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Original Research

Design and Simulation of Forced Solar Coffee Dryer Using Computational Fluid Dynamics (CFD)

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Abstract

The solar drying system is the oldest processing technique utilizes solar energy to heat up air and to dry any food substance loaded, which is beneficial in reducing wastage and preservation of agricultural products used for food such as fruits, vegetables, grains and etc. The current paper outlines the methodology applied for the design and optimization of the solar coffee dryer, which has been achieved through the analysis of the flow field by means of computational fluid dynamics. The prediction of the 3D flow problem was accomplished through the solution of the steady-state incompressible, Reynolds-Averaged Navier-Stoke (RANS) equations with the incorporation of the standard k-ε turbulence model. The measurement and control instrumentation with the inclusion of the innovative, computer-controlled, 3D traverse system that serves detailed surveys of the temperature and velocity inside the drying chamber, are also discussed. The solar collector and dryer system configuration has been optimized for minimal pressure drop by incorporating guide vanes and minimizing flow separation tendency using numerical simulation on ANSYS. High collector outlet temperature and efficiency were observed in a collector with flat absorber plate. The results obtained during the CFD simulation period revealed that the temperatures inside the dryer and solar collector were much higher than the ambient temperature during most hours of the day-light. 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 partially overcast day. The dryer exhibited sufficient ability to dry coffee beans reasonably rapidly to a safe moisture level and simultaneously it ensures a superior quality of the dried product. Average thermal efficiency of the dryer was found to be 50.6% for clear sunshine day and 36.8% for partial overcast day.

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INTRODUCTION

Coffee (Coffee Arabica) is a genus of flowering plants whose seeds, called coffee beans, are used to make coffee drink. Coffee ranks as one of the world's most valuable and widely traded commodity crops and is an important export product of several countries.

One of the major objectives of this research is to design and Simulation of Forced Solar Coffee Dryer using Computational Fluid Dynamics (CFD) for the drying process to achieve uniform moisture content in the final product. The use of forced convection can be reduced drying time by three times and decreases the required collector area by 50%.

The uniformity of the moisture in the final dried product may be achieved through the proper distribution and guidance of the drying air inside the drying chamber. The air distribution depends on the drying process, the product to be dried and the geometry of the drying unit. The above factors determine the uniformity of drying and the final product quality. The velocity distribution can be determined based on the conservation equations for mass and momentum (Ozdinc, 2008). Analytical solutions can be found only in simple cases. The variables involved in the air flow can be determined experimentally, but it is a tedious, time consuming and costly process. Moreover, it can only be applied to in service units. Hence, it cannot be used to optimize the drying chamber at an early phase of the design. In cases of complex geometry the employment of CFD, is an efficient way to evaluate the quality of the airflow. The CFD technique is a very powerful tool with great applications in both industrial and non-industrial installations. CFD has been used in several studies that focused on the design and optimization of drying process. The paper shows the wide use of CFD for predicting the air velocity and pressure drop in drying chambers (Kiranoudis, 1999).

MATERIALS AND METHODS

Methods

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 insulation 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.

Climatic Data Collection

The data was collected in Gimbi, which is 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^2and723.6W/m^2 during drying period for partial overcast and clear sunshine days respectively. The flat plat absorber collector made of a glass cover and black absorber plate was inclined at an inclination angle of about $18^0$to the horizontal to allow the heated air to rise up the unit with little resistance (Bolaji, 2005).In this paper the work is subdivided in to, solar dryer and basic concepts, data collection, research design, CFD simulation of the solar collector.

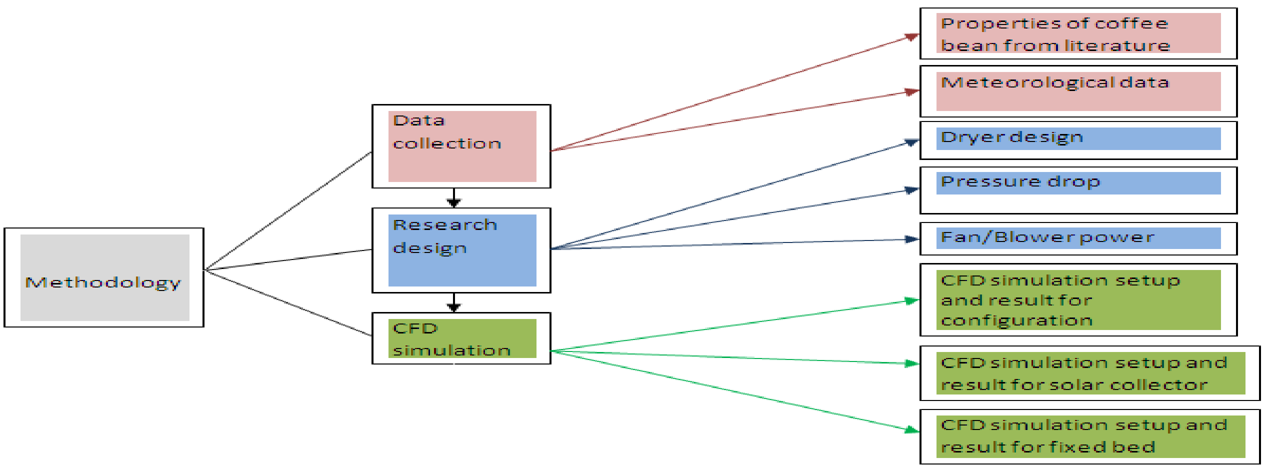

Fig.1. Flow Diagram of CFD simulation process

Description and Design Aspects of the Solar Coffee Dryer

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.

An indirect type of solar coffee dryer was considered as it does not affect the colour and nutrient content of the produce as in the case with a direct type (Mohanraj, 2008). Also, the drying is uniform without any localized heating. Flat plate collector is used since it is easy to fabricate and also economical (Sarsavadia, 2007).

The collector is made up of sheet metal of 1mm thick as it is a good conductor and economical.

In the design a flat plate collector with dimension of 2m*1m*0.15m channel depth, and 29 mm thick on the bottom chip wood and plywood insulation was considered.

The drying chamber has 1m x 1 m x 0.54 m inner dimensions. Inside the drying chamber three shelves were prepared on which the coffee to be dried was placed. Tray one is 5cm deep with wire mesh in the bottom and its cross-sectional area is A1 = 0.45 m^2 and tray two is 5cm deep with wire mesh in the bottom and its cross sectional area is A2 = 0.45 m^2. The relative positions of these trays are: the bottom tray (tray T1) is placed 0.05m above the drying chamber's base (hot air's entry point); the middle tray (tray T2) is located at 0.15m and the top tray (tray T3) at 0.25m above the chamber's base, respectively.

It was painted black to increase the absorption of heat (Othieno, 1987). 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 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.

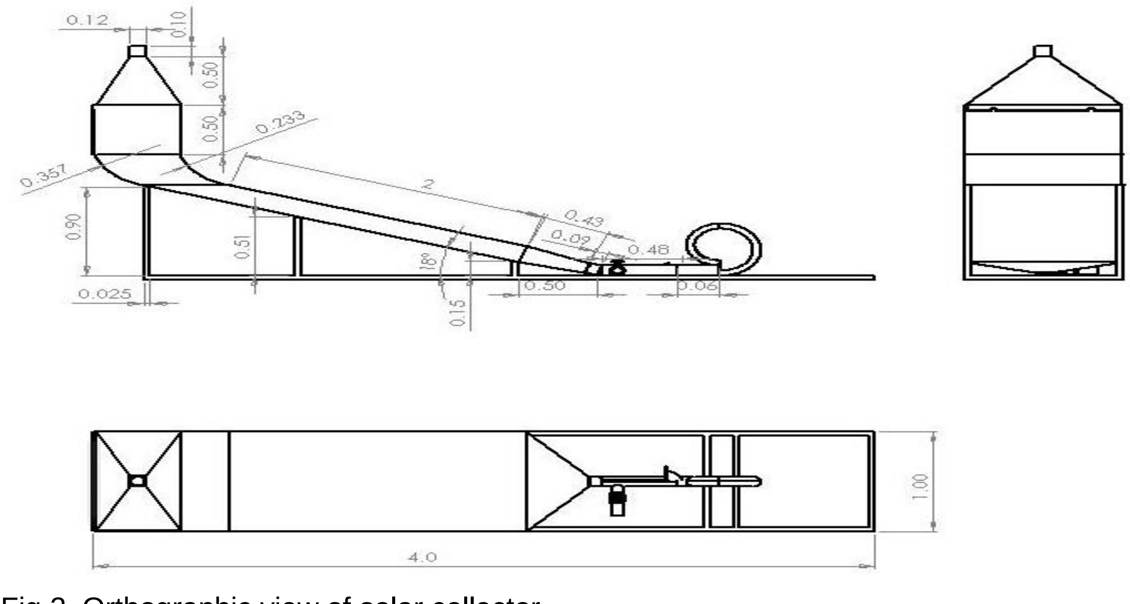

Fig.2. Orthographic view of solar collector

The performance of the collector is described by an energy balance that indicates the conversion of solar radiation into useful energy gain and losses (Bagheri, 2011). 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 (Fox, 2004; Hallenbeck, 2007).

Considering merits and demerits of different configurations and to minimize the pressure drop throughout the system by using ANSYS12.1, different dryer configuration based on pressure drop and uniform air flow distribution have been compared(White, 2003).

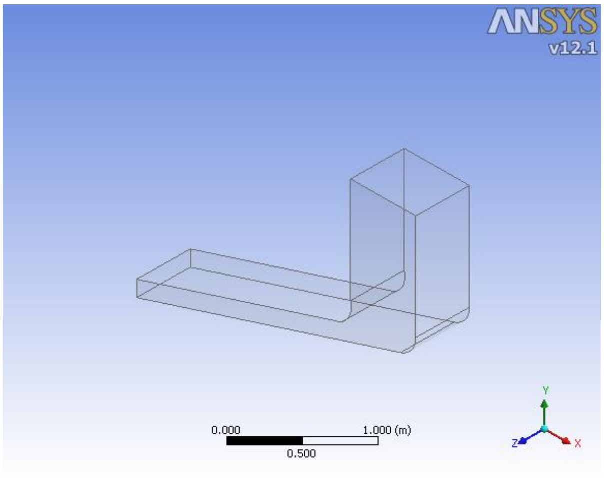

Fig.3. Smooth edge connected dryer configuration Set up

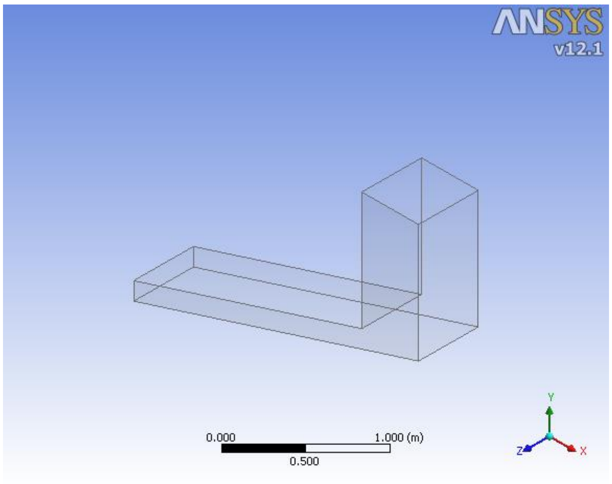

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Fig. 4. Sharp edge connected configuration set up.

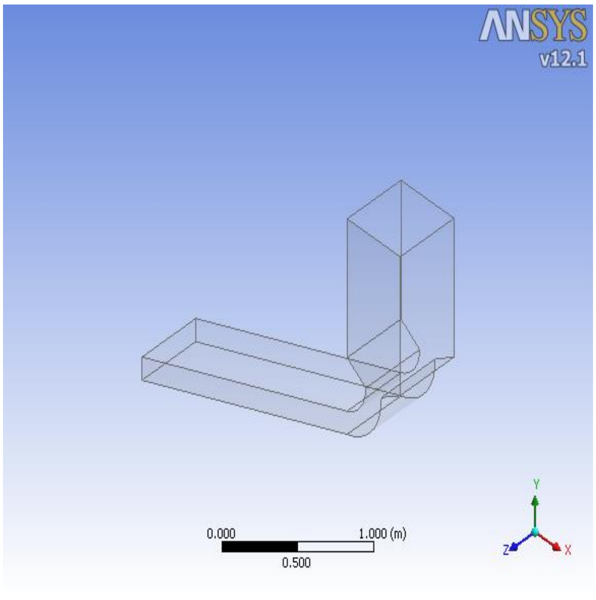


Fig.5. Smooth curve then diffuser connected dryer

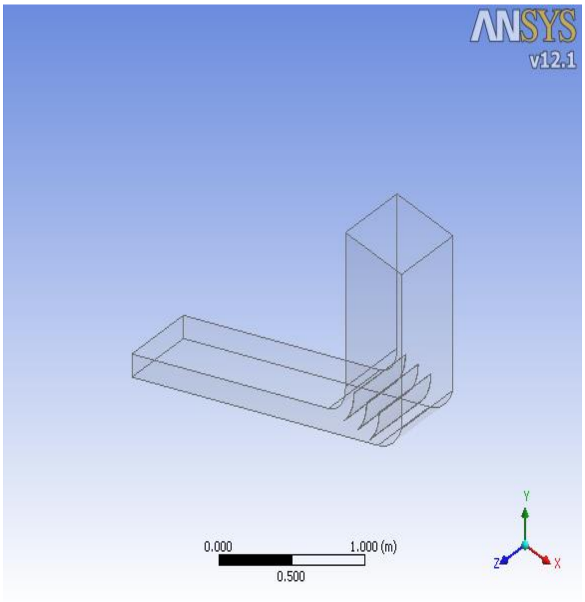
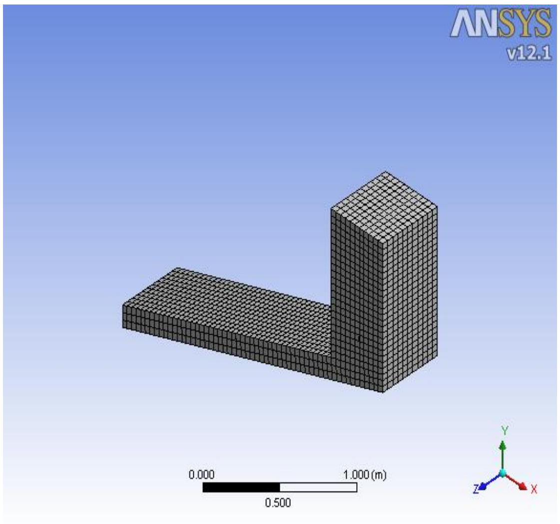


Fig.6. Smooth curve connection with guide vanes



Mesh statics

Generally, there are four criteria to evaluate the qualities of the solid mesh, which are aspect ratio, skewness, Element quality, and mesh smoothness. Aspect ratio is the most important criteria to evaluate the qualities of each individual element.

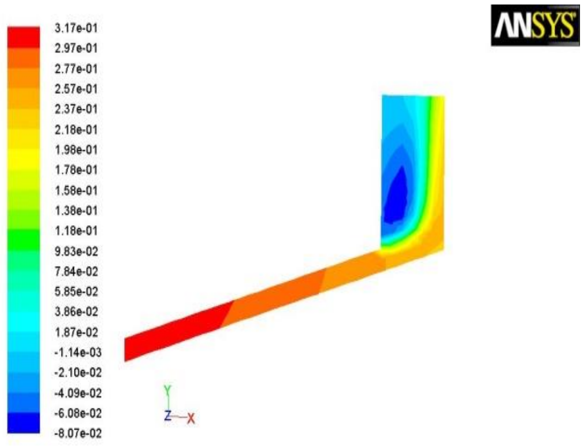
Fig.7.the 3D computation mesh/grid used in computer simulations

Table 1: Mesh statics of Sharp edge connected, Smooth edge connected, smooth curve then diffuser connected &smooth curve connection with guide vanes geometry configuration type

Geometry type	No. Nodes	No. Elements	Mesh metrics	Minimum	Maximum	Average	Standard deviation
Sharp edge connected	5952	4543	Element quality	0.945	0.998	0.976	0.012
			Aspect ratio	1.038	1.201	1.018	0.050
			Skewness	0.007	0.195	0.115	0.052
Smooth edge connected	5280	3950	Element quality	0.351	0.865	0.628	0.147
			Aspect ratio	1.416	4.148	2.228	0.589
			Skewness	0.007	0.737	0.327	0.248
smooth curve then diffuser connected	5880	4433	Element quality	0.808	0.998	0.944	0.04
			Aspect ratio	1.045	1.501	1.175	0.081
			Skewness	1.031	0.381	0.179	0.1
smooth curve connection with guide vanes	6094	4580	Element quality	0.225	0.999	0.948	0.092
			Aspect ratio	1.018	24.95	1.49	2.348
			Skewness	1.306*10^-10	0.798	0.121	0.129

CFD Simulation Results

Comparing four different dryer configurations based on the pressure drop and eddy formation on CFD simulation results



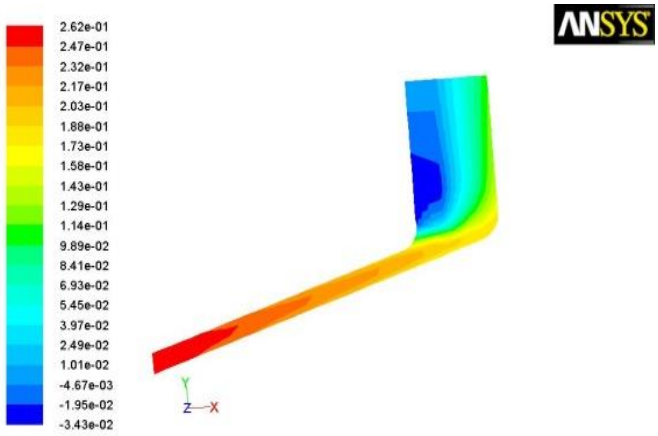
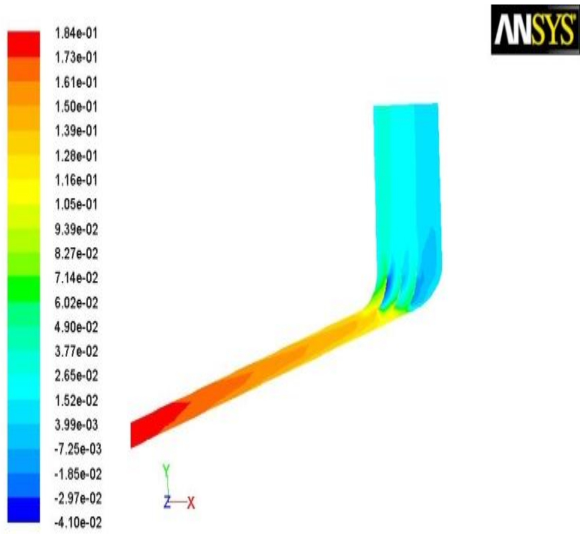


Fig.8.Pressure contour for sharp edge configuration

Fig.9. Pressure contour for smooth edge connected



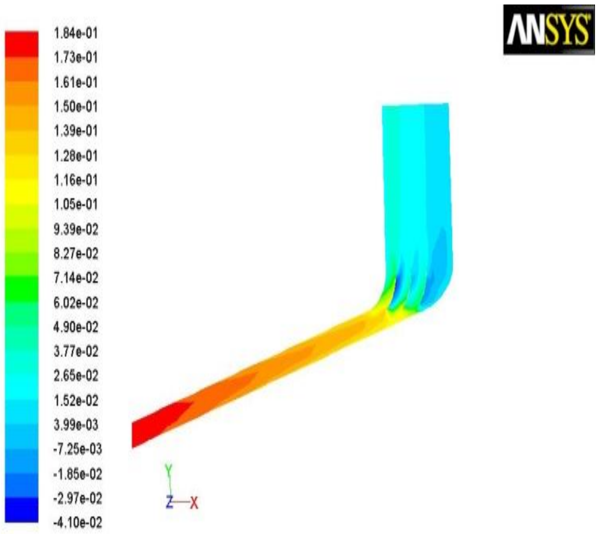
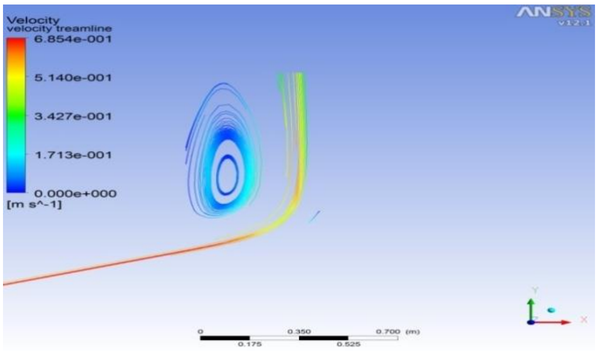


Fig.10. Pressure contour for smooth curve then diffuser connected

Fig.11. Pressure contour for smooth curve dryer configuration connected with guide vanes



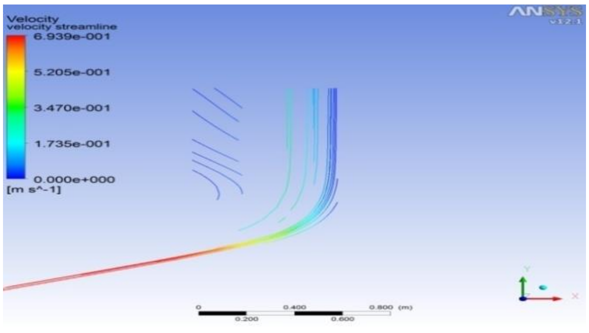


Fig.12 velocity stream line for sharp edge Connected configuration

Fig.13. Velocity streamline for smooth edge

CFD Simulation Setup and Simulation Results for Solar Collector

Computer simulations are a nice inexpensive way to verify the effectiveness of a design before prototyping it. During the design process of the solar dryer, several computational fluid dynamic (CFD) simulations will be performed to validate design decisions (Sarsavadia, 2007).The simulations were performed using ANSYSFLUENT, commonly used and commercially available CFD soft ware. It was used these simulations to find the design criteria necessary to get the most optimal uniform temperatures and air flow (the two most important parameters for dryer).

Inputs to Model:

Material properties
Dimensional solar dryer domain
Boundary conditions of design-temperature of incoming air and insulation properties of the walls

Outputs to Model:

Steady-state temperature
Flow field within input solar dryer design

Assumptions:

Input air temperature is constant
Absorber top and drying cabinet of the solar dryer are black bodies
Solar flux, amount of light incident on the collector, is assumed to be constant.

CFD Simulation Setup for Solar Collector

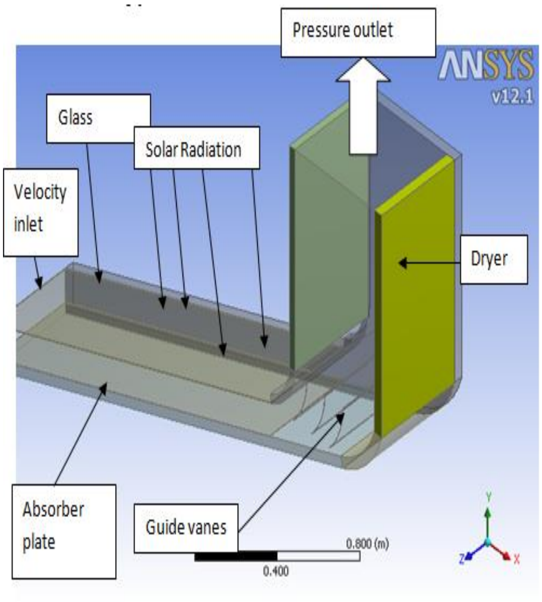


Fig 16 CFD simulation setup and Boundary Conditions

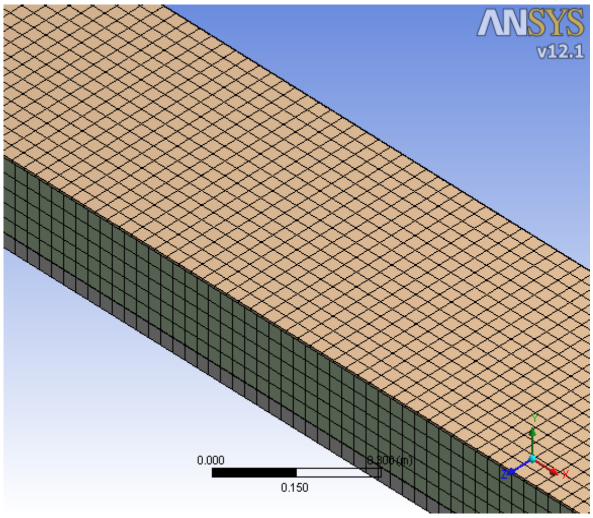


Fig. 17 The 3D computation grid used in computer simulation

Table 2: Mesh statics including geometry type, number of nodes, number elements& standard deviation for solar collector

Geometry type	No. Nodes	No. Elements	Mesh metrics	Minimum	Maximum	Average	Standard deviation
Solar collector	652152	587048	Element quality	0.939	0.999	0.975	0.017
			Aspect ratio	1.001	1.19	1.087	0.050
			Skewness	0.001	0.205	0.123	0.057

Table3: Specification of computer simulation model parameters

Parameter	**Value or description**
Solver type	pressure based/segregated
Computational domain type	axially symmetrical
Radiation model	Discrete ordinate (DO)
Hydraulic diameter (m)	0.095,0.182,0.222,0.261 and0.4
Multiphase flow model	Eulerian
Number of phases in the flow	2 (air, coffee bean)
Air density [kg/m3]	0.95
Air viscosity [kg/ms]	$1.87*10^{-5}$
coffee density [kg/m3]	683.6-1000
Grain diameter [mm]	7
Type of interaction between phases	Gidaspow's model
Bed height [m]	0.05
packing coefficient	0.4
Maximum packing coefficient	6.3
Energy equation	switched on
Turbulence model	κ-ε Standard, Standard Wall Function (SWF), Mixture
Inlet type	velocity inlet
Outlet type	pressure outlet
Outlet air pressure [Pa]	0 (relative to operational pressure)
Volume fraction of air in inlet and outlet streams	1
Volume fraction of grain in inlet and outlet streams	0

CFD Simulation Result for Solar Collector

The following tables shows simulated temperature rise of air and calculated values of useful power and drying time.

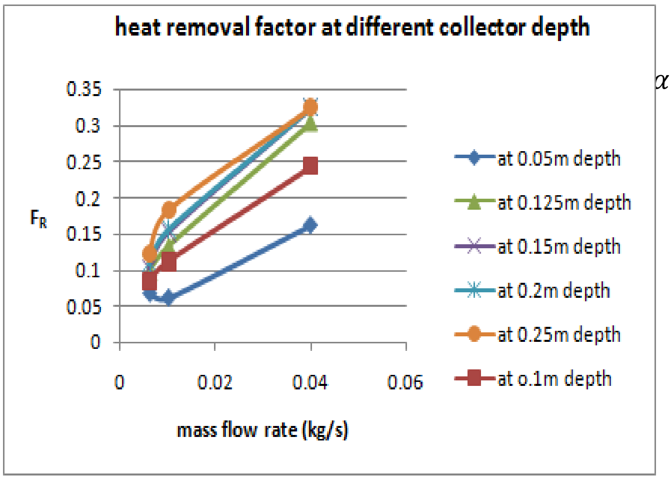
Table4: Simulated temperature rise of air& calculated values of useful power and drying time

Collector depth(m)	Mass flow rate(kg/s)	Temperature rise(^{0}C)	Useful power(w)	drying time(h)
0.05	0.006	11	66.66	105.2099
0.05	0.01	6	60.6	115.7309
0.05	0.04	4	161.6	43.3991
Collector depth(m)	Mass flow rate(kg/s)	Temperature rise(^{0}C)	Useful power(w)	drying time(h)
0.1	0.006	14	84.84	82.66495
0.1	0.01	11	111.1	63.12596
0.1	0.04	6	242.4	28.93273
Collector depth(m)	Mass flow rate(kg/s)	Temperature rise(^{0}C)	Useful power(w)	drying time(h)
0.125	0.006	16	96.96	72.33183
0.125	0.01	13	131.3	53.41428
0.125	0.04	7.5	303	23.14619
Collector depth(m)	Mass flow rate(kg/s)	Temperature rise(^{0}C)	Useful power(w)	drying time(h)
0.15	0.006	17	103.02	68.07702
0.15	0.01	15	151.5	46.29237
0.15	0.04	8	323.2	21.69955
Collector depth(m)	Mass flow rate(kg/s)	Temperature rise(^{0}C)	Useful power(w)	drying time(h)
0.2	0.006	18	109.08	64.29496
0.2	0.01	15.4	155.54	45.08997
0.2	0.04	8	323.2	21.69955
Collector depth(m)	Mass flow rate(kg/s)	Temperature rise(^{0}C)	Useful power(w)	drying time(h)
0.25	0.006	20	121.2	57.86533
0.25	0.01	18	181.8	38.57689
0.25	0.04	8	323.2	21.6995

By using simulated result, different collector parameters (like instantaneous collector efficiency, heat removal factor, etc) were determined.

Heat removal factor was calculated by using the following equation at different collector depth (assuming ambient temperature equal with fluid inlet temperature)

$$F_R = \frac{Q_u}{A_C I_t(\tau\alpha)} \quad (1)$$



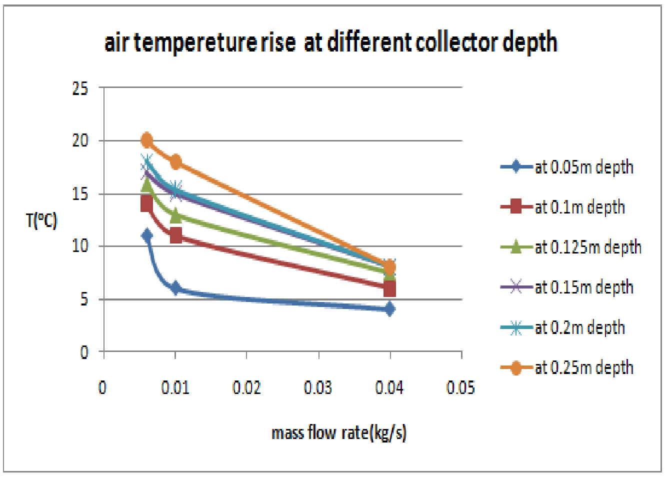


Fig.18. Temperature rise of air at different collector depth different collector depth

Fig.19.heat removal factor at at different collector depth

Instantaneous Collector efficiency was calculated by using following equation at different collector depth (assuming ambient temperature equal with fluid inlet temperature) (Bagheri, 2011).

$$\acute{\eta}_i = \frac{Q_u}{A_c I_t} = F_R(\tau\alpha) - \frac{F_R U_L (T_i - T_a)}{I_t} = \frac{m_a C_a (T_o - T_i)}{A_c I_t} \quad (3)$$

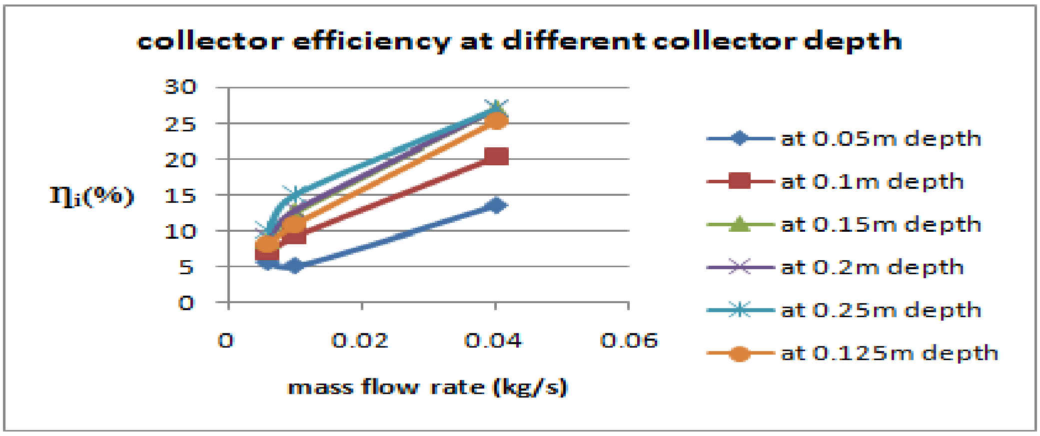


Fig.20.Collector efficiency at different collector depth

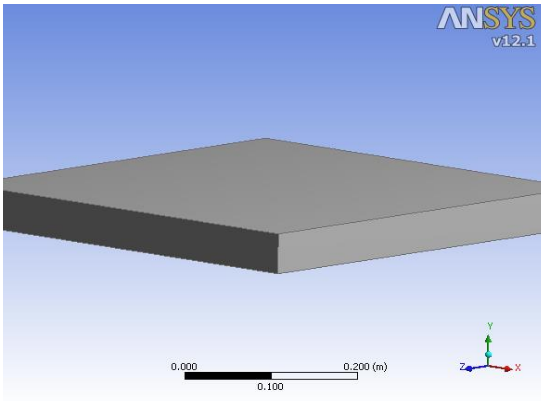


Fig.21 CFD simulation setup and Boundary conditions for fixed bed

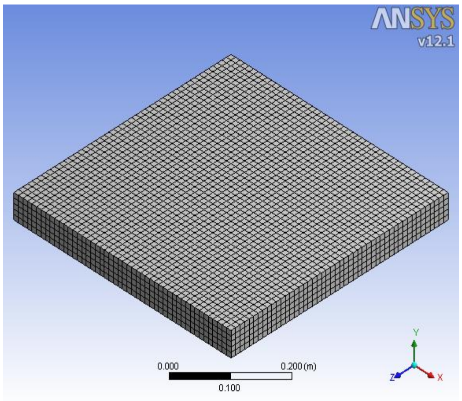


Fig.22.The computation grid used in computer for fixed bed

Table 5: Mesh statics including geometry type, number of nodes, number of elements & standard deviation for fixed bed.

Geometry type	No. Nodes	No. Elements	Mesh metrics	Minimum	Maximum	Average	Standard deviation
Solar collector	14406	11520	Element quality	0.939	0.999	0.975	0.017
			Aspect ratio	1.001	1.19	1.087	0.050
			Skewness	0.001	0.205	0.123	0.057

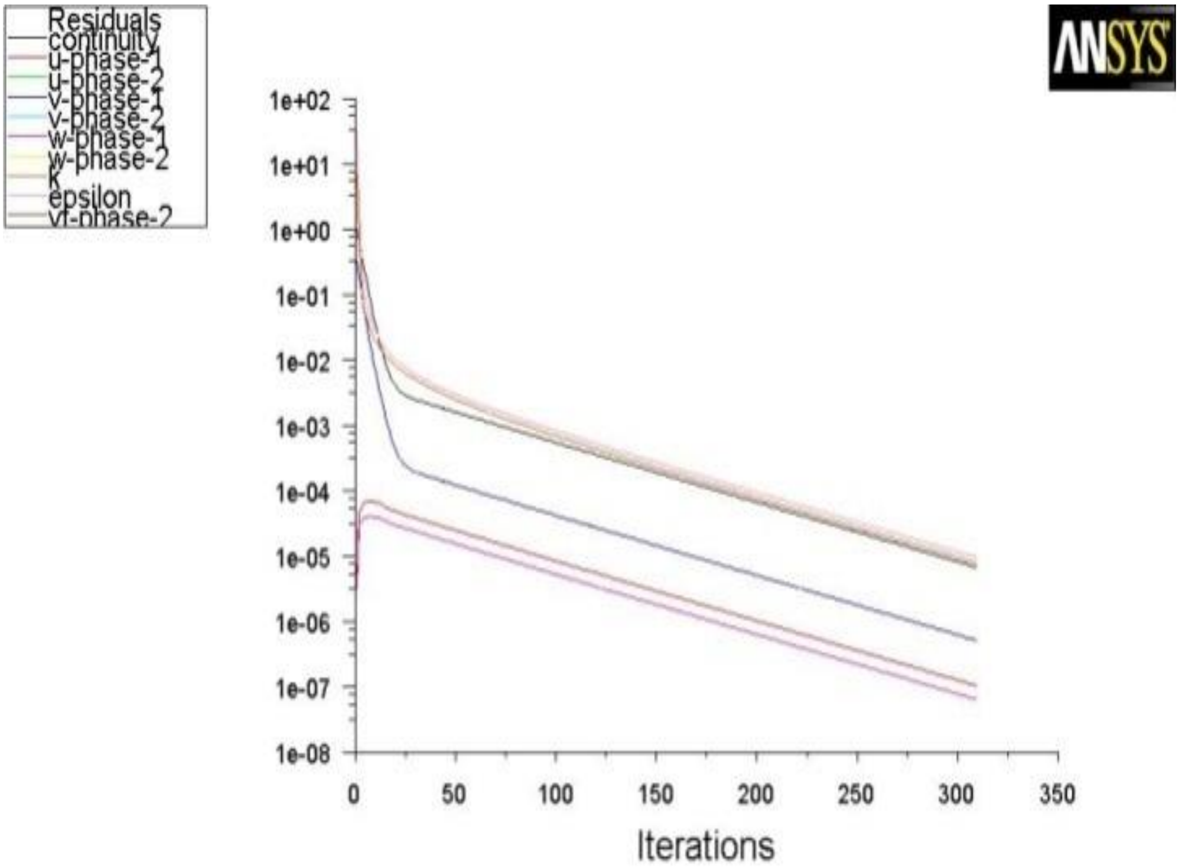
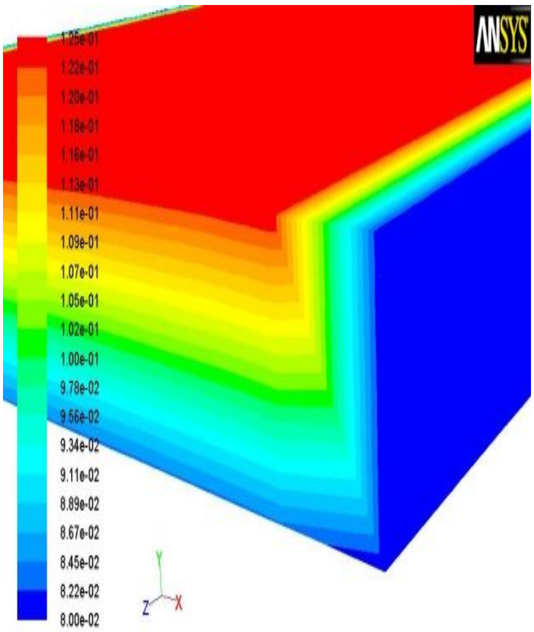


Fig.23. Convergence history residuals for fixed bed



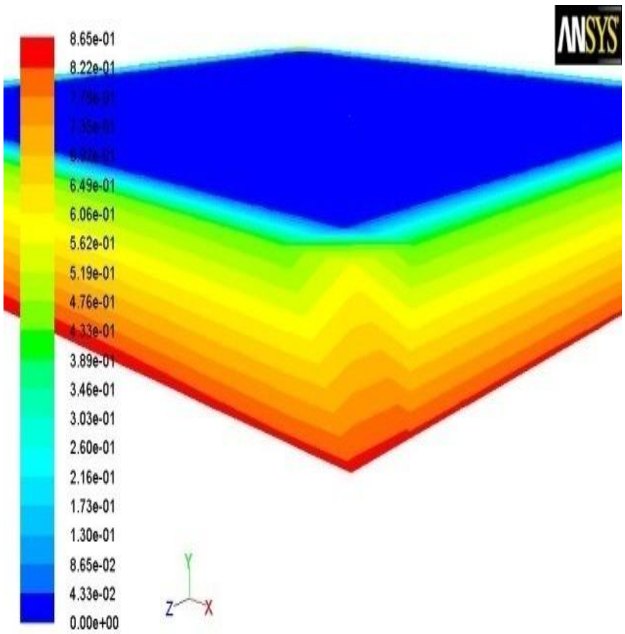


Fig.24. Velocity contour for fixed bed

Fig.25.Pressure contour for fixed bed

RESULTS AND DISCUSSION

Comparing sharp edge connected, smoothly, with diffuser and with guide-vane based on eddy or secondary flow formation qualitatively: Smooth curve connection with guide vanes configuration (Fig.11.& Fig.15) has very small eddy or secondary flow formation as compared to other remaining three(Fig.8.,Fig.9.& Fig.10) configuration types. Therefore, smooth curve connection with guide vanes is best among others (White, 2003).Comparing them based on pressure drop quantitatively: Smooth curve c onnection with guide vanes configuration has very small pressure drop than any other three dryer configurations as shown in Fig. below

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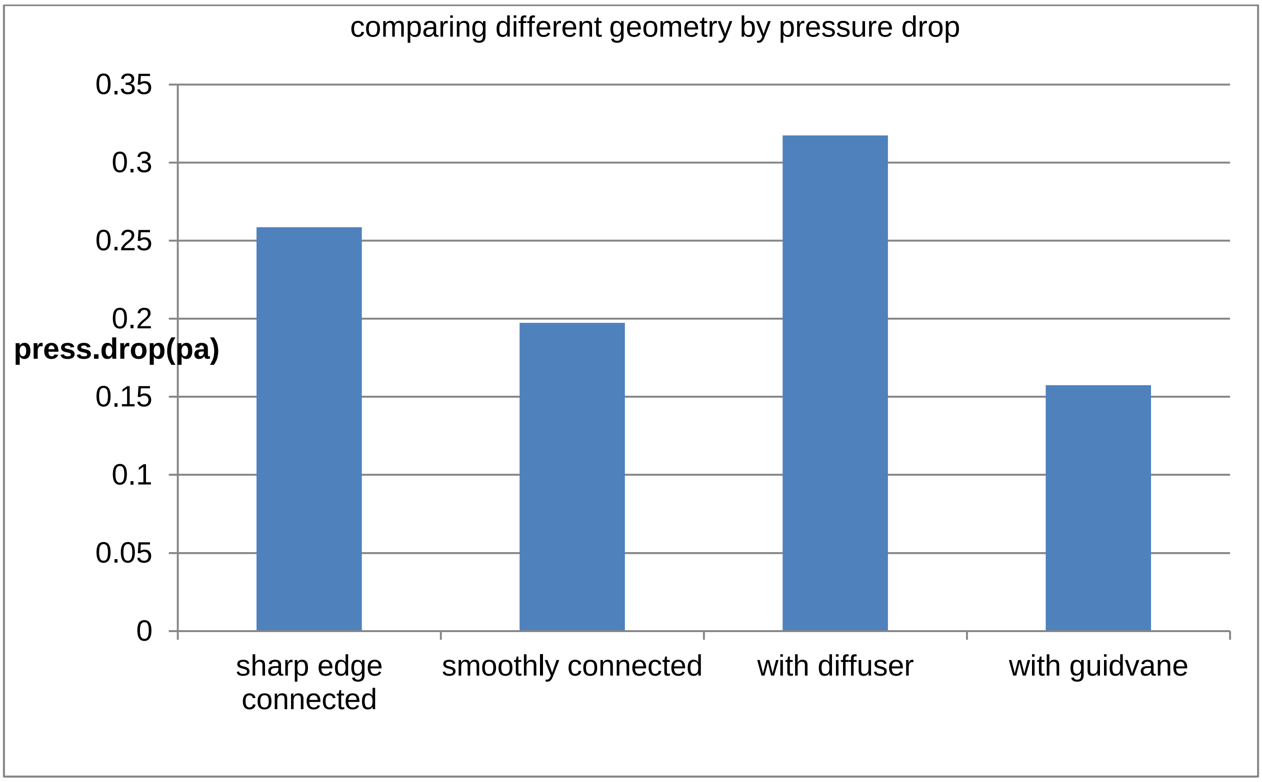


Fig.26. comparing different geometry by pressure drop

By velocity streamline comparing four dryer configurations qualitatively, velocity streamline for smooth curve connection with guide vanes (Fig.11. & Fig.15) is better than any other dryer configuration type. Velocity streamlines shows for both smooth edge connected dryer configuration and for smooth curve then diffuser connected dryer configuration have high recirculation flow in the one side of dryer cross-section. This recirculation flow makes non uniform drying rate for grain. For smooth edge connected dryer configuration, recirculation flow is small as compared to velocity streamline for sharp edge connected and velocity streamline for smooth curve then diffuser connected but as compared to velocity streamline for smooth curve connection, still there is flow disturbance.

Finally, comparing for dryer configuration based on pressure drop and air flow uniformity smooth curve connection with guide vanes better than any other three configuration type (smooth curve then diffuser connected dryer configuration, smooth edge connected dryer configuration and sharp edge connected configuration).

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

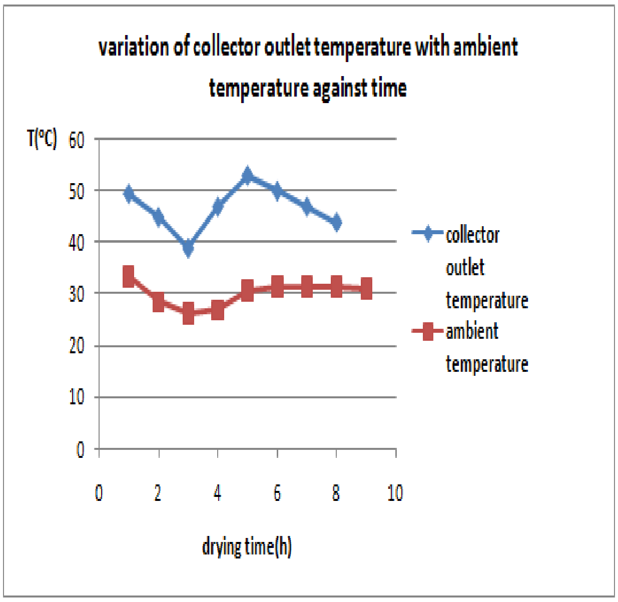


Fig. 27.Variation of Ambient and solar collector outlet temperatures against drying time for partial overcast day

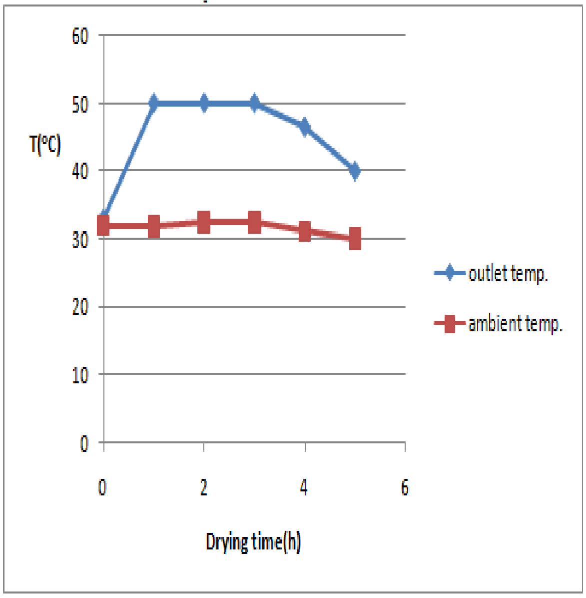


Fig. 28 Variation of ambient and solar collector Outlet temperatures during drying time for clear sunshine day

The variation of solar intensity and ambient relative humidity with 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 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.

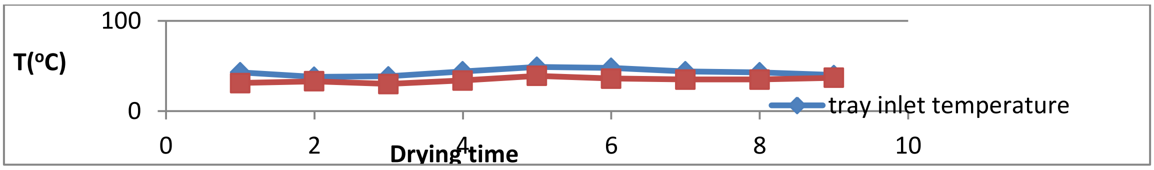
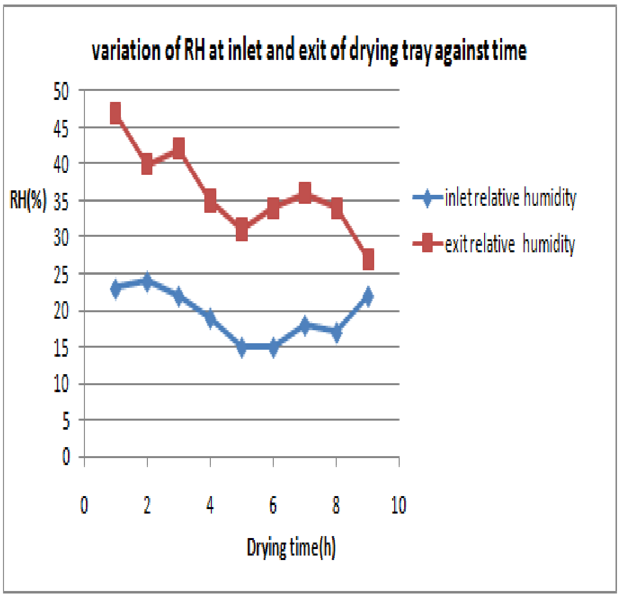


Fig.29.Variation of drying tray inlet temperature and tray outlet temperature during drying time for partial overcast day

The variation of relative humidity and humidity ratio of air at the drying tray inlet and exit with drying time is shown in Fig. 30. It is observed that the relative humidity and humidity ratio of the air at drying tray exit is higher during the initial stages of drying and gets decreased with drying time as drying proceeds. Maximum relative humidity at exit 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 exit 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.



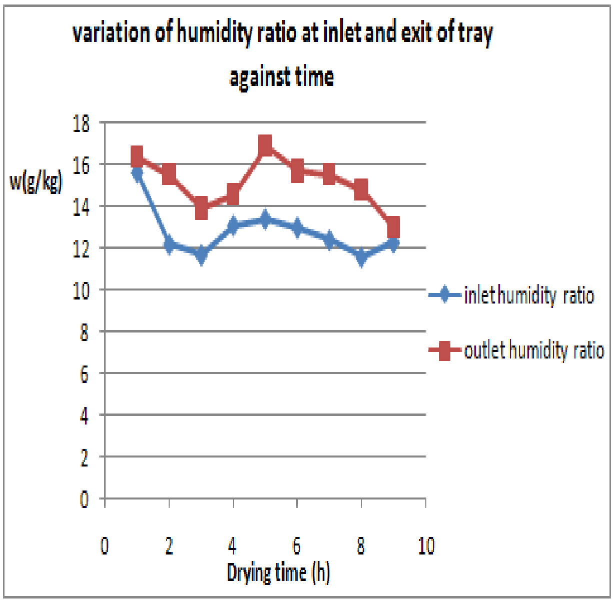


Fig.30. Variation of drying tray inlet relative humidity and humidity ratio and tray outlet relative humidity and humidity ratio during drying time for partial overcast day

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. 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.

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.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.

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 CFD simulation to predict the effect of different parameters on solar collector-dryer system thermal performance and pressure drop for flat plate collector has been conducted. It is found that increasing the mass flow rate through the air heaters results in higher efficiency but the pressure drop is also increased at fixed channel depth. Increasing the channel flow depth results in increasing the system efficiency and collector outlet temperature at the same time the pressure drop decreased for fixed mass flow rate of air.

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 57oC and 43oC 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 simulation of the drying process has 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. 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 using numerical simulation on ANSYS, 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 are recommended:

Further studies in the whole system optimization by using CFD including pressure drop, heat transfer and mass transfer without separating collector and dryer are needed. Further improvement to the system model to account for deeper coffee beds and bed shrinkage by using CFD is also mandatory.

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