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THERMAL ANALYSIS OF A GRAIN DRYER INCORPORATED WITH HEAT PIPES OPERATING ON SOLAR/BIOMASS ENERGY UNDER FORCED CONVECTION CONDITIONS FOR PIGEON PEA AT DIFFERENT BED THICKNESSES

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*Drying of food grains is an important operation for a longer safe storage. Pigeon pea (Toor grain), C*anjanus cajan(L), is *one of the world's most important food legumes and is the major source of proteins in the Indian diet. Drying of pigeon pea after harvest for a safe storage and also later during milling in the production chain of dhal is an important operation. This paper presents design and constructional features of a modified solar dryer with heat pipes operating on solar /biomass energy. Drying studies were conducted in the drying system by varying moisture content and grain bed thickness under forced convection conditions to evaluate the performance. Moisture content and moisture ratio variation on an hourly basis are reported. The moisture ratio variation with time followed the power law model in the form of Page's equation. Heat transfer coefficients were determined using forced convective heat transfer correlations. Moisture removal and overall efficiency of drying for different bed thicknesses of drying are reported.*

Keywords: *Modified solar dryer, heat pipe, drying, solar energy, biomass energy*

INTRODUCTION

World pigeon pea production in 2003 was 2.85 million tones (FAO year book 2003). India accounts for 78% of the global output with current production of 2.21 million tones and the increasing trend in production makes it an important crop in several countries. Drying is one of the most important steps of post harvest handling of pigeon pea. In open sun drying the product is exposed directly to the sun allowing the solar radiation to be absorbed by the material and is one of the oldest techniques employed in developing countries. The sun drying method is used for pulse or dhal production in spite of its many inherent disadvantages: season bound, poor quality and drying time of over a month. There is no control over the drying process in open sun drying, and therefore the dried product may turn out to be under dried or over dried. Under drying results in deterioration due to fungi or bacteria, where as over drying may result in

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spoilage. Both these conditions are overcome in controlled drying where the crop is dried reasonably rapidly to a safe moisture level ensuing a superior quality with better nutritional and germination characteristics of the product. Drying of pigeon pea is an important operation in the dhal or pulse industry. The disadvantages associated with open sun drying have led to improved methods of sun drying scientifically termed as solar drying. It can be considered as an elaboration of sun drying and is an efficient system of utilizing solar energy [1-8]. One significant limitation of solar dryer is that it can only be used during the daytime when there is adequate solar radiation. For commercial large-scale production of pulses or dhal, the ability to process continuously with reliability is important to satisfy their markets. Therefore it is necessary to provide solar dryer with any form of back up heating. The back up heater used in this work is a biomass burner which uses saw dust or any agricultural waste as fuel and thus supplying heat to dry crop through a heat pipe heat exchanger and thus making entire unit as an all time dryer for the drying.

In this paper, a drying study on pigeon pea was conducted using a four tray drying chamber of solar drying system based on basic energy balance equations and heat transfer correlations. System performance was evaluated in terms of crop temperature, moisture evaporation and overall efficiency. Effect of parameters like thickness of crop and relative humidity on overall efficiency and rate of moisture evaporation were evaluated.

WORKING OF HEAT PIPES

A heat pipe is a simple device that can quickly transfer heat from one point to another (10). They are often referred to as superconductors of heat as they posses extraordinary heat transfer capacity and rate with almost no heat loss. They are widely used as heat transmission devices due to their high heat transfer rate with small temperature drop. In a heat pipe, working fluid is evaporated at the evaporator section and condensed at the condenser section. The three basic components of a heat pipe are the container, the working fluid and the wick or capillary structure. The function of the container is to isolate the working fluid from the outside environment .Therefore it should be leak proof, should be able to maintain the pressure difference across it's wall and enable transfer of heat to take place from and into the working fluid. Based on the availability of operating temperature and pressure, the distilled water is selected as the working fluid and stainless steel mesh as the wick structure for the application considered. The heat pipes instead of gravity or mechanical work, utilizes capillary induced flow for their operation. The heat pipe wick should act as an effective capillary pump. The surface tension developed between the fluid and the wick structure must be sufficient to overcome all viscous and other pressure drops in the pipe and still maintain the required fluid circulation .

MATERIAL AND METHODS

The study was conducted at the department of mechanical engineering, M.S. Ramaiah Institute of Technology, Bangalore, India. The dryer system mainly consists of : (1) Multi-tray drying chamber, (2) Solar flat plate collector, (3) Parabolic trough type solar concentrators (4) Heat pipes and (5) Biomass burner. Fig. (1) shows the schematics of the system.

Multi-tray Drying Chamber

The drying chamber is of rectangular cross section of size 1.0 m x 1.0m and is built of MS sheet metal of thickness 0.5 mm. Drying chamber consists of 4 trays made of sheet metal and the trays are vertically stacked one over the other with a gap of 5 cm.

Solar Flat Plate Collector

A conventional type of solar air heater, a flat plate collector, size 1.0 m x 1.5 m, is used to heat the air. It is made of 0.5 mm thick galvanized sheet metal of length of 1.5 m and 1.0 m wide and is coated with energy absorbent black paint. The surface of the absorber is corrugated with V-grooves and it provided a cross section of ridges and valleys. A blower, 0.25 hp, fitted at the entrance forces the air through the system thus providing forced convection heat transfer. Heated air from the collector enters into the drying chamber at the bottom and strikes the first tray, then rises up through the remaining trays. As the air moves through the trays it progressively looses its heat and the wet air exits through the chimney at the top. The flat plate collector is placed on the front side of the drying chamber and is aligned to face South and is tilted at 20^{o} for maximum solar incidence.

Heat Pipes and Parabolic trough Concentrator

With the objective of enhanced and efficient heat transfer, a heat pipe is used in the system to provide further heating of the air inside the drying chamber. There are two heat pipes placed one each between the two trays in the drying chamber (Fig. 1) and the other end of the heat pipe runs all along a parabolic trough concentrator out side the drying chamber. The size of the heat pipe is 0.0762 m diameter and 3 m long with a heat capacity of 400 W. These heat pipes are powered by two parabolic solar concentrators each placed at either side of the drying chamber. The parabolic trough concentrator consists of a reflecting surface mounted on a reflector support structure having the profile of a parabola. A receiver assembly comprising a circular absorber heat pipe with black coating and enclosed in a glass envelope is centered along the reflector focal line. The incident energy is absorbed by a working fluid, distilled water, through heat pipe absorber tube. This energy activates the heat pipes, thus making the distilled water inside to evaporate at its heating end and condense at its condenser end (inside the dryer) on a closed cycle. These heat pipes basically receive the solar energy and transfer the same to the hot air in the drying chamber and in turn further compliment the drying process resulting in more and quick moisture removal from the product. Stainless steel wick is provided inside the heat pipe for easy flow of distilled water due to capillary pressure difference.

3.4 Bio Mass Burner and Heat Pipe

For an uninterrupted drying operation even on cloudy days and during night times, a back up heating along with a separate heat pipe is provided in the form of a bio mass burner in the solar drying system Fig. (1). The biomass burner is of square cross section of size 0.70 m x 0.70 m and 0.70 m deep, constructed of refractory bricks, which also acts as a heat storage (accumulator). A door of 0.15 m x 0.15 m was provided at the front side to serve as a door to feed the biomass fuel into the burner. The evaporator end of the heat pipe is inserted inside the biomass burner

Figure 1
Modified Heat Pipes Incorporated Solar cum Biomass Multi Tray Grain Dryer

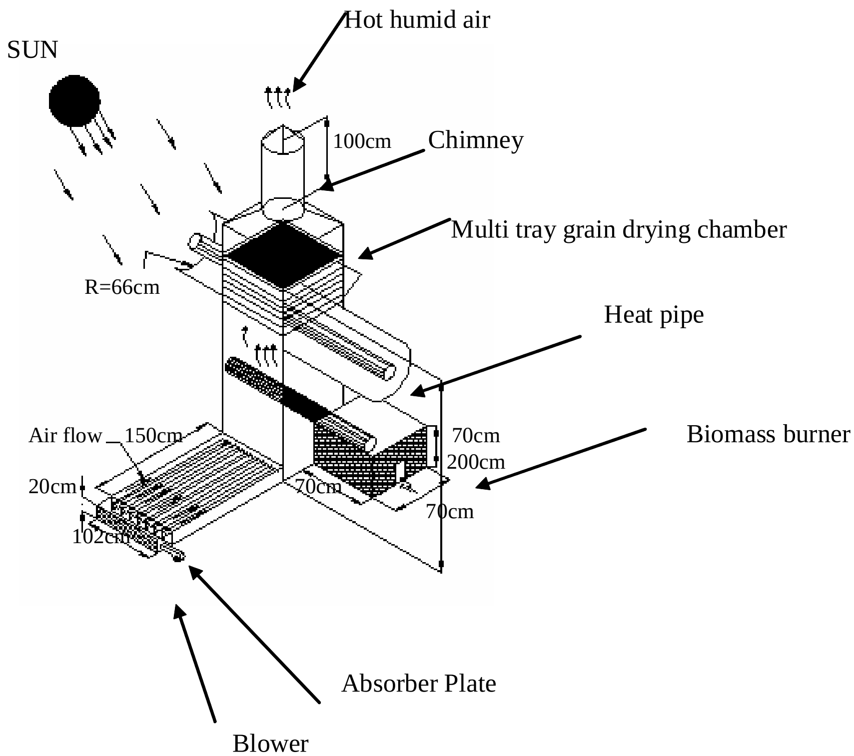


Figure 2
Parboic Trough Concentrator (PTC) with Heat Pipe

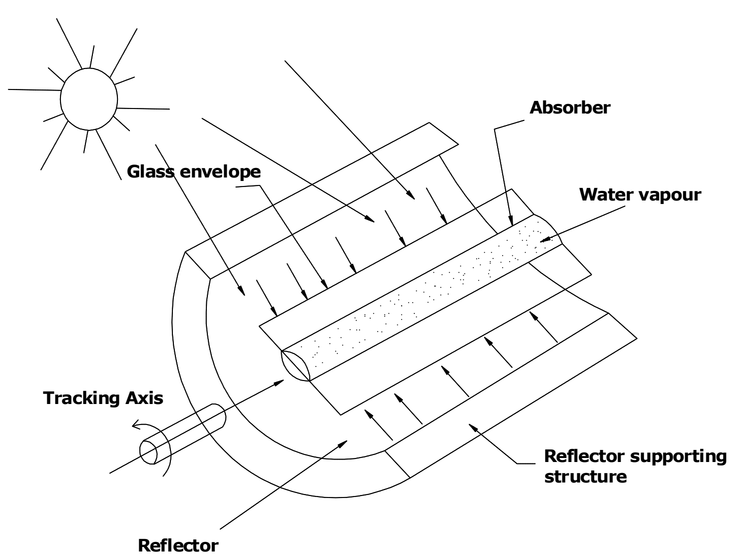
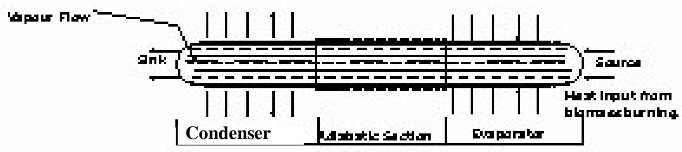


Figure 3
Working of a Heat Pipe



and the condenser end with longitudinal fins on the periphery is kept inside the multi-tray crop drying chamber. Due to the burning of biomass, the water present inside the heat pipe absorbs heat and transforming itself into a vapor and then flowing to the other end located inside the drying chamber (condenser end). At this end the hot vapor comes in thermal contact with the surrounding colder air in the drying chamber and gets condensed on loosing its latent heat of vaporization. The heat exchange takes place and the heated air then goes up to the top trays and furthers the drying process.

The exhaust gas and smoke from burning of fuel escapes to atmosphere through a chimney. The chimney is attached to biomass burner at the top. By this way, it was expected that more heat will be gained from the exhaust gas and smoke that further heats up the internal wall of the drying chamber which in turn gives heat to heat pipe present inside the biomass burner.

EXPERIMENTAL METHODS

The drying experiments were conducted during the months of February to May'2008 and fresh Pigeon pea of about 25% moisture content (wb) were used as the test samples. Biomass burner was used at nights and only during the cloudy days while solar energy was used during the day times. During the trials the parameters measured were: temperatures of the grain and hot air, moisture content levels, solar radiation, mass of pigeon pea dried and the wood burnt, relative humidities and mass flow rate of air through the dryer. A combination of hand held instruments and sensors connected to a data logger were used to make and record the measurements. K-type thermocouples were used to read the temperatures. The relative humidity was calculated from wet bulb and dry bulb temperature using a psychrometer. Solar radiation was measured with a pyranometer. Air velocities were measured with a hot wire air anemometer with an accuracy of 0.01 m / sec while the biomass of wood fuel and saw dust was measured with a digital balance of an accuracy of 0.002 kg.

Details of Experiments

The different drying experiments were:

(1) Open sun drying

(2) Indirect solar dryer with parabolic trough concentrator collector with heat pipes under forced convection conditions.

(3) Biomass burner with heat pipe heat exchanger.

In open sun drying, 20 Kg of pigeon pea at about 25% m.c.(w.b) was spread over a known area for reducing the moisture present to 10-12% (w.b.). During drying the grain temperature, ambient temperature , relative humidity and solar insolation were measured . These measurements were carried out on an hourly basis for different thickness of pigeon pea varying from 1 cm to 5 cm. The weight of pigeon pea grain on an hourly basis was recorded.

In an indirect type solar dryer with parabolic trough concentrator collector incorporated with heat pipes, a total of 20 kg of wet pigeon pea sample was spread on four trays with 5 kg in first tray, 2.5 kg in second tray, 4.2 kg in third tray and 8.3 kg in fourth tray of different thicknesses in all the trays [9]. Hot air from an indirect solar air heater enters the trays from the bottom in to the multi tray grain drying chamber. The heat pipes were placed in the space between the first and second tray, second and third tray for enabling further heating of the hot air flowing through the pigeon pea grains resulting in the more moisture removal. The ambient temperature, crop temperature and hot air temperatures were measured on an hourly basis throughout the day. Relative humidity inside the drying chamber and solar insolation which falls on the V-corrugated absorber plate and parabolic trough concentrator was recorded an hourly basis throughout the day using psychrometer and pyranometer respectively. Digital weight balance was used to measure the weight of pigeon pea grains present in the four trays on an hourly basis throughout the day. The experiments were conducted for different thickness of pigeon pea at a velocity 0.3 m/s of air.

Biomass burner with heat pipe heat exchanger was designed mainly to compliment the solar operation of the dryer and to combine the drying process even during cloudy weather condition and night time. The total amount of thermal energy required to supply the hot air by the heat pipe heat exchanger between 45-50° C was calculated. Accordingly quantity of wood and saw dust required as biomass fuel in the biomass burner was calculated to supply the heat to heat pipe which in turn transfers to hot air flowing inside the multi tray grain drying chamber. The ambient temperature, grain temperature, hot air temperature inside the dryer and relative humidity of flowing hot air were recorded on an hourly basis throughout the day. The weight of Pigeon pea grain present in four trays was recorded on an hourly basis throughout the day by using digital weight balance with an accuracy of 2 grams. Experiments were repeated for different thicknesses of pigeon pea grain at a velocity 0.3 m/s of air.

MATHEMATICAL MODELING

Forced Convection Heat Transfer

The convective heat transfer coefficient (h_c) and moisture evaporated (Mev.) can be obtained using the following relations.

For forced convection heat transfer

$$Nu = \frac{h_c . x}{k_v} = c.(\text{Re}.\text{Pr})^n$$

$$h_c = \frac{k_v}{x}.c.(\text{Re}.\text{Pr})^n \tag{1}$$

Where Nu, Re and Pr are Nusselt, Reynolds and Prandts numbers, respectively and c and n are constants to be determined. k_v and x are thermal conductivity of humid air and characteristic dimension.

The rate of heat utilized to evaporate moisture (q_{ev}) is given as (11-15),

$$q_{ev} = 0.016.h_c \,.\, [P(T_c) - \gamma \cdot P(T_f)] \tag{2}$$

Where $P(Tc)$, γ and $P\,(T_f)$ are partial vapour pressure at grain temperature, relative humidity of the air and partial vapour pressure at enclosure fluid temperature respectively.

$$q_{ev} = 0.016\frac{k_v}{x.\lambda}.c.(R_e.P_r)^n.\,[P(T_c) - \gamma.P(T_f)] \tag{3}$$

The moisture evaporated (m_{ev})is determined by dividing equation (3) by the latent heat of vaporization (λ) and multiplying the area of the tray (A_t) and time interval (t).

$$m_{ev} = \frac{q_{ev}}{\lambda}.A_t\,.t = 0.016\ \frac{k_v}{x.\lambda}.c.[R_e.P_r]^n.[P(T_c) - \gamma.P(T_e)].Ac.t \tag{4}$$

let
$$0.016\frac{K_v}{x.\lambda}[P(T_c) - \gamma.P(T_f)].At.t = z$$

$$\therefore\ \frac{m_{ev}}{Z} = c.(R_e.P_r)^n \tag{5}$$

Taking logarithm of both sides of equation (5), we obtain

$$\ln\left(\frac{m_{ev}}{Z}\right) = \ln(R_e.P_r) + \ln c$$

This is the form of a linear expression, $Y = m\,x_0 + c_0$, where

$$Y = \ln\left(\frac{m_{ev}}{Z}\right),\ m = n,\ X_0 = \ln(\mathrm{Re}\,.\,\mathrm{Pr})$$

and $C_0 = \ln$ c, thus $C = \exp\,(c_0)$

The convective heat transfer coefficient, h_c and moisture evaporation (m_{ev}) can be evaluated from equations (1) and (5) after getting 'c' and 'n'

The values of m_{ev}, T_c, T_e and γ are experimentally determined at time interval, t. The R_e and P_r have been computed by using the temperature dependent physical properties of humid air.

For finding the values of constants m & c in finding the convective heat transfer coefficient for forced convection heat transfer in the modified solar dryer, biomass dryer, the following statistical relations are used (11)

$$m = \frac{N \times \Sigma x_0 \cdot y}{N.\Sigma x_0^{\ 2} - (\Sigma x_0)^2}, n = m$$

$$c_0 = \frac{\Sigma x_0^{\ 2}.\Sigma y - \Sigma x_0.\Sigma x_0 y}{N\Sigma x_0^{\ 2} - (\Sigma x_0)^2}, c = \exp(c_0)$$

5.2 Page Model for Moisture Variation

The drying in the open sun , modified solar dryer with heat pipe and biomass dryer with heat pipe followed the Page drying model as below.

$$MR = \exp(-kt^n) \tag{6}$$

Where $$MR = \frac{M(t) - M_e}{M_i - M_e}$$

MR = Moisture ratio

$M(t)$ = Moisture content at any time (Kg)

M_i = Initial moisture content (Kg)

M_e = Equilibrium moisture content (Kg)

t = time (hrs)

k and n = constants.

R^2 = Co-efficient of determination.

5.3 Relations used for Computing Moisture Ratio and Dryer Efficiency

(1) Moisture ratio (M.R.) = $\frac{M(t) - Me}{Mo - Me}$

M(t) – Moisture present in the grain at any time t in kg

Me- Equilibrium moisture content in kg

Mo- Initial moisture in kg

(2) Solar Dryer Efficiency:

$$\eta \ solar = \frac{M_v x L}{I x A_p x t} \times 100$$

Where M_v – Mass of water vapour removed from the grain in kg

L – Latent heat of water vapour in J/ kg

I – Solar intensity in W/m^2

Ap – Absorber plate area with concentrating collector in m^2

t – Time in seconds

(3) Biomass dryer efficiency:

$$\eta_{Biomass} = \frac{M_v \times L}{m_f \times c.v.} \times 100$$

m_f – Mass of biomass fuel in kg

c.v. – Calorific value of the fuel in J/kg

RESULTS AND DISCUSSION

The variation of moisture content with time for various thicknesses of pigeon pea grain in open sun drying, modified solar dryer with heat pipes and biomass dryer with heat pipe on an hourly basis are shown in figures (4), (5) and (6) respectively. It was observed that as bed thickness increases, time of drying increases. However, in open sun drying, the effect of bed thickness on drying appeared to be marginal as compared to drying in modified solar dryer (Figs. 4 and 5). From Fig. 5 it could be seen that for a drying time of 15 h, for bed thicknesses of 1, 3 and 5 cm, the final moisture content reached were 15%, 12% and 10 %, respectively. Whereas in case of open sun drying the final moisture content reached was only 20% in 15 h, and there was no significant difference between the different thicknesses. Fig (6) shows a higher moisture content reduction in biomass dryer when compared to Fig. (4) and(5), because the heat supplied was constant by burning the biomass fuel as compared to the variation in solar energy throughout the day in open sun drying and modified solar dryer.

Figure 4
Variation of Moisture Content (%) with Time in Open Sun Drying

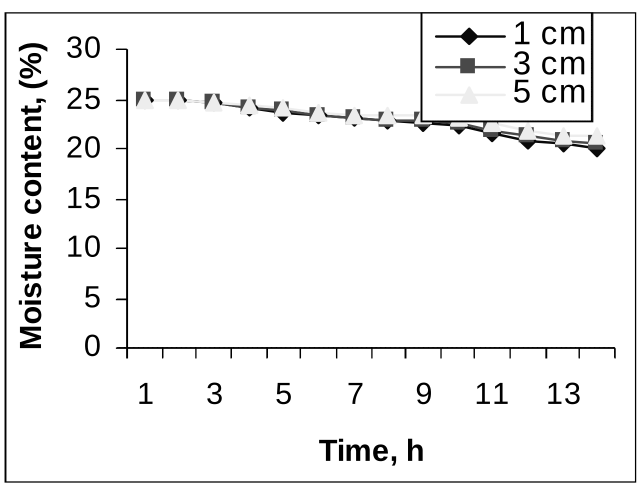


Figure 5
Variation of Moisture Content with Time in a Modified Olar Dryer (0.3 m/s)

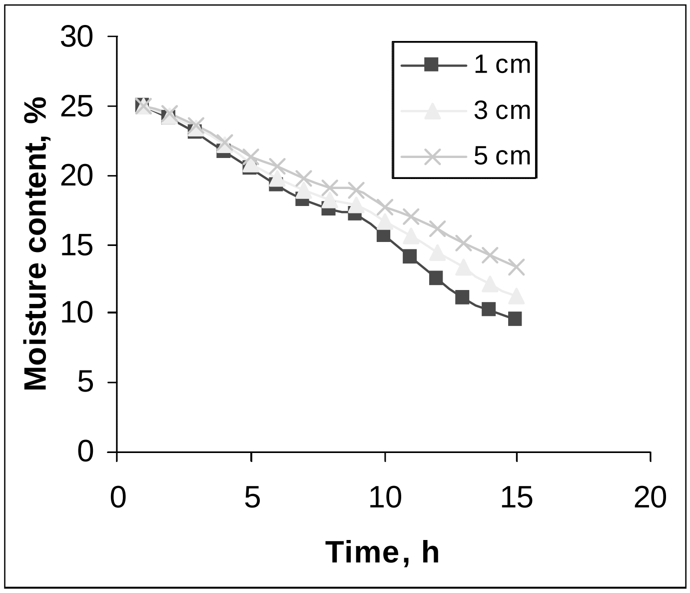
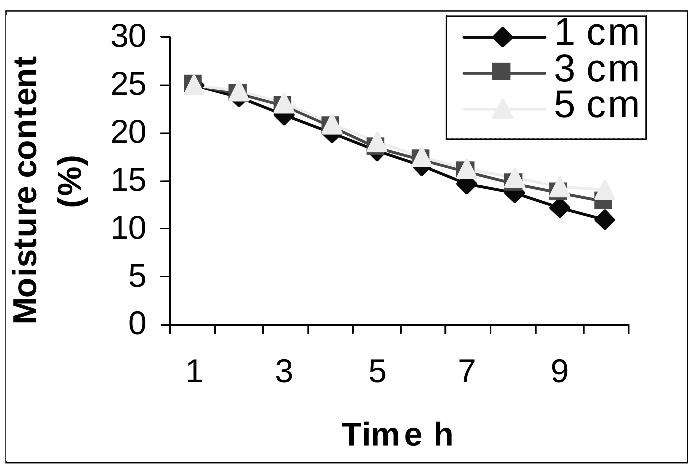


Figure 6
Variation of Moisture Content (%) with Time in a Biomass Dryer (V = 0.3 m/s)



The variation of moisture ratio with time for various thicknesses of pigeon pea grain in open sun drying, modified solar dryer with heat pipe and biomass dryer with heat pipe on an hourly basis are compared in figures (7), (8) and (9), respectively. The moisture ratio variation with time follows the page equation in all the above drying cases and their constant values of '*k* ' and 'n' are given in the table (1) below. From the above figures, it shows that, as the thickness of grain increases, moisture ratio decrease takes more time, because of more moisture concentration in the grain bed resulting in the lower amount of moisture evaporation. And, also biomass dryer consumed less time in reaching any moisture ratio compared to open drying and modified solar dryer for all the thicknesses of Pigeon pea grain due to the constant heat energy supplied to the grains unlike a variational solar energy supplied in open sun drying and modified solar dryer with heat pipes.

Figure 7
Variation of Moisture Ratio with Time in Open Sun Drying

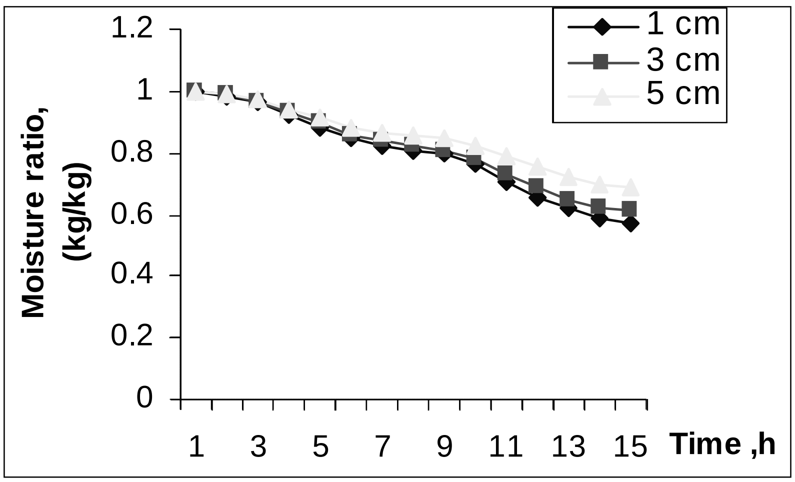


Figure 8
Variation of Moisture Ratio with Time in a Modified Solar Drier with Heat Pipes (V = 0.3 m/s/).

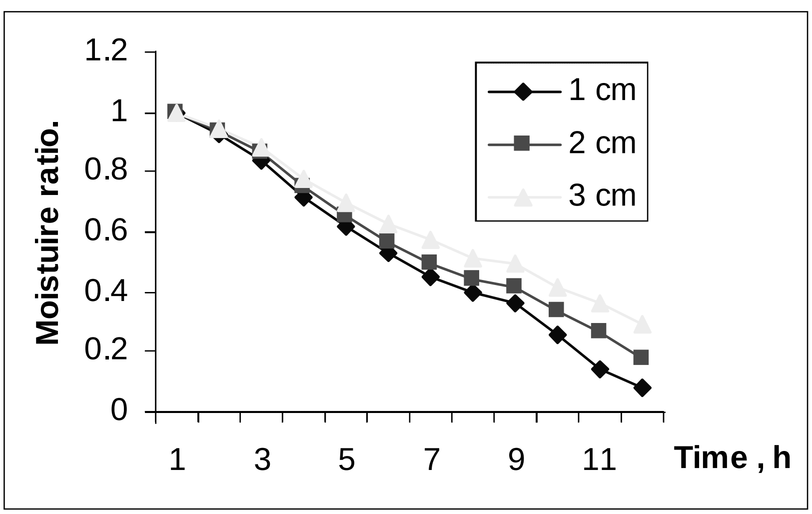


Figure 9
Variation of Moisture Ratio with Time in a Blomass Dryer (V = 0.3 m/s)

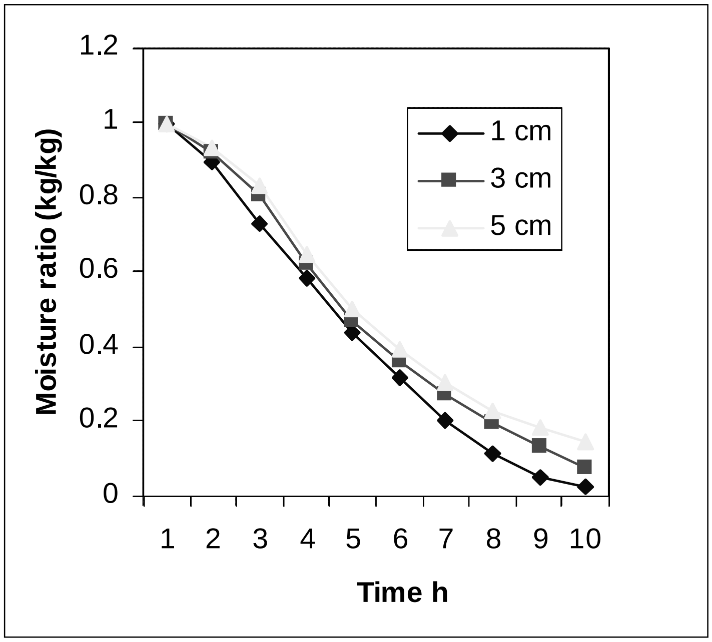


Table 1
Computed Values of Constants of Page model for a Thickness of 1cm Bed Thickness in Open Sun Drying, Modified Solar Dryer with Heat Pipe and Biomass Dryer with Heat Pipe

Type of drying	*k*	*n*	R^2
Open sun drying	1.0493	-0.0318	0.981
Modified solar drying with heat pipe	1.0264	-0.0752	0.9809
Biomass drying with heat pipe	1.07	-0.1153	0.9746

The variation of total moisture removed for the same time and overall efficiency of drying for different thicknesses grain in open sun drying, modified solar dryer with heat pipes and biomass dryer with heat pipes are shown in figures (10), (11) and 12 respectively. From the figure results, it indicates that total moisture removed for the same time decreases in all the types of drying as the thickness of grain bed increases. The overall efficiency of drying also decreases as the thickness of grain increases in modified solar dryer with heat pips and biomass dryer with heat pipe due to more moisture concentration in the direction of flow of the hot air through the grain bed. But in open sun drying, overall efficiency increases as the thickness of grain increases due to the more thermal energy stored in the grain lump makes more moisture diffusion from the inside grain to surface resulting in more efficiency.

The computation of convection heat transfer coefficients for modified solar dryer with heat pipes and biomass dryer are given in tables (2) and (3) respectively.

Figure 10
Variation of Moisture Removed, Overall Efficiency with Thickness of Grain

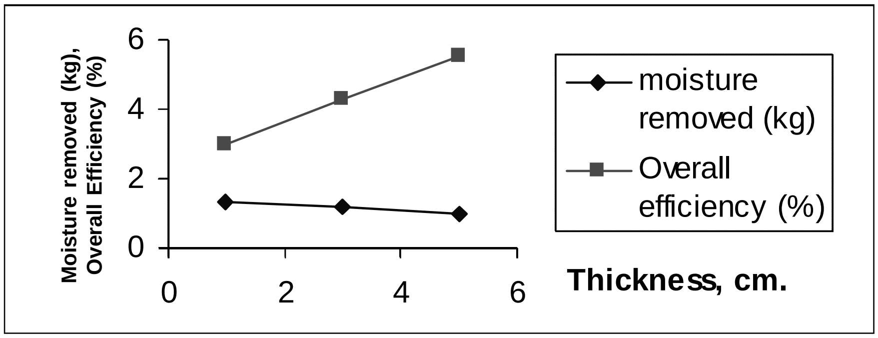


Figure 11
Variation of Moisture Removed (kg), Overall Efficiency (%) with Thickness of Grain

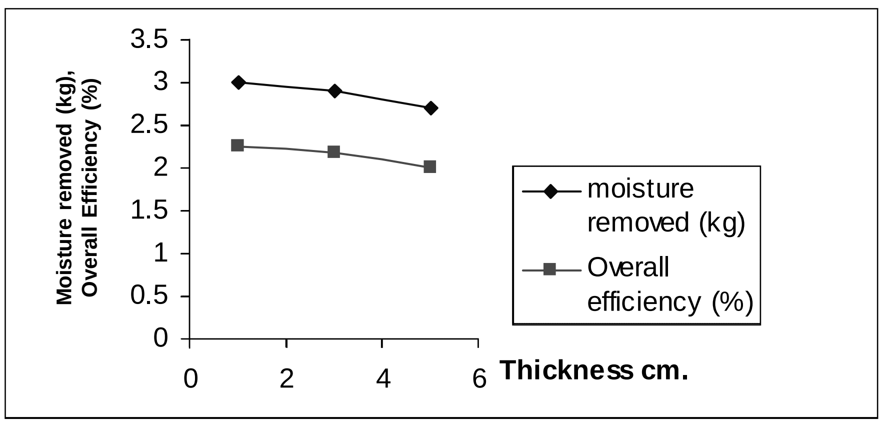
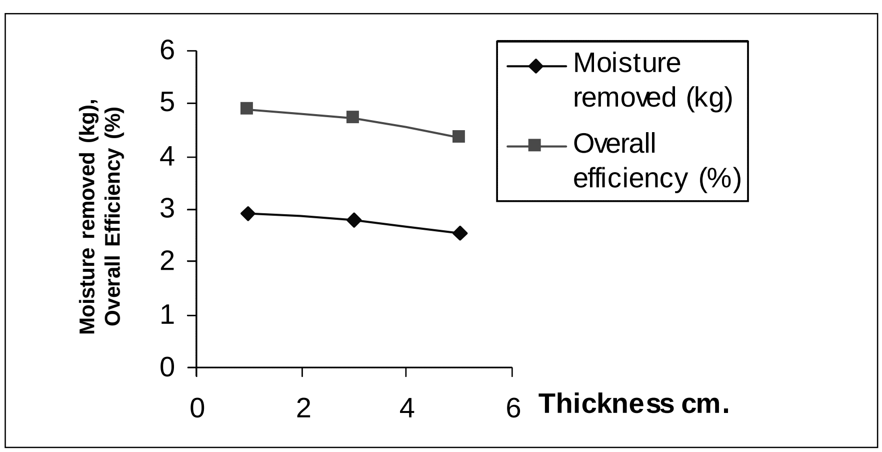


Figure 12
Variation of Moisture Removed, Overall Efficiency with Thickness of Grain



The variation of convection heat transfer coefficient with time for modified solar dryer with heat pipes and biomass dryer with heat pipes shown in fig (13). From the figure results, it indicates that the convection heat transfer coefficient was more for modified solar dryer with heat pipes compared to biomass dryer with heat pipes and in both cases, it remains almost same for all the time because the heat supplied in modified solar dryer and biomass dryer was almost constant for the whole period of drying even though the moisture removal was more during the beginning due to the mass transfer effect than the heat transfer.

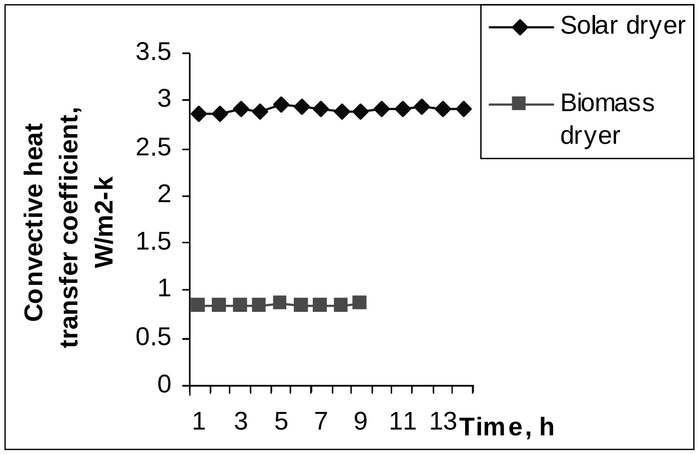
Table 2
Computed Values of Convective Heat Transfer Coefficient for a Thickness of 1cm Pigeon Pea Grain in a Modified Solar Dryer

$Y = ln(m_{ev}/z)$	$X0 = ln\ (Re.Pr)$	$X0^2$	$X0 * y$	$hc, w/m^2\text{-}k$
0.139843	4.909667	9.819333	0.686581	2.86E+00
–0.00016	4.888348	9.776697	-0.00079	2.85E+00
0.165494	4.863237	9.726474	0.804834	2.91E+00
–0.14395	4.853956	9.707913	-0.69873	2.89E+00
–0.54394	4.832672	9.665343	-2.6287	2.96E+00
–0.67002	4.841813	9.683626	-3.24413	2.94E+00
–1.146	4.853917	9.707834	-5.56258	2.92E+00
–0.80237	4.888063	9.776126	-3.92205	2.89E+00
0.157042	4.881519	9.763037	0.766603	2.88E+00
0.075768	4.87558	9.75116	0.369413	2.90E+00
–0.69367	4.863237	9.726474	-3.37349	2.91E+00
–1.27055	4.853632	9.707263	-6.1668	2.93E+00
–1.7363	4.847545	9.69509	-8.41678	2.92E+00
–3.25342	4.860327	9.720653	-15.8127	2.91E+00

Table 3
Computed Values of Convective Heat Transfer Coefficient for a Thickness of 1cm Pigeon Pea Grain in a Biomass Dryer with Heat Pipe

$Y = ln(m_{ev}/z)$	$X0 = ln\ (Re.Pr)$	$X0^2$	$X0 * y$	$hc, w/m^2\text{-}k$
1.159372	4.891333	23.92514	5.670876	8.30E-01
1.466159	4.89062	23.91817	7.170425	8.33E-01
1.564239	4.889907	23.91119	7.648981	8.36E-01
0.950275	4.88762	23.88883	4.644581	8.50E-01
–1.19311	4.887906	23.89163	-5.83179	8.60E-01
–0.4152	4.88762	23.88883	-2.02935	8.46E-01
–0.81882	4.887334	23.88604	-4.00183	8.30E-01
–1.23634	4.88905	23.90281	-6.04452	8.46E-01
–2.76132	4.886905	23.88184	-13.4943	8.58E-01

Figure 13
Variation of Convective Heat Transfer Coefficient with Time



CONCLSIONS

A grain dryer incorporated with heat pipes operating on solar/biomass energy under forced convection conditions was designed, constructed and tested for its performance. A parabolic solar concentrator was provided to enhance drying and a biomass burner was also provided to work as a backup power pack. Drying studies conducted on wet pigeon pea indicated that bed thickness has a significant effect on rate of drying and drying time. Drying times were shorter with thinner beds and it varied from 10- 16 h to get dried from 25% moisture content to a final moisture content of 12%. Page's equation could be modeled with a high degree of fitment and the exponential constants were different for different methods of drying.

The heat pipe heat exchanger used in the modified solar dryer with parabolic trough concentrator supplies more heat to pigeon pea grain resulting in the improvement of efficiency of drying. And, also the use of heat from biomass burner to the air ,inside the multi tray grain drying system facilitates clean and continuous drying of pigeon pea grain placed on the trays during cloudy weather conditions in day time and also in night time, thus making it an all time dryer operating on solar / biomass energy. The pigeon pea grain dried was of superior quality and consumed less time compared to the unscientific open sun drying.

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