DEVELOPMENT AND PERFORMANCE EVALUATION OF A SOLAR DRYER FOR COPRA

by

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(2015 - 18 - 014)

Department of Food and Agricultural Process Engineering

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2017

DECLARATION

I hereby declare that this thesis entitled **"Development and Performance Evaluation of a Solar Dryer for Copra"** is a bonafide record of research work done by me during the course of research and the thesis has not previously formed the basis for the award of any degree, diploma, associateship, fellowship or other similar title of any other University or Society.

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(2015-18-.14)

Date:

CERTIFICATE

Certified that this thesis entitled **"Development and Performance Evaluation of a Solar Dryer for Copra"** is a record of research work done independently by **Mr. V Sai Krishna (2015-18-014)** under my guidance and supervision and that it has not previously formed the basis for the award of any degree, diploma, fellowship or associateship to him.

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V Sai Krishna

Dedicated to
My beloved parents

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF PLATES

SYMBOLS AND ABBREVIATIONS

AC	:	Alternative current
A	:	Ampere
ANOVA	:	Analysis of variance
cm	:	Centimetre
CPC	:	Compound parabolic concentrator
CFM	:	Cubic feet per meter
Db	:	Decibels
ºC	:	Degree Celsius
ETC	:	Evacuated tube collector
EUR	:	Energy utilization ratio
FAO	:	Food and Agriculture Organization
Fig.	:	Figure
Hz	:	Hertz
H	:	Hour
kg	:	Kilogram
m		Meter
mg	:	Milligram
mm	:	Millimetre
min	:	Minute
MCG	:	Milling coconut grade
MIR	:	Mid Infrared
No.	:	Number
Pa	:	Pascals
PVC	:	Poly vinyl chloride
Rpm	:	Revolution per minute
s	:	Second

UV : Ultra violet

V : Volt

W : Watt

Wb : Wet basis

et al. : and others

~ : Approximately

@ : At the rate

μF : Micro farad

% : Per cent

Ø : Phi

LIST OF APPENDICES

CHAPTER I

INTRODUCTION

India is the 3rd largest coconut producing country in the world. Tamil Nadu, Kerala, Andhra Pradesh and Karnataka are the major coconut producing states in India. The net area under cultivation in Kerala during the year 2013-14 was 2.05 million ha, which occupied 52.78 per cent of the total area in the State under which coconut cultivation was 0.81 million ha. Kerala produced 7429.39 million nuts in the year 2015-16, which contributes 33.5% of India's coconut production (Coconut Development Board, 2016). Considering the area under cultivation of crops, coconut occupies the first place among them. Coconut provides a principal source of agricultural income in Kerala- from coir industry to coconut shell artifacts; coconuts bring much economic gains to Kerala (Coir Board, 2015).

Fresh coconut contains moisture content of about 52 per cent (wb) which has to be reduced down to 6-7 per cent by drying process to concentrate the oil content (Sachidananda *et al.*, 2014). On an average, 5 -7 coconuts are required to produce 1 kg of copra, although this depends on the grade of product. Copra is one of the major traditional products processed from coconuts. The objective of making copra is to reduce the moisture content of coconut kernel to a safe storage level and thereby prevent microbiological attack and spoilage. Copra is available as an year round dried fruit. Copra is dried not only for preservation purposes, but also for modification of the taste, flavor and texture to meet consumer preferences and to increase market value of the product. (Daghigh and Shafieian, 2016)

Drying is the process of removing partial moisture from a product and is an energy intensive operation. It is a basic unit operation that consists of reducing the moisture of a product so that the final product presents very different characteristics from the initial one. The other objectives of drying apart from extended storage life are also to improve the quality, ease of handling, further processing and is probably the oldest method of food preservation practiced by humankind. The decision of what type energy source used for drying should be made on the basis of economic, environmental and safety considerations.

The utilization of solar energy as an energy source to dry foods in India has a great potential. Sun shines in India over an average of 3000-3200 $h.year^{-1}$
delivering about 2000 $kWh.m^{-2}year^{-1}$ (8 $kWh.m^{-2}day^{-1}$) of solar radiation on horizontal surface (Kulanthaisami *et al.,* 2009). This abundantly available solar energy can be used for drying of coconut kernels. Because of its desirable environmental and safety aspects, solar energy is widely used instead of other alternative energy forms, even when the costs involved are slightly higher. Various methods such as sun drying, solar drying, and the traditional smoke drying, indirect drying, etc. are used mainly to make copra.

Open sun drying and kiln drying is the most commonly used method for drying coconut kernels in most of the developing countries. Drying under hostile climate conditions usually leads to severe losses in the quantity and quality of the product. They produce poor quality copra and also take time to attain the equilibrium moisture content. In kiln drying, smoke has direct contact with the coconut and result in poor quality copra due to smoke deposits which alters polycyclic aromatic hydrocarbons in the copra. Sun drying takes 7 to 8 days and if the weather is rainy the copra obtained will be contaminated with fungi which produce a grey rancid product. Moreover, produce could be of low quality copra due to deposits of dirt and dust. Also, microorganisms can cause rancidity, increase the acid content and reduce the amount of oil extracted from the product resulting in low quality coconut oil. The oil extracted from poor-quality copra also requires additional refinement to meet international standards (Shanmugam and Natarajan, 2006). Also natural sun drying has many disadvantages such as uncontrolled drying, contamination by birds, insects, dust and climatic adversities etc. resulting poor quality which is not suitable for export. It also requires more labour and the process is found to be slow. To reduce the processing losses during the drying and to retain the quality of dried product, it is necessary to dry coconuts in the close chamber.

On the other hand, mechanical drying is an energy consuming operation. Solar dryers are now being increasingly used since they are better and more energy efficient option. The benefits from the installation and operation of solar energy systems can be divided into three categories: energy saving, generation of job opportunities and a decrease in environmental pollution. Therefore, using solar energy can be considerably reduced energy costs. The efficiency of a solar dryer depends on its type and model as well as on the rate of heat loss during operation.

Experiments conducted in many countries have clearly shown that solar energy can effectively be used to dry agricultural crops.

Considering the above facts a study was undertaken on **"Development and Performance Evaluation of a Solar Dryer for Copra"** with the following objectives:

- Development of a solar dryer for copra.
- Performance evaluation of the developed solar copra dryer.
- Comparison of the developed solar copra dryer with traditional drying.

CHAPTER II

REVIEW OF LITERATURE

In this chapter, a brief review of research works carried out in the development of a solar copra dryer and the methods adopted for its performance evaluation were presented.

2.1 Characteristics of Coconut

According to Ganguly (2013) coconut (*cocos nucifera* L.) obtained from coconut palm has numerous medical and commercial benefits. It was reported that coconut contains a source of saturated fat that would not elevate the lipid profile in the body. It is not recommended to patients suffering from cardiovascular ailments and hypertension.

According to Shankar *et al.* (2013) coconut and its by-products have been used as culinary, cosmetic, and medicinal agents. By-products of coconut were used for centuries as culinary, cosmetic, and medicinal agents. It was observed that coconut oil has a high proportion of medium-chain triglycerides, which unlike the long-chain triglycerides, are oxidized to energy in the liver.

Table 2.1: Proximate composition of coconut copra (*West coast tall* variety). (Ghosh *et al*., 2014)

Analysis parameter Composition (% on dry weight basis)	Analysis parameter Composition (% on dry weight basis)
Moisture	3.94
Ash	1.59
Crude fat	71.62
Crude protein	8.80
Crude fiber	7.15
Carbohydrate (by difference)	6.90

Kappally *et al.* (2015) states that coconut oil is an edible oil obtained from the kernel of harvested mature coconuts of the coconut palm. According to him a number of health benefits have been attributed like skin care, hair care, stress relief, weight loss and cholesterol level maintenance, immune modulatory effects, cardiovascular uses, and more recently in Alzheimer's disease.

2.2 Dryer for copra

Sankat and Rolle (1990) designed a dryer specifically for the drying of split coconuts for small farmers. Simplicity in design, low cost and ease of construction were the essential elements in the design considerations. It consisted of a wooden-sided cabinet with a corrugated galvanized base sheet located 0.20 m from the top. Screened air inlet and exit ports were provided for at the front and rear ends of the dryer. A transparent plastic cover was made to fit snugly over the sides of the cabinet. The cover was made with a wooden frame to which clear plastic sheeting was attached. When operating, the air exit side was raised and supported above the air inlet side, so as to provide a cover with a slope of 10° to the horizontal.

The Modified Kukum Dryer is an indirect natural draught dryer measuring 1.83 m in width, 3.66 m in length and 2.13 m in height. About 2000 nuts of average size can be accommodated in dryer with a volume of 2.8 m^3. The heat exchange of kukum is made of 3 standard oil drums which were welded together with five semi-circular baffles. The furnace is 3 feet long and 2 feet wide and it was made of steel plaster. The furnace is provided with a slanting grate and door to regulate air entry. A butterfly valve was provided at the chimney to control the hot air temperature. About 30 hours were needed to dry one batch to 6 per cent moisture content. (FAO, 2006)

The improved version of modified kukam dryer is Cocopugon. Cocopugon uses bricks instead of using metal drums. The Cocopugon is 260 cm wide, 360 cm in long and 200 cm height. Standard fire bricks and 2.5" crown bricks are used for the chimney and the heat exchanger, respectively. The dryer can accommodate 2000 nuts per batch whose bed volume was 3.33 m^3. To facilitate ease of handling, a removable wall was placed. (FAO, 2006)

Ayyappan and Mayillsamy (2010) developed a natural convection solar tunnel drier for drying of copra. The capacity of the dryer was 5000 nuts per batch. It was observed that moisture content reduced from 52.2 to 8 per cent in 57 h under full load condition and 52 h under half load condition, respectively. Drying rate in bottom tray was lower than that of top tray by two per cent. Average efficiency of the solar tunnel dryer was estimated as 20 per cent. Quality of copra was good as compared to sun drying.

Rajagopal *et al.* (2014) developed and fabricated an indirect forced convection solar dryer for copra. The temperature of the drying chamber ranges from 49 to 78 °C for natural and forced convection while the ambient temperature range from 28 to 32ºC. Initial moisture content of copra range from 51.7to 52.3 per cent and the final moisture content obtained about 7 to 8 per cent. The forced convection solar dryer took less time than the natural convection solar dryer to attain the equilibrium moisture content. Results showed that during the forced convection, the minimum and maximum temperatures were 48 °C and 68°C respectively.

Padmanaban *et al.* (2015) designed and developed laboratory scale forced convection based solar dryer for drying copra under the climatic condition of Coimbatore region, Tamil Nadu, India. The experimental results showed that reduction of drying time of copra was nearly 82 per cent in comparison to open sun drying. The average time required to dry 1 kg copra was found to be 28 h whereas in open sun drying it takes 6 days to achieve the same drying rate. Thermal efficiency of the solar dryer was estimated to be 21.4 per cent with specific moisture extraction rate about 0.87 kg kW h^{-1}.

2.3Development of solar dryer

Ahmad *et al.* (2002) fabricated a solar cabinet dryer for fruits and vegetables drying. Evaporation rate in the dryer ranged from 0.091 to 0.106 g.cm^{-2} h^{-1}with an average of 0.1±0.004 during August month. A temperature of 80 °C and 60 °C was achieved during summer and winter, respectively. The dried produce was acceptable to the consumers.

Togrul and Pehlivan (2002) used an indirect forced convection solar dryer consisting of a solar air heater with conical concentrator and a drying cabinet to conduct a solar drying experiment in thin layers of apricots grown in Turkey. Hot air was passed over the apricots using blower. The sulphured apricots were dried from 77.81 per cent (wb) average initial moisture content to 18 per cent (wb) using air at different flow rates (70, 60, 50 kg.h^{-1}) in the drying cabinet. The satisfactory drying was observed in the ranges of 50.1 to 58.5 °C temperature, 0.11 to 0.15 m.s^{-1} air velocity and 13 to 19 per cent relative air humidity.

Abene *et al.* (2003) carried out a study on solar air flat plate collector and they stated that the insufficiency of the thermal exchange between the fluid and the absorber obliges the user to enhance their optimization.

Bennamoun and Belhamri (2003) conducted a study on simple and efficient solar batch dryer consisting collector surface of 3 m^2 and a heater at 50 °C allows drying onions of about 250 kg.day^{-1}. During periods of low sunshine a heater was used. Results showed that at 60 °C, 500 minutes were needed to reach the purposed moisture. At 50 °C, 700 minutes were still insufficient. However, for 40 °C and after 900 minutes, the purposed moisture was not obtained.

Chua and Chou (2003) reviewed on low cost drying methods for developing countries for drying agricultural foodstuffs, and proposed several low cost dryers for application in farming areas where raw materials and labor are readily available.

Hebbar *et al.* (2004) developed a combined infrared and hot air heating system having three chambers which was fitted with mid-infrared (MIR) heaters for radiative heating for drying of vegetables. The performance evaluation studies indicated that combination drying of carrot and potato at 80 °C with air at a velocity of 1 m s^{-1} and temperature of 40°C reduced the drying time by 48 per cent, besides consuming 63 per cent less energy compared to hot air heating. The energy utilization efficiency of the dryer was estimated to be 38 per cent for both carrot and potato drying.

Kadam and Samuel (2006) developed a flat plate forced convective solar heat collector for drying cauliflower. Its main components were galvanized iron sheet with black paint, transparent glass over it and a closed duct. The average midday thermal efficiency was around 16.5 per cent. Cauliflower was blanched for 3 minutes in boiling water and dipped in sodium chloride, potassium meta-bisulphite and sodium benzoate for 15 minutes in 1.0 per cent preservative concentration level before drying cauliflower in solar dryer. The treatments were found to be significantly different (probability $P<0.0001$) for all preservatives.

Jain (2007) used a transient analytical model to study the new concept of a solar crop dryer having reversed absorber plate type collector and thermal storage with natural airflow. The performance of 1 x 1 m^2 area of crop dryer with packed bed and airflow channel was evaluated for drying of onions. A 30° inclined absorber plate with in-built thermal storage and 0.12 m width of airflow channel induced the mass flow rate in the range of 0.032–0.046 $kg.s^{-1}$ during the drying process.

Kulanthaisami *et al.* (2009) designed and installed a solar tunnel dryer for drying coconuts. The dryer is semi-cylindrical tunnel shaped structure covered with UV stabilized polyethylene sheet. The floor area (18.0 x 3.75 m) of the tunnel dryer was black coated to attain the maximum drying efficiency. The temperature inside the solar tunnel dryer gets boosted up by 15-20 °C more than the ambient.

Mohod *et al.* (2011) had used solar tunnel dryer for drying fish. The experiments were conducted with and without fish to evaluate the performance of solar tunnel dryer. It was observed that the average temperature and relative humidity inside the solar tunnel dryer were 45.14 °C and 39.22 per cent respectively while average ambient temperature and relative humidity were 30.71 °C and 36.90 per cent respectively. The average 28 per cent saving in time was observed using solar tunnel dryer over open sun drying method with average drying efficiency of 19 per cent.

Almuhanna (2012) had evaluated the feasibility of using a solar greenhouse as a solar dryer for drying dates. Results revealed that the daily average solar energy available outside the solar dryers was 15.921 kWh, and 12.335 kWh was available inside the solar greenhouse for an average effective transmittance of 77.48 per cent. The solar energy available inside the solar greenhouse produced a 14.1°C increase in the inside air temperatures versus the outside temperature (33.6°C) and reduced the relative humidity of the inside air versus the outside air (35.3 per cent) by 9.6 per cent. The daily average overall thermal efficiency of the solar greenhouse during the experimental period was 60.11 per cent.

Vendan *et al.* (2012) designed an evacuated tube solar collector for high temperature steam generation. They stated that evacuated tube collectors (temperature up to 200 °C) were more efficient compared to Flat Plate Collectors (temperature °C) as the former eliminates the convective heat losses. From the study, they concluded that the carbon foot print can be reduced to great extent by replacing the conventional methods by a solar thermal collector.

Manaa *et al.* (2013) presented experimental results of drying, which were made in the south of Algeria, Adrar. The experiment was performed on tomatoes, which have water content ranging from 68 to 75 per cent depending on the degree of ripeness. The time of average solar drying was from 2 to 3 days. They suggested that the increase in the temperature of the air of drying and the reduction thickness of the slices make decrease the time of drying and make increase the speed of drying.

Panchal *et al.* (2013) designed and constructed a simple solar dryer with roughened surface with solar air heater. The designed dryer with a collector area of $0.5 m^2$was expected to dry 1kg of sliced mango from 60to 10 per cent (wb) in two days under ambient conditions during harvesting period.

Shameer and Nishath (2013) developed a working model of the active solar air heater with the capacity of thermal storage. In this study paraffin wax was used as the thermal storage material, blower was used for forcing air into the air heater and aluminum was used for collector plate due to its high thermal conductivity. The chemical properties of paraffin wax such as melting point, density, specific heat capacity and heat of fusion values were 46 °C, $0.9 g.cm^{-3}$, $2.9 J.g^{-1}k^{-1}$ and $220 J.g^{-1}$ respectively. The efficiency of the solar air heater was found 75 per cent under test conditions.

Ayala and Topete (2014) carried out experimental study on pineapple (*Ananascomosus* L.) drying in a new solar hybrid dryer. Evaporation efficiencies were higher in the traditional process; such efficiencies ranging between 22.7 and 24.0 per cent; while the efficiency of the hybrid dryer ranges between 9.3 and 14.0 per cent. This dryer ended the process in a range of 6.0 to 6.8 hours while the traditional solar process took between 8.0 and 8.8 hours.

The total drying time when operating in solar mode was in average 31.2 per cent longer than the dryer operated in hybrid mode.

Pastrana (2014) developed an indirect solar dryer having a solar air heater built into its structure with plywood wood 1inch thick, both the base and sides, with dimensions of 140 cm long and 60 cm width, a cover glass thickness of 3 mm and an inclination of 17.5° to the horizontal in order to dry Nopal (*Opuntia Lasiacantha*). The drying chamber was constructed of plywood wood ½ inch thickness and dimensions of 60 cm long, 40 cm wide and 55 cm high with four nylon mesh trays, allowing initial drying mass about 2 kg. Results showed that the initial moisture content of Nopal "*Opuntia Lasiacantha*" was m_s=33.13 per cent (db) and an average speed of drying of 0.132 g cm^{-2} h were observed.

Romero *et al.* (2014) reported the simulation and validation of vanilla drying process in an indirect solar dryer prototype designed for 50 kg capacity. Initial vanilla mass load was 1.6 kg and the drying time was one month, normally the traditional drying lasts for 3 months. ANSYS design modeler program was used for design geometry and discretization of the control volume. The initial and final weights of vanilla were 1267.5 and 491.2 g, respectively, so the loss weight in water was 776.3 g, almost 61.25 per cent.

Sabiha *et al.* (2015) had reviewed on solar evacuated tube collector, types of evacuated tube collectors, their structure, applications and challenges. The collector efficiencies were found to be 46.1 per cent and 60.7 per cent and the system efficiencies were found to be 37.9 per cent and 50.3 per cent for flat plate collector and heat pipe evacuated tube solar collector, respectively. The average output of evacuated tube solar collectors over an entire year was 25–40 per cent higher than flat plate collectors per m^2.

Wang *et al.* (2015) designed a set of evacuated tube solar high temperature air heaters with simplified CPC (compound parabolic concentrator) and concentric tube heat exchanger to provide flow air with a temperature of 150 – 230 °C for industrial production. It was observed that the thermal efficiency corresponding to the air temperature of 70 °C reaches 0.52. With the increase of air temperature, thermal efficiency reaches 0.35 at an air temperature of 150 °C, and 0.21 at an air temperature of 220 °C.

Akpan *et al.* (2016) designed and developed an agricultural and bio-material dryer for local farmers to reduce agricultural material wastage and to improve their storage conditions. It consists of three units: drying chamber, blower and heat exchanger. The performance test and evaluation were conducted using analysis of variation (ANOVA) using okro, pepper and groundnut as the test materials at an average drying chamber temperature of 50°C for safe drying of the produce. The dryer had a mean drying capacity of 60.3 kg per batch with a thermal efficiency of 76.9 per cent and drying rate of 0.041 kg.hr^{-1}, it was observed that, at relative humidity of 35 per cent improved the drying time of the agricultural materials and was recommended for local farmers.

Daghigh and Shafieian (2016) designed and constructed a heat-pipe evacuated tube solar dryer with heat as recovery system in which water was used as working and recovery fluid, and air was used as intermediate fluid in the dryer section. At volumetric flow rate of 0.0328 m^3.s^{-1}, the maximum outlet air temperature of dryer was approximately 44.3 °C. The maximum solar radiation in these days was 980 W.m^{-2} and maximum wind velocity approached 3.2 m.s^{-1}. The mass flow rate of the working fluid of the solar cycle was 1.1 l.min^{-1}. The maximum outlet air temperature of exchanger observed in this experiment was about 44.3 °C. The reduction of inlet air flow rate causes an increase in outlet temperature. At the end of the day, the exegetic efficiency of the system reaches its maximum rate, approximately 11.7 per cent.

Muhammad *et al.* (2016) experimentally examined the thermal performance of both flat-plate and evacuated tube collectors under similar conditions. The results demonstrated a higher efficiency for evacuated collector. In their study, water-based CuO nano fluid was used as working fluid. Their experimental results showed that the optimal filling ratio to the evaporator was 60per cent and the thermal performance of the thermo syphon increase with the increase of the operating temperature. By using water based CuO nano fluid, the thermal performance was enhanced by about 30 per cent compared to those of de-ionized water and the optimal enhancement was found at CuO nano particles mass concentration of 1.2 per cent.

2.4 Performance Evaluation of solar dryer

Simate (2003) conducted a study on comparison of optimized mixed-mode and indirect-mode natural convection solar dryers for maize. The models are run under variable solar conditions in order to optimize the dryers and compare their performance. The results showed that the grains were dried from a moisture content of 38.9 per cent to final moisture of 13.7 per cent dry basis with 8 h of drying per day. The difference between the maximum and minimum moisture content was about 5.89 and 12.31 per cent for the mixed mode and indirect-mode dryers, respectively.

Jain (2007) observed that the crop moisture content and drying rate decreases with the drying time of the day. A reversed absorber plate of 1 m length and 1 m breadth with 0.15 m packed bed could dry 95 kg of onion from a moisture content of 6.14–0.27 kg water per kg of dry matter in a 24 h drying period. The onion slices were dried from an initial moisture content of 6.14 kg water per kg dry matter. The final moisture content obtained was 0.30 and 0.27 kg water per kg dry matter in crop tray-I and II, respectively.

According to Kulanthaisami *et al.* (2009) the coconut kernels being dried in the solar tunnel dryer was completely protected from rain, insects and dust. The coconut kernel having initial moisture content of 50-55 per cent was reduced to 6 per cent during drying operation for safe storage and to maintain food quality.

Akpinar (2010) investigated the thin-layer drying characteristics in solar dryer with forced convection and under open sun with natural convection of mint leaves. Energy utilization ratio (EUR) values of drying cabinet varied in the ranges between 7.826 and 46.285 per cent. The values of exergetic efficiency were found to be in the range of 34.76–87.71 per cent. The values of improvement potential varied between 0 and 0.017 $kJ.s^{-1}$.

Sengar *et al.* (2012) developed a rotary solar dryer and evaluated for kokam drying. Time required reducing the moisture content up to 10 per cent as a safe storage for solar dryer was observed for ripen and unripe kokam fruits. Overall collection efficiency was found as 70.97 per cent. Maximum drying efficiency for salted ripen kokum was 9.88 per cent and unsalted salted ripen kokum was 7.66 per cent.

Sengar *et al.* (2012) developed and evaluated multi-rack foldable solar dryer for mango flakes drying. The drying chamber was provided with 16 trays of 70 x 50 cm size. The capacity of each tray was 0.6 kg. UV stabilized 200 µm plastic film was used for collection of solar energy. The developed dryer mainly divided into three parts as collector, drying chamber and inlet and outlet openings. Overall collection efficiency was found to be 0.97 per cent, whereas pickup efficiency was found to be 15 per cent.

Vijaykumar *et al.* (2012) had evaluated the performance of a solar tunnel dryer of 18 m x 3.75 m size in Kotnekal village of Raichur district of Karnataka for chilly drying. A maximum temperature of 58.5 °C was recorded at 14:00 h inside the solar tunnel dryer which was 41.02 per cent higher than the maximum ambient temperature. On an average, a total drying time of 50 drying hours (6–7 sunny days) were required for solar tunnel dryer to reduce the moisture content of chilly from initial value of 76 per cent (wb) to a final moisture content of 9 per cent (wb) while the open sun drying required on an average 105 drying hours (13-14 sunny days).

Arun *et al*. (2014) designed and developed a natural convection solar tunnel greenhouse dryer coupled with biomass backup heater for studying the drying characteristics of coconuts in Pollachi region of Tamil Nadu. It was found that the coconuts which have an initial moisture content of 53.84 per cent (wb) were dried to final moisture content of 7.00 per cent (wb) in 44 h whereas the open sun drying method took 148 h. The biomass backup heater was used after 5PM where there would be no sufficient solar radiation and was loaded with the remains of coconut such as coconut fronts, coconut husk and coconut shells which could be used as a fuel for biomass heater.

Benhamou *et al.* (2014) conducted a study to determine the drying curve and the change rate of drying by solar energy on two plant materials, olive pomace, and colocynth, depending on solar radiation. Colocynth consists of 65 per cent water. The speed varies from 0.75 m s^{-1} to 1.5 m s^{-1}, with a mass of 15 kg and a temperature of 333 K. The change in product water content at different speed showed that increasing the air speed will decrease product water content, and consequently, a decrease in drying time.

Dina *et al.* (2014) developed a continuous solar dryer integrated with desiccant thermal storage for drying cocoa beans. The results revealed that drying times for intermittent directs sun drying, solar dryer integrated with adsorbent, and solar dryer integrated with absorbent were 55 h, 41 h, and 30 h, respectively. Specific energy consumptions for direct sun drying, solar dryer integrated with adsorbent, and solar dryer integrated with absorber were 60.4 MJ kg^{-1} moist, 18.94 MJ kg^{-1} moist, and 13.29 MJ kg^{-1}moist, respectively. They concluded that, solar dryer integrated with desiccant thermal storage makes drying using solar energy more effective in term of drying time and specific energy consumption.

According to Velmurugan and Kalaivananhas (2016) energy and exergy performance of solar air heater is improved by employing double pass with different absorber surface geometries. The mass flow rate was controlled by varying the blower speed using 1.5 kW AC variance.

2.4 Comparison between Solar Dryer with traditional drying

Fraser and Muir (1980) performed cost predictions for drying grain with ambient and solar- heated air in Canada using a computer simulation model. In ambient air drying, the cost of electricity was the lowest component while the highest component was the cost of the drying equipment. The over drying penalty was nearly twice the cost of electricity needed for drying wheat. The predicted mean cost of drying wheat with ambient air was about 20 per cent higher in the humid region of Manitoba than in the semiarid and sub-boreal regions of Saskatchewan and Alberta. The cost of drying corn with ambient air was 35per cent higher in southern Ontario than in Manitoba. Adding a solar collector with a solar collector coefficient of 5 °C increased the drying cost in 83 per cent of the sets of conditions and locations simulated, but if the over drying penalty were removed this figure would decrease to 40 per cent. An equation to predict drying costs for different cost parameter values was developed.

Mittal and Otten (1982) developed and validated a model to simulate low temperature corn drying under Ontario conditions. The model predicted the grain moisture profiles at different depths to within ± 1 per cent point of residual rot mean square. Hourly weather records of Toronto and London for the period 1965-1978 were used to study the performance of the system. Weather conditions, harvest date, and initial moisture content were shown to influence greatly the performance of the low-temperature drying system when continuous airflow without supplement heat was employed. Ambient drying of corn in Southern Ontario was not energy efficient in comparison with high temperature drying in 62 per cent of the years.

Otten and Brown (1982) studied the performance of a low-temperature corn-drying system in 1978 and 1979. Low-temperature drying treatments involved ambient air drying of corn directly from the field, and drying of partially dried corn in a combination high-low temperature approach. One of the two low-temperature bins used in each year had a bin-wall solar collector for supplemental heating. The specific energy consumption for all four experiments was found to vary between 3.9 and 4.1 $MJ.kg^{-1}$ of water removed, which was similar to the energy use in a conventional high-temperature, continuous flow dryer. The corn quality in the combination drying experiment was superior to that of conventionally dried corn.

Shanmugam and Natarajan (2006) designed and fabricated an indirect forced convection and desiccant integrated solar dryer to investigate its performance under the hot and humid climatic conditions of Chennai, India. The system consists of a flat plate solar air collector, drying chamber and a desiccant unit. The desiccant unit was designed to hold 75 kg of $CaCl_2$-based solid desiccant consisting of 60 per cent bentonite, 10 per cent calcium chloride, 20 per cent vermiculite and 10 per cent cement. Drying experiments have been performed for green peas at different air flow rate. The equilibrium moisture content was reached in 14 h at an air flow rate of 0.03 $kg.m^{-2}s^{-1}$. The dimension of flat plate collector is 1.2 x 2.4 m^2 and was kept facing south tilted at an angle of 30°.The drying chamber of dimensions 1.2 x 1.2 x 1.0 $m^3$was fabricated from 19 mm thick insulated plywood. A 1.47 kW centrifugal blower rotating at 2800 rpm is used to circulate the hot air to the drying chamber through the flat plate collector. At a given air flow rate of 0.01, 0.02 and 0.03 $kg.m^{-2}s^{-1}$ the product dries to its equilibrium moisture content at about 22, 18 and 14 h, respectively. The performance of the system was promising, showed a satisfactory pickup efficiency of 63 per cent at 10.30 am and more or less uniform during desiccant drying. The specific moisture extraction rate varies from 0.55 to 0.82 $kg.kW^{-1}h^{-1}$.

Mohanraj and chandrasekar (2008) fabricated an indirect forced convection solar drier integrated with sensible heat storage material and tested for copra drying. It reduces moisture content (wb) from 52 per cent to 7.8 per cent and 9.5 per cent in 66 h for trays at bottom and top milling coconut grade (MCG1), 18 per cent MCG2 and 6 per cent MCG3. Specific moisture extraction rate was estimated to be 0.84 $kg.kWh^{-1}$. In sun drying, moisture content reduced from 52.3 per cent (wb) to about 9.2 per cent in 7 days. Copra obtained was graded as 53 per cent MCG1, 24 per cent MCG2 and 23 per cent MCG3. Average drier thermal efficiency of sun drying was estimated to be about 21 per cent.

Sachidananda *et al.* (2014) designed, developed and tested a biomass fired copra dryer in Andaman Islands. The aim was to increase in employment generation to the rural households who are engaged with traditional method of copra production. The results indicated that biomass fired copra took 22 h to reduce initial moisture content from 57.4to 6.8 per cent (wb) which saved 40 per cent and 47 per cent of total drying time compared to two traditional methods namely Machine drying and sun drying. Coconut shell of 80-85 kg was used as fuel. Two persons were required to feed the fuel and maintain the constant temperature to obtain better quality copra. The copra obtained was graded as 82 per cent MCG1, 13 per cent MCG2 and 5 per cent MCG3. The cost benefit ratio and payback period was found to be 1.4 and 1.5 month respectively. The coconut shell may be used for fuel which saves manpower and energy, thereby enhancing net return to the farmers.

Sallam *et al.* (2015) used two identical prototype solar dryers (direct and indirect) having the same dimensions to dry whole mint. Both prototypes were operated under natural and forced convection modes. In case of forced convection dryer the ambient air was entered the dryer with the velocity of 4.2 $m.s^{-1}$. The effect of flow mode and the type of solar dryers on the drying kinetics of whole mint were investigated. Ten empirical models were used to fit the drying curves; nine of them represented well the solar drying behavior of mint. The results indicated that drying of mint under different operating conditions occurred in the falling rate period, where no constant rate period of drying was observed. Also, the obtained data revealed that the drying rate of mint under forced convection was higher than that of mint under natural convection, especially during first hours of drying (first day). The values of the effective diffusivity coefficient for the mint drying ranged between 1.2 x 10^{-11} and 1.33x10^{-11} $m^2.s^{-1}$.

2.5Evacuated tube collector dryer

Arora *et al.* (2011) enumerated a detailed design of the evacuated tube collectors followed by the thermal network analysis of this collector. The temperature of each component was determined empirically. The generator of a typical 1 kW capacity refrigeration system was designed based on the hot water made available from outlet of evacuated tube collectors. The total heat transfer from the array of 6 collector tubes in parallel was determined as 475.86 W commensurate with the performance of most commercially available collectors as 9.992 $W.m^{-2}K^{-1}$ with the temperature of the copperplate as 107.62°C. Approximately 20 tubes were required to power the generator of an absorption machine with 1 kW (0.285 TR) capacity. The log mean temperature difference in the heat exchanger was calculated to be 17.65°C with the heat transfer coefficient 1192 $W.m^{-2}K^{-1}$. The generator must be a single pass pool type heat exchanger with 2.2 m long copper tube.

Hlaing and Soe (2014) investigated the heat transfer analysis of heat pipe evacuated tube solar collector was made of borosilicate glass with length

1.8 m, 0.058 m and 0.049 m diameter of outside and inside tubes respectively. The inner surface was covered with black coating to enhance the absorption rate of solar radiation. Heat pipe was made of copper with length 1.8 m and 0.015 m and 0.012 m diameter of outside and inside tubes respectively. Working fluid, ethylene glycol (0.1 l) was used within the heat pipe 30 numbers of tubes were used to generate 300 l of hot water. Manifold casing is 2.19 m length, 0.13 m height and 0.14 m width with aluminum. Heat transfer between the inner and outer glass tubes, heat transfer through the heat pipe wall of heat pipe ETC were analyzed by COMSOL Multi-physics. The maximum hot water temperature was 43 ºC at ambient temperature 21 ºC and collector efficiency was 72 per cent for December. The collector efficiency was obtained 72 per cent vary to daily heat required. The result showed that higher solar radiation was required to obtain maximum hot water temperature, and heat pipe ETC was more efficient than ETC without heat pipe & flat plate collector. The surface heat flux value due to the heat conduction was 1417.60 W.m^{-2} and the values of surface heat flux evacuated glass tube and heat pipe are 1478.4 W.m^{-2} and 1499.7 W.m^{-2} by utilizing COMSOL Multi-physics.

CHAPTER III

MATERIALS AND METHODS

This chapter describes the development of a solar dryer incorporated with evacuated tube collectors for drying copra. The material used for fabrication of the various components and the instrumentation employed for measurements of parameters were explained. The process of evaluation and optimization of process parameters for drying of coconuts are also detailed in the chapter.

3.1 DEVELOPMENT OF SOLAR DRYER FOR COPRA

Based on a thorough review of works carried out on different existing solar dryers, the design of a small capacity solar dryer with evacuated tubes was fabricated. The developed experimental system consists of the following main components:

1. Evacuated tube collector

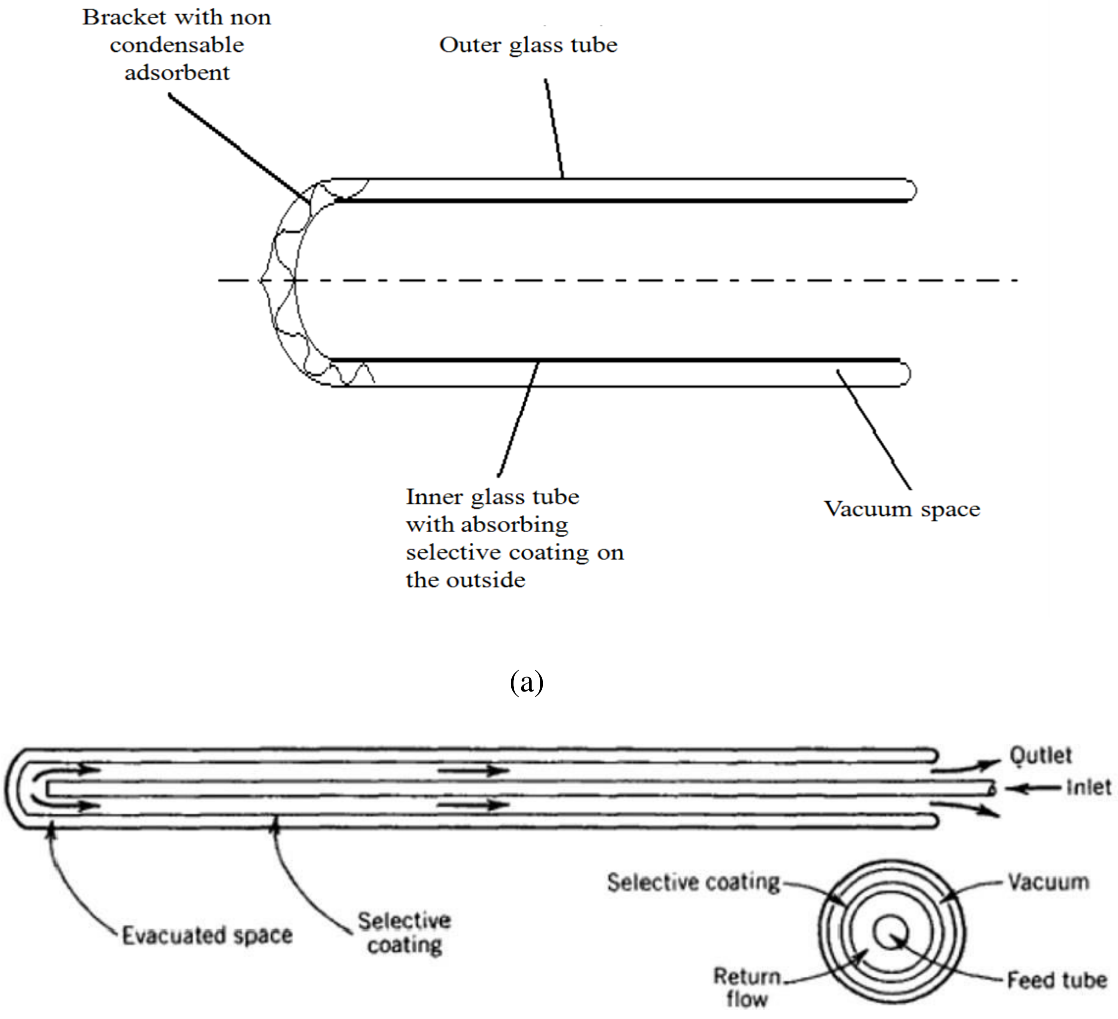
2. Air blower

3. Drying chamber

4. Supporting stand

3.1.1 Evacuated tube collector

Each evacuated tube consisted of two glass tubes made from extremely strong borosilicate glass. The outer tube consisted of transparent borosilicate glass allowing light rays to pass through with minimal reflection. The inner tube of the collector is coated with a three layer magnetron sputter coating (SS - Al/Cu) for giving excellent solar radiation absorption and minimal reflection properties. There are galvanized iron metal tubes placed inside the evacuated tubes. All the evacuated tubes were attached to a cylindrical manifold incorporated with two concentric cylinders. Both the cylinders were separated by glass wool insulation in order to minimize heat transfer loss. The test section of the evacuated tube used in this system is shown in figure 3.1.



(a)

(b)

Figure 3.1. Evacuated glass tube

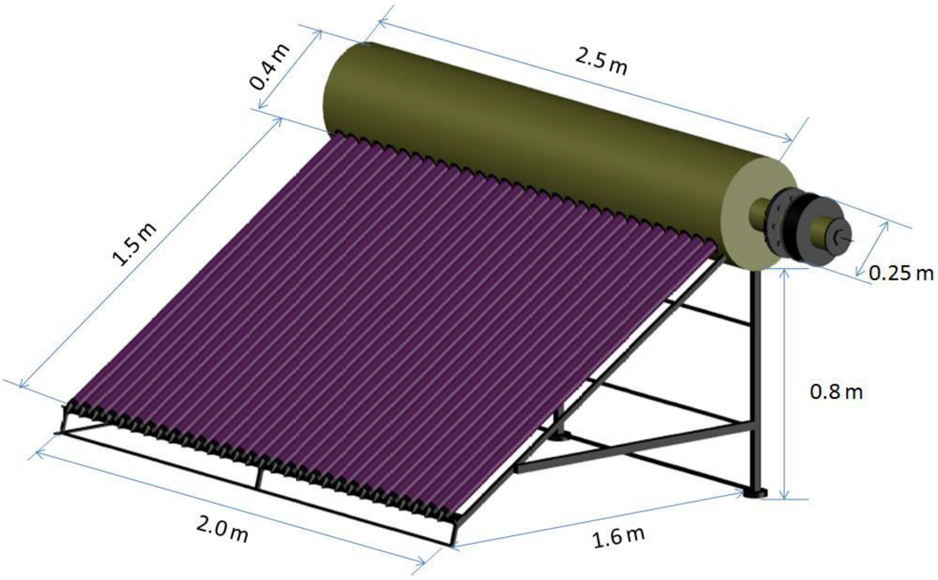


Figure 3.2. Isometric view of solar air heater

3.1.2 Air blower

An Air blower was connected to the manifold at right side of the solar air header which forces the air to the drying chamber. The blower was connected to drying chamber by galvanized metal tube. The air flow (m/s) of the blower was controlled by using a regulator.

Table 3.1 Specifications of blower

Sl. No	Details	Specifications
1	Model no.	MB 1255-B
2	Voltage, V	Single phase 110
3	Frequency, Hz	50
4	Current, A	1.3
5	Speed, rpm	2850 (18 $m.s^{-1}$)
6	Max. air flow, $m^3.s^{-1}$	4.4 (180 CFM)
7	Static pressure, Pa	309 (1.77 in H_2O)
8	Noise level, dB	67
9	Capacitor, μF	10

3.1.3 Drying chamber

The chamber was designed using galvanized iron metal sheets. Apart from the door, the chamber consists of 2 openings, one at top and the other at bottom. Top opening was provided with a chimney which was made of PVC pipe for ducting the exhaust air. A 24 gauge galvanized iron sheet was used to fabricate the chamber. Two perforated metal trays of 10-mesh was fitted inside the chamber for placing the fresh coconuts for drying and for the passage of air through the coconuts. The drying chamber and the solar air heater were connected by metal duct. All the sides were welded in order to prevent air leakages. Blower was placed in between the dryer and solar air heater in order to force the hot air into the drying chamber. A door was provided at one side of the chamber for loading and unloading of the product.

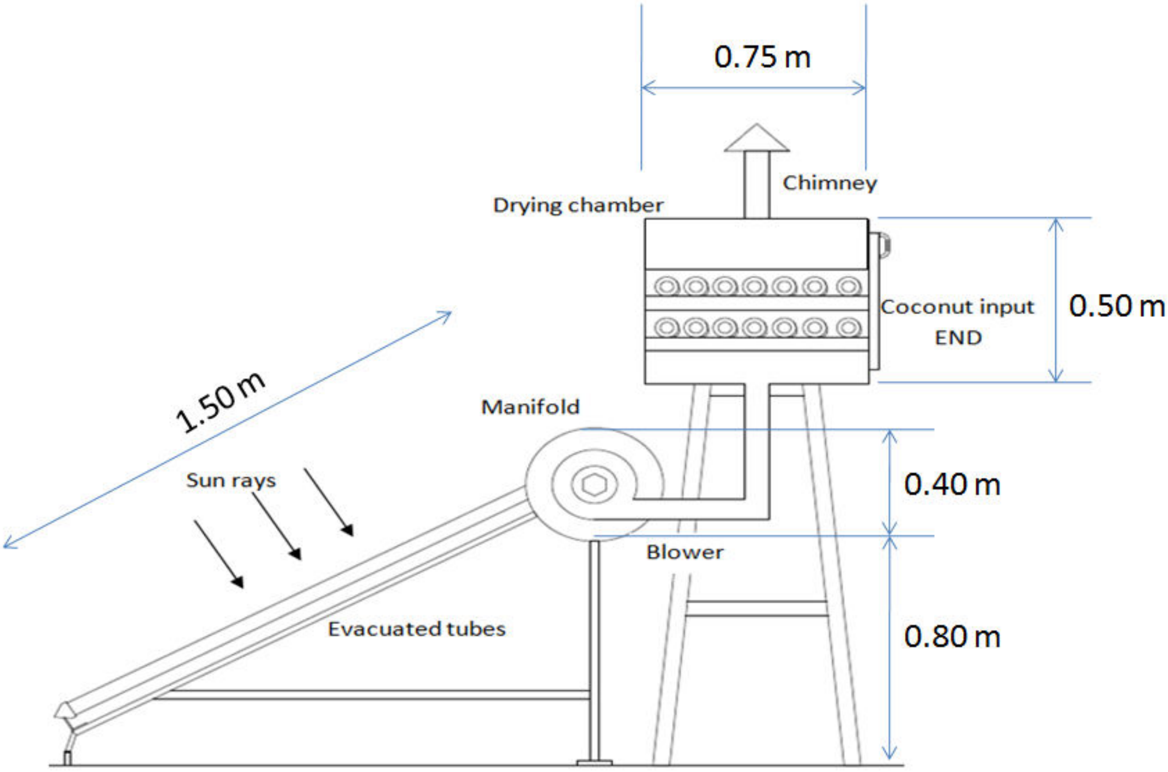


Figure 3.3. Side view of solar copra dryer

3.1.4 Supporting stand

A supporting stand was fabricated for placing the header and evacuated tubes in fixed positions. The collector was placed at angle of 30° facing south by means of the fixed stand.

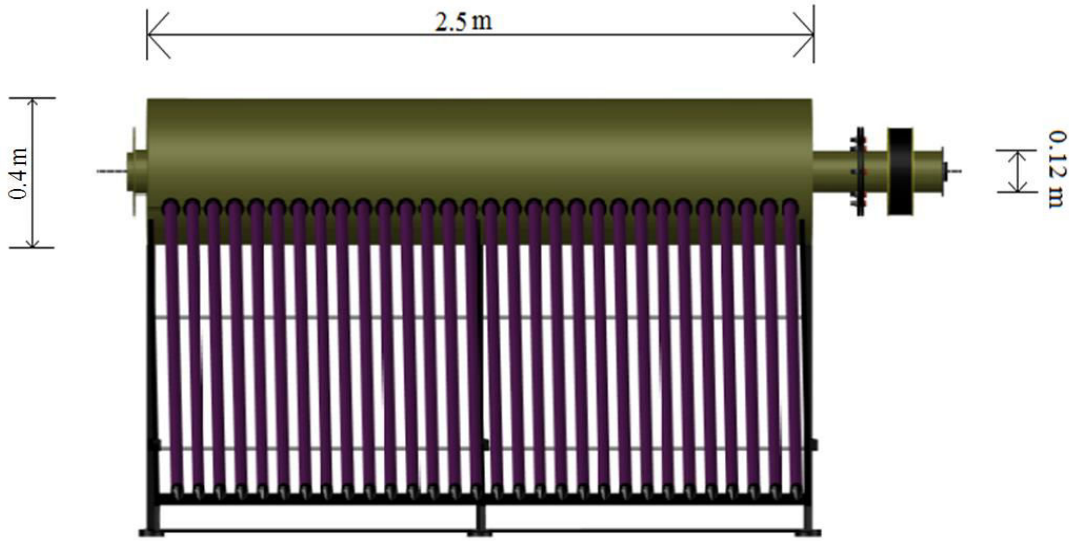


Figure 3.4. Front view of solar air heater

3.2 WORKING PRINCIPLE

In the above figure 3.5, the direction of air passing through the solar air heater is shown. It is a forced convection solar air heater where the ambient air is drawn inside the evacuated tube collector setup using a centrifugal blower.

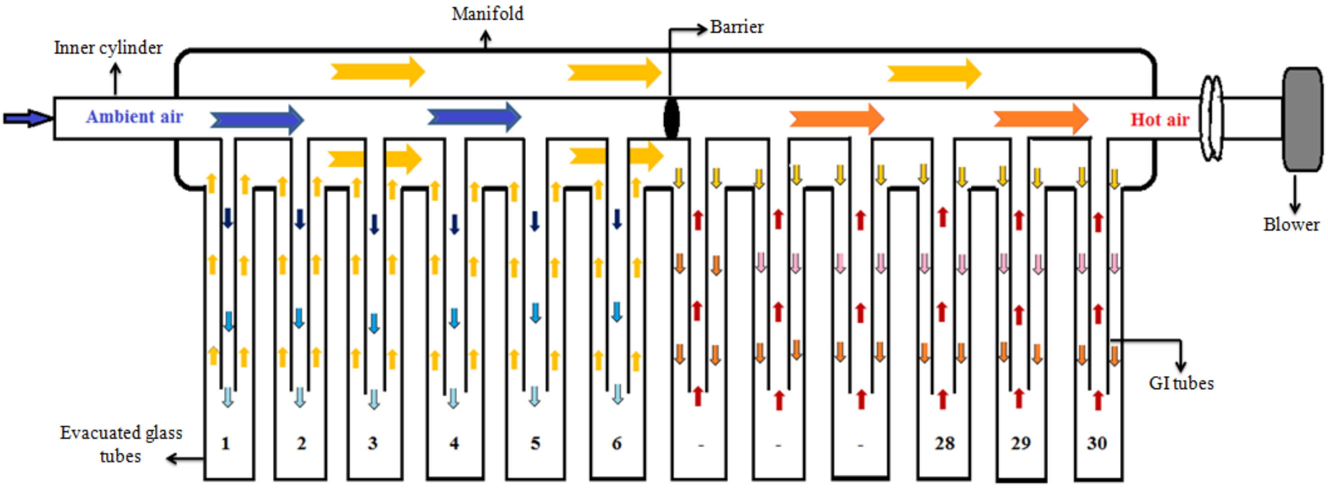


Figure 3.5. Air flow direction of solar air heater

Solar air heater consists of a manifold which is provided with two concentric cylinders. Evacuated glass tubes are connected to the outer cylinder and the galvanized iron tubes inside the evacuated glass tubes are connected to the inner cylinder. The solar radiation falling on the evacuated tubes helps to heat the galvanized iron tubes. Since the evacuated tubes are double glass vacuum tubes, the loss of heat is reduced to a great extent. The inner cylinder of the manifold is split into two divisions. The ambient air enters the manifold through the inner cylinder and passes through first 15 inner galvanized iron tubes, then enters into the outer cylinder. The hot air again enters the next 15 tubes from outer cylinder to evacuated tubes and passes through the galvanized iron tubes. The air gets further heated and it enters to inner cylinder of the manifold which is connected to the blower on the other end.

3.3 EXPERIMENTAL DESIGN

Based on a thorough review of literature, the process parameters which would influence the drying rate and drying time were chosen as independent variables. The physical quality characteristics which are characteristics of the product were selected as dependent variables.

3.3.1 Independent variables

a) Inlet Temperature

1) T_1= 50-60°C

2) T_2= 61-70°C

3) T_3= 71-80°C

b) Blower velocity

1) V_1= 0.2ms^{-1}

2) V_2 = 0.5ms^{-1}

3) V_3= 0.8ms^{-1}

c) Insulation thickness

1) I_1= 12.5 mm

2) I_2= 0 mm

3.3.2 Dependent variables

Solar evacuated tube dryer output parameters:

a. Drying time
b. Moisture content
c. Relative humidity inside the chamber
d. Temperature inside the chamber

3.3.3 Main items of observations to be made

1. Radiation measurement
2. Temperature measurement
3. Measurement of moisture content
4. Measurement of velocity of air
5. Measurement of relative humidity
6. Drying time

3.4 DESIGN CALCULATIONS

The design of solar dryer was done by taking into consideration the following parameters:

1. Amount of moisture to be removed
2. Quantity of air required for drying
3. Quantity of heat required for drying
4. Collector area of evacuated glass tubes
5. Number of evacuated tubes
6. Heat transfer rate
7. Selection of drying chamber volume
8. Thickness of insulation

3.4.1 Amount of moisture to be removed

The amount of moisture to be removed in kg (M_R)from fresh sample was given as (Mohanraj and Chandrasekar, 2008):

$$M_R = M\left(\frac{Q_1 - Q_2}{100 - Q_2}\right) \qquad \text{…..(3.1)}$$

Where,

M_R =amount of moisture to be removed (kg)

M = dryer capacity per batch (kg)

Q_1=initial moisture content of the product (percent)

Q_2= maximum desired final moisture content (percent)

3.4.2 Quantity of air required (Q_a) for drying

The quantity of air required to effect drying in kg was calculated using formula given below (Ajisegiri*et al.*, 2006):

$$Q_a = \left(\frac{M_R}{H_{r2} - H_{r1}}\right) \quad \ldots\ldots(3.2)$$

Where,

Q_a=Quantity of air required (kg)

H_{r1}=initial humidity ratios (kg.kg^{-1} dry air)

H_{r2} = final humidity ratios (kg.kg^{-1} dry air)

M_R = moisture to be removed (kg)

3.4.3 Quantity of heat required for drying

The quantity of heat required (S) for drying in kJ is given by (Akpan*et al.*, 2016):

$$S = S_1 + S_2 + S_3 \quad \ldots(3.3)$$

$$S_1 = M_p \times C_p \times (T_p - T_1) \quad \ldots(3.4)$$

$$S_2 = M_w \times C_w \times (T_w - T_1) \quad \ldots(3.5)$$

$$S_3 = M_w \times \lambda \quad \ldots(3.6)$$

Where,

S = Total heat required for drying (kJ)

S_1= Sensible heat of the product (kJ)

S_2= Sensible heat of water in the product (kJ)

S_3 = latent heat of water (kJ)

M_p = dryer capacity per batch (kg)

C_p = specific heat of the product ($kJ.kg^{-1}K^{-1}$)

C_w = specific heat of the water ($kJ.kg^{-1}K^{-1}$)

T_p = product temperature (°C)

T_w = water temperature inside coconut (°C)

T_1 = ambient temperatures (°C)

λ = latent heat of vaporization ($kJ.kg^{-1}$)

M_w = amount of moisture to be removed (kg)

3.4.4 Collector area of evacuated glass tubes

The actual Collector area (A) is the area of solar evacuated tubes which is projected towards the sun direction, it can be calculated as,

$$\text{Collector area (A)} = [L_g \text{ x } C] \text{ x } n \qquad \text{….(3.7)}$$

Where,

L_g = length of evacuated glass tube (m)

C = circumference of evacuated glass tube (m)

n = number of evacuated glass tubes

And, the required collector area is calculated based on the amount of heat energy required to dry the copra and amount of solar energy available at the location. The calculation of required solar energy is clearly mentioned under the section of 4.3.6.

$$\text{Required collector area} = \frac{\text{Amount of heat energy required}}{\text{Amount of solar energy available} \times \eta} \qquad \text{….(3.8)}$$

Where,

η = Assumed solar collector efficiency

3.4.5 Number of evacuated tubes

The determination of number of tubes depends on the size of each tube available commercially. It is given by the following equation:

$$\text{Number of tubes} = \left(\frac{\text{collector area required}}{\text{projected area of standard tube}}\right) \quad \ldots\ldots (3.9)$$

3.4.6 Heat transfer rate (Q_{ht})

The heat transfer rate (Q_{ht}) was determined (Comwel, 1978) as:

$$Q_{ht} = hAT_B \qquad \ldots\ldots(3.10)$$

Where,

h = convective heat transfer coefficient ($W.m^{-2}K^{-1}$)
A = surface area of the heating medium (m^2)
T_B = temperature of hot air in the blower (°C)

The convective heat transfer coefficient (h)was calculated by using the following expression (Geankoplis, 2011).

$$h = \frac{(\overline{N}_{nu}K_f)}{L} \qquad \ldots.(3.11)$$

Where,

$\overline{N}_{nu}$= Nusselt number
K_f = Thermal conductivity of working fluid ($W.m^{-1}K^{-1}$)
L = Characteristic linear dimension (m)

Nusselt number ($\overline{N}_{nu}$) is the function of Reynolds number (R_e) and Prandtl number (N_{Pr}). Therefore, Reynolds number is estimated by using the following expression,

$$Re = \frac{v \times L}{\gamma} \qquad \ldots.(3.12)$$

and, $\overline{\mathrm{N}}_{nu} = 0.664\, N_{Re}^{0.5} N_{Pr}^{0.33}$ ....(3.13)

Where,

v = ambient air velocity ($m.s^{-1}$)

L =characteristic linear dimension (m)

γ = kinematic viscosity ($m^2.s^{-1}$)

3.4.7 Selection of drying Chamber volume

The shape of the dryer chamber is square, the split coconut height and diameter was measured in order to determine the area of the tray and height of the chamber. The area of the tray is given by,

Area of tray (A_T) = L^2 ...(3.14)

Length of tray (L) = n x D_c ... (3.15)

Volume of dryer chamber (V_c) = A_T x h ...(3.16)

Where,

n = number of split coconuts

D_c = diameter of coconut (m)

h = height of chamber (m)

3.4.8Thickness of insulation

Glass wool material is selected for insulating the drying chamber to avoid heat losses. The critical thickness of the glass wool is calculated by using the following equation:

$$R_c = \frac{k}{h_o} \qquad ....(3.17)$$

Where,

R_c= critical thickness (m)

h_o =heat transfer coefficient of ambient air ($W.m^{-2}K^{-1}$)

k = thermal conductivity (W.m^{-1}K^{-1})

3.5EXPERIMENTAL PROCEDURE

The solar drying was conducted at Kelappaji College of Engineering and Technology, Tavanur. This place is situated at 10°51'8.88" north latitude and 75°59'8.61" east longitude. Solar evacuated tube collector was installed at roof top of college guest house at 10°51'13.75" north latitude, 75°59'14.08" east longitude and altitude of 27m above mean sea level, inside the campus.

The experiments were carried out from 2nd March to 29th May 2017. The capacity of dryer was 20 kg which can accommodate 50 coconuts. In order to perform comparative studies 2kg of sample was dried in open sun and, the solar dryer is run at full load of 20 kg coconuts. The coconuts were procured from KCAET Farm.

Plate 3.1 Split coconuts arranged on drying tray

The procured coconuts were split into two halves and the water is removed. The split coconuts were exposed to sun for 10-15 min before placing into the drying chamber in order to remove the surface moisture. The solar air heater was run for 1 h before placing the coconuts inside the drying chamber.

The experiments were conducted at different combinations of temperatures and velocities. After performing the preliminary studies it was observed that the solar air heater was producing temperature of about 75-90 ° C at a velocity of 1.0 m/s. Hence, based on this different temperatures and velocities were selected. By using 30 evacuated tubes it was easy to maintain 70-80 ° C at 0.8 ms^{-1}. The temperature was regulated by providing shade to the evacuated tubes and the blower velocity was adjusted by using regulator. In this way all the nine experiments were conducted and necessary observations were recorded.

A comparative study was conducted on open-air sun drying by taking same quality coconuts as in the drying chamber. The sample was collected for every 2 h for determination of moisture content.

3.5.1 Estimation of Global Solar Radiation

According to Sukhatme (2006), monthly average daily solar radiation of Tavanur region was estimated using the following standard procedure. It was suggested that the amount of sunshine by a simple linear relation of the form;

$$\frac{H_g}{H_0} = a+b\left(\frac{S}{S_{max}}\right) \qquad ....(3.18)$$

Where,

H_g = monthly average of the daily global radiation on a horizontal surface at a location ($kJ.m^{-2}day^{-1}$)

H_0 = monthly average of the daily extra-terrestrial radiation which would fall on a horizontal surface at the location ($kJ.m^{-2}day^{-1}$)

S = monthly average of the sunshine hours per day at the location (h)

S_{max} = monthly average of the maximum possible sunshine hours per day at the location, i.e. the day length on a horizontal surface (h)

a and *b* = constants obtained by fitting data.

Values of *a* and *b* have been obtained for many cities in the world by Lof *et al.,* 1966. They are given in table 3.2.

Table. 3.2 Constants *a* and *b* for cities near to Tavanur region. Sukhatme (2006)

Location	***A***	***B***	**Mean error (per cent)**
Mangalore	0.27	0.43	4.2
Thiruvananthapuram	0.37	0.39	2.5

The Constants *a* and *b* for Tavanur region are not available, it is necessary to derive them from the existing constants of the nearest locations. The location of Tavanur is located in between the Mangalore and Thiruvananthapuram, therefore, the mean of both the cities is taken as the constants for Tavanur region.

H_0 is obtained by integrating over the day length as follows:

$$H_0 = \frac{24}{\pi} I_{sc} \left(1 + 0.033 \cos\frac{360n}{365}\right) (w_s \sin\emptyset \sin\delta + \cos\emptyset \cos\delta \sin w_s) \quad \text{....(3.19)}$$

$$w_s = \cos^{-1}\{-\tan\emptyset \tan\delta\} \quad \text{....(3.20)}$$

$$\delta = 23.45 \sin\frac{360}{365}(284 + n) \quad \text{....(3.21)}$$

$$S_{max} = \frac{2}{15} \times w_s \quad \text{....(3.22)}$$

Therefore, $\frac{H_g}{H_o} = \{a + b(\frac{S}{S_{max}})\}$

Where,

I_{sc} = solar radiation constant ($W.m^{-2}$)

n = number of days

$\emptyset$ = latitude of the location (degrees)

δ = declination (degrees)

w_s= sunrise hour angle

3.5.2 Measurement of temperature and relative humidity

The temperature and relative humidity of the ambient atmosphere and the inside chamber were measured using digital temperature and humidity meter. The laboratory thermometer was used to measure the machine outlet temperature. The measurements were noted from morning 8’ O clock to evening 4’ O clock in an interval of 2 h. The dryer was operated for 8 h per day.

3.5.3 Measurement of air velocity

Hot air produced inside the solar evacuated tubes is forced inside the drying chamber through blower. The velocity of the hot air was measured by using digital anemometer. A regulator was used to monitor the velocity of hot air passing inside the drying chamber. The selected air velocities are 0.2 $m.s^{-1}$, 0.5 $m.s^{-1}$, 0.8 $m.s^{-1}$.

3.5.4 Determination of moisture content

The initial weight of the sample was taken as $W_0$and then it was kept in the oven for 24 h at 105 °C in order to determine the amount of moisture content present in the fresh coconut sample. The sample kept in oven undergoes charring and looses all the moisture and reaches bone dry state. The weight of this bone dry matter is considered as final weight W_t. All the measurements were recorded by using digital weighing balance. The moisture content was determined as follows (Mohanraj and Chandrasekar, 2008)

$$M_{wb} = \left(\frac{W_0 - W_t}{W_t}\right) \times 100 \quad \ldots..(3.23)$$

Where,

M_{wb} = moisture content in wet bases (%)

W_0= weight of initial sample (kg)

W_t = weight of final bone dry sample (kg)

3.5.5 Determination of drying rate

It should be proportional to the difference in moisture content between material to be dried and equilibrium moisture content (M_e) and calculated as follows (Mohanraj and Chandrasekar, 2008)

$$DR = \left(\frac{dM}{dt}\right) \qquad \ldots(3.24)$$

Where,

DR = Drying rate (kg/s)

dM = change in mass of sample (kg)

dt = change in time (s)

3.5.6 Estimation of oil content

The oil content of the dried copra at optimized condition was measured by using soxhlet apparatus. Five grams of ground copra (W_1) was extracted with petroleum ether in a soxhlet apparatus at a rate of 150 drops per min. The sample was extracted for 4.5 h, then the thimble containing the sample was removed and the solvent allowed to evaporate for 2 h at 115°C, and then cooled to room temperature. The weight of the final product was noted as W_2. (Asis, 2006)

$$\text{Oil content} = \frac{W_2}{W_1} \times 100 \qquad \ldots..(3.25)$$

Where,

W_2 = Weight of final product (g)

W_1= Weight of initial product (g)

3.5.7 Microbial analysis

The sample units were selected at random for microbiological analysis. Freshly dried samples were collected directly from the dryer to sterile polyethylene bag and brought into the laboratory. Randomly selected samples were cut into small pieces of 1 cm cube size with a sterile blade. 25 g of sample were put into a sterile conical flask with 225 ml sterile peptone water as dilution. This flask was incubated for about 30 minutes in a shaking incubator. This sample was serially diluted in sterile 9ml peptone water upto the dilution of 10^{-6}. The serially diluted samples were placed on sterile agar plates by using standard pour plate technique. The samples were inoculated into nutrient agar plate to get standard plate count for total microbial load, EMB agar for coliforms and Rose Bengal for mould and yeast. All the plates were incubated at 30^0C for 24 to 48 h for mesophilic organisms and 27^0C for 48 to 96 h for mould growth.

3.6 STATISTICAL ANALYSIS

The effect of different combinations of temperatures and velocities introduced inside the drying chamber in each experiment was statistically analyzed by ANOVA. The statistical analysis of the data was carried out using Design Expert software (version 7.0.0).

CHAPTER IV

RESULTS AND DISCUSSION

This chapter outlines the results on development of a solar evacuated tube dryer and its performance evaluation. The outcomes of the evaluation leading to the standardization of the main process parameters are discussed in detail. Also, the effect of various process variables on the drying rate, moisture loss and drying time of the copra through solar evacuated tube dryer are analyzed, discussed and compared with natural sun drying.

4.1 DEVELOPMENT OF A SOLAR DRYER

A solar copra dryer incorporated with evacuated tube collector for drying fresh coconuts was developed which consists drying chamber, evacuated tube collector, air blower and supporting stand. The amount of energy generated by the solar evacuated tube collector in the testing period was 63668.80 kJ (Appendix D). The developed experimental system consists of the following main components:

1. Evacuated tube collector
2. Air blower
3. Drying chamber
4. Supporting stand

4.1.1 Evacuated Tube Collector

The source of heat collection was evacuated tube collectors. The length of evacuated tube is 1500 mm and the outer and inner diameters were 47 mm and 37 mm. The length of manifold is 2.5 m and its inner and outer diameters of cylinder are 12.5 cm and 40 cm, respectively.

4.1.2 Air Blower

The blower was selected based on the required air flow rate which was 529.38 kg per 30 h. The required air flow rate for drying within was 0.29 $kg.s^{-1}$.

Higher capacity blower of 110 W was selected in order to test the product and to increase the product capacity inside the drying chamber.

4.1.3 Drying Chamber

A 24 gauge galvanized steel sheet was used to fabricate the chamber of 75 x 75 x 50 cm by length, width and height, respectively. The thickness of the galvanized metal sheets is 2 mm. The height of the exhaust duct was 120 cm and diameter of 11 cm. The drying chamber and the solar evacuated tube collector were connected by metal duct of 60 x15x 20 cm length, breadth and height, respectively.

4.1.4 Supporting Stand

The evacuated tube collector setup was placed on a supporting stand fabricated out of 2 x 2 cm square tube having 2 mm.

Plate 4.1. Full load drying chamber

Plate. 4.2. Side view of ETC setup

Plate 4.3. Front view of solar ETC setup

4.2 EXPERIMENTAL DESIGN

Based on the design and the preliminary studies conducted, the temperature, velocity and insulation was fixed. The following shows the independent variable and its corresponding values.

4.2.1 Independent Variables

Since the solar energy is intermittent in nature, it was not possible to regulate a fixed temperature. Hence a range of 10 °C temperature was taken as one unit as shown below;

a) Temperature (°C)

1) T_1 : 50-60
2) T_2 : 61-70
3) T_3 : 71-80

b) Velocity (ms^{-1})

1) V_1 : 0.2
2) V_2 : 0.5
3) V_3 : 0.8

c) Insulation (mm)

1) I_1 : With insulation (12.5)
2) I_2 : Without insulation (0)

4.3 DESIGN CALCULATIONS

The dryer is developed for drying 20 kg coconuts; hence the details of each parameter are considered and calculated accordingly.

4.3.1 Amount of Moisture to be Removed

The moisture content of the fresh coconuts which was collected from KCAET farm, was determined by using hot air oven method, where the initial moisture content (Q_1) and final moisture content (Q_2) were 55 and 7 percent, respectively. In order to avoid poor quality of copra the moisture content of the product must be reduced to 35 percent within 12 h of drying and in next 12 h the moisture need to be reduced from 35 percent to 20 percent and remaining time is taken to reach its final moisture content of seven percent. So the amount of moisture to be removed from 55 to 35 percent was calculated as 6.15 kg. The amount of moisture removed from 35 to 20 percent was 2.59 kg and from 20 to 7 per cent moisture content was 1.57 kg. The amount of moisture to be removed in kg (M_R) from fresh sample was given as (Mohanraj and Chandrasekar, 2008):

$$M_R = M\left(\frac{Q_1 - Q_2}{1 - Q_2}\right)$$

$$= 20\left(\frac{0.55 - 0.07}{1 - 0.07}\right)$$

$$= 10.32 \text{ kg}$$

Hence, the total amount of moisture to be removed (M_R) for drying 20 kg coconut was calculated as 10.32 kg.

4.3.2 Quantity of Air Required for Effective Drying

The quantity of air required for effective drying (Q_a) depends on the initial humidity ratios (H_{r1}), final humidity ratios (H_{r2}) and moisture to be removed (M_R) which was observed as 0.0215 kg water vapour.kg^{-1} dry air, 0.041 kg water vapour.kg^{-1} dry air and 10.32 kg, respectively. The quantity of air required to effect drying in kg was calculated using formula given below (Ajisegiri *et al.*, 2006):

$$Q_a = \left(\frac{M_R}{H_{r2} - H_{r1}}\right)$$

$$= \left(\frac{10.32}{0.041 - 0.0215}\right)$$

$$= 529.38 \text{ kg}$$

The quantity of air required for effective drying was calculated as 529.38 kg.

4.3.3Quantity of Heat Required

The quantity of heat required for effective drying is mainly dependent on two parameters, amount of moisture to be removed and rate at which it has to be removed. The dryer capacity per batch (M) was 20 kg, Specific heat of the product (C_p) was 2.93 kJ.kg^{-1}K^{-1}. Temperature gradient (ΔT) between ambient temperature (30 °C) and inside dryer chamber temperature (70 °C) was 40 °C. Latent heat of vaporization (λ) is 2260 kJ.kg^{-1} and amount of moisture to be removed (M_w) was 10.32 kg. The ambient temperature (T_1) is 30 °C and air heater outlet temperature (T_2) is 70 °C. The quantity of heat required (S) for drying in kJ is given by (Akpan *et al.*, 2016):

S = Sensible heat of the product (S_1) + Sensible heat of water (S_2) +Latent heat of vaporization (S_3)

$$S_1 = M_p \times C_p \times (T_2 - T_1)$$

$$= 9.678 \times 2.93 \times (70-30)$$

$$= 1134.26 \text{ kJ}$$

$$S_2 = M_w \times C_w \times (T_2 - T_1)$$

$$= 10.322 \times 4.186 \times (70-30)$$

$$= 1728.315 \text{ kJ}$$

$$S_3 = M_w \times \lambda$$

$$= 10.322 \times 2260$$

$$= 23327.72 \text{ KJ}$$

$$S = 1134.26 + 1728.315 + 23327.72$$

$$= 26190.29 \text{ kJ}$$

By considering external heat losses of 20 per cent, the final heat requirement was calculated as

$$= 26190.29 + 0.20 \times 26190.29$$

$$= 31428.348 \text{ KJ}$$

Therefore, the total quantity of heat required by considering external heat losses of 20 percent was calculated as 31428.35kJ.

4.3.4 Collector Area of Evacuated Glass Tubes

The collector area is calculated based on the amount of energy required to perform the drying operation. The total solar energy available at KCAET, Tavanur in the month of March was 24394.18 kJ.m^{-2}day^{-1} (Appendix D).

To dry the coconuts in 25 h, the amount of heat required was calculated as 31428.35 kJ in section 4.3.3. Hence, the amount of heat required per hour is calculated as 1257.133kJ.

$$\text{Available solar energy per hour} = \frac{24394.18}{11}$$

$$= 2217.65 \text{ kJ.m}^{-2}\text{h}^{-1}$$

Therefore, the area of collector surface required calculated as following,

$$\text{Required collector area} = \frac{1257.1339}{2217.65 \text{ x } 0.40}$$ (assuming 40% collector efficiency)

$$= 1.42 \text{ m}^2$$

Including 15% extra area, the final required area is calculated as,

$$= 1.42 + (1.42 \text{ x } 0.15)$$

$$= 1.64 \text{ m}^2$$

It is also known that it is necessary to reduce the moisture content of copra from 55 to 35 per cent within 8 h of drying operation. The amount of water which has to be removed within 8 h of drying period is estimated as 6.15 kg (M_R). The quantity of heat required is given as,

Heat required = $m_p\, C_p(T_2 - T_1) + m_w\, C_w (T_2 - T_1) + (M_R \times \lambda)$

$= 13.85 \times 2.93 \times (70-30) + 6.15 \times 4.186 \times (70-30) + (6.15 \times 2260)$

$= 1623.22 + 1029.75 + 13899$

$= 16551.97$ kJ per 8 h

$= 2068.99$ kJ.h^{-1}

Hence, required collector area = 2068.99/2217.65 x 0.4

$= 2.33\ \text{m}^2$

Since the area required for reducing moisture content from 55 to 35 per cent is more than the overall heat required for drying the coconuts, the higher value is selected as the required area for safe drying. Therefore, the required area of the collector is calculated as 2.33 m^2.

4.3.5Number of Evacuated Tubes

The determination of number of tubes depends on the size of each tube available commercially. It is given by the following equation:

$$\text{Number of tubes} = \left(\frac{\text{collector area required}}{\text{projected area of standard tube}}\right)$$

$$= \left(\frac{2.33}{0.087}\right)$$

$$= 26$$

The collector area is calculated as 2.33 m^2 and the projected area of solar evacuated tubes is 0.087. The number of tubes is calculated as 26 where as 30 tubes were taken for this experiment considering the fact that we may require a temperature higher that 70 °C in some cases.

The length of the each tube is 1.5 m and the diameter is 0.037 m. The total numbers of tubes are 30. The Collector area (A) is the area of solar evacuated tubes which is projected towards the sun direction, it can be calculated as,

$$\begin{aligned}\text{Maximum Collector area (A)} &= [L_g \text{ x } C/2] \text{ x } n \\ &= [1.5\times 0.058] \times 30 \\ &= 2.61 \text{ m}^2\end{aligned}$$

The area of the dryer collector can be altered according to the requirement of heat energy. Hence, the maximum collector area was calculated as 2.61 m^2.

4.3.6 Heat Transfer Rate

In order to compute heat transfer rate the convective heat transfer coefficient of ambient air was calculated. The Reynolds number was calculated to be 35356.51 which was less than 3 x 10^5, therefore the flow was laminar. And, Nusselt number was calculated as 111.43. By using thermal conductivity of air at 40 °C, *i.e.,* 0.0271 $W.m^{-1}K^{-1}$ the convective heat transfer coefficient is determined as 4.02 $W.m^{-2}K^{-1}$.The heat transfer rate (Q_{ht}) can be determined as follows (Comwel, 1978)

$$Q_{ht} = hAT_B$$

The convective heat transfer coefficient can be calculated by using the following expression (Geankoplis, 2011).

$$h = \frac{(\bar{N}_{nu}K_f)}{L}$$

Nusselt number ($\overline{N}_{nu}$) is the function of Reynolds number (Re) and prandtl number (N_{Pr}).

Therefore, Reynolds number is estimated by using the following expression,

$$\mathrm{Re} = \frac{v \times \mathrm{L}}{\gamma}$$

$$= \frac{0.8 \times 0.75}{16.97 \times 10^{-6}}$$

$$= \quad 35353.61$$

$$\overline{N}_{nu} = 0.664\ N_{\mathrm{Re}}^{0.5}\ N_{\mathrm{Pr}}^{0.33}$$

Where, $N_{pr} = 0.711$, $\gamma = 16.97 \times 10^{-6}\ \mathrm{m^2.s^{-1}}$, $K_f = 0.0271\ \mathrm{W.m^{-1}K^{-1}}$

$$= 0.664 \times 35353.61^{0.5} \times 0.711^{1/3}$$

$$= 111.43$$

$$h = \frac{(\overline{N}_{nu} K_f)}{L}$$

$$= \frac{111.43 \times 0.0271}{0.75}$$

$$= 4.02\ \mathrm{W.m^{-2}.K^{-1}}$$

Heat transfer, $Q_{ht} = hAT_B$, Where area (A) = 2.61 $\mathrm{m^2}$

$$= 4.02 \times 2.61 \times (70-30)$$

$$= 419.68\ \mathrm{W}$$

Hence, the heat transfer rate is calculated as 419.68 W.

4.3.7 Volume of drying chamber of the dryer

In order to accommodate 20 kg of coconuts, there must be sufficient area for placing the coconuts; hence two trays having an area of 0.75 x 0.75 $\mathrm{m^2}$ were selected. By considering the ergonomic aspects and necessary spacing between the trays, the height of the chamber was selected to be 0.5 m. The height of one split coconut was 5 cm and maximum diameter was 10 cm.

The shape of the dryer chamber is cuboidal, the split coconut height and diameter was measured in order to determine the area of the tray and height of the chamber. The area of the tray is given by,

$$\text{Surface Area of tray } (A_T) = L^2$$

It is estimated that 7 coconuts having an average diameter of 10 cm can be kept in a side of the tray,

Therefore, $\text{Length of tray } (L) = n \text{ x } D_c$

$\text{Volume of dryer chamber } (V_c) = A_T \text{ x } h$

$L = 7 \text{ x } 10 = 70$

For better performance, tray length is taken as 75 cm.

Therefore, $A_T = 0.75 \times 0.75$

$= 0.5625 \text{ m}^2$

The height of the drying chamber was fixed based on height of the split coconut, spacing between the two trays and free hand movement for easy handling. Hence, the height was fixed as 0.5 m.

$Vc = 0.5625 \times 0.5$

$= 0.28125 \text{ m}^3$

By using this data, 7-8 split coconuts can be arranged in 75 cm length. If the diameter of the coconuts is smaller than 10 cm then the dryer can accommodate 8-9 split coconuts in a row which gives 64 split coconuts per tray. The opening was provided on one side with air tight locking system in order to minimize heat loss and escape of hot air from the chamber.

4.3.8 Thickness of Insulation

It is essential to estimate the critical thickness of insulation in order to minimize heat losses, if the thickness of insulation is more than the critical value, it will increase heat transfer also it adds cost of insulation. The thermal conductivity of glass wool slab was 0.043 $W.m^{-1}K^{-1}$ (Tittarelli *et al.,* 2013).

The critical thickness of the glass wool is calculated by using the following equation:

$$R_c = \frac{k}{h_o}$$

Where h_0 = convective heat transfer coefficient

$$R_c = \frac{0.043}{4.026}$$

$$= 10 \text{ mm}$$

The critical thickness was calculated as 10 mm and for better performance 12.5 mm thick glass wool is provided as insulating material.

4.4EXPERIMENTAL PROCEDURE

The process of optimization was carried out by measuring and estimating the following parameter.

4.4.1 Estimation of Global Solar Radiation

Monthly average daily solar radiation of Tavanur region was estimated using the standard procedure (Appendix D). Declination, sunrise hour angle and day length of Tavanur region was estimated as -2.81°, 89.46 ° and 11.92 h, respectively, by using the latitude of the location and values of constants *a* and *b*.

Monthly average of the daily global radiation of Tavanur region was estimated as 24394.18 kJ. Since, the estimated value is the minimum solar radiation of Tavanur region; it is used for calculation of power developed by solar dryer. (Appendix D)

4.4.2 Measurement of Temperature and Relative Humidity

The temperature and relative humidity of the ambient atmosphere and inside chamber was measured using digital temperature and humidity meter. It was observed that minimum ambient temperature was 28.17 °C at 79.79 per cent relative humidity and maximum ambient temperature was measured as 39.98°Cat 48.07 per cent relative humidity. Also, the maximum and minimum inside drying chamber temperatures were measured as 64.68 °C at 30.87 per cent relative humidity and 34.24°C at 56.9 per cent relative humidity, respectively, (Appendix A).The maximum temperature attained by the solar air heater was 91 °C at ambient temperature of 39.83 °C and 41.66 % relative humidity.

Plate 4.4. Variation of solar air heater temperature with ambient temperature and relative humidity

4.4.3 Measurement of Air Velocity

The maximum velocity of the hot air coming out of the solar air heater was measured as 3.8 ms^{-1}.The velocity of the hot air was measured by using digital anemometer at the outlet of the duct. The outlet was rectangular duct which was 10x 15 cm. By using the regulator the velocities were adjusted to 0.2 m.s^{-1}, 0.5 m.s^{-1}, 0.8 m.s^{-1}.

4.4.4 Determination of Moisture Content

The final moisture content of the dried copra was measured using hot air oven method and the minimum moisture content measured was 6.7 and 6.47 in top and bottom trays of the dryer, respectively at temperature 70-80 °C

(T_3), at velocity 0.8 $m.s^{-1}$ (V_3) and insulation of 12.5 mm (I_1) (Table 4.3). And, the maximum moisture content measured was 9.1 and 8.8 per cent in top and bottom trays, respectively at temperature 50-60 °C (T_1), at velocity 0.2 $m.s^{-1}$(V_1) and insulation of 12.5 mm (I_1). (Appendix C)

4.4.5 Determination of Drying Rate

Drying rate was determined for all the experiments and the results showed that there was no constant rate of drying. This might be due to uneven supply of heat to the drying chamber. The drying rate of the solar dryer was acceptable when compared to sun dried product in figure 4.16 and 4.17.

4.4.6 Oil Content

The amount of oil content present in the dried sample was calculated for 5 g sample which was extracted using soxhlet apparatus to 3.32 g.

$$\text{Oil content} = \frac{W_2}{W_1} \times 100$$

$$= \frac{3.32}{5} \times 100$$

$$= 64.46\ \%$$

Hence, the oil content measured was 64.46 per cent.

4.4.7 Microbial Analysis

After incubation, the plates were observed for microbial growth and recorded the results as colony forming units (CFU). The results were presented in the table.

After 48 h of incubation, up to 10^{-3} dilution, there is no microbial growth detected except nutrient agar with 3 CFU, however 10^{-2} dilution with 96 CFU. In EMB agar, there is no growth observed up to 10^{-3} dilution while few non lactose fermenting colonies were observed on 10^{-2} dilution (40 CFU). However, the sample was totally free from *E. coli* or other coli forms.

Table 4.1. Microbiological analysis of copra

Media	**Dilutions (24-48 h)**				
	10^{-2}	10^{-3}	10^{-4}	10^{-5}	10^{-6}
Nutrient agar	96	3	nil	nil	Nil
Eosin Methylene Blue	40	nil	nil	nil	Nil
Rose Bengal Agar	nil	nil	nil	nil	Nil

There was no fungal growth observed on Rose Bengal Agar after 72 h of incubation. The data is presented in the above table 4.1. Based on the observations, the tested samples are microbiologically safe for human consumption.

4.5 STANDARDIZATION OF PROCESS PARAMETERS OF THE SOLAR DRYER SYSTEM

In order to evaluate the performance of the solar dryer and to optimize the process parameters, a series of experiments were conducted as per the experimental design. There are 3 input variables; input temperature (50-60, 61-70 and 71-80 °C), blower velocity (0.2, 0.5, 0.8 $m.s^{-1}$), insulation thickness (0, 12.5 mm) employed for the experiment as shown in table 4.2. The experiments were conducted as per the methodology described in chapter III under section 3.4. The process of drying the copra by using the solar evacuated tubes was then standardized.

Table 4.2. Independent variables for performance evaluation of solar dryer

Sl. No.	**Input variables**	**Symbol**	**Value**
1	Temperature (°C)	T_1	55 ± 5
2		T_2	65± 5
3		T_3	75± 5
4	Velocity ($m.s^{-1}$)	V_1	0.2

5		V_2	0.5
6		V_3	0.8
7	Insulation (mm)	I_1	12.5
8		I_2	0

All the experiments were performed under the insulated condition, where the drying chamber was insulated with 12.5 mm thick glass wool (I_1). From the Table 4.2, it is clear that $T_3V_3I_1$ showed best results with minimum moisture content and less drying time.

Table 4.3. Effect of process variables towards drying of copra

Sl. No.	**Sample**	**Moisture Content (%)**		**Time (h)**	**Average RH (%)**	**Average Temperature (°C)**
		Top tray	**Bottom tray**			
1.	$T_1V_1I_1$	9.1	8.8	42	44.84	42.96
2.	$T_2V_1I_1$	7.9	7.8	38	37.05	46.87
3.	$T_3V_1I_1$	7.4	7.13	31	48.11	49.68
4.	$T_1V_2I_1$	8.9	8.8	40	44.18	43.43
5.	$T_2V_2I_1$	7.5	7.4	37	37.44	47.01
6.	$T_3V_2I_1$	7.11	6.76	28	41.224	57.49
7.	$T_1V_3I_1$	8.5	8.2	40	50.70	45.05
8.	$T_2V_3I_1$	7	6.82	36	46.70	49.16
9.	$T_3V_3I_1$	6.7	6.47	28	40.22	54.68
10.	$T_3\ V_3\ I_2$	11.2	10.8	52	34.21	38.20
11.	Sun dried	15.18		84	59.95	33.40

Now, the same experiment was repeated without insulation ($T_3V_3I_2$) and the results showed poor outcome (Table 4.3). It was observed that the moisture content was more than 10 per cent which is not recommended for either storage or oil extraction. It was also noticed that due to absence of insulation, the drying time had increased to 52 hours. Therefore, the experiments without insulation were not further carried out.

4.6 EFFECT OF PROCESS PARAMETERS ON OUTPUT CHARACTERISTICS OF SOLAR DRYER

4.6.1 Moisture Content

The effects of solar drying parameters on moisture content of solar dried copra are shown in Fig. 4.1. It was observed that the moisture content decreased significantly with increase in inlet air temperature. Constant rate of moisture removal during the early stages of drying was not observed as found in other studies (Cardenas, 1968; Guarte *et al.*, 1996; Rajasekharan *et al.,* 1961).The moisture content varied from 6.43 to 9.1 per cent (w.b). It was also observed that the loss of moisture content was more at higher velocity of hot air. Case hardening, the formation of a hard layer on the outer layer of the product that restricts the passage of moisture movement from the interior to the surface, was not observed even at drying temperatures of 80°C (Guarte *et al.*, 1996).

Hence, it was concluded that a temperature of 70-80 °C and velocity of 0.8 m.s^{-1} was favorable for drying when compared to all other temperature and velocity levels.

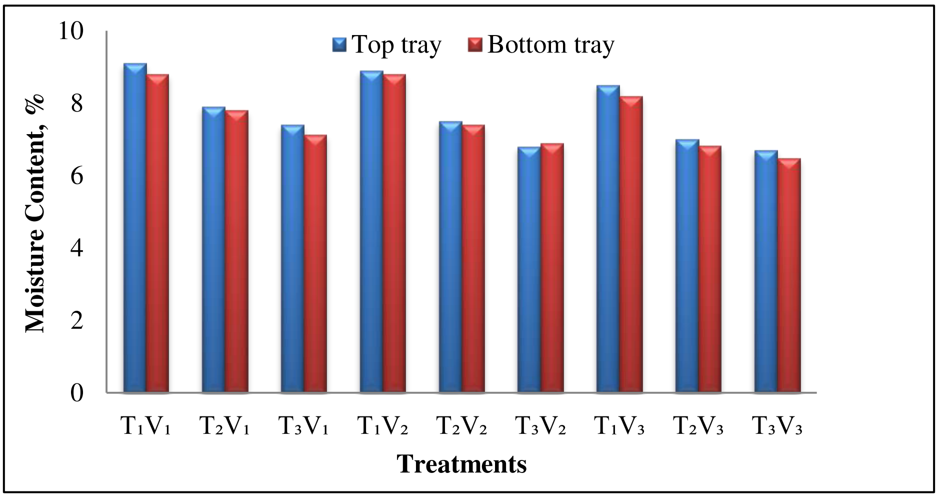


Figure 4.1. Effect of process parameter on final moisture content

Figure 4.1 also shows the effect of process parameters on moisture content of the coconuts which are drying on two trays inside solar dryer. The change in moisture content in both the trays are almost similar; bottom tray dries quicker than top tray as the bottom tray is first exposed to hot air which enters the drying chamber.

4.6.2 Drying time

Figure 4.2 shows the effect of process parameters on drying time of the coconuts. Different combinations of temperatures and velocities were used to conduct experiments. The temperature at 70-80°C and velocity of 0.8 m.s^{-1} took 28 h to reach final moisture content of 6.69 per cent and 6.47 per cent in top and bottom tray, respectively. It was evident that as the inlet temperature increased, the drying time decreased accordingly. A similar trend in drying time was observed in cabinet dryer while drying copra (Deepa *et al.,* 2015; Adom *et al.,* 1997)

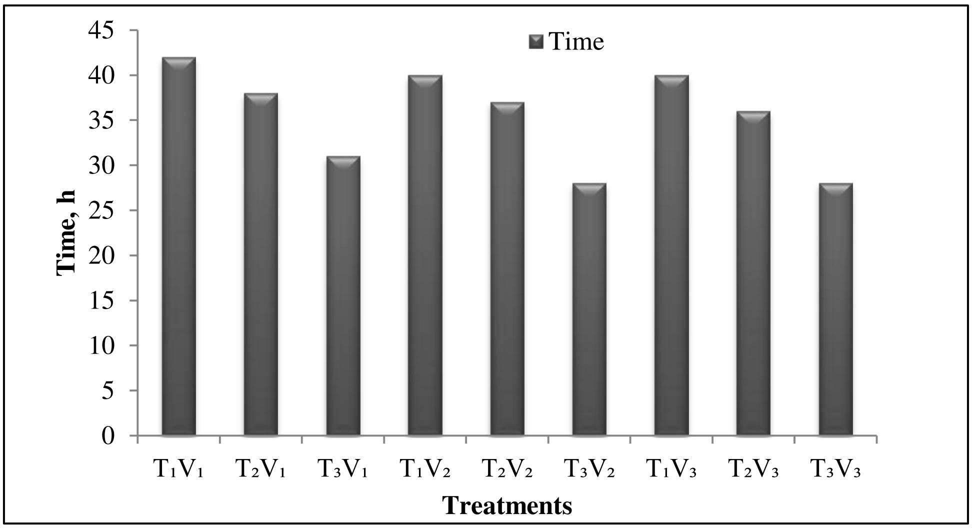


Figure 4.2. Effect of process parameter on drying time

4.6.3 Temperature inside drying chamber

Figure 4.3 shows the variation of drying chamber temperature at different combination of temperature and velocity. It was observed that as the inlet temperature increased the chamber temperature also increased. The average drying chamber temperature varied between 42.96 °C and 54.68 °C. And the maximum drying chamber temperature was 68.5 °C under no load condition and 64.4°C under full load condition.

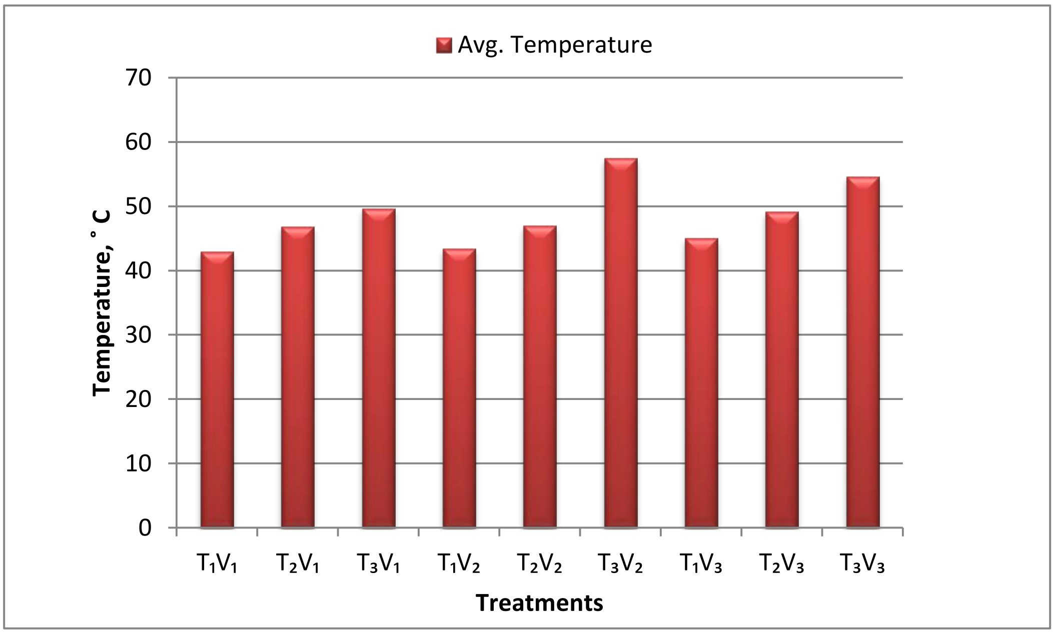


Figure 4.3. Effect of process parameter on drying chamber temperature

4.6.4 Relative humidity inside drying chamber

In figure 4.4, it is shown that there is uniform effect of process parameters on relative humidity of the chamber. The non uniformity is due to the huge fluctuation in ambient humidity and variation in moisture content per cent in the coconut product which has to be dried. The relative humidity should be less in order to effectively remove moisture from the product. The maximum average relative humidity was observed at 55 °C temperature and 0.8 $m.s^{-1}$.

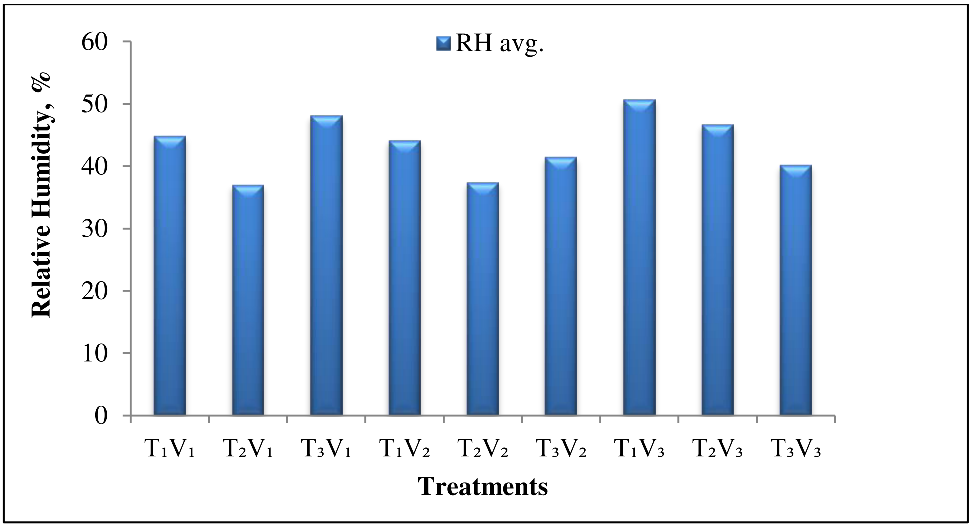


Figure 4.4. Effect of process parameter on average relative humidity inside drying chamber

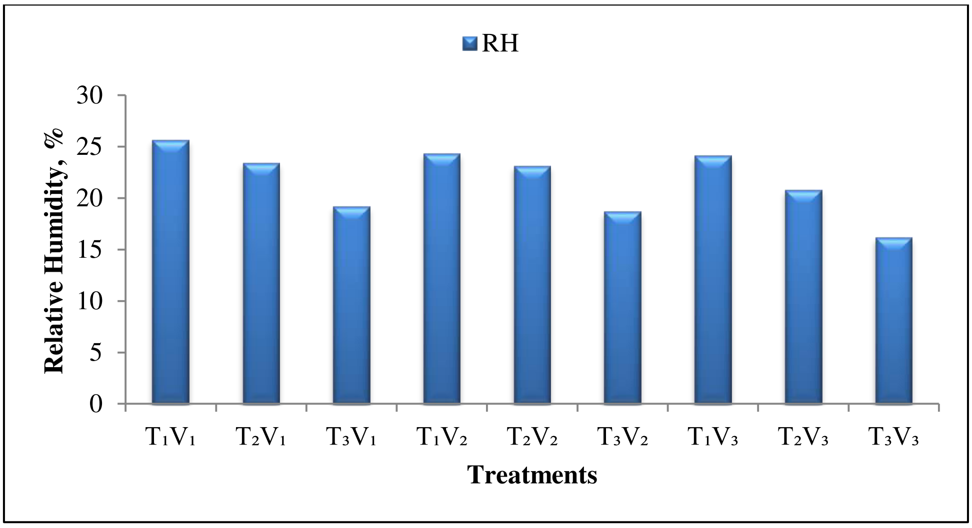


Figure 4.5. Effect of process parameter on final relative humidity inside drying chamber

Figure 4.5 shows the final relative humidity inside the drying chamber. The relative humidity was observed to be reducing as the temperature and velocity increased. As the relative humidity reduces inside the dryer chamber, the rate of drying increases.

4.7 DRYING CHARACTERISTICS OF COPRA

For experiment with full load, 20 kg of fresh coconuts having initial moisture content 50% to 55% (w.b.) was divided into two trays and then the product was loaded in solar drying chamber during the month of March, 2017.The experimental data were recorded after every two hours from 8 a.m. to 4 p.m. on each day during drying period. To determine the moisture content, 12 g of sample was taken from each tray and the moisture content present inside the product at different stages of drying was calculated by weighing the sample for every 2 h duration. It was observed that initial weight of coconut sample (top tray) was reduced from 12 g to 5.68 g with initial moisture content 55.37 per cent (w.b) to final moisture content of 6.69 per cent (w.b). Similarly initial weight of coconut sample (bottom tray) was reduced from 12 g to 5.87 g with initial moisture content 54.24 per cent (w.b) to final moisture content of 6.43 per cent (w.b).The drying time was observed as 28 to 30 h which took 4 days to reduce moisture content of copra. (Table B.9 Results, Appendix B)

Figure 4.6 shows variation of moisture content reduction per cent (w.b) for every two hours in the month of March. During this period solar dryer was loaded with coconuts with initial moisture content as 53.5 per cent (w.b) to 6.47 per cent (w.b) and drying was completed in four days. Similar trend in moisture content was observed in cabinet dryer for copra (Deepa *et al.*, 2015). It was also observed that the moisture content of copra reduced to 35 per cent from initial moisture content of 53.5 per cent by the end of the first day (8 h) which was necessary to prevent microbial attack.

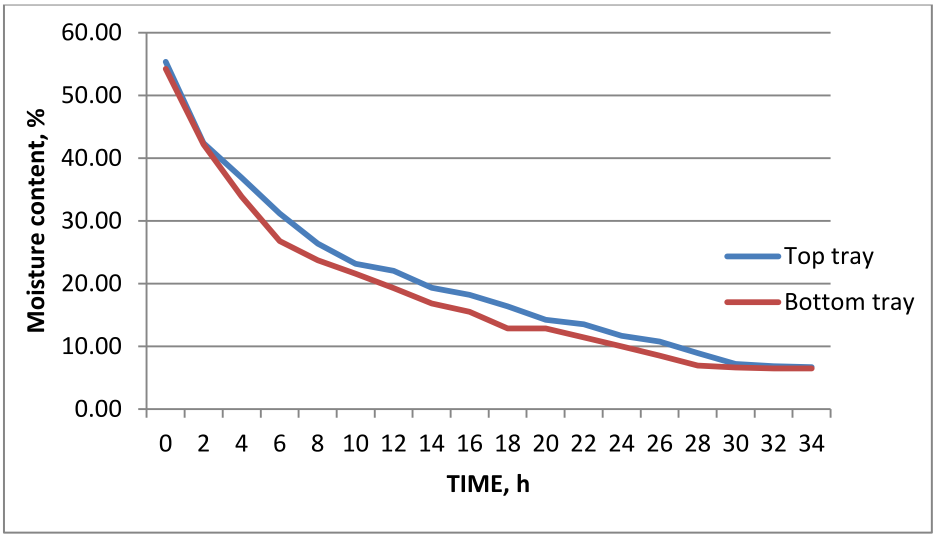


Figure 4.6 Variation of moisture content with time

Figure 4.7 shows variation of moisture loss (g) with time (h). It was observed that rate of water loss from the product was high in the beginning stage of the drying where as the rate gradually reduced and attained an equilibrium state with the chamber temperature and relative humidity. The total amount of water loss was 6.3 g (Top tray) and 6.1 g (Bottom tray) out of 12 g of sample.

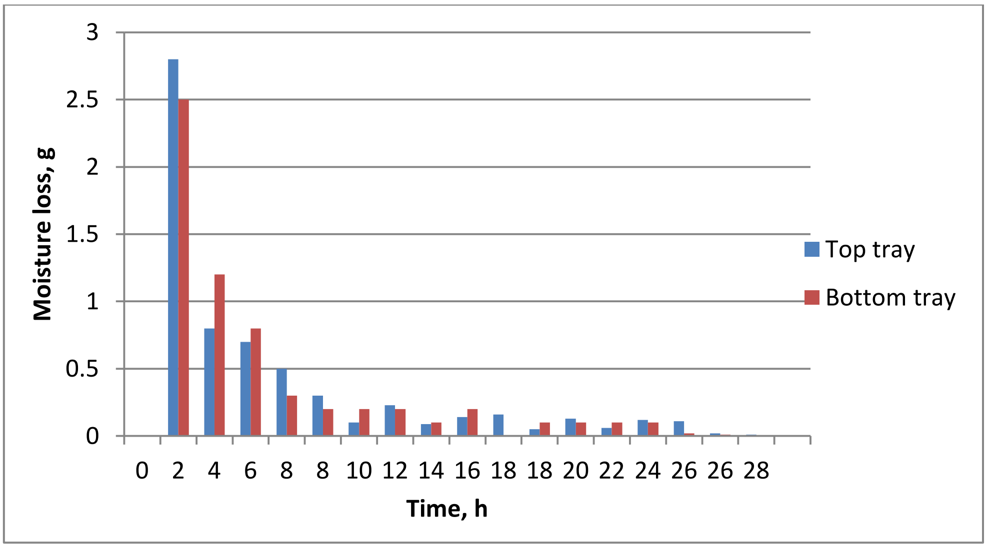


Figure 4.7. Variation of moisture loss with time

Figure 4.8 show the drying rate trend for different trays carried out during the evaluation of dryer. From the graph, the drying rate was almost same in both the trays and it was initially more due to more availability of free moisture inside the coconut. Uniform drying rate was observed when compared to open sun drying by Mohanraj and Chandrasekar (2008) while drying copra.

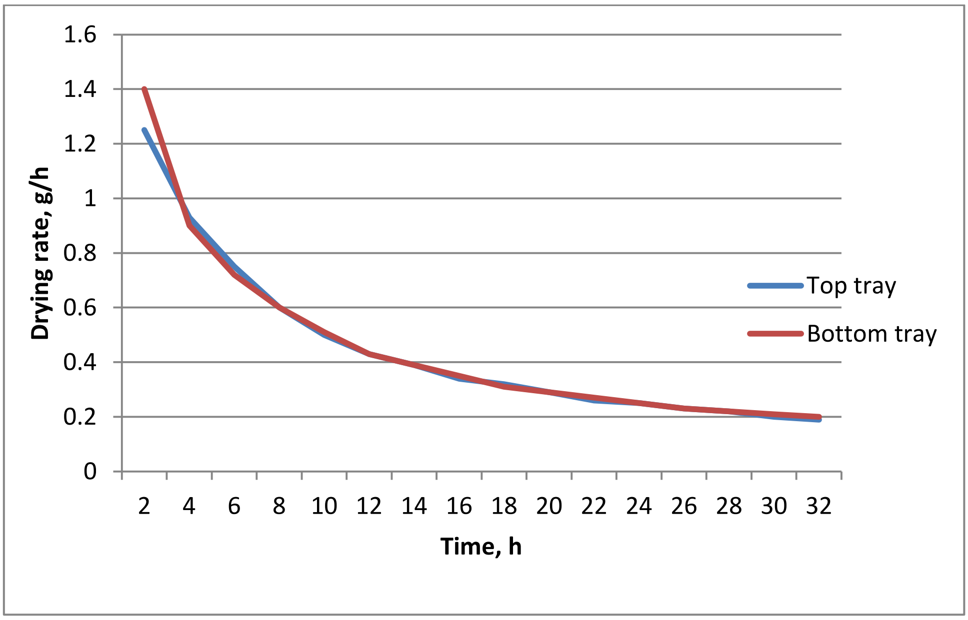


Figure 4.8. Variation of drying rate with time

Figure 4.9 shows moisture content reduction and drying rate variation for every 2 h. It was observed that drying rate was higher during the starting period of drying as compared to the end period. The decreasing trend was uniform with gradual reduction in moisture content.

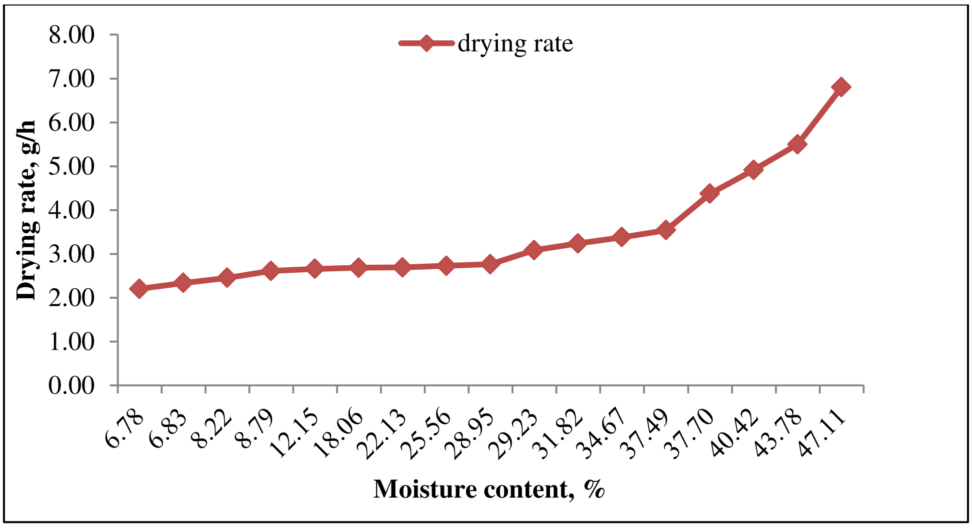


Figure 4.9. Drying rate variation with moisture content

4.8 COMPARISON OF SOLAR DRYER WITH OPEN SUN DRYING

The solar dryer developed at KCAET, Tavanur, was evaluated and it was compared to the most commonly adopted method in Kerala, i.e., open sun drying. The figure 4.10 shows the ambient temperature (°C), air heater outlet temperature (°C) and dryer chamber temperature (°C) at two hour intervals during the month of March when the solar dryer was at full load conditions with fresh split coconuts. The maximum temperature inside solar air heater observed was85°C while minimum temperature was 49°C on the typical day of the March against the maximum and minimum ambient temperature 35.84°C and 29.4 °C respectively. It was also observed that maximum and minimum temperature inside the dryer chamber was 64.68 and 38.36°C, respectively.

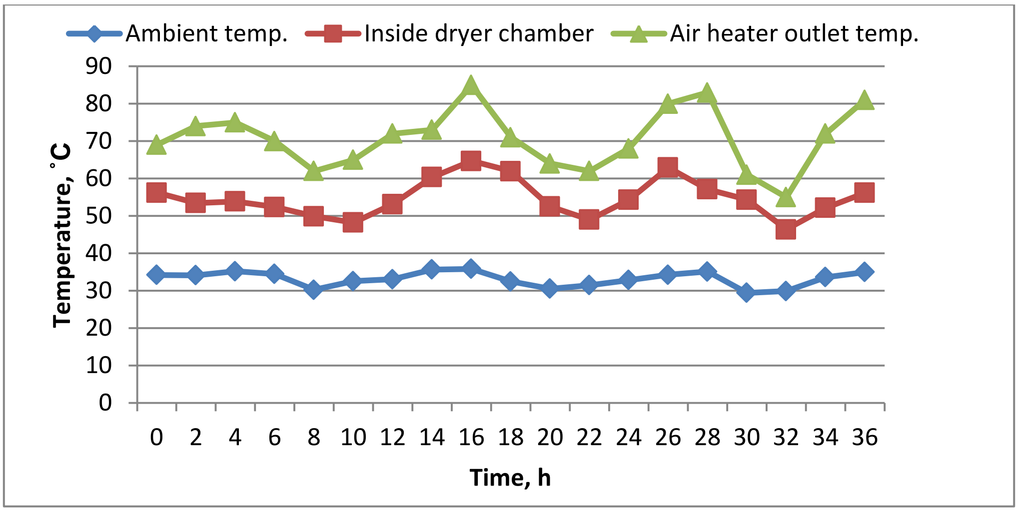


Figure 4.10. Variation of temperatures with time

Figure 4.11 shows the change in relative humidity of ambient atmosphere and dryer chamber with time. From the graph, the relative humidity inside the chamber was high initially and gradually decreased. It was observed that relative humidity is low inside the dryer chamber. Similar trend was found in solar dryer cabinet with thermal energy Storage drying experiment which was carried out by Pakhareand Salve, 2016.

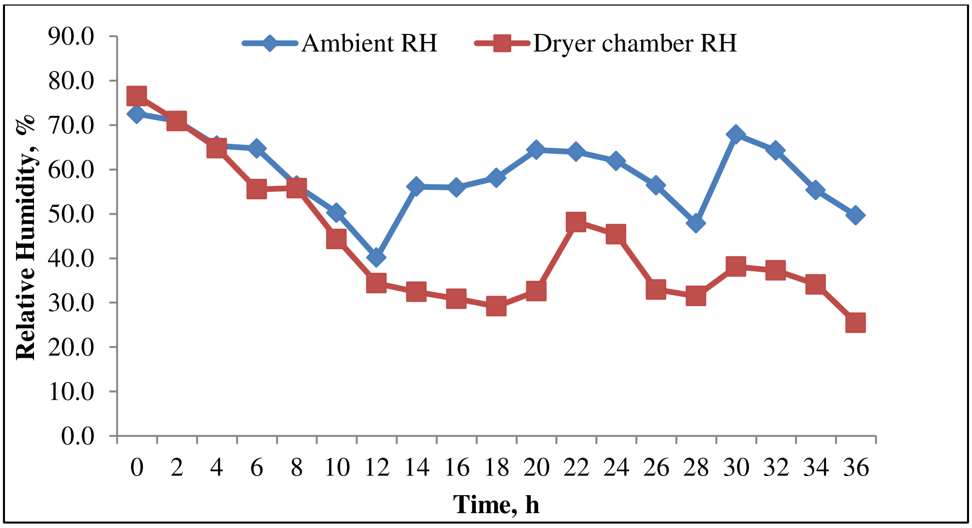


Figure 4.11. Variation of relative humidity with time

Figure 4.12 shows the change in solar air heater temperature and relative humidity with time, it was observed that as the temperature increase, the relative humidity reduces accordingly. The temperature reaches peak range in middle of the day and at the same time relative humidity is minimum. Similar trend was observed by Sanket and Rolle, 1990.

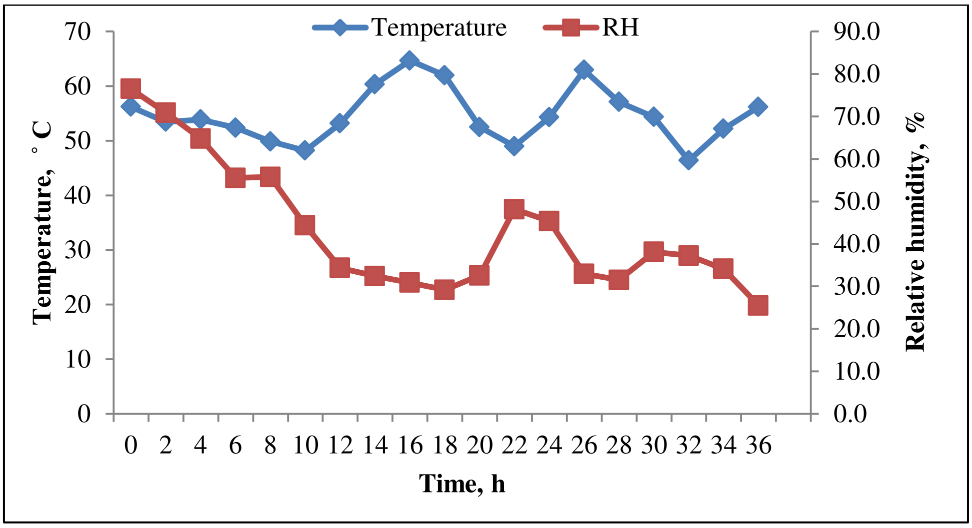


Figure 4.12. Variation of temperatures and relative humidity with time

It took 28 h to reach optimum moisture content in solar dryer where as it took 88 h in open sun drying. Similar results were found in copra drying experiment which was done by Akpan *et al.* (2016).The final moisture content in open sun drying was 15.18 per cent which is not suitable for oil extraction. Similar trend was observed in solar assisted heat pump dryer (Amer *et al.*, 2010; Yahya, 2016). Coconuts dried under natural sun drying process were wrapped inside the polyethylene sheet by the end of the day in order to prevent moisture infusion inside the dried product. In this way the product was dried without any moisture regain. Similar trend between moisture content and time was observed in open sun dried coconut which was conducted by Saravanapriya and Mahendiran, 2017.

Figure 4.13 and 4.14 represents the change in drying rate with time. In case of solar drying, there is no uneven drying as the drying rate is uniformly reducing with time. In case of open sun drying, there is fluctuation in drying rate which creates uncontrolled and uneven drying of the product. It is observed that the drying time of copra is higher than the studies made by Ayyappan and Mayilsamy, 2010 and Mohanraj and Chandrasekar, 2008.

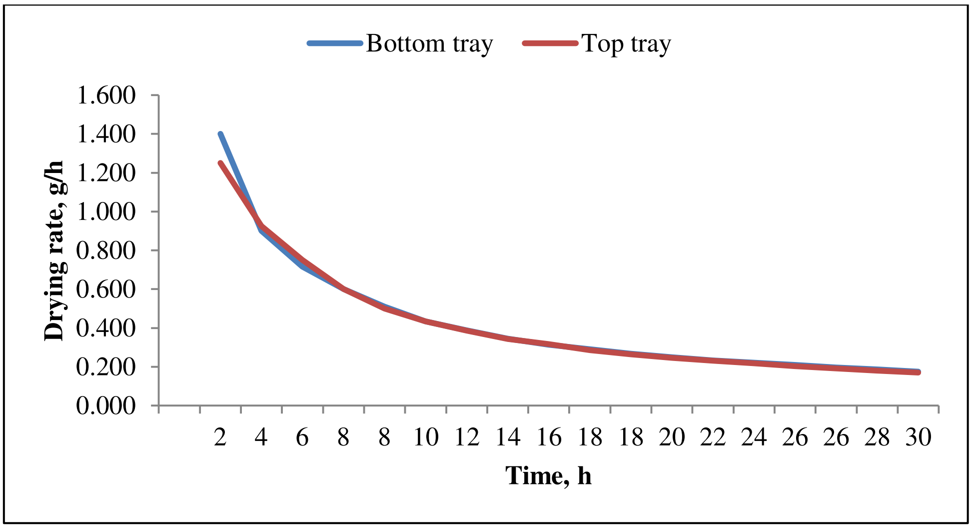


Figure 4.13. Variation of drying rate of copra inside chamber with time

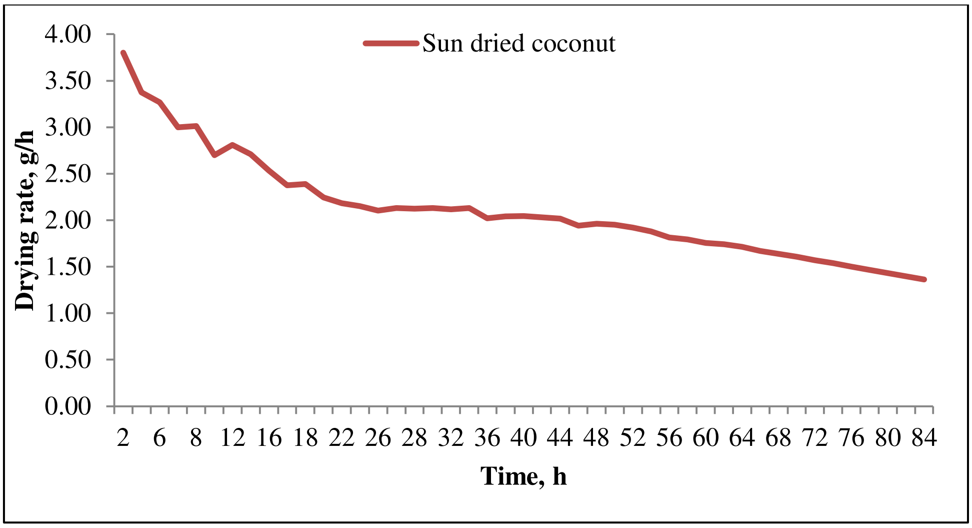


Figure 4.14. Variation of drying rate of sun dried copra with time

CHAPTER V

SUMMARY AND CONCLUSION

The present investigation was under taken to develop a solar dryer for copra and to evaluate the performance of the developed solar dryer. Drying is an excellent way to preserve food and solar food dryers are an appropriate food preservation method for a sustainable world. Traditional sun drying methods often yield poor quality, since the produce is not protected against dust, rain and wind, or even against insects, birds, rodents and domestic animals while drying. The solution of all these problems is use of solar dryer instead of open sun drying. Solar dryer can be used to dry most of the spices, vegetables, fruits and other perishable crops with maximum retention of intrinsic quality and for better shelf life.

Evacuated tubes were selected as the source of heating medium and the experimental tests were carried out at Department of Food and Agricultural Process Engineering, Kelappaji College of Agricultural Engineering and Technology, Tavanur, Kerala. Coconuts were prepared for drying and then loaded into the dryer chamber for drying at the rate of 50 coconuts per batch. At full load conditions, moisture content versus time and drying rate versus moisture content relationships were determined.

The energy produced by the solar evacuated tube collector in the testing period was 63668.80 kJ. Evacuated tube collector consisted of 30 borosilicate glass tubes of 1500 mm length and the outer and inner diameters were 47 mm and 37 mm. The length of manifold is 2.5 m and its inner and outer diameters of cylinder are 12.5 cm and 40 cm, respectively. A 24 gauge galvanized iron sheet was used to fabricate the chamber of 75 x 75 x 50 cm. The thickness of the galvanized iron sheets was 2 mm and it was completely insulated using glass wool of thickness 12.5 mm. The height of the exhaust duct was 120 cm and diameter of 11 cm. The drying chamber and the solar evacuated tube collector were connected by metal duct of 60 x 20 x 15 cm.

The evacuated tube collector setup was placed on a supporting stand fabricated out of 2 x 2 cm square tube having 2 mm thickness.

In order to evaluate the developed solar dryer for copra, the process parameters which would influence the time of drying, final moisture content and inside chamber temperature were selected as independent variables based on thorough review of literature and the preliminary studies conducted. Three levels of solar air heater outlet temperatures (50-60 ˚C, 61-70 ˚C and 71-80 ˚C), blower velocities (0.2 ms^{-1}, 0.5 ms^{-1} and 0.8 ms^{-1}) and insulation thickness (12.5 mm and 0 mm) were selected as independent variables for the experiments.

At no load conditions, the temperature inside solar dryer varies from 48 - 70 °C and was higher than the outside temperature by 16°C to 42 °C at solar insolation of 24394.18 $kJ.m^{-2}day^{-1}$. At full load conditions, it was found that the copra can be dried from an initial moisture content of 52.5 per cent (wb) to the required moisture level of 6.5 to 7.1 per cent (wb) in 28 to 32 h, which took 4 days. Poor quality copra was noticed at lower temperature and lower velocity, which was due to insufficient removal of moisture. The maximum and minimum dryer outlet temperature noticed was 91 ˚C and 36 ˚C.

The process parameters were statistically analyzed for its optimization. Analysis of variance (ANOVA) for the final predictive equation was carried out using statistical software Design Expert (Trail version 7.0.0, STAT-EASE Inc.). There were four responses moisture content of copra, drying time, inside chamber temperature and inside chamber relative humidity. ANOVA was performed and all the responses were varying significantly. The results showed that quality copra with minimum drying time was obtained during the experiment $T_3V_3I_1$ or in other words at a temperature of 70-80 ˚C and blower velocity of 0.8 $m.s^{-1}$ with insulation of 12.5 mm thickness was selected as the best combination for drying of copra.

The quality of dried sample was excellent when compared to sun dried sample. Microbial analysis showed that there was no fungal growth observed and based on the observations it was concluded that the tested samples are microbiologically safe for human consumption.

The following are the suggestions for future research work on the solar dryer for copra:

1. For obtaining higher temperature, the galvanized iron tubes should be replaced with copper tubes.
2. The insulation on the dryer chamber must be made water proof in order to minimize deterioration of glass wool insulation and also to use the supplementary heat source in rainy and cloudy climates.
3. Reflectors can be used under the evacuated glass tubes to increase the efficiency of the solar air heater and to deliver more output temperature.

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Appendix A

Results of experiment performed at different temperatue and velocity levels

Table A.1 Results of $T_1V_1I_1$

Time interval (h)	Ambient Condition		Inside Chamber Conditions			Weight of sample	
	Temp.	Humid. (%)	Chamber temp (˚c)	Machine outlet temp (˚c)	Chamber humidity (%)	Top tray (g)	Bottom tray(g)
9	34.2	72.5	45.2	60	79.24	235.6	257.4
11	34.1	70.91	42.6	58	75.15	221.2	243.9
1	35.2	65.33	46.12	58.5	69.14	208.4	232.3
3	31.5	64.71	45.36	56	50.45	200.8	224.2
5	30.25	56.31	42.51	54	55.77	191.2	215.1
8	32.53	50.26	38.15	49	45.87	190.5	211
10	33.04	40.15	45.91	56	36.18	182.3	208.3
12	35.66	56.11	46.21	58	28.49	174.2	204.9
2	35.84	55.92	43.25	59	27.44	166.8	198.4
4	32.45	58.1	42.8	55	28.19	159.2	196.6
5	30.51	64.39	38.63	49	36.43	154.2	193.5
8	31.46	63.94	39.24	51	56.9	153.6	191.8
10	32.82	61.9	41.43	53	51.41	147.68	189.5
12	34.26	56.39	43.84	57	34.75	142.3	187.3
2	35.1	47.85	49.1	61	31.94	138.62	184.9
4	29.4	67.86	38.44	48	41.64	134.68	181.1
8	29.87	64.25	37.41	47	62.12	134.5	181.3
10	33.61	55.31	43.65	54	54.36	130.2	178.2
12	34.9	49.65	46.82	59	52.65	127.1	175.7
2	31.65	73.41	42.82	51	48.01	123.4	173.8
4	32.15	77.24	46.94	53	30.63	120.8	174.5
9	31.96	75.61	41.36	52	55.26	120.4	174.3
11	31.34	69.54	45.21	53	34.19	118.62	172.9
1	36.59	67.56	43.27	56	28.44	116.47	172.4
3	33.15	69.23	42.15	54	25.64	115.82	172

Table A.2 Results of $T_1V_2I_1$

Time interval (h)	Ambient Condition		Inside Chamber Conditions			Weight of sample	
	Temp. (˚c)	Humid. (%)	Chamber temp (˚c)	Machine outlet temp (˚c)	Chamber humidity (%)	Top tray (g)	Bottom tray(g)
11	35.5	71.1	48	51	72.5	182.9	232.3
1	36	59.3	47.25	57	66.1	173.1	223.6
3	32.5	62.18	52.9	54	64.9	164.5	214.1
5	31.51	54.7	49.9	56	60.48	158.4	206.8
8	33.35	54.7	31.4	50	31.1	157.2	205.2
10	34.4	48.8	43	50	32.09	151.6	198.5
12	36.6	31	51.8	57	22.08	148.2	192.6
2	36.48	54	46.6	60	30.1	144.3	185.4
4	33.6	56.01	50.4	57	25.3	140.8	178.2
8	32.6	61.1	34.24	53	56.9	140.6	177.4
10	33.28	59.09	37.1	62	42.9	136.7	171.6
12	35.3	54.93	49.01	57	58.2	131.4	165.6
2	36.9	45.58	56.3	52	63.25	125.1	159.7
4	30.8	65.58	36.8	46	53.61	121.2	154.1
8	30.78	62.11	37.1	55	66.8	120.7	152.8
10	34.16	53.13	47	56	52.1	115	147.3
12	35.1	47.19	49.7	58	48.3	108.7	141.7
2	30.3	71.44	39.5	54	45.61	103.6	135.5
4	28.17	79.79	32.17	49	44.7	99.23	129.4
9	28.69	77.16	43.16	53	32.14	98.47	128.2
11	32.4	63.63	41.29	59	29.62	95.8	123.4
1	37.95	65.96	41.45	61	27.83	93.47	121.6
3	31.15	72.45	39.39	50	27.1	91.5	119.3
8	30.25	64.21	38.2	48	26.5	90.75	118.7
10	34.2	58.36	42.1	51	24.36	90.63	118.0
12	34.6	57.45	43.2	53	24.35	90.63	118.0

Table A.3 Results of $T_1V_3I_1$

Time interval (h)	Ambient Condition		Inside Chamber Conditions			Weight of sample	
	Temp.	Humid. (%)	Chamber temp (˚c)	Machine outlet temp (˚c)	Chamber humidity (%)	Top tray (g)	Bottom tray(g)
10	36.38	71.82	52.11	62	69.98	192.2	208.3
12	36.74	64.88	48.32	56	63.2	185.6	197.2
2	34.66	62.88	47.51	55	61.16	178.2	193.4
4	33.91	61.8	40.17	55	58.9	173.6	187.5
8	30.48	82.96	40.12	49	52.67	172.8	183.6
10	32.85	72.9	42.68	51	65.75	169.2	182.9
12	34.18	65.71	42.01	58	53.6	164.3	176.84
2	34.9	64.18	50.25	59	58.11	159.8	171.24
4	34.5	65.64	46.83	58	62.62	154.6	165.68
9	31.33	69.09	42.1	51	60.66	154.1	164.35
11	35.48	66.78	46.32	54	58.17	149.2	157.8
1	36.6	63.68	43.29	61	52.28	143.7	150.3
3	35.04	60.47	43.1	58	60.47	138.8	144.25
5	31.25	62.36	43.2	51	55.86	135.2	138.6
8	30.37	84.26	39.89	48	64.83	134.8	137.4
10	31.91	78.41	47.93	54	59.81	129.4	132
12	33.17	66.11	50.19	57	53.49	125.1	127.14
2	36.18	56.48	52.27	59	54.84	121.4	122.7
4	37.82	56.27	46.34	55	62.48	115.9	117.2
8	31.38	70.43	40.14	50	32.67	115.2	116.2
10	34..11	57.18	48.6	54	29.17	109.5	111.35
12	33.58	56.2	45.6	55	28.5	105.2	107.3
2	34.25	54.82	45.82	56.5	25.96	102.1	105.7
4	33.65	59.67	42.34	52	24.68	100.2	104.5
8	32.5	65.61	40.5	49.5	24.26	99.9	104.05
10	34.6	58.6	46.2	56	24.12	99.9	104.05

Table A.4 Results of $T_2V_1I_1$

Time interval (h)	Ambient Condition		Inside Chamber Conditions			Weight of sample	
	Temp.	Humid. (%)	Chamber temp (˚c)	Machine outlet temp (˚c)	Chamber humidity (%)	Top tray (g)	Bottom tray(g)
10	34.25	71.82	44.57	66.1	66.24	244.8	170.9
12	35.44	64.88	48.36	64.58	64.84	236.7	160.8
2	36.98	62.88	47.25	70.15	58.95	230.5	152.6
4	32.95	61.8	44.18	68.4	54.65	224.3	147.5
8	31.61	82.96	32.65	58	53.87	223.6	147.1
10	33.45	72.9	45.85	62.74	48.26	217.2	141.2
12	33.29	65.71	49.67	67.56	39.77	211.4	135.8
2	35.1	64.18	52.18	69.6	30.74	205.9	129.24
4	33.6	65.64	52.62	70.08	27.84	198.4	124.5
9	32.44	69.09	40.47	55.14	28.44	197.7	123.7
11	34.58	66.78	48.36	66.45	32.98	191.4	118.36
1	35.64	63.68	45.82	62.41	51.8	184.5	113.8
3	35.04	60.47	52.14	63.58	49.56	178.7	109.6
5	31.25	62.36	48.34	59.65	35.65	171.6	104.8
8	30.37	84.26	39.55	48.26	32.77	170.8	99.8
10	32.58	78.41	51.27	61.74	38.91	163.4	95.14
12	36.46	66.11	48.65	62.41	31.29	156.7	90.6
2	38.65	56.48	52.18	70.16	24.66	150.8	87.3
4	37.82	56.27	52.15	68.86	22.16	144.6	86.2
8	31.38	70.43	41.24	59.22	26.46	139.4	86.1
10	34.11	57.18	48.25	61.07	22.55	135.5	84.7
12	34.56	65.74	49	60.94	23.93	132.12	84.12
2	36.55	55.26	52	62.54	23.14	130.2	83.94
4	32.13	62.98	48	68.17	23.41	129.85	83.84
8	31.95	72.85	39	56.45	23.45	129.85	83.84
10	34.65	61.68	45	56.18	27.15	129.85	83.69

Table A.5 Results of $T_2V_2I_1$

Time interval (h)	Ambient Condition		Inside Chamber Conditions			Weight of sample	
	Temp.	Humid. (%)	Chamber temp (˚c)	Machine outlet temp (˚c)	Chamber humidity (%)	Top tray (g)	Bottom tray(g)
10	32.14	71.82	45.07	64	65.99	157	235.5
12	36.25	64.88	49.13	62	63.45	148.3	221.9
2	33.25	62.88	51.35	64	58.95	140.9	208.4
4	35.15	61.8	45.87	61	54.65	133.8	199.8
8	30.05	82.96	42.69	59	53.87	132.5	193.21
10	34.26	72.9	46.9	63	45.65	127.1	188.4
12	35.78	65.71	53.2	68	39.77	122.4	183.24
2	33.64	64.18	46.08	65	30.74	118.4	179.7
4	32.74	65.64	50.25	61	26.74	114.98	174.8
9	31.21	69.09	44.21	62	28.44	114.2	174.6
11	32.85	66.78	43.68	68	32.98	109.4	170.5
1	36.65	63.68	49.54	71	53.41	105.1	164.37
3	36.84	60.47	51	69	49.56	101.4	158.18
5	33.87	62.36	43	65	35.65	98.2	151.91
8	30.55	84.26	41.35	50	33.65	97.8	145.68
10	33.62	78.41	47	66	38.91	94.4	139.45
12	34.91	66.11	50.2	68	31.29	91.74	134.87
2	36.94	56.48	50	68	25.48	87.15	129.9
4	32.47	56.27	42.52	56	22.16	83.4	126.4
8	31.38	70.43	42.25	57	26.46	81.37	125.98
10	34..11	57.18	43.56	61	25.45	78.65	122.4
12	35.5	56.54	48.66	61	23.93	76.7	120.25
2	34.1	56.36	50.32	63	22.62	75.89	119.88
3	34.5	57.14	48.95	62	23.15	75.66	119.88
4	33.45	59.7	48.65	60	23.15	75.66	119.88

Table A.6 Results of $T_2V_3I_1$

Time interval (h)	Ambient Condition		Inside Chamber Conditions			Weight of sample	
	Temp.	Humid. (%)	Chamber temp (˚c)	Machine outlet temp (˚c)	Chamber humidity (%)	Top tray (g)	Bottom tray(g)
10	38.98	48.07	45.75	63.5	74.9	220.8	205.4
12	37.58	61.49	47.28	70	62.14	206.8	193.2
2	34.52	60.5	46.28	68	56.25	194.25	184.1
4	33.19	63.3	48.26	62	58.98	185.24	176.1
8	30.98	80.01	42.57	44	82.04	184.26	174.3
10	34.34	76.6	45.85	66.7	63.56	176.8	165.9
12	35.66	71.2	48.54	69	49.17	170.21	159.4
2	36.02	73.15	52.18	71	36.22	165.29	153.24
4	33.12	77.9	53.62	59	76.88	159.47	148.1
9	31.03	67.4	40.47	64	75.04	158.62	142.65
11	33.17	61.3	53.62	68	50.04	152.95	137.1
1	34..9	61.7	58.66	69	45.13	147.37	133.6
3	35.59	57.8	52.14	70	42.65	141.6	129.1
5	32.23	63.2	48.34	58	55.92	136.24	124.9
8	31.33	75.5	40.15	50	68.14	135.45	124.4
10	35.51	61.4	51.27	68	35.16	130.4	121.5
12	37.81	58.1	53.15	71	28.11	125.6	117.25
2	36.11	65.8	59.68	58	22.78	122.14	113.48
4	33.12	62.14	45.19	47	24.56	118.8	111.8
8	32.45	67.25	46.52	32.6	26.5	118.6	110.2

10	34.26	61.36	49.68	46	23.65	116.5	109.5
12	34.55	59.24	49.42	51	21.4	115.62	108.9
2	35.15	58.64	50.25	52	20.82	115.54	108.5
4	34.18	61.02	51.14	51	20.8	115.54	108.5

Table A.7 Results of $T_3V_1I_1$

Time interval (h)	Ambient Condition		Inside Chamber Conditions			Weight of sample	
	Temp.	Humid. (%)	Chamber temp (˚c)	Machine outlet temp (˚c)	Chamber humidity (%)	Top tray (g)	Bottom tray(g)
10	36.71	56.14	52.14	69	71.24	206.1	146.5
12	36.45	57.19	51.45	76	65.25	190.6	132.4
2	35.88	60.2	51.98	71	57.85	176.45	119.7
4	35.64	64.78	48.66	76	58.98	169	110.1
8	35.16	58.21	45.98	68	73.2	169.8	102.4
10	34.21	52.43	42.82	70	54.36	158.4	101.9
12	36.47	53.67	45.91	71	45.35	150.64	94.15
2	34.87	49.76	53.87	75	38.24	145.21	88.95
4	32.89	52.84	52.15	72	46.98	145.1	85.35
9	34.28	68.42	47.25	68	62.12	140.66	85.21
11	33.17	63.87	51	74	55.31	133.74	83.65
1	35.85	59.46	41.43	79	46.47	127.41	81.2
3	35.59	57.8	53.34	80	49.54	122.89	79.6
5	33.78	61.28	57.11	68	52.77	117.45	76.1
8	32.65	72.4	54.35	65	67.86	116.24	75.9
10	36.45	58.14	52.35	74	48.19	112.48	73.14
12	37.81	56.36	47.58	76	30.4	108.66	71.5
2	35.18	58.37	50.69	68	26.7	106.42	70.42
4	34.87	61.75	49.68	68	21.27	105.42	69.9
5	32.15	62.15	46.94	66	19.16	105.37	69.8
6	30.75	66.8	46.8	60	19.16	105.37	69.8

Table A.8 Results of T_3V_2 I_1

Time interval (h)	Ambient Condition		Inside Chamber Conditions			Weight of sample	
	Temp.	Humid. (%)	Chamber temp (˚c)	Machine outlet temp (˚c)	Chamber humidity (%)	Top tray (g)	Bottom tray(g)
9	34.33	68.58	58.98	74.1	77.64	87.28	79.33
11	34.48	64.58	59.35	76.8	74.52	80.21	74.4
1	37.22	61.87	60.14	80.15	68.67	74.62	70.2
3	36.76	67.14	56.28	78.4	52.33	68.35	66.41
5	32.34	68.24	52.68	72.5	54.42	64.12	63.1
8	32.19	70.30	53.7	71.4	49.91	64.06	63.05
10	36.28	66.45	56.14	77.56	46.72	59.84	59.11
12	37.73	65.27	60.5	79.6	42.86	56.57	56.92
2	38.66	60.52	62.52	80.08	37.65	54.12	53.14
4	35.65	54.47	55.11	74.87	34.35	52.74	51.21
8	33.46	59.36	52.72	66.48	36.47	52.56	49.84
10	35.09	63.88	54.28	69.16	35.82	50.74	47.65
12	36.32	58.14	55.25	72.14	34.57	49.12	45.1
2	36.80	54.97	52.36	78.65	31.14	48.71	43.37
4	33.03	67.51	58.52	75.74	33.65	47.86	42.80
8	32.96	60.60	56.65	72.56	29.56	47.64	42.54
10	34.97	56.54	58.25	73.32	24.71	46.73	40.98
12	36.42	52.83	61.65	75.95	20.67	45.89	40.12
2	35.54	63.74	62.63	74.22	18.84	45.21	39.9
4	33.02	63.22	62.11	72.18	19.98	45.00	39.9

Table A.9 Results of T_3V_3 I_1

Time interval (h)	Ambient Condition			Inside Chamber Conditions		Weight of sample	
	Temp.	Humid.	Chamber temp (˚c)	Machine outlet temp (˚c)	Chamber humidity (%)	Top tray (g)	Bottom tray(g)
9	34.2	72.5	56.22	69	76.5	12	12
11	34.1	70.91	53.46	74	70.9	9.2	9.5
1	35.2	65.33	53.87	75	64.8	8.4	8.3
3	34.45	64.71	52.39	70	55.54	7.7	7.5
5	30.25	56.31	49.88	62	55.77	7.2	7.2
8	32.53	50.26	48.21	65	44.35	6.9	7
10	33.04	40.15	53.16	72	34.36	6.8	6.8
12	35.66	56.11	60.35	73	32.44	6.57	6.6
2	35.84	55.92	64.68	85	30.87	6.48	6.5
4	32.45	58.1	61.95	71	29.18	6.34	6.3
6	30.51	64.39	52.51	64	32.56	6.18	6.3
8	33.12	63.94	48.99	62	48.17	6.13	6.2
10	31.46	61.9	54.29	68	45.38	6	6.1
12	32.82	56.39	62.94	80	32.96	5.94	6
2	34.26	47.85	57.11	83	31.51	5.82	5.9
4	35.1	67.86	54.35	61	28.4	5.71	5.88
8	29.4	64.25	46.38	55	18.25	5.69	5.87
10	33.61	55.31	52.17	72	16.17	5.68	5.87
12	34.97	49.65	56.19	81	16.17	5.68	5.87

Table A.10 Results of Sun Dried coconut

No. of Days	Time (h)	Ambient Condition		Weight of Sample
		Temperature	Humidity	
1	9	34.20	72.50	255.20
	11	34.10	70.91	247.60
	1	35.20	65.33	241.70
	3	34.45	64.71	235.60
	5	30.25	56.31	231.20
2	8	32.53	50.26	231.10
	10	33.04	40.15	228.20
	12	35.66	56.11	221.50
	2	35.84	55.92	217.27
	4	32.45	58.10	214.66
	6	30.51	64.39	212.45
3	8	33.12	63.94	212.20
	10	31.46	61.90	210.29
	12	32.82	56.39	207.21
	2	34.26	47.85	203.60
	4	35.10	67.86	200.50
4	8	29.40	64.25	199.80
	10	33.61	55.31	195.70
	12	34.97	49.65	191.30
	2	36.02	45.25	187.50
	4	33.12	51.70	182.80
5	8	31.03	75.50	182.50
	10	33.17	61.40	177.57
	12	34.90	58.10	173.41
	2	35.59	65.80	169.87
	4	32.23	62.14	166.50
6	8	31.33	67.25	165.96
	10	35.51	61.36	161.00
	12	37.81	59.24	157.60
	2	36.11	58.64	155.30

	4	33.12	56.11	153.80
7	8	31.46	55.92	153.60
	10	32.82	58.10	151.28
	12	34.26	64.39	149.82
	2	35.10	63.94	147.20
	4	31.44	66.12	145.60
8	8	30.44	68.52	144.92
	10	33.41	62.10	143.68
	12	35..87	54.60	142.70
	2	35.68	56.48	142.10
	4	32.11	56.27	141.30
9	8	30.85	70.43	141.20
	10	33.14	57.18	140.90
	12	32.25	65.74	140.80
	2	35.60	55.26	140.70
	4	33.21	58.55	140.70

Appendix B

Calculations of drying parameters of experiments

Table B.1 Calculation of Drying parameters of T_1V_1 I_1

Time (h)	Moisture Loss (g)		Moisture Content (%)		Drying Rate (gh^{-1})	
	Top tray	Bottom tray	Top tray	Bottom tray	Top tray	Bottom tray
0	-	-	55.41	54.25	-	-
2	14.40	13.50	52.51	51.72	7.20	6.75
4	12.60	11.60	49.59	49.31	6.80	6.27
6	7.60	8.10	47.68	47.48	5.80	5.53
8	8.60	9.10	45.06	45.25	5.55	5.29
8	4.40	4.10	44.86	44.19	4.51	4.64
10	2.00	2.70	42.38	43.47	4.44	4.09
12	2.90	3.40	39.70	42.53	4.39	3.75
14	5.00	8.65	37.02	39.99	4.30	3.82
16	0.90	5.65	34.01	38.22	4.24	3.71
16	2.60	5.18	31.87	36.49	4.07	3.60
18	1.30	2.12	31.61	35.76	3.73	3.37
20	2.10	5.68	28.87	33.70	3.66	3.32
22	1.80	5.42	26.18	31.61	3.59	3.28
24	3.90	3.55	24.22	30.17	3.46	3.17
24	0.80	5.37	22.00	27.88	3.36	3.14
26	0.10	0.98	21.90	27.44	3.16	2.97
28	0.80	5.70	19.32	24.80	3.10	2.96
30	2.00	8.40	17.35	20.54	3.01	3.03
32	0.80	4.60	14.87	17.99	2.95	2.99
34	1.10	5.40	13.04	14.79	2.87	2.98
36	0.10	1.40	12.75	13.92	2.74	2.87
36	0.50	4.30	11.44	11.12	2.66	2.84
38	0.50	2.35	9.81	9.52	2.59	2.77
40	0.50	0.89	9.30	8.90	2.50	2.67
42	0.00	0.00	9.09	8.90	2.40	2.56

Table B.2 Calculation of Drying parameters of T_1V_2 I_1

Time (h)	Moisture Loss (g)		Moisture Content (%)		Drying Rate (gh^{-1})	
	Top tray	Bottom tray	Top tray	Bottom tray	Top tray	Bottom tray
0	-	-	54.85	53.60	-	-
2	9.8	8.70	52.30	51.83	4.90	4.35
4	8.6	9.50	49.81	49.70	4.60	4.55
6	6.1	7.30	47.87	47.92	4.08	4.25
8	1.2	1.60	47.47	47.51	3.21	3.39
8	5.6	6.70	45.53	45.74	3.13	3.38
10	3.4	5.81	44.28	44.11	2.89	3.30
12	3.9	7.27	42.78	41.92	2.76	3.35
14	3.5	7.22	41.36	39.56	2.63	3.38
16	0.2	0.80	41.27	39.29	2.35	3.05
16	3.9	5.80	39.60	37.24	2.31	3.04
18	5.3	6.00	37.16	34.96	2.34	3.03
20	6.29	5.90	34.00	32.56	2.41	3.03
22	3.91	5.60	31.87	30.11	2.37	3.01
24	0.5	1.30	31.59	29.52	2.22	2.84
24	5.7	5.48	28.20	26.89	2.26	2.83
26	6.24	5.62	24.08	23.99	2.32	2.83
28	5.11	6.20	20.34	20.52	2.33	2.85
30	4.42	6.10	16.79	16.77	2.32	2.86
32	0.76	1.12	16.15	16.04	2.22	2.74
34	2.67	4.83	13.81	12.76	2.18	2.72
36	2.33	1.84	11.66	11.44	2.13	2.64
36	1.97	2.25	9.76	9.77	2.08	2.57
38	0.75	0.61	9.01	9.31	2.00	2.47
40	0.12	0.66	8.89	8.80	1.92	2.38

Table B.3 Calculation of Drying parameters of T_1V_3 I_1

Time (h)	Moisture Loss (g)		Moisture Content (%)		Drying Rate (gh^{-1})	
	Top tray	Bottom tray	Top tray	Bottom tray	Top tray	Bottom tray
0	-	-	52.44	54.14	-	-
2	6.60	11.10	50.75	51.56	3.30	5.55
4	7.40	3.80	48.70	50.61	3.50	3.73
6	4.60	5.90	47.34	49.06	3.10	3.47
8	0.80	3.90	47.10	47.97	2.43	3.09
8	3.60	0.70	45.98	47.77	2.30	2.54
10	4.90	6.06	44.36	45.99	2.33	2.62
12	4.50	5.60	42.80	44.22	2.31	2.65
14	5.20	5.56	40.87	42.35	2.35	2.66
16	0.50	1.33	40.68	41.88	2.12	2.44
16	4.90	6.55	38.73	39.47	2.15	2.53
18	5.50	7.50	36.39	36.45	2.20	2.64
20	4.90	6.05	34.14	33.78	2.23	2.67
22	3.60	5.65	32.39	31.08	2.19	2.68
24	0.40	1.20	32.19	30.48	2.05	2.53
24	5.40	5.40	29.36	27.64	2.09	2.54
26	4.30	4.86	26.93	24.87	2.10	2.54
28	3.70	4.44	24.70	22.15	2.08	2.52
30	5.50	5.50	21.13	18.50	2.12	2.53
32	0.70	1.00	20.65	17.80	2.03	2.42
34	5.70	4.85	16.52	14.22	2.07	2.42
36	4.30	4.05	13.11	10.98	2.07	2.40
36	3.10	1.60	10.47	9.63	2.05	2.33
38	1.90	1.20	8.77	8.59	2.00	2.26
40	0.30	0.45	8.50	8.20	1.92	2.17
42	0.00	0.00	8.50	8.20	1.85	2.09

Table B.4 Calculation of Drying parameters of $T_2V_1I_1$

Time (h)	Moisture Loss (g)		Moisture Content (%)		Drying Rate (gh^{-1})	
	Top tray	Bottom tray	Top tray	Bottom tray	Top tray	Bottom tray
0	-	-	51.14	54.75	-	-
2	8.10	10.10	49.47	51.91	4.05	5.05
4	6.20	8.20	48.11	49.33	3.58	4.58
6	6.20	5.10	46.68	47.57	3.42	3.90
8	0.70	0.40	46.51	47.43	2.65	2.98
8	6.40	5.90	44.94	45.23	2.76	2.97
10	5.80	5.40	43.42	43.06	2.78	2.93
12	5.50	6.56	41.91	40.17	2.78	2.98
14	7.50	4.74	39.72	37.89	2.90	2.90
16	0.70	0.80	39.50	37.49	2.62	2.62
16	6.30	5.34	37.51	34.67	2.67	2.63
18	6.90	4.56	35.18	32.05	2.74	2.60
20	5.80	4.20	33.07	29.44	2.75	2.55
22	7.10	4.80	30.30	26.21	2.82	2.54
24	0.80	5.00	29.98	22.52	2.64	2.54
24	7.40	4.66	26.81	18.72	2.71	2.53
26	6.70	4.54	23.68	14.65	2.75	2.51
28	5.90	3.30	20.69	11.42	2.76	2.46
30	6.20	1.10	17.29	10.29	2.78	2.35
32	5.20	0.10	14.20	10.19	2.77	2.23
34	3.90	1.40	11.73	8.70	2.73	2.16
36	3.38	0.58	9.48	8.07	2.68	2.07
36	1.92	0.18	8.14	7.87	2.60	1.98
38	0.35	0.10	7.89	7.76	2.50	1.89
40	0.00	0.00	7.89	7.76	2.50	1.89

Table B.5 Calculation of Drying parameters of $T_2V_2I_1$

Time (h)	Moisture Loss (g)		Moisture Content (%)		Drying Rate (gh^{-1})	
	Top tray	Bottom tray	Top tray	Bottom tray	Top tray	Bottom tray
0	-	-	55.42	52.86	-	-
2	8.70	13.60	52.81	49.97	4.35	6.80
4	7.40	13.50	50.33	46.73	4.03	6.78
6	7.10	8.60	47.69	44.44	3.87	5.95
8	1.30	6.59	47.18	42.54	3.06	5.29
8	5.40	4.81	44.93	41.08	2.99	4.71
10	4.70	5.16	42.82	39.42	2.88	4.36
12	4.00	3.54	40.89	38.22	2.76	3.99
14	3.42	4.90	39.13	36.49	2.63	3.79
16	0.78	0.20	38.71	36.42	2.38	3.38
16	4.80	4.10	36.02	34.89	2.38	3.25
18	4.30	6.13	33.41	32.46	2.36	3.23
20	3.70	6.19	30.98	29.82	2.32	3.22
22	3.20	6.27	28.73	26.92	2.26	3.22
24	0.40	6.23	28.44	23.80	2.11	3.21
24	3.40	6.23	25.86	20.39	2.09	3.20
26	2.66	4.58	23.71	17.69	2.04	3.14
28	4.59	4.97	19.69	14.54	2.05	3.11
30	3.75	3.50	16.08	12.18	2.04	3.03
32	2.03	0.42	13.99	11.88	1.99	2.88
34	2.72	3.58	11.01	9.31	1.96	2.83
36	1.95	2.15	8.75	7.68	1.91	2.74
36	0.81	0.37	7.77	7.40	1.84	2.63
38	0.23	0.00	7.49	7.40	1.77	2.63
40	0.00	0.00	7.49	7.40	1.77	2.63

Table B.6 Calculation of Drying parameters of $T_2V_3I_1$

Time (h)	Moisture Loss (g)		Moisture Content (%)		Drying Rate (gh^{-1})	
	Top tray	Bottom tray	Top tray	Bottom tray	Top tray	Bottom tray
0	-	-	51.33	50.78	-	-
2	14	12.2	48.04	47.68	7.00	6.10
4	12.55	9.1	44.68	45.09	6.64	5.33
6	9.01	8	41.99	42.60	5.93	4.88
8	0.98	1.8	41.68	42.00	4.57	3.89
8	7.46	8.4	39.22	39.07	4.40	3.95
10	6.59	6.5	36.87	36.58	4.22	3.83
12	4.92	6.16	34.99	34.03	3.97	3.73
14	5.82	5.14	32.61	31.74	3.83	3.58
16	0.85	5.45	32.25	29.13	3.45	3.49
16	5.67	5.55	29.74	26.27	3.39	3.42
18	5.58	3.5	27.08	24.33	3.34	3.26
20	5.77	4.5	24.11	21.70	3.30	3.18
22	5.36	4.2	21.12	19.06	3.25	3.10
24	0.79	0.5	20.66	18.74	3.05	2.89
24	5.05	2.9	17.59	16.80	3.01	2.80
26	4.8	4.25	14.44	13.78	2.98	2.75
28	3.46	3.77	12.02	10.92	2.90	2.70
30	3.34	1.68	9.55	9.58	2.83	2.60
32	0.2	1.6	9.39	8.27	2.69	2.51
34	2.1	0.7	7.76	7.68	2.61	2.40
36	0.88	0.6	7.06	7.17	2.50	2.30
36	0.08	0.4	6.99	6.83	2.39	2.20
38	0	0	6.99	6.83	2.39	2.20

Table B.7 Calculation of Drying parameters of $T_3V_1I_1$

Time (h)	Moisture Loss (g)		Moisture Content (%)		Drying Rate (gh^{-1})	
	Top tray	Bottom tray	Top tray	Bottom tray	Top tray	Bottom tray
0	0	0	52.65	55.75		
2	15.50	14.10	48.80	51.04	7.75	7.05
4	14.15	12.70	44.70	45.85	7.41	6.70
6	7.45	9.60	42.26	41.13	6.18	6.07
8	0.80	1.70	41.99	40.20	4.74	4.76
8	9.80	6.50	38.40	36.39	4.77	4.46
10	7.76	7.75	35.22	31.15	4.62	4.36
12	5.43	5.20	32.80	27.13	4.35	4.11
14	0.11	3.60	32.75	24.05	3.81	3.82
16	4.44	0.14	30.63	23.93	3.64	3.41
16	6.92	1.56	27.04	22.51	3.62	3.14
18	6.33	2.45	23.41	20.17	3.58	2.97
20	4.52	1.60	20.60	18.57	3.47	2.79
22	5.44	3.50	16.92	14.82	3.41	2.71
24	1.21	0.20	16.05	14.60	3.21	2.52
24	3.76	2.76	13.25	11.38	3.12	2.45
26	3.82	1.64	10.20	9.34	3.05	2.34
28	2.24	1.08	8.31	7.95	2.93	2.24
30	1.00	0.52	7.44	7.27	2.80	2.13
32	0.05	0.10	7.39	7.13	2.65	2.02
34	0.00	0.00	7.39	7.13	2.65	2.02

Table B.8 Calculation of Drying parameters of $T_3V_2I_1$

Time (h)	Moisture Loss (g)		Moisture Content (%)		Drying Rate (gh^{-1})	
	Top tray	Bottom tray	Top tray	Bottom tray	Top tray	Bottom tray
0	-	-	51.74	53.6	-	-
2	13.60	12.80	47.11	49.17	6.80	6.40
4	8.40	7.62	43.78	46.11	5.50	5.11
6	7.50	8.30	40.42	42.33	4.92	4.79
8	5.50	5.78	37.70	39.36	4.38	4.31
8	0.40	0.69	37.49	38.98	3.54	3.52
10	5.16	5.71	34.67	35.70	3.38	3.41
12	4.80	3.30	31.82	33.63	3.24	3.16
14	4.02	5.01	29.23	30.23	3.09	3.08
16	0.42	0.87	28.95	29.60	2.77	2.78
16	4.80	5.59	25.56	25.29	2.73	2.78
18	4.43	3.29	22.13	22.49	2.68	2.68
20	4.77	5.25	18.06	17.57	2.66	2.68
22	6.15	4.55	12.15	12.77	2.69	2.64
24	3.14	2.02	8.79	10.46	2.61	2.53
24	0.51	1.34	8.22	8.85	2.45	2.40
26	1.22	1.28	6.83	7.27	2.34	2.29
28	0.04	0.29	6.78	6.90	2.20	2.17
30	0.00	0.00	6.78	6.90	2.20	2.17

Table B.9 Calculation of Drying parameters of $T_3V_3I_1$

Time (h)	Moisture Loss (g)		Moisture Content (%)		Drying Rate (gh^{-1})	
	Top tray	Bottom tray	Top tray	Bottom tray	Top tray	Bottom tray
0	-	-	55.37	54.24	-	-
2	2.80	2.50	42.39	42.21	1.40	1.25
4	0.80	1.20	36.90	33.86	0.90	0.93
6	0.70	0.80	31.17	26.80	0.72	0.75
8	0.50	0.30	26.39	23.75	0.60	0.60
8	0.30	0.20	23.19	21.57	0.51	0.50
10	0.10	0.20	22.06	19.26	0.43	0.43
12	0.23	0.20	19.33	16.82	0.39	0.39
14	0.09	0.10	18.21	15.54	0.35	0.34
16	0.14	0.20	16.40	12.86	0.31	0.32
16	0.16	0.00	14.24	12.86	0.29	0.29
18	0.05	0.10	13.54	11.45	0.27	0.26
20	0.13	0.10	11.67	10.00	0.25	0.25
22	0.06	0.10	10.77	8.50	0.23	0.23
24	0.12	0.10	8.93	6.95	0.22	0.22
24	0.11	0.02	7.18	6.63	0.21	0.20
26	0.02	0.01	6.85	6.47	0.20	0.19
28	0.01	0.00	6.69	6.47	0.19	0.18
30	0.00	0.00	6.69	6.47	0.18	0.17

Table C.10 Calculation of Drying parameters of open sun drying

Time (h)	Moisture Loss	Moisture Content	Drying Rate
0	-	53.24	-
2	7.60	51.81	3.80
4	13.50	50.63	3.38
6	19.60	49.35	3.27
8	24.00	48.39	3.00
8	24.10	48.36	3.01
10	27.00	47.71	2.70
12	33.70	46.13	2.81
14	37.93	45.08	2.71
16	40.54	44.41	2.53
16	42.75	43.83	2.38
18	43.00	43.77	2.39
20	44.91	43.25	2.25
22	47.99	42.41	2.18
24	51.60	41.39	2.15
24	54.70	40.48	2.10
26	55.40	40.28	2.13
28	59.50	39.02	2.13
30	63.90	37.62	2.13
32	67.70	36.36	2.12
32	72.40	34.72	2.13
34	72.70	36.14	2.02
36	77.63	33.60	2.04
38	81.79	31.10	2.04
40	85.33	28.40	2.03
40	88.70	26.70	2.02
42	89.24	28.10	1.94
44	94.20	26.74	1.96
46	97.60	24.17	1.95

48	99.90	23.16	1.92
48	101.40	21.88	1.88
50	101.60	22.86	1.81
52	103.92	20.51	1.79
54	105.38	18.24	1.76
56	108.00	16.74	1.74
56	109.60	15.98	1.71
58	110.28	17.66	1.67
60	111.52	16.95	1.64
62	112.50	16.38	1.61
64	113.10	16.02	1.57
64	113.90	15.55	1.54
66	114.00	17.25	1.50
68	114.30	16.20	1.47
70	114.40	15.25	1.43
72	114.50	15.19	1.40
72	114.50	15.19	1.40

APPENDIX C

ANOVA of output characteristics of Solar dryer for copra

Table C.1 ANOVA for moisture content (Top Tray)

Source	Sum of Squares	Df	Mean Square	F Value	p-value Prob> F	
Model	19.45	8	2.43	28.67	< 0.0001	Significant
A- temperature	16.81	2	8.40	99.10	< 0.0001	
B- velocity	2.43	2	1.21	14.31	0.0002	
AB	0.21	4	0.053	0.63	0.6481	
Pure Error	1.53	18	0.085			
Cor Total	20.97	26				

R^2 =0.9272 Adj R^2 =0.8949 Pred R^2 = 0.8362

Adeq precision = 14.275

Table C.2 ANOVA for moisture content (Bottom tray)

Source	Sum of Squares	Df	Mean Square	F Value	p-value Prob> F	
Model	17.75	8	2.22	27.45	< 0.0001	Significant
A- temperature	14.90	2	7.45	92.17	< 0.0001	
B- velocity	2.67	2	1.33	16.51	<0.0001	
AB	0.18	4	0.045	0.56	0.6939	
Pure Error	1.45	18	0.081			
Cor Total	19.20	26				

R^2 =0.9242 Adj R^2 =0.8906 Pred R^2 = 0.8295

Adeq precision = 14.196

Table C.3 ANOVA for drying time

Source	Sum of Squares	Df	Mean Square	F Value	p-value Prob> F	
Model	774.00	8	96.75	56.43	< .0001	Significant
A- temperature	722.00	2	361.00	210.54	< 0.0001	
B- velocity	42.00	2	21.00	12.25	0.0004	
AB	10.00	4	2.50	1.46	0.2561	
Pure Error	30.86	18	1.71			
Cor Total	804.86	26				

R^2=0.9617 Adj R^2 = 0.9446 Pred R^2 = 0.9137

Adeq precision = 21.164

Table C.4 ANOVA Relative Humidity

Source	Sum of Squares	Df	Mean Square	F Value	p-value Prob> F	
Model	241.45	8	30.18	46.55	< .0001	Significant
A- temperature	209.71	2	104.86	161.72	< 0.0001	
B- velocity	26.83	2	13.41	20.69	<0.0001	
AB	4	1.23	1.89	0.1553		
Pure Error	11.67	18	0.65			
Cor Total	253.12	26				

R^2 = 0.9539 Adj R^2 = 0.9334 Pred R^2 =0.8963

Adeq precision = 20.392

Table C.5 ANOVA for chamber temperature

Source	Sum of Squares	Df	Mean Square	F Value	p-value Prob> F	
Model	397.68	8	49.71	15.42	< .0001	Significant
A- temperature	341.40	2	170.70	52.95	< 0.0001	
B- velocity	44.12	2	22.06	6.84	0.0062	
AB	4	3.04	0.94	0.94	0.4618	
Pure Error	58.02	18	3.22			
Cor Total	455.70	26				

$R^2 = 0.8727$ Adj $R^2 = 0.8161$ Pred $R^2 = 0.7135$

Adeq precision = 11.306

APPENDIX D

Amount of energy produced by Solar Dryer

No. of tubes (n) = 30

length of each tube (l) = 1.5 m

Diameter of tube (d) = 0.037 m

Therefore, the collector area is calculated as;

$$\text{Collector Area} = n \text{ x } l \text{ x } \pi r$$

$$= 30 \text{ x } 1.5 \text{ x } \pi \text{ x } 0.0581$$

$$= 2.61 \text{ m}^2$$

Calculation for solar radiation in the month of March (15th)

No. of days = 74 days

Latitude ($\emptyset$) = 10 °

(i) Declination = $\boldsymbol{\delta = 23.45 \sin \{\frac{360}{365}(284+74)\}}$

$$= -2.81^\circ$$

(ii) Sunrise Hour Angle = $\boldsymbol{w_s = \cos^{-1}\{-\tan \emptyset \tan \delta\}}$

$$= \cos^{-1}\{-\tan (10.51) \tan (-2.81^\circ)\}$$

$$= 89.46^\circ$$

(iii) Day length = $\boldsymbol{S_{max} = \frac{2}{15} \text{ x } w_s}$

$$= \frac{2}{15} \text{ x } 89.46 = 11.92 \text{ h}$$

(iv) Monthly average of the daily extra-terrestrial radiation

$$H_0 = \frac{24}{\pi} I_{sc} \left(1 + 0.033 \cos \frac{360n}{365}\right) (w_s \sin\emptyset \sin \delta + \cos \emptyset \cos \delta \sin w_s)$$

$$= \frac{24}{\pi} \text{ x } 1.367 \text{ x } 3600 \left(1 + 0.033 \cos \frac{360}{365} x\, 74\right) (1.56 \sin(10^\circ) \sin(-2.81) + \cos 10^\circ \cos(-2.81) \sin(89.46))$$

$= 37595.19 \times 1.009 \times 0.967$

$= 36708.5\ \text{kJ.m}^{-2}$ per day

(v) Monthly average of the daily global radiation

$$\frac{H_g}{H_0} = a+b\left(\frac{S}{S_{max}}\right)$$

$$H_g = (0.32+0.41(\frac{10}{11.9}) \times 36708.5$$

$$= 24394.18\ \text{kJ.m}^{-2}\text{day}^{-1}$$

(vi) Energy Produced by ETC dryer (P_{ETC})

$$P_{ETC} = \text{Collector area} \times \text{Solar radiation}$$

$$= 2.61 \times 24394.18$$

$$= 63668.80\ \text{kJ. Day}^{-1}$$

DEVELOPMENT AND PERFORMANCE EVALUATION OF A SOLAR DRYER FOR COPRA

By
V Sai Krishna
(2015-18 - 014)

ABSTRACT

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Kerala Agricultural University

Department of Food and Agricultural Process Engineering

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ABSTRACT

Copra is one of the major traditional products dried from fresh coconut kernels. It contains about 65% oil. It is produced from various methods such as direct sun drying, solar drying, and traditional smoke drying, indirect drying, etc. The objective of making copra is to reduce the moisture content of coconut kernel to a safe storage level and thereby prevent microbiological attack and spoilage. It is also used to extract coconut oil. There are many solar drying methods introduced and developed to meet the requirements of drying. The quality of copra and its cake is influenced by the method of drying the coconut kernel. Improperly dried copra gives rise to certain moulds, the most harmful of which is the yellow green mould called *Aspergillus flavus* and other aflatoxin related moulds. Aflatoxin is harmful both for man and animals. Improper processing results in low oil yield. Proper post-harvest practices, as well as proper drying and storage can increase the oil yield. Proper drying of coconut results in copra with lower moisture content and lower incidence of aflatoxins. Since Kerala is the region with high humidity and comparatively low solar radiation, there are chances of uneven and uncontrolled drying of copra. Hence, an attempt was made to develop an advanced forced convection solar dryer. Evacuated tube collector was used to generate hot air and it was used to dry coconuts. In the drying chamber, the basic function of solar dryer is to heat air to a constant temperature which facilitates extraction of moisture from copra kept inside an insulated drying chamber. The coconut meat is not directly exposed to the sunlight which will retain the nutritive values. The performance evaluation of the developed solar dryer was tested at KCAET, Tavanur. The average energy produced by the solar evacuated tube collector in dry day was 63668.80 kJ. Evacuated tube collector consisted of 30 borosilicate glass tubes of 1500 mm length and the outer and inner diameters were 47 and 37 mm. The length of manifold is 2.5 m and its inner and outer diameters of cylinder are 12.5 cm and 40 cm, respectively. A 24 gauge galvanized steel sheet was used to fabricate the chamber of 75 x 75 x 50 cm. The thickness of

the galvanized iron sheets was 2 mm and it was completely insulated using glass wool of thickness 12.5 mm. The height of the exhaust duct with 11 cm diameter was 120 cm. The drying chamber and the solar evacuated tube collector were connected by metal duct of 60 x 15 x 10 cm. The evacuated tube collector setup was placed on a supporting stand fabricated out of 2 x 2 cm square tube having 2 mm thickness. The solar drying was performed at full load condition using heated air at 50-60 °C, 61-70 °C and 71-80 °C and by using different blower velocities of 0.2 $m.s^{-1}$, 0.5 $m.s^{-1}$ and 0.8 $m.s^{-1}$ with and without glass wool insulation. The temperature was controlled by providing required shade to the evacuated tubes and theblower was controlled by using a regulator for getting various air velocities ($V_{1,}$ $V_{2,}$ and V3). Drying time, moisture content, relative humidity inside chamber and temperature inside the chamber were considered as the dependent variables. Statistical analysis (ANOVA) was performed using Design Expert software (Trail version 7.0.0). The optimized operating conditions of temperature, blower velocity and insulation were found to be of 71-80 °C, 0.8 $m.s^{-1}$ and insulation with critical thickness of 12.5 mm. Hence, the developed solar dryer operated at the optimized condition yielded good quality copra. Microbiological analysis was conducted for dried copra and it was found that the tested samples were microbiologically safe for human consumption.