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Original Research

Design, Fabrication and Experimental Testing of Indirect- Mode Forced Solar Coffee Dryer

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Abstract

Considering the size and relevance of coffee industry to the Ethiopian economy an indirect, active-type, environmentally friendly, low-cost solar dryer presents the design, fabrication and experimental testing, as well as experimental investigation on forced solar coffee dryer. The solar collector and dryer system configuration has been optimized for minimal pressure drop by incorporating guide vanes and minimizing flow separation tendency during experimental testing. In addition, thermal performance of the solar air heater was evaluated experimentally at different airflow rates on a collector with flat absorber plate and with open drying on the ground by taking the same amount of wet coffee and area that coffee in machine and on ground occupies. High collector outlet temperature and efficiency were observed in a collector with flat absorber plate. The effect of depth of grain, moisture content on wet basis, airflow rate and humidity of air were explored for parametric sensitivity during drying time. The capacity of the drying rate of the machine in kg/h are about 1.1 kg/ h and 0.53 kg/h during clear sunshine day and partial overcast sunshine day respectively. Within 6hours, coffee bean dried from 29% moisture content to12.1% on a clear sunny day and within 7hours from 17% moisture content to 11.1% on a partially overcast day. Results show that the average drying thermal efficiency of the dryer was found to be 50.6% for clear sunshine day and 36.8% for partial overcast day. A great agreement has been observed between the experimental results and the design temperature rise predicted output with a deviation of 7.6%. Analytically predicted drying time compared with experimentally measured drying time within a 12.8% deviation. The cost -to-benefit analysis has been done and the payback period is found to be 1.05 years.

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INTRODUCTION

Coffee is one of the most important primary export commodities of developing countries and it is the second most internationally traded product in which more than 80 countries including Ethiopia cultivate it to be exported as raw, roasted/soluble product to more than 177 countries worldwide and provide a livelihood for an estimate of 100million people around the world (Dejene, 2011).

According to United States Department of Agriculture; Ethiopia is the world's fifth largest coffee producer and exporter in Africa for the 2016/2017 crop year. Ethiopia is widely regarded as the home of the Arabica beans which have a richer, fuller flavor and account for roughly 80% of the total coffee consumed worldwide.

The agriculture based Ethiopian economy is highly dependent on coffee since it accounts for more than 25% of the GNP and 65% foreign currency of all export earnings. Coffee production in Ethiopia is the driving force since over a million coffee farming households and about 25% of the total population of the country is dependent on production, processing, distribution & export of coffee (Dejene, 2011).

The coffee harvesting process starts with picking the coffee cherry from the tree, taking out the pulp, washing, fermenting and drying the coffee grain. The humidity level of a coffee cherry is between 50 and 70% of the total weight of the grain and a high quality coffee grain has to have only 11- 13% of humidity (Brazilian National Food Safety Programme).

The majority of Ethiopian coffee is dried using a natural/sun-dried system, which means cherries are harvested and sun-dried as a whole. The coffee cherries are dried on bare ground or by using bed in most cases, or on polythene sheet. The sun-dried method practiced by the majority of farmers can cause fermentation process to take place, due to slow or poor drying systems, and as a result may spoil the natural aroma and sweetness characteristics of coffee. It affects the quality of coffee very significantly.

Conventional coffee dryers consume large amounts of wood and electricity to dry the beans after the washing process and conventional coffee processing has the potential for considerable global impacts on the environment. These impacts include the consumption of energy, water and land. These impacts are reduced substantially through the use of alternative technologies (Bagheri1, 2011).

This study focused on designing and developing a small-scale indirect-mode forced solar coffee dryer with appropriate solar dryer configuration by minimizing pressure drop through the system in view of its local contextual relevance and significance.

MATERIALS AND METHODS

Material Selection

The materials used were obtained locally at gate market in Nekemte, Ethiopia, the materials were critically considered based on strength, availability, reasonable cost, durability and corrosiveness to prevent machine damage, ease construction work and maintenance and prevent rusting or corrosion of the machine parts hence, mild steel angle iron was used for the frame and stainless steel for the drying chamber. The dryer was constructed using wood, stainless steel mesh, wooden skewers, clear glass, galvanized aluminum sheet and fan for operation of the dryer which are locally available with low cost.

Climatic Data Collection

The design process of the dryer first involved the collection of the climatic data of the study location. Further, the other important data such as insolation was studied and calculated as per the collector configuration. For the initial phase of dryer design, many existing designs were studied and some of the design parameters were determined. The performance of the dryer was then analyzed. Once the dimensions of the dryer were fixed, an appropriate fan was selected to obtain the required flow rates.

The experimental testing was carried out in Gimbi, located in the West Wollega Zone of the Oromia Region, Ethiopia, it has a Latitude of 9°10′ N, Longitude of 35°50′E and Altitude of 1,954 m above sea level. Coffee is an important cash crop of this Zone. Over 5,000 hectares are planted with coffee plant. Maximum solar intensity recorded were about 720.5 W/m^2 and 723.6 W/m^2 during drying period for partial overcast and clear sunshine days respectively. Collector was mounted on a stand facing south at an inclination angle equal to 18^0 collector slope.

Design Consideration and Analysis

The design considerations included to reduce power requirement, economy and ergonomics, solar dryer efficiency and product quality, simple operational and maintenance requirements to meet the need of local farmers and small scale industrialist, portability and detachability for easy transportation and low space consumption.

An indirect type of solar coffee dryer was considered as it does not affect the colour and uniform without any localized heating. Flat plate collector is used since it is easy to fabricate and also economical. The collector is made up of sheet metal of 1mm thick as it is a good conductor and economical. It was painted black to increase the absorption of heat. The recommended glass thickness for collector is 5 mm. The insulating material was selected to be wood as it is a good insulator as well as environmentally friendly. It also does not have any carcinogenic effects which other popular insulating materials like glass wool have. To further reduce the heat loss by radiation and to avoid moisture absorption by wood, aluminum foil is wrapped on the inside of the chamber Food grade stainless steel mesh for the trays and food grade wooden skewers were selected for placing nutrient content of the produce as in the case with a direct type. Also, the drying is of coffee. To ensure the constant flow rate of air during the experimentation, an axial flow fan was selected based on the calculations of pressure drop in the system and the required flow rate limit of air at 2.5m/s. For the purpose of experimentation, 20 kg of coffee bean which is locally available is used (Janjai, 2003).

In the design, a flat plate collector with dimension of 2m*1m*0.15m is considered. The performance of the collector is described by an energy balance that indicates the conversion of solar radiation into useful energy gain and losses.. The Pressure drop analysis was done to calculate the heat gain and losses for flow of air between glass cover and absorber plate, which is the top flow, and flow of air between absorber plate and bottom insulation.

Component Parts of the Machine

The solar coffee dryer machine could be divided into the following major units including: the frame, diffuser, drying chamber, door, blowing fan, collector, guide vanes, butterfly valve. Their pictorial views are the following Figures1 a),b),c),d),&e).

a) Diffuser during fabrication

b) Solar collector after fabrication

c) Guide vanes during fabrication

d) drying chamber during fabrication

e) door after fabrication

Fig.1: pictorial views of solar dryer Components

Overall Design of the Machine

The machine was developed from indigenous materials and could dry the coffee and protect the coffee beans from direct solar radiation simultaneously. The isometric, orthographic and component drawings of the solar dryer are shown in Figure below:

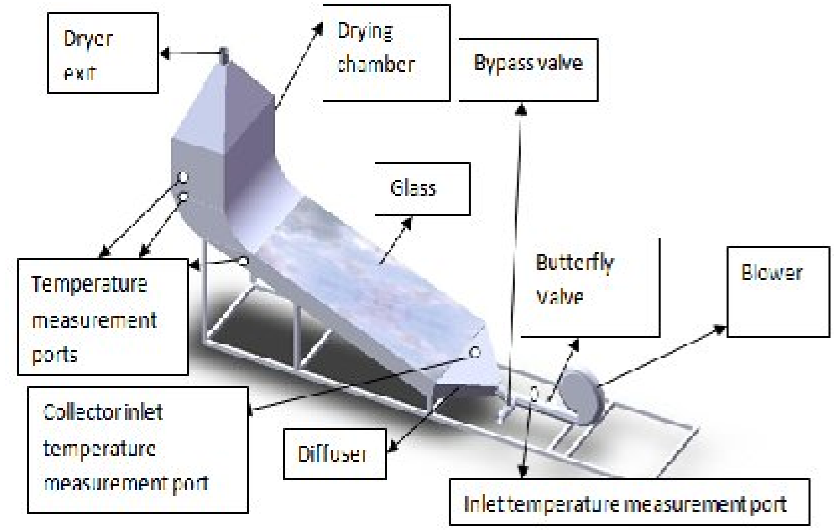


Fig.2: Designed Solar Coffee Drying Machine

Fig.3: Constructed Solar Coffee Drying Machine

RESULTS AND DISCUSSION

Performance Evaluation and Procedure of the Machine

The solar dryer was placed on the ground based on the design. Axial flow fan was fixed at the entry of the drying chamber and tested. The experiments were conducted in the month of December, from daily 9 am to 5 pm. These several performance parameters were measured at an interval of 60 min for 6hr during potential sunshine days. The K-type thermocouples were used for the measurement of temperature in the collector assembly. The temperature was measured each hour from 9am to 5 pm at three points, namely entry, middle and exit of the glass cover absorber plate .The temperature of the air in the drying chamber and the atmosphere were measured by the infrared thermometer. Anemometer vane probe type is used to measure the air velocity. The weight and the moisture of the coffee are measured using a CBK16 portable bench scale and Draminski Grain Moisture Meter respectively.

Table1: Specification of the dryer

Absorber plate inner dimension	1m x 1 m x 0.54 m
Glass cover thickness	0.005 m
Insulation total thickness (bottom)	0.001m
Gap between absorber plate and glass cover	0.15 m
Gap between absorber plate and insulation	0.029 m
Number of trays	3
Tray dimension	0.45 m^2
Distance between trays	0.05 m
Tilt angle of the collector	18° N–S

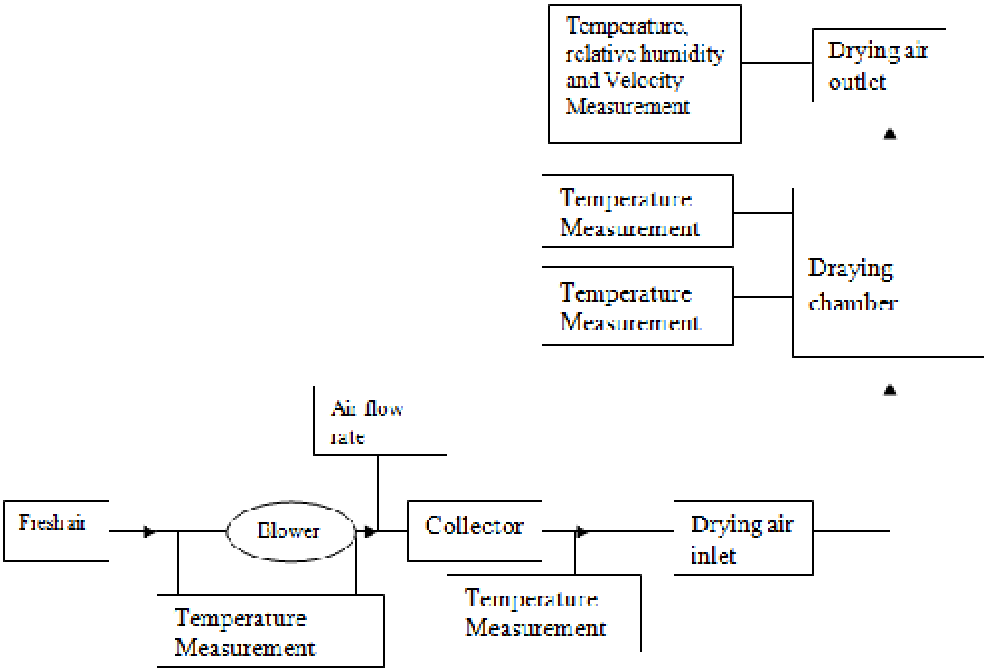


Fig.4. Flow Diagram of drying process

All the experiments were repeated to confirm the repeatability of the data obtained.

a. The wet basis moisture, MCw, is calculated by using (Arkema, 1999).

MC_{wf} = ———*100[%]=11.5%   (1)

Where:

= initial coffee mass or wet coffee mass = 20 kg

= final coffee mass or wet coffee ma

b. The amount of water to be removed from coffee bean, $m_{w,}$ *is calculated by using following equation*

m_{w} = ——————[Kg] = 9.83 Kg   (2)

Where:

MC_{wi} = Initial percentage moisture content of coffee on wet basis = vary from 50-70% (by taking 55%)

MC_{wf} = Final percentage moisture content of coffee on wet basis

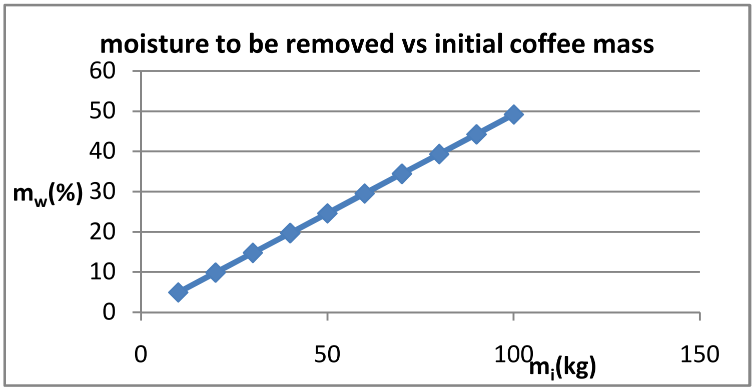


Fig.5.initial moisture content varies at fixed coffee mass.

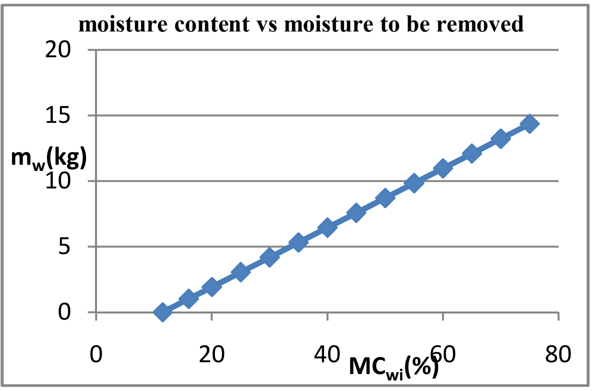


Fig.6.initial coffee mass at fixed initial moisture content (MC_{wi} = 55%)

c. Equation for the latent heat of vaporization of moisture, h_{fg}, in coffee beans (kJ/kg) is given by (Arkema, 1999).

$h_{fg} = (2501+1.775T_b)[1+1.872\exp(-20.601MC_d)] = 2568.45$ kJ/kg (3)

Where:

MC_d = moisture content of coffee (decimal dry basis) = vary from 1-1.222 (100%-122%) = 1

T_b = coffee bean temperature (^{0}C)

Assuming that at infinite time coffee bean temperature is equal to Maximum allowable temperature for drying coffee beans = 38^{0}C

d. *The quantity of heat required to evaporate 9.83kg of H_2O can be calculated by using equation* (Bagheri1,et al. 2011)

$q_{ev} = h_{fg}m_w = 25247.86$kJ (4)

Where:

m_w = amount of water to be removed from coffee bean(kg)

h_{fg} = latent heat of vaporization of water in coffee and calculated by using equation

e. *Equilibrium moisture content, MC_e,* The equilibrium moisture content is expressed as a decimal on a dry basis (Garg, et al, 2005). Equilibrium moisture content equation for coffee as given by Guggenheim-Anderson-de Boer (GAB) model (Correa, 2006) *can be calculated by using equation*

$$= \frac{. \quad . \quad .}{[(\quad . \quad).(\quad . \quad \quad . \quad . \quad)]} =$$

11.5%wb (5)

Where:

= 12.994%db = 11.5%wb

a, b, c = parameters of the models (a = 13.43, b = 0.4733, c = 3.0941)

RH = relative humidity, decimal = 0.7437

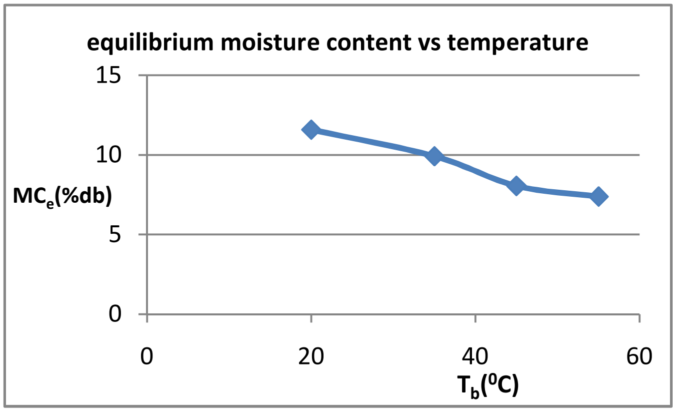


Fig.7 MC_e & T_b of drying air at fixed relative humidity

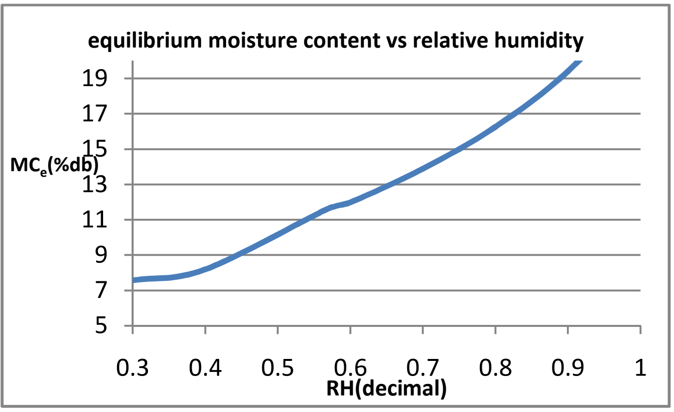


Fig.8 RH, at fixed temperature

f. *Average drying rate, , can be calculated by using following equation*

$= \text{——} =$1.38kg/h (6)

- ○ Assuming that at the collector inlet and exit humidity ratio of air is the same
- ○ Average Ambient air dry bulb temperature and relative humidity is 20^{0}C and 58-83% respectively
- ○ From psychometric chart at collector inlet humidity ratio = 0.0121 kg of H_20 vapor/kg of dry air (i.e. given T_{db} = 20^{0}C and = 83%)
- ○ At collector outlet humidity ratio = 0.0133kg of H_20 vapor/kg of dry air = initial humidity ratio (drying chamber inlet humidity ratio of air),
- ○ From psychometric chart calculator wet bulb temperature at the dryer inlet, Twb = 23.4^{0}C (i.e. given = 0.0121kg of H_20 vapor/kg of dry air and at temperature = 38^{0}C)

- Assumed that throughout the drying period the air will exhaust from the bed at a constant wet bulb temperature and in equilibrium with the uppermost layers of grain.
- From psychometric chart calculator final humidity ratio (drying chamber exit humidity ratio of air), = 0.0185kg of H_20 vapor/kg of dry air (i.e. given that T_{wb} = 23.4^{0}C and = 100%)

g. *Mass of air needed, ˙, for drying can be calculated by using following equation*

$$\dot{} = \frac{}{} = 0.06\text{kg/s} \qquad (7)$$

Where:

= final humidity ratio (drying chamber exit humidity ratio of air)

= initial humidity ratio (drying chamber inlet humidity ratio of air)

h. *Estimation of deep layer Drying Time,*

$$= \frac{}{*(\qquad)} \qquad (8)$$

Where:

= final humidity ratio (drying chamber exit humidity ratio of air)

= initial humidity ratio (drying chamber inlet humidity ratio of air)

The variation of drying time with air mass flow rate at different coffee mass (10-100kg) was calculated and sketched as flow.

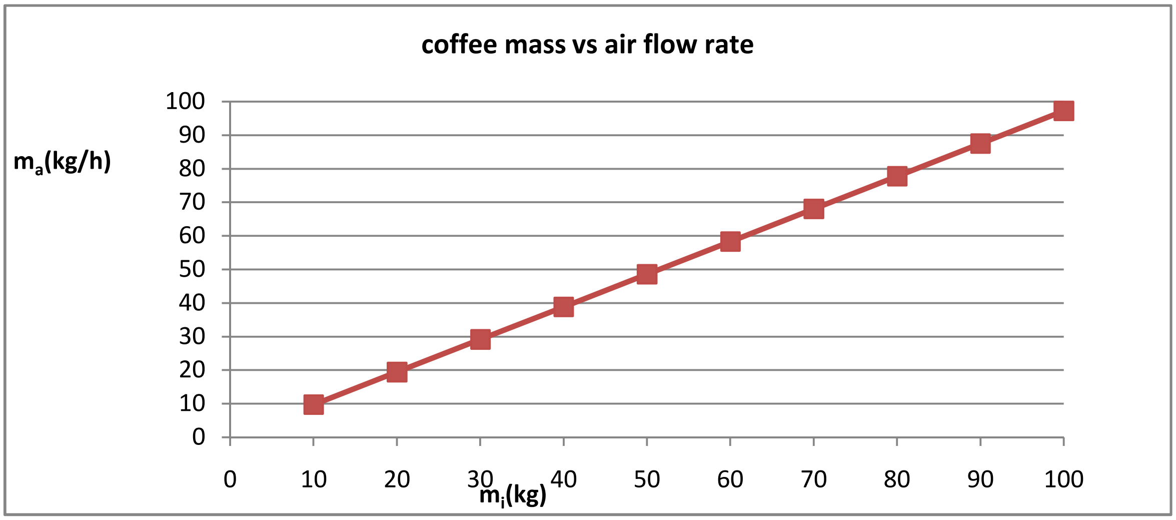


Fig.9 Air mass flow rate a different mass of coffee varies at fixed drying time

i. *The mass of dry matter of grain, DM,*

The depth factor, D, is defined as the depth of the bed that contains the mass of dry matter of grain, DM, that can be dried from the initial moisture ratio MR_i = 1 to a final moisture ratio MR_f = 0 with the sensible heat available over the period of one half-response time as the air cools to its wet bulb temperature.

$$DM = \frac{* \quad * \quad . \; *(\qquad)}{*(\qquad)} \qquad (9)$$

Where:

Ma = mass flow rate

$t_{0.5}$ = half-response time

T_{db} = dry bulb temperature

T_{wb} = wet bulb temperature

d = is the bed depth

A_d = cross sectional area of the dryer

MC_{di} = Initial moisture content of grain on dry basis, decimal

MC_e= Equilibrium moisture content

j. *The number of depth factors, D, within the bed is found from the expression*

$$D = d*\frac{}{} \qquad (10)$$

Where: d - is the bed depth.

Table 2: shows the variation of depth factor with depth and mass flow rate of air

		D									
		0.01	0.03	0.05	0.07	0.09	0.11	0.20	0.30	0.40	0.50
a	DM	D									
0.004	0.010	9.00	27.00	45.00	63.00	81.00	99.00	180.00	270.00	360.00	450.00
0.006	0.015	6.00	18.00	30.00	42.00	54.00	66.00	120.00	180.00	240.00	300.00
0.008	0.020	4.50	13.50	22.50	31.50	40.50	49.50	90.00	135.00	180.00	225.00
0.01	0.024	3.75	11.25	18.75	26.25	33.75	41.25	75.00	112.50	150.00	187.50
0.02	0.049	1.84	5.51	9.18	12.86	16.53	20.20	36.73	55.10	73.47	91.84
0.04	0.098	0.92	2.76	4.59	6.43	8.27	10.10	18.37	27.55	36.73	45.92
0.08	0.196	0.46	1.38	2.30	3.21	4.13	5.05	9.18	13.78	18.37	22.96
0.2	0.489	0.18	0.55	0.92	1.29	1.66	2.02	3.68	5.52	7.36	9.20

k. *Cross sectional area of the drying chamber,*

$$= \frac{}{*}(m^2), \qquad (11)$$

$$= \frac{}{} = *$$

Bulk density is much more important than true density in drying and aeration practices (Chong, 560-756, Korea). It is affected by moisture content, the amount of fines and foreign material and the degree of filling.

l. *The effect of moisture content on bulk density of coffee (ρc) is given by the equation (*Arkema, 1999).

$$= 371.78+255.17MC_d\ (kg/m^3) = 683.6\ kg/m^3 \qquad (12)$$

Where: MC_d = *moisture content of grain on dry basis* = 1.222

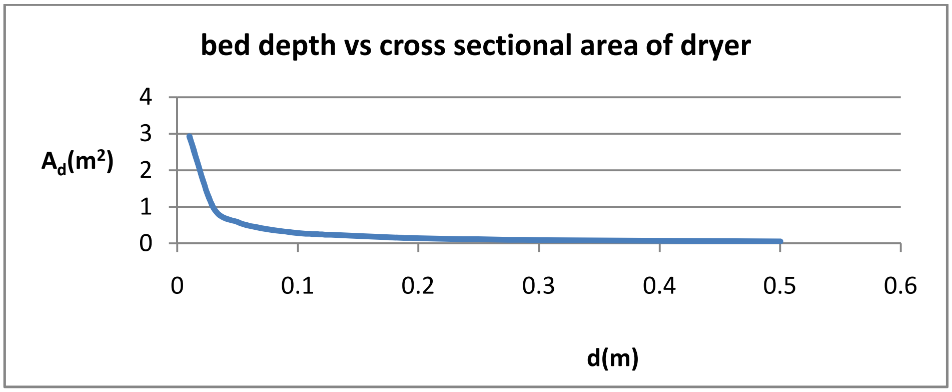


Fig.10: variation of cross sectional area of dryer with the bed depth at fixed coffee mass and bulk density

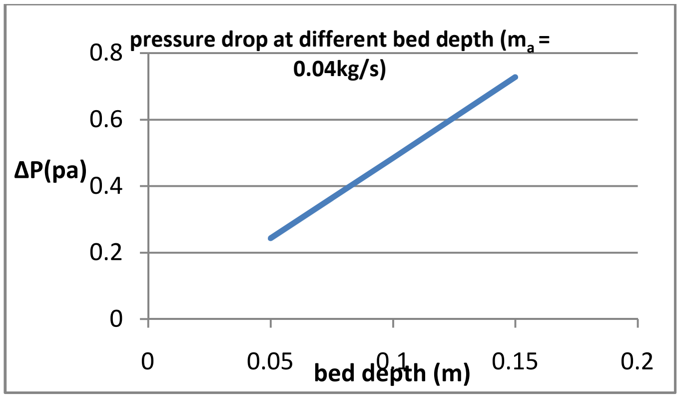
Pressure drop within the system

Pressure drops occur at entrances, transitions, exits and elbows due to energy dissipation by eddies and by distortion of velocity profiles. However, the major pressure loss in a dryer is caused by the coffee bed. The pressure drop through packed beds is the result of frictional losses and inertia characterized by the linear dependence of flow velocity and quadratic dependence of flow velocity respectively as can be seen

m. *from the well-known Ergun's Equation (*Ozdinc, 2008)

$$\Delta = \frac{}{} \qquad (13)$$

Typically these minor losses are accounted for by the loss coefficient, K_L, which is usually experimentally found (Munson, 2002).



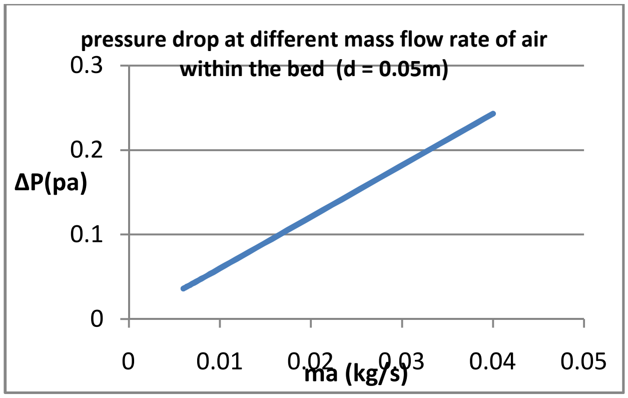


Fig.11 Pressure drop at fixed mass flow rate of air *Fig.12 Pressure drop at different mass flow rate of air*

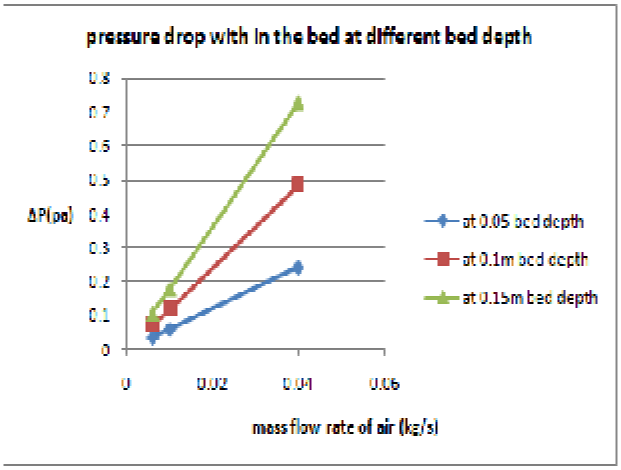


Fig.13 Pressure drops by varying bed depth at different mass flow rate of air

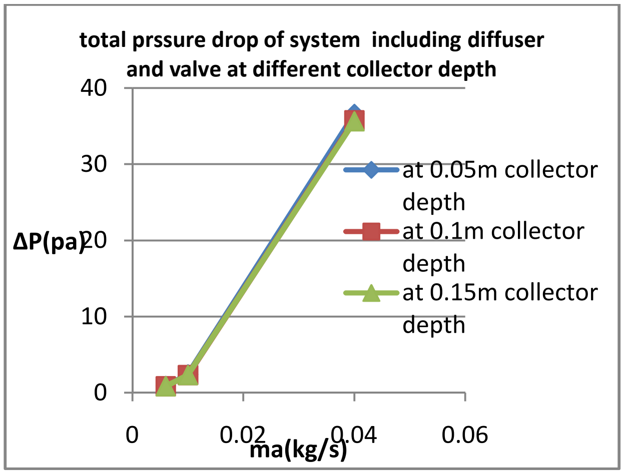


Fig.14.Total pressure drop within the system including diffuser and valve by varying collector depth at different mass flow rate of air

Therefore, smooth curve connection with guide vanes configuration for dryer small scale development was used.

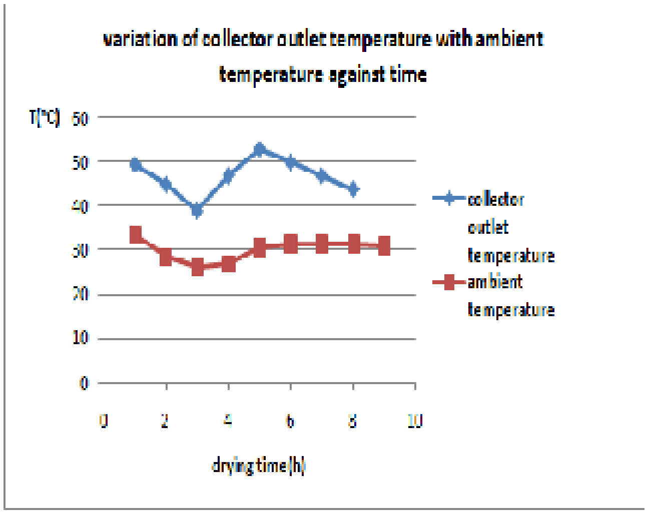


Fig: 15. Variation of Ambient and solar collector outlet temperatures during drying time for partial overcast day

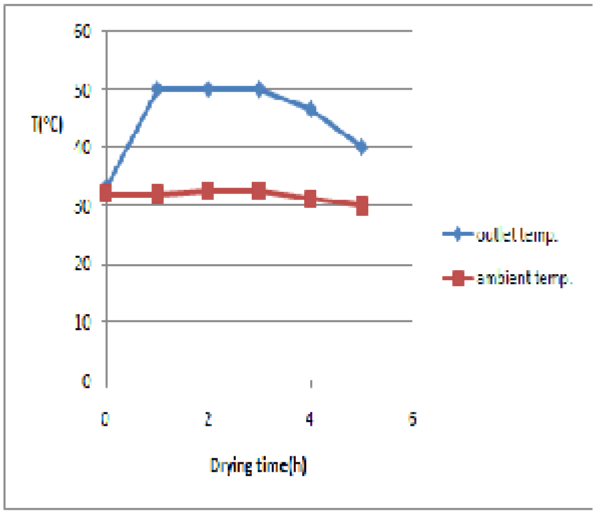


Fig. 16: Variation of ambient and solar collector outlet temperatures during drying time for clear sunshine day

The variation of solar intensity during drying time is illustrated in maximum solar intensity recorded were about 720.5 W/m^{2}and 723.6 W/m^2 during drying period for partial overcast and clear sunshine days respectively. The average ambient relative humidity during drying period was 29.5% and 39.5% for partial overcast and clear sunshine days respectively.

Variation of drying tray inlet temperature and tray outlet temperature with drying time is illustrated at the beginning of experimentation was 12^{o}C and 17^{o}C for partial overcast day and clear sunshine day respectively. The variation decreases gradually and at the end of drying period was 3^{o}C and 1^{o}C for partial overcast day and clear sunshine day respectively.

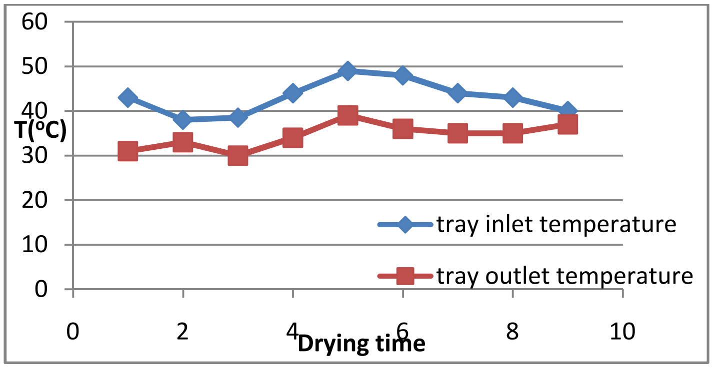


Fig.17. Variation of drying tray inlet temperature & tray outlet temperature during drying time for partial overcast day.

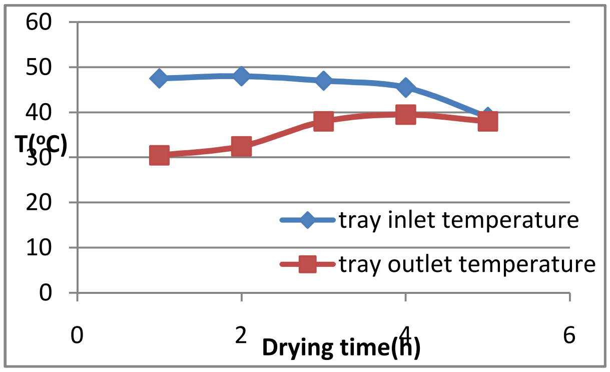
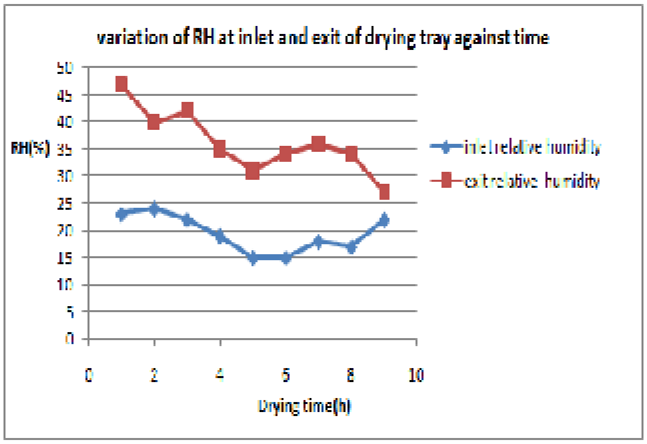


Fig.18.Variation of drying tray inlet temperature & tray outlet temperature during drying time for clear sunshine day.

The variation of relative humidity and humidity ratio of air at the drying tray inlet and outlet with drying time is shown in Fig. 19. It is observed that the relative humidity and humidity ratio of the air at drying tray outlet is higher during the initial stages of drying and gets decreased with drying time as drying proceeds. Maximum relative humidity at outlet of drying tray about 46.9% and 41% during initial stages of drying and gradually reduced to about 27% and 21% at the end of drying was observed for partial overcast and clear sunshine day respectively. Similarly, maximum humidity ratio at the outlet of drying tray was about 15.6g/kg dry air and 15.9 g/kg dry air during initial stages of drying and gradually reduced to about 12.3 g/kg dry air and 11.1 g/kg dry air at the end of drying was observed for partial overcast and clear sunshine day respectively.



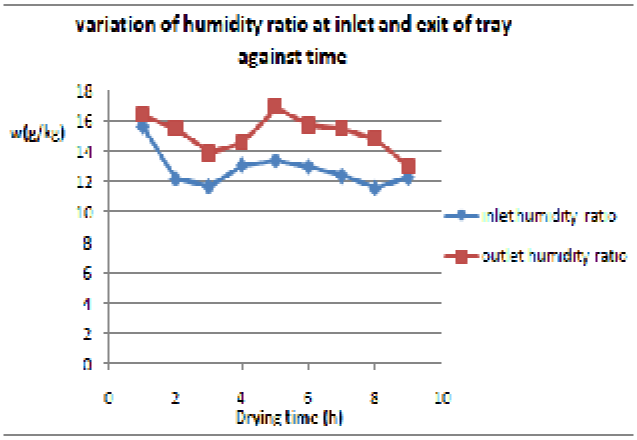


Fig.19.Variation of drying tray inlet relative humidity and tray outlet relative humidity during drying time for partial overcast day

Fig.20.Variation of drying tray inlet relative humidity ratio and tray outlet relative humidity ratio during drying time for partial overcast day

The moisture content of the coffee was reduced from 29% to 12.1% after 6h for clear sunshine day and from 17% to 11.1% after 7 hours for partial overcast day (Fig. 21). The higher moisture reduction during the initial stages of drying was observed due to evaporation of free moisture from the outer surface layers and then gets reduced due to internal moisture migration from inner layers to the surface, which results in a process of uniform dehydration.

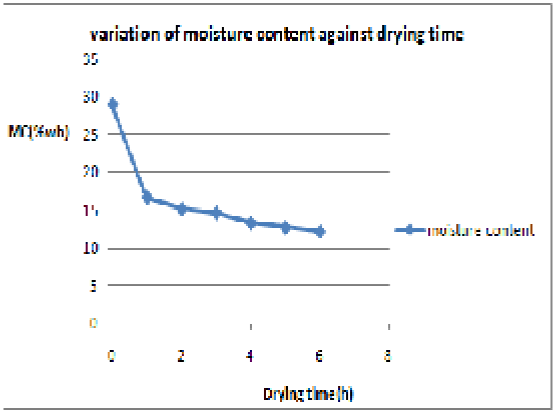


Fig.21. Variation of moisture content against drying time for clear sunshine day

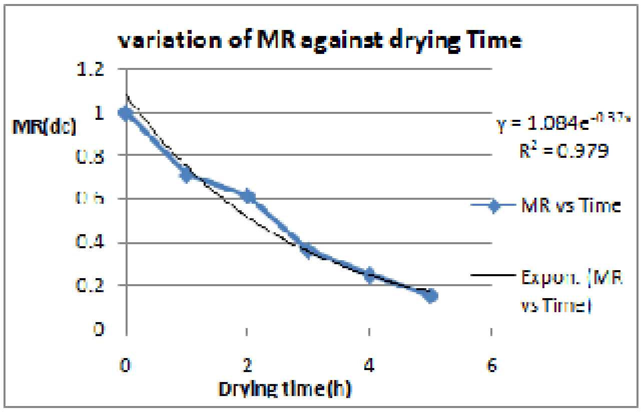


Fig.22. Variation of moisture ratio against drying time for clear sunshine day

The time required to dry coffee from an initial moisture ratio of around 1 to the final moisture ratio of around 0.15 was 5hours for clear sunshine day. For partial overcast day time required was 7 hours to dry coffee from an initial moisture ratio of around 1 to the final moisture ratio of around 0.017.

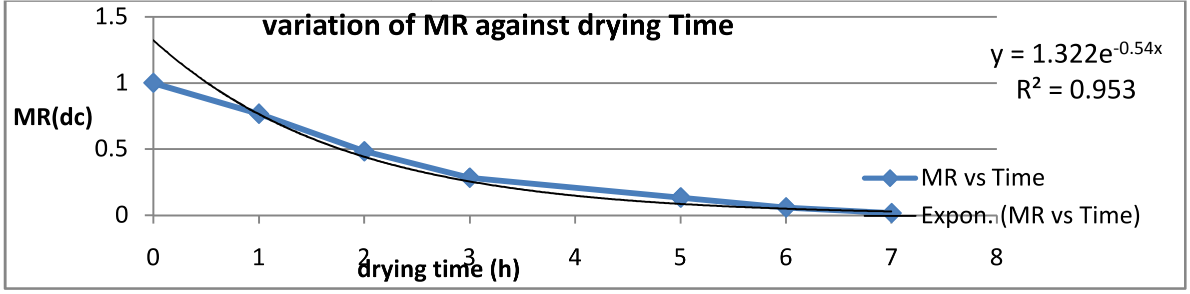


Fig.23. Variation of moisture ratio against drying time for partial overcast day

n. *Dryer efficiency can be calculated as (*Bagheri1, 2011)

$$\eta = \frac{}{(\quad)\quad(\quad)} \tag{14}$$

Variation of thermal efficiency of the dryer during drying time is illustrated Variation of thermal efficiency of dryer during drying time for partial overcast day and for clear sunshine day during experimentation. Average thermal efficiency of the dryer was 50.6% for clear sunshine day and 36.8% for partial overcast day

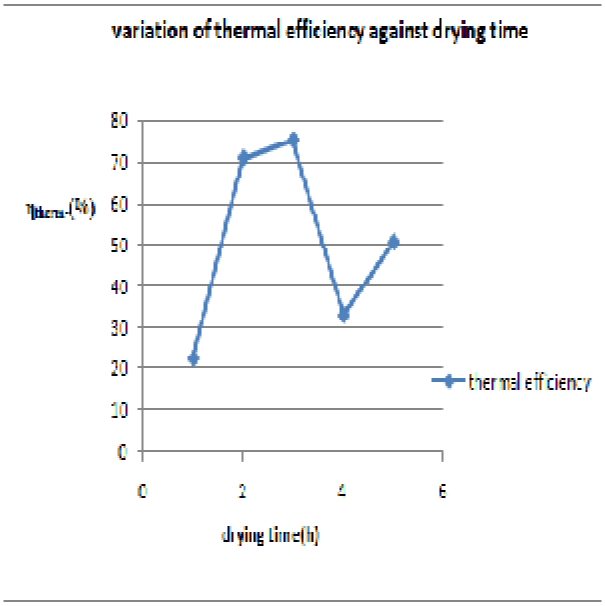


Fig.24. Variation of thermal efficiency of dryer during drying time for clear sunshine day day during experimentation

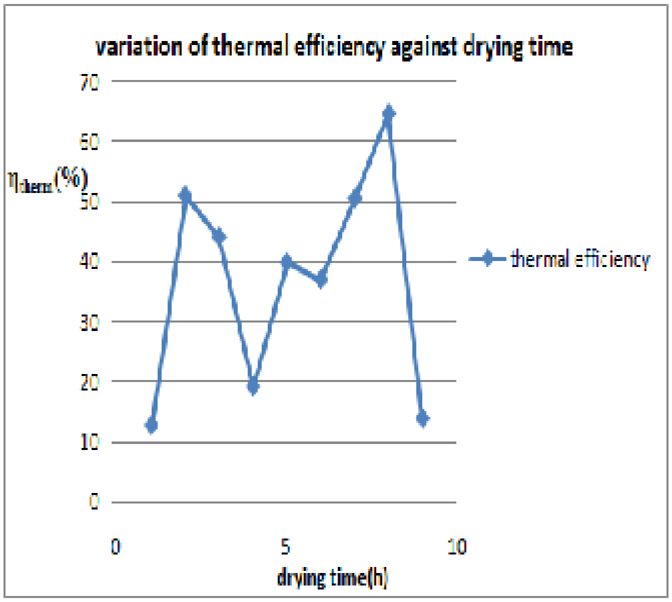


Fig. 25. Variation of thermal efficiency of dryer during drying time for partial overcast day during experimentation

CONCLUSIONS AND RECOMMENDATIONS

From the literature review on solar drying technology it was found that solar dryers are of three types' viz., solar natural dryers, solar active dryers and solar hybrid dryers. The solar natural dryers are used for drying small quantities of crops as they use only ambient energy and natural convection for air flow. Solar active dryers are used for low moisture content crops. A solar collector and a fan/blower are used for the purpose. Solar hybrid dryers are used for drying large quantity of crops as they are designed with a solar collector, heat storage system and auxiliary energy source.

A small-scale solar dryer was designed and constructed for drying coffee bean based on the optimized configuration. The dryer is rectangular shaped with the drying chamber made of chip wood, sheet metal and angle irons. The inner wall of the chamber is painted black to ensure maximum absorption of thermal energy. The clear glass cover and black painted aluminum sheet metal absorber plate was used to maximize absorption of solar radiation. Blower is used to force air and three trays are used in layers for drying coffee beans.

Thermal performance of the solar air heater was evaluated experimentally at three different airflow rates on the flat plate collector configurations. The maximum outlet air temperature of 57^{o}C and 43^{o}C was obtained from the smooth absorber plate collector for the lowest (0.0416 kg/s) and highest (0.0905 kg/s) airflow rates, respectively.

The thermal efficiency as well as drying time of solar drying system is affected by the properties of drying materials like moisture content as well as ambient conditions, which include solar radiation, ambient temperature, ambient relative humidity and mass flow rate of air. In this regard analytical principles of the drying process have been carried out.

The moisture content of the coffee was reduced from 29% to 12.1% after 6h for clear sunshine day and from 17% to 11.1% after 7 hours for partial overcast day, and average thermal efficiency of the dryer was determined to be 50.5% for clear sunshine day and 36.9% for partial overcast day.

The cost-saving when solar drier compared to tray drying: for tray drying 200kg on ground of 1m*25m area, drying time is 15 days and capacity of coffee dried per month is 400kg while for solar dryer 100 kg on ground 1m *4m area, drying time is 3 days and capacity of coffee dried per month is 100kg. From cost analysis solar dryer was better alternative to tray drying technique in cost as well as on coffee bean drying capacity.

Although the findings of present study have shown that a considerable improvement can be achieved in dryer configuration, pressure drop and temperature rise within collector by incorporating guide vanes and minimizing flow separation tendency. Further studies both experimental and numerical are needed to improve the model and to test its performance in the field. It is in light of this that the following is recommended that further improvement to the system model to account for deeper coffee beds and bed shrinkage by using CFD simulation.

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