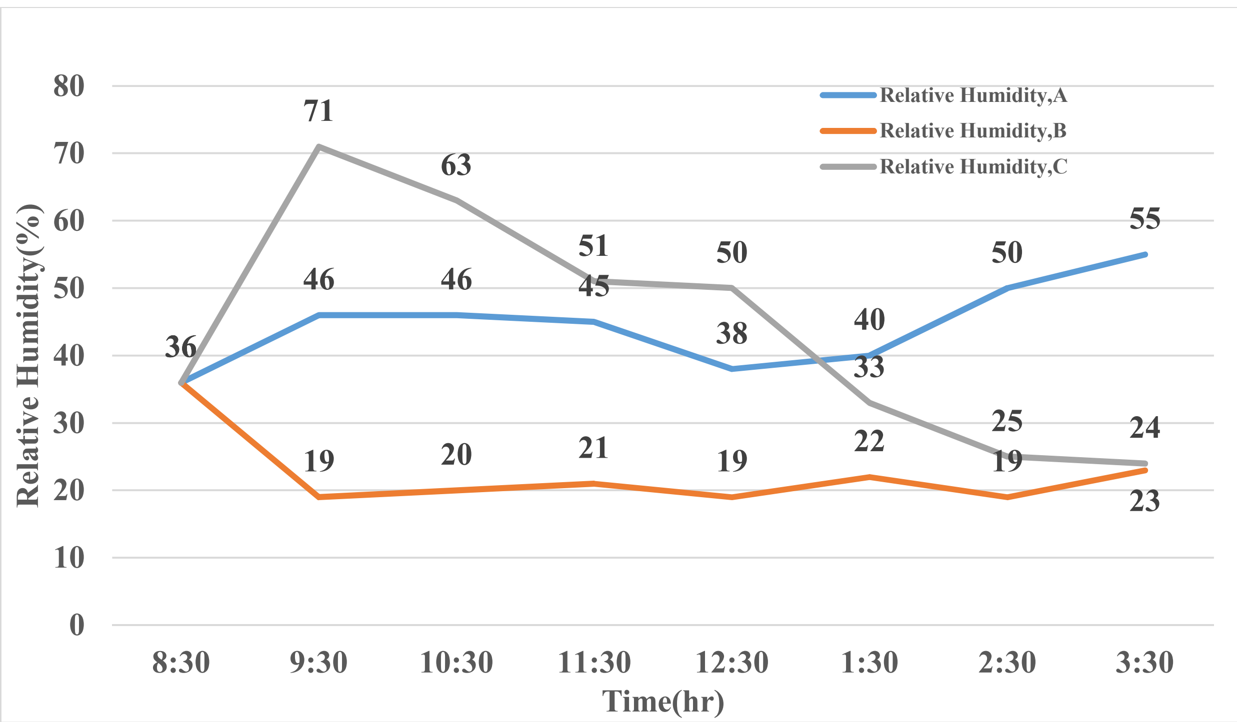


Figure 5-1 Relative humidity vs Time

Dry bulb temperature at three sections were measured and plotted against time. The highest temperature attained inside the solar drying chamber was 58^0C at 9.30 a.m. and minimum temperature was 49^0C at 3.30 p.m. The maximum temperature at the chamber outlet was 46^0C and minimum was 40^0C. The highest temperature of ambient was 33^0C.

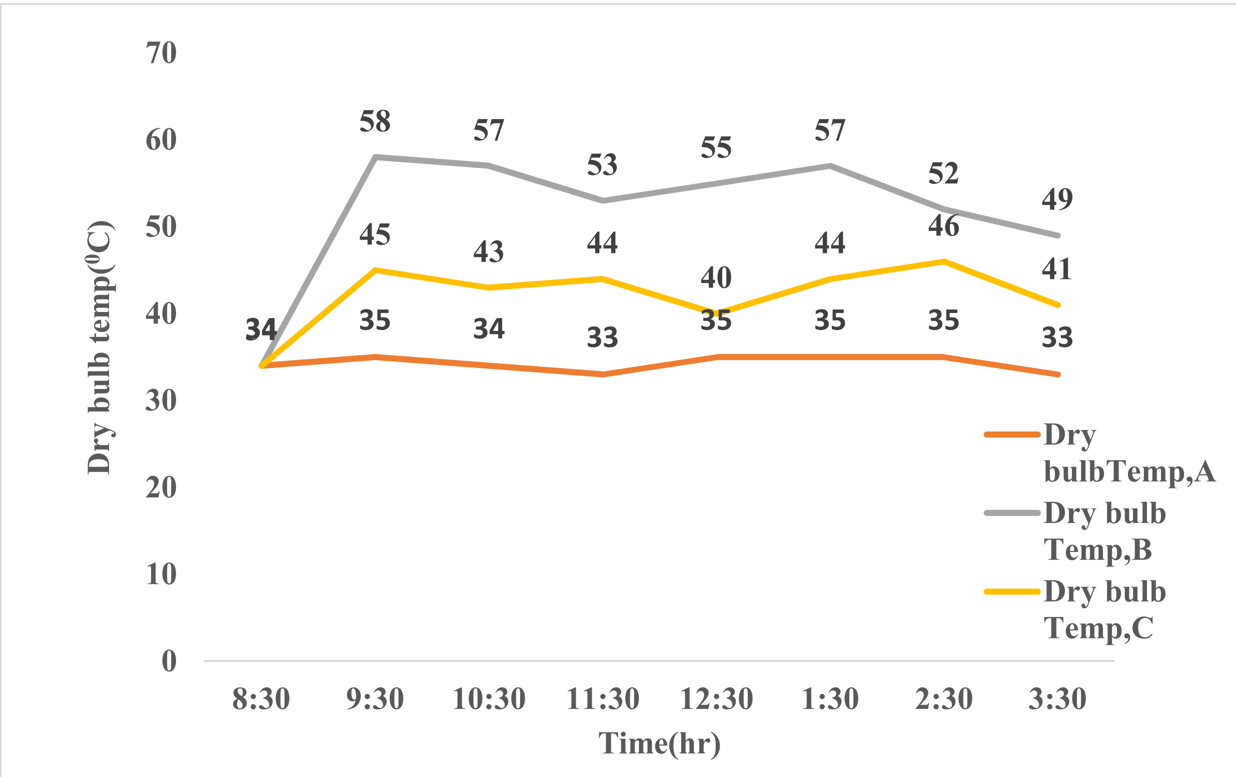


Figure 5-2 Dry bulb temp vs Time

Solar intensity vs time graph was plotted from 8.30 a.m. to 3.30 p.m. and maximum solar intensity was found 634 W/m2 at 10.30 a.m. andthe minimumm was 243 W/m2. The solar intensity first increase, from 8.30 a.m. to 10.30 a.m. and then began to decrease to 243 W/m2.

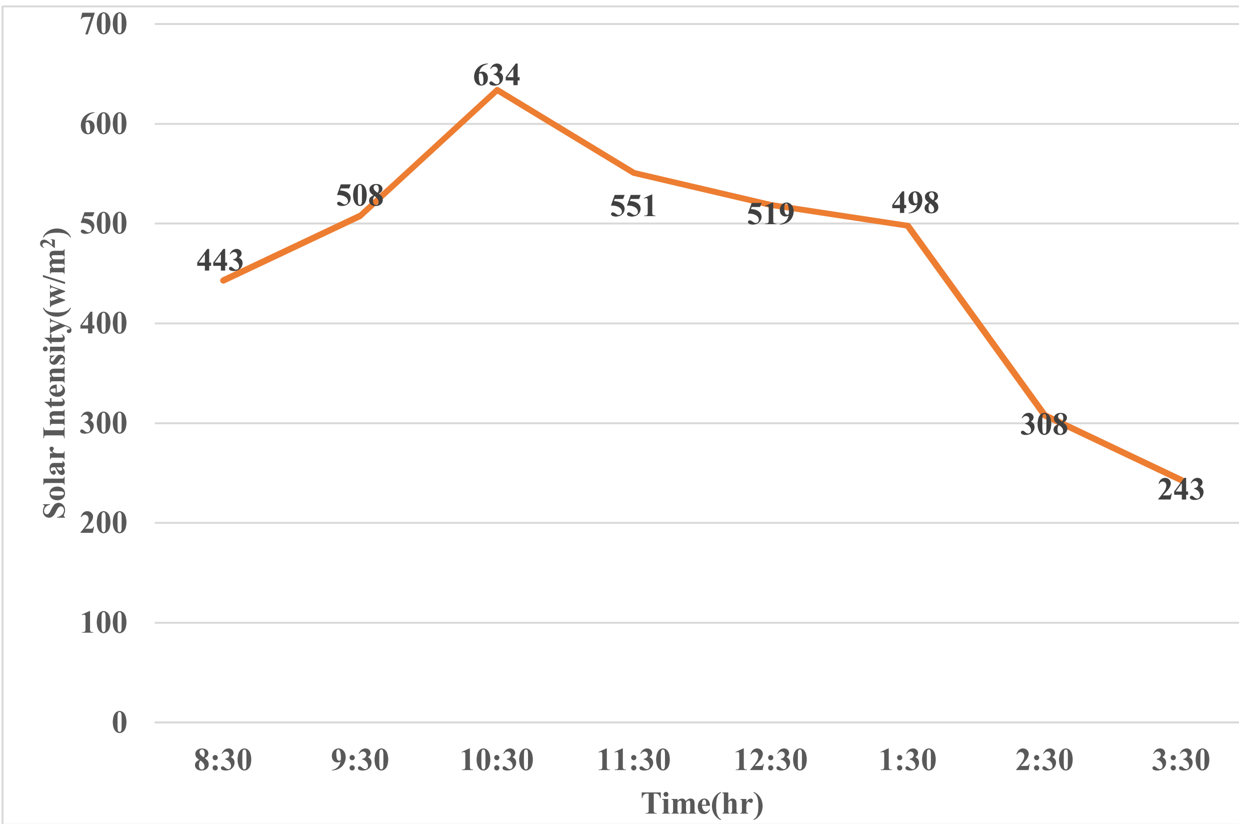


Figure 5-3 Solar intensity vs Time

Total weight of potato vs time was plotted from 8.30 a.m. to 3.30 p.m. Initial weight of 1.089 kg and as it dried the weight of potatoes decreased gradually until it reached to the final weight 0.214 kg.

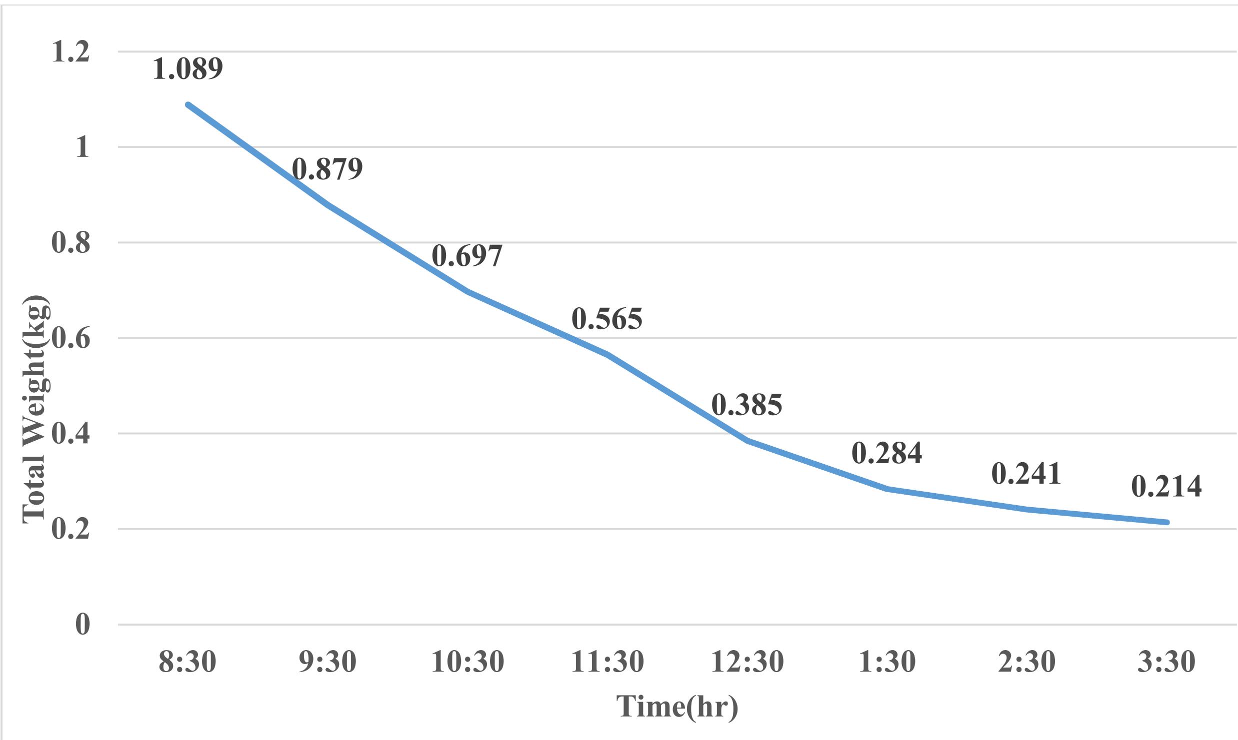


Figure 5-4 Total weight vs Time

The flow rate was changed according to the intensity of solar using a LM2596 module and maximum value was 1.2 m/s at solar intensity 634 W/m^2.

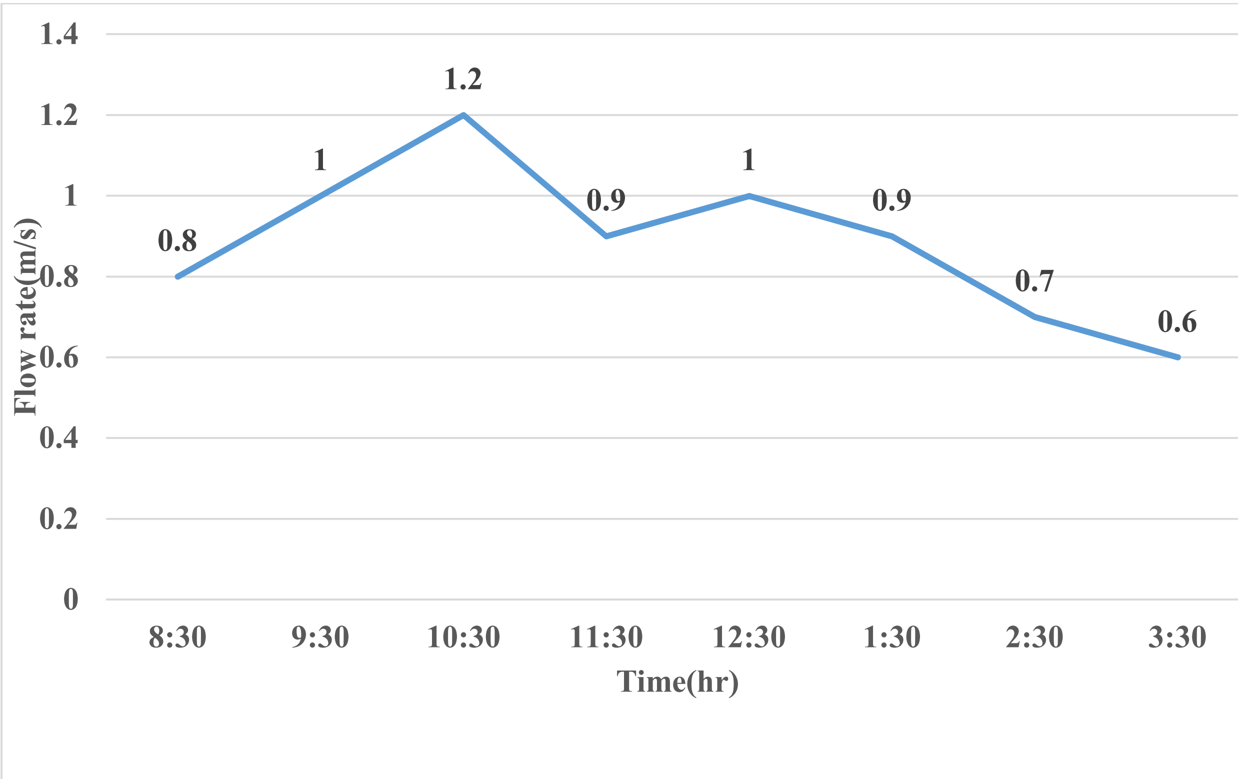


Figure 5-5 Flow rate vs Time

The efficiency of the solar collector found 60.71% and the dryer efficiency was found 23.08%. It is seen that the efficiency of the collector is much higher than dryer efficiency, so this solar collector could dry more products within that time period. Efficiency of dryer could have been increased if the dryer capacity was more.

In order to compare the performance between indirect solar dryer and traditional sun drying method another experiment was conducted. From the graph it was seen that at 12 p.m. the potato weight in indirect dryer 0.696 kg and in open sun drying 0.81 kg. At 4 p.m. potato weight in solar dryer was 0.44 kg and in traditional method 0.512 kg. It was seen that potato weight in solar dryer is much less than in the open sun drying method. The drying rate was 0.1223 kg/hr and 0.1173 kg/hr in solar dryer and open sun drying method respectively. The rate was much faster in the solar dryer than open sun drying method.

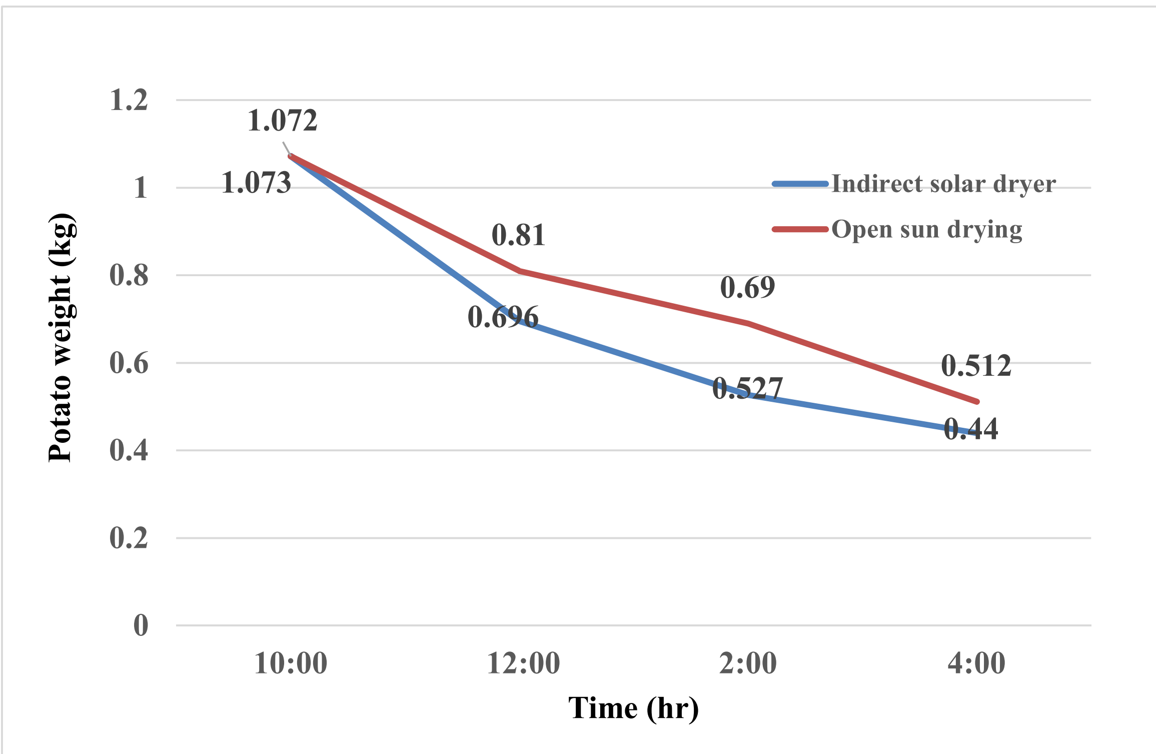


Figure 5-6 Potato weight vs Time (for indirect solar dryer and open sun drying method)

CHAPTER 6

CONCLUSION, RECOMMENDATION AND LIMITATION

6.1 CONCLUSION

Designing the solar dryer, design considerations, design calculations these are very important parameters. From the above parameters the solar dryer can raise the ambient air temperature to a considerable high value for increasing the drying rate of agricultural products. Although the dryer was used to dry potatoes, it can be used to dry other products like banana, grape, mango, apple etc. The collector and dryer efficiencies was 60.01% and 23.08% respectively, moisture content removal of 80.35% and average drying rate of .1161 kg/hr were recorded during solar drying of potato. To compare the performance between solar dryer and open sun drying another experiment was conducted. From that experimental data it was seen that solar dryer performance was better compared to the open sun drying.

6.2 RECOMMENDATIONS

Thermal energy can be implemented for drying purposes. Methods of storing solar energy are as sensible heat (in a bed of rocks or in the water tank) or as latent heat (in a material which changes phase, Glaubers salt). Using these drying period may be extended into the evening.

The mass flow rate of air must be kept as low as possible considering the outlet air temperature so that reduced drying time with increased efficiency can be obtained.

The performance of the designed solar dryer can be increased by doing mathematical modeling and simulation.

Here fan speed was controlled manually depending on the solar intensity. In future temperature controlled fan can be incorporated where specific temperature can be set in the drying chamber and to maintain that temperature fan speed will regulate automatically.

The temperature inside the drying chamber can be increased by incorporating baffles in the solar collector. Baffle restrains the flow of air so that more air can take up heat from the screen absorber. It strengthens the convective heat transfer process and lessen the radiation heat loss.

In future solar tracker can be used to minimize the angle of incidence between the incoming sunlight and solar collector.

In the future capacity of the drying chamber can be increased to take it to the commercial stage.

6.3 LIMITATION

From the meteorological data it was seen that maximum solar irradiation in Dhaka is in the month of April to June. Experiments were conducted in the month of October to November in which solar irradiation was not high. If the experiment could be conducted in the month of April to June higher efficiencies could have been achieved.

Heavy rain and cloudy weather were the major problems while data collection in the month of October. The efficiency of the solar dryer was found minimum in winter season.

Financial problem was one of the problems while conducting this thesis.

The primary concern of performance evaluation is the drying performance in terms of drying rate and moisture content of the product. The characteristics of the product such as texture, uniform dryness and color will only be evaluated using naked senses. Those characteristics does not deserve deeper consideration in this study because the main purpose of drying is to eliminate moisture in the raw material therefore it is the moisture content that really matters.

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APPENDIX A

Nomenclature

T Temperature, ^0C
I Average Solar intensity, W/m^2
m Amount of moisture removal, kg
Q_e Quantity of heat used in evaporating moisture, kJ/kg
h_{fg} Latent heat of vaporization, J/kg
A_c Area of solar collector, m^2
V Average Velocity of air, m/s
Q Volumetric flow rate, m^3/s
Q_o Heat output from collector, J/s
C_p Specific heat capacity, kJ/ kg ^0K
γ Moisture removal %
t Drying time, s
$\dot{m}$ Mass flow rate, kg/s
ΔT Temperature difference, ^0C
ρ Air density, kg/m^3
η Efficiency, %
m_{ave} Average drying rate, kg/hr
D Air Duct diameter, m

Subscript

i Initial
f Final
w Wet product
d Drying chamber, dried product
c Collector
ave Average

APPENDIX B

Detailed calculation for measuring the performance of solar collector and dryer (Experiment conducted on 12.10.2017)

Percentage moisture removed from product, $\gamma\%$

$$\gamma\% = \frac{100(m_w - m_d)}{m_w} \quad wet\ basis$$

$$= \frac{100(1.089 - .214)}{1.089}$$

$$= 80.35\%$$

Final moisture content of product, m_f

$$m_f = m_i \frac{100 - \gamma}{100}\%$$

$$= 78.58 \times \frac{100 \qquad .35}{100}\%$$ (inital moisture [29])

$$= 15.44\%$$

Amount of moisture removal, m

$$m = \frac{m_w(m_{i-}m_f)}{100 - m_f}$$

$$= \frac{1.089(78.58 - 15.44)}{100 - 15.44}$$

$= .813$ kg

Quantity of heat used in evaporating moisture, Q_e

$$Q_e = mh_{fg}$$

$= .813 \times 2257$ (latent heat of vaporization h_{fg} [29])

$$= 1834.941\ {}^{kj}/_{kg}$$

Average drying rate, m_{ave}

$$m_{ave} = \frac{m}{t_d}$$

$$= \frac{.813}{7}$$

$$= .1161 \, {}^{kg}/_{hr}$$

Where, $t_d = sunshine\ hours\ per\ day$

Efficiency of dryer, η_d

$$\eta_d = \frac{Q_e}{A_c I t}$$

$$\frac{1848.48 \times 10^3}{.94 \times .73 \times 463 \times 7 \times 3600}$$

$$= 23.08\ \%$$

Where, t = drying time

$$Q = A_c V = \frac{\pi}{4} \times D^2 \times V$$

$$= .94 \times .73 \times .9125$$

$$= .00717 \text{m}^3/\text{s}$$

Heat output from collector $Q_O = \dot{m} c_p \Delta T = \rho Q C_p \Delta T$

$$= 1.0656 \times .00717 \times (58 - 33) \times 1.01 \times 10^3$$

$$= 192.91 \, {}^{J}/_{S}$$

Here,

$\rho = 1.0656\ kg/m^3, C_p = 1007 \, {}^{J}/_{kg.k}$ (ρ and C_p are taken from [21] at 58^0C)

Solar collector efficiency, η_c

$$\eta_c = \frac{heat\ energy\ out}{solar\ energy\ in} = \frac{\rho Q C_p \Delta T}{I A_C}$$

$$= \frac{192.91}{463 \times .94 \times .73}$$

$$= 60.71\%$$

Experiment conducted on 12.12.2017 to compare the performance between indirect solar dryer and open sun drying method. The drying rate of the two system were calculated as follows:

For indirect solar dryer:

Percentage moisture removed from product, $\gamma\%$

$$\gamma\% = \frac{100(m_w - m_d)}{m_w} \quad wet\ basis$$

$$= \frac{100(1.073 - .440)}{1.073}$$

$$= 58.99\%$$

Final moisture content of product, m_f

$$m_f = m_i \frac{100 - \gamma}{100}\%$$

$$= 78.58 \frac{100 - 58.99}{100}\%$$

$$= 32.22\%$$

Amount of moisture removal, m

$$m = \frac{m_w(m_{i\_}m_f)}{100 - m_f}$$

$$= \frac{1.073(78.58 - 32.22)}{100 - 32.22}$$

$= .734$ kg

Average drying rate, m_{ave}

$$m_{ave} = \frac{m}{t_d}$$

$$= \frac{.734}{6}$$

$= .1223\ {}^{kg}/_{hr}$

For open sun drying method:

Percentage moisture removed from product, $\gamma\%$

$$\gamma\% = \frac{100(m_w - m_d)}{m_w} \ \ wet\ basis$$

$$= \frac{100(1.072 - .512)}{1.072}$$

$$= 52.23\%$$

Final moisture content of product,m_f

$$m_f = m_i \frac{100 - \gamma}{100}\%$$

$$= 78.58 \frac{100 - 52.23}{100}\%$$

$$= 37.54\%$$

Amount of moisture removal, m

$$m = \frac{m_w(m_{i-}m_f)}{100 - m_f}$$

$$= \frac{1.073(78.58 - 37.54)}{100 - 37.54}$$

= .704 kg

Average drying rate, m_{ave}

$$m_{ave} = \frac{m}{t_d}$$

$$= \frac{.704}{6}$$

$$= .1173\ {}^{kg}/_{hr}$$

APPENDIX C

The code that was used to measure the temperature and humidity with three DHT11 sensor is given below:

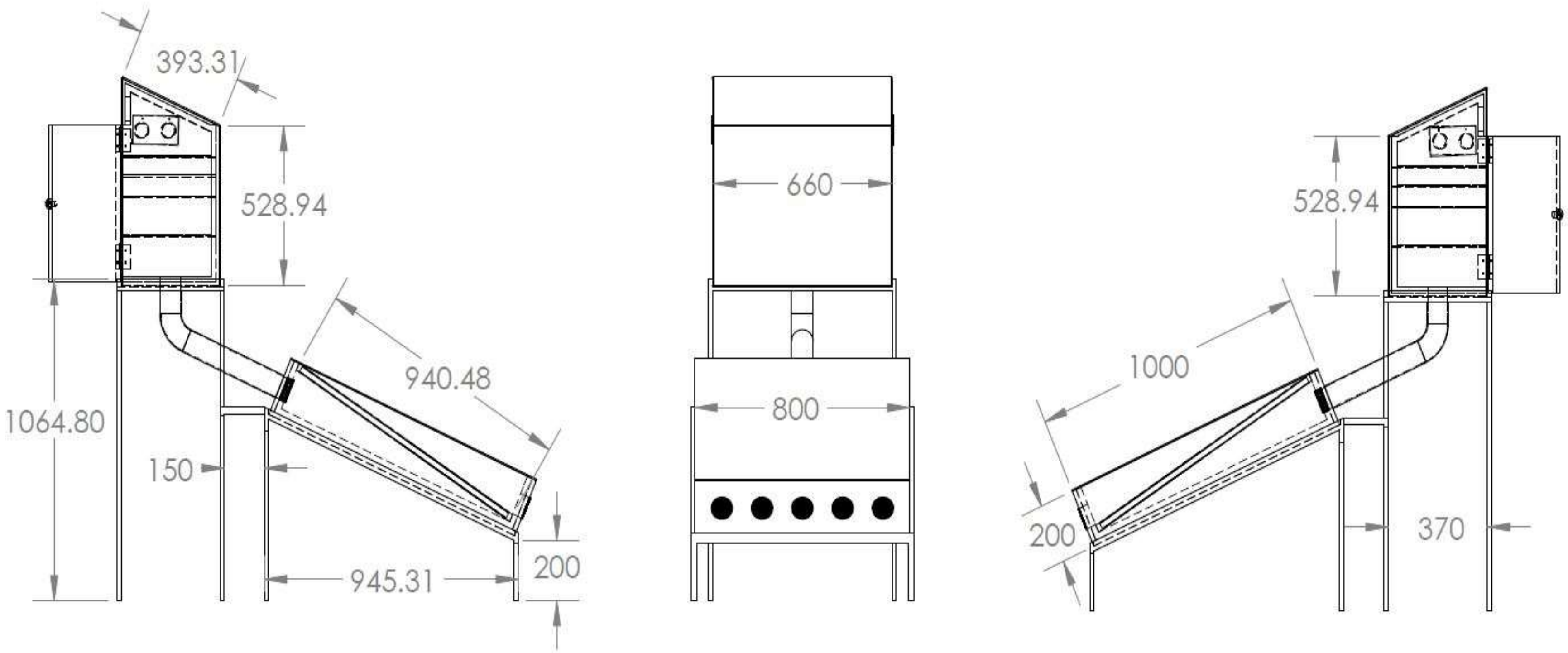
```
#include "DHT.h"

#define DHT1PIN 2     // what pin we're connected to
#define DHT2PIN 3
#define DHT3PIN 4

// Uncomment whatever type you're using!
#define DHT1TYPE DHT11   // DHT 11
#define DHT2TYPE DHT11   // DHT 11  (AM2302)
#define DHT3TYPE DHT11
//#define DHTTYPE DHT21   // DHT 21 (AM2301)

// Connect pin 1 (on the left) of the sensor to +5V
// Connect pin 2 of the sensor to whatever your DHTPIN is
// Connect pin 4 (on the right) of the sensor to GRO
// Connect a 10K resistor from pin 2 (data) to pin 1 (power) of the sensor
int val1;
int val2;
int val3;
int tempPin1 = 1;
int tempPin2 = 2;
int tempPin3 = 3;
DHT dht1(DHT1PIN, DHT1TYPE);
DHT dht2(DHT2PIN, DHT2TYPE);
DHT dht3(DHT3PIN, DHT3TYPE);
void setup() {
  Serial.begin(9600);
  Serial.println("DHTxx test!");

  dht1.begin();
  dht2.begin();
  dht3.begin();
}
void loop() {
  // Reading temperature or humidity takes about 250 milliseconds!
  // Sensor readings may also be up to 2 seconds 'old' (its a very slow sensor)
```

```
  float h1 = dht1.readHumidity();
  float t1 = dht1.readTemperature();
  float h2 = dht2.readHumidity();
  float t2 = dht2.readTemperature();
  float h3 = dht3.readHumidity();
  float t3 = dht3.readTemperature();
  val1 = analogRead(tempPin1);
float mv1 = ( val1/1024.0)*5000;
float cel1 = mv1/10;
float farh1 = (cel1*9)/5 + 32;
val2 = analogRead(tempPin2);
float mv2 = ( val2/1024.0)*5000;
float cel2 = mv2/10;
float farh2 = (cel2*9)/5 + 32;
val3 = analogRead(tempPin3);
float mv3 = ( val3/1024.0)*5000;
float cel3 = mv3/10;
float farh3 = (cel3*9)/5 + 32;
  // check if returns are valid, if they are NaN (not a number) then something went wrong!
  if (isnan(t1) || isnan(h1)) {
    Serial.println("Failed to read from DHT #1");
    delay(2000);
  } else {
    Serial.print("Humidity 1: ");
    Serial.print(h1);
    Serial.print(" %\t");
    Serial.print("TEMPRATURE 1st of LM35= ");
Serial.print(cel1);
Serial.print("*C");
Serial.println();
     delay(2000);
    Serial.print("Temperature 1: ");
    Serial.print(t1);
    Serial.println(" *C");
     delay(2000);
  }
  if (isnan(t2) || isnan(h2)) {
    Serial.println("Failed to read from DHT #2");
     delay(2000);
  } else {
    Serial.print("Humidity 2: ");
    Serial.print(h2);
    Serial.print(" %\t");
```

```
    Serial.print("TEMPRATURE 2nd of LM35= ");
Serial.print(cel2);
Serial.print("*C");
Serial.println();
     delay(2000);
    Serial.print("Temperature 2: ");
    Serial.print(t2);
    Serial.println(" *C");
     delay(2000);
  }
  if (isnan(t3) || isnan(h3)) {
    Serial.println("Failed to read from DHT #3");
     delay(2000);
  } else {
    Serial.print("Humidity 3: ");
    Serial.print(h3);
    Serial.print(" %\t");
    Serial.print("TEMPRATURE 3rd of LM35= ");
Serial.print(cel3);
Serial.print("*C");
Serial.println();
     delay(2000);
    Serial.print("Temperature 3: ");
    Serial.print(t3);
    Serial.println(" *C");
     delay(2000);
  }
  Serial.println();
}
```

APPENDIX D

Indirect solar dryer was designed by Solidworks.



Left side view

Front view

Right side view

Fig: Three different views of solar dryer designed (2D view with detailed dimension, Scale 1:25 in solidworks)