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Analysis of Flat Plate Solar Air Collector in Different Convection Mode with Induced Turbulence

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***Abstract*— The most rustic application which could be used to exploit sun's free energy bombarded on earth annually which is 15000 (aboltins et al. 2009) [1] times more than the whole world's industrial energy requirement is the solar air heater to pre-heat air for further drying, heating, lithe delicate parts and many more purposes. The solar air heaters performance rely on collector's material, absorber and its orientation in the collector, air velocity in the collector (Lauva et al. 2006; Palabinskis et al. 2008) [2], passage given to air flow as single pass or double pass air flow or multi-pass flow (Forson, Nazha, and Rajakaruna. 2003) [3] and weather conditions. The study ponders over the various design parameters considered while designing the experimental set-up along with the effects of these parameters on performance of solar air collector. Two different convection modes were analyzed namely; Natural mode and Forced convection mode to contemplate over the heat transfer coefficient associated with each case. Double glass as top cover is used to minimize losses pertaining to radiation. To reduce shading losses glass is used to make air flow through multi passes. CFD modelling is applied to predict the temperature pattern of air with radiation model DTRM (Discrete Transfer Radiation Model) and turbulence model. The setup works at an atmospheric pressure of 1.013N/m2. The modelling gives good results when compared experimentally with natural convection mode. The temperature characteristics of air are plotted comparing it with both the convection modes. Artificial roughening of absorber unit is crucial to increasing heat transfer rates to air (Anil Singh Yadav et al. 2014) [4] and is done in the passages taken by air. Twisted wires is used which would set the air in the vicinity into circular motion analogous to swirling of fuel in internal combustion engines. It has been found that number of passages increases residence time of air and heat transfer to air, although increases pressure loss. The shading losses are compensated with glass partitions. Peak efficiencies are achieved on a sunny day from 12 noon to 2 pm.**

Keywords—Solar collector; Double glass cover; Turbulence; CFD; Solar drying

I. INTRODUCTION

Most basic Form of application of sun is the of Solar Air Heating collector because of its simplicity in construction, Eco-Friendly, Wide usage particularly in Grain Drying Field. Radiations from sun in form of heat are accumulated and the heat is transferred to the fluid (water/Air). Solar collectors may be Active or Passive solar heating Systems. The most economic, environment friendly use of such rustic device is the drying of spices, fruits, vegetables, and crops to preserve them for longer period of time. The moisture content retained by a crop, fruit or vegetable plays a crucial role in deciding the time before it starts to addle. Solar collectors are easy to use and easy to construct and could be made of any size corresponding to the amount of crops, fruits or vegetables to be dried. The size of solar air heater bears direct relation with the mass flow of air required at collector exit at specific temperature. The Major categorization of solar collector are the single pass with Front and back duct and the Double pass Double duct.

- Flat plate collectors with temperature of fluid not rising above 80 $^{\circ}$ C.
- Concentrating collectors with temperature of fluid going above 140 $^{\circ}$ C.

Rhushi Prasad, Byregowda and Gangavati (2010) [5] categorized collectors as:-

- Hydronic collector – Water as working fluid.
- Air collectors – Air as working fluid.

The conventional air heaters comprises of opaque Black Board (Dull) color painted absorber plate, Glass cover, Air duct, Bottom plate and Insulation. They are simple to construct and many times the absorber plate may be of irregular shape to increase heat transfer to air. The major cons to solar air heaters are the copious amount of air to be dealt with leading to significant power consumptions if pressure drop is not monitored. Cost associated increases profusely upon selection material of absorber plate.

Solar Flat Plate collector depends upon these factors as per Palabinkskis et al:-

- Absorber material of plate.
- Air velocity in collector.
- Thermo-Hydraulic efficiency. [6]
- Roughness/turbulence introduced with aid of external body.
- Air Temperature growth further depends upon (Wind, Clouds, Ambient air temperature etc.

Novel designs improves solar collector efficiency because of they entertain large flow contrary to less drop in pressure. Usually the absorbing surface is porous. Pressure drop is less if flow is maintained uniform. In some cases it has been found that pressure loss is 200 times [7] less than conventional air heaters leading to huge savings in power consumption.

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The solar radiation is incidented on porous absorber through which air flows thus providing large area to air flow thereby increasing heat transfer to air.

II. CFD MODELING OF SOLAR AIR COLLECTOR

A. Introduction of CFD Modeling

Computational fluid dynamics was used to predict the air flow over the absorber plate. Air behavior was predicted on both natural and forced convection modes of air. Results obtained from CFD are compared with experimental analysis. The pressure inside solar air heater was kept atmospheric pressure with gravity [8] assistance in upward direction positive so as to assist flow of air inside solar air heater.

B. Model preparation

CFD model comprises of various steps assembled together and then applied on the boundary conditions to simulate the behavior of air. The following steps were taken to make a model in CFD model:-

- Geometry preparation
- Meshing of model
- Models to predict flow
- Materials defining components
- Cell zone conditions
- Boundary conditions.

C. Geometry Preparation

Inlet cover - The inlet cover is the part from which air enters the set-up. Usually the temperature of air is simpatico with ambient temperature unless heated externally before entry. The cover is sometimes artificially roughened to enhance the turbulence right from the very starting of air's embarking journey.

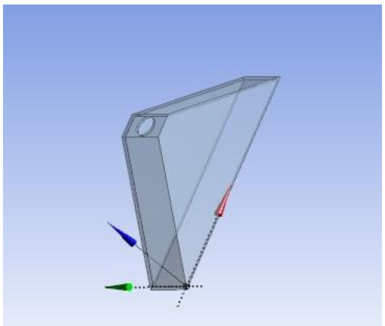

Fig.1 Inlet/Outlet covers of model solar air heater.

Bottom plate - Bottom plate is made of glazed iron sheet. Convection occurs on this section of the plate. Conduction losses are minimized with expanded polystyrene sheet. Insulation is filled all over the plate:

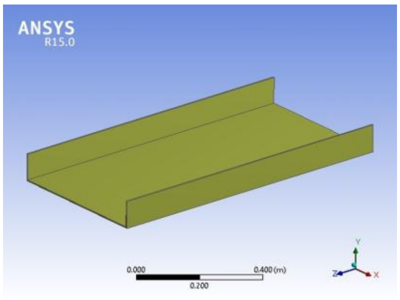

Fig.2 Absorber plate of collector.

Glass cover - Glass cover on top reduces the losses by radiation by not allowing long wavelength radiation through the mirror. Toughened or simple mirror could be used for the purpose. Mirror with transmissivity of 98% is used. Two glass covers are used to curb the conduction losses as well.

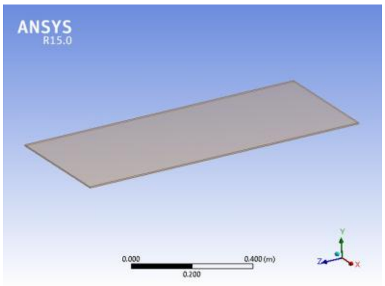

Fig.3 Double glass covers of solar air heater.

Solar air heater model in CFD (ANSYS 15.01) –

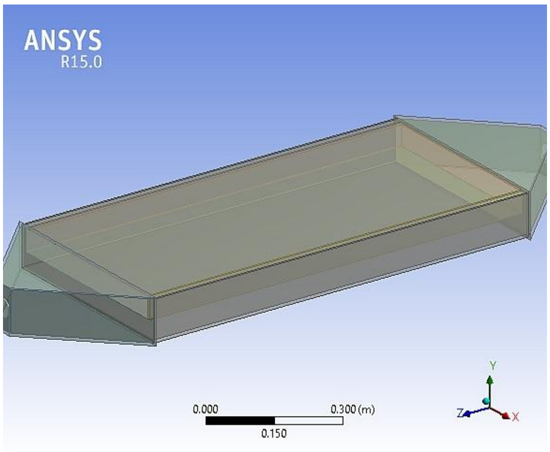

Fig.4 Solar air flat plate collector.

The model comprises of parts mentioned earlier. Air enters the inlet cover and flows over absorber plate with black colored dull paint deposited over it. Absorber plate delivers heat to the air. The behavior of air is predicted with various fluid prediction modals. Heated air leaves the set-up from outlet cover which could be used for various other purposes.

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Dimensions of the geometry –

Table.1 Dimensions of geometry.

Part	Length (mm)	Breadth (mm)	Height (mm)	Thickness (mm)
Glazed sheet	1000	500	100	5
Insulation	1000	490	95	15 & 50
Absorber plate	1000	450	0.5	0.5
Iron sheet	1000	5	45	5
Glass cover	1000	450	5	5
Inlet/Outlet cover	250	510	110	5

D. Results of Modeling

Temperature profiles of air with different parameters. The Reynold number corresponding to velocity and inlet area of duct leads to turbulent flow therefore turbulent models were used to predict the flow pattern of air over absorber plate.

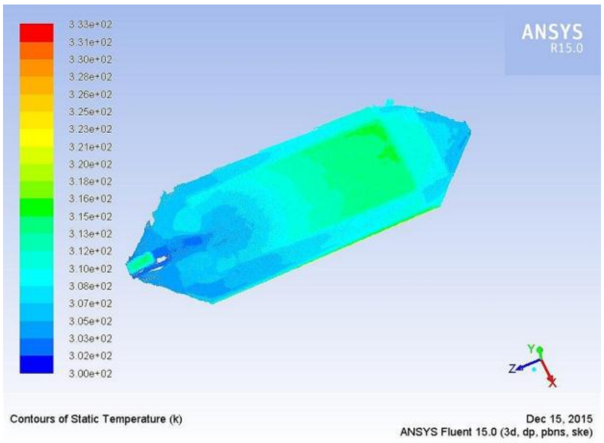

Fig.5 Temperature profile of air with velocity 3 m/s with constant heat flux.

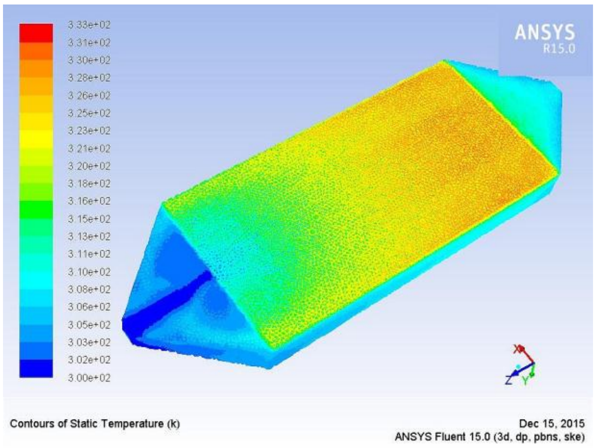

Fig.6 Temperature profile of air with air velocity 3 m/s and Solar ray tracing on corresponding to 18/06/2016.

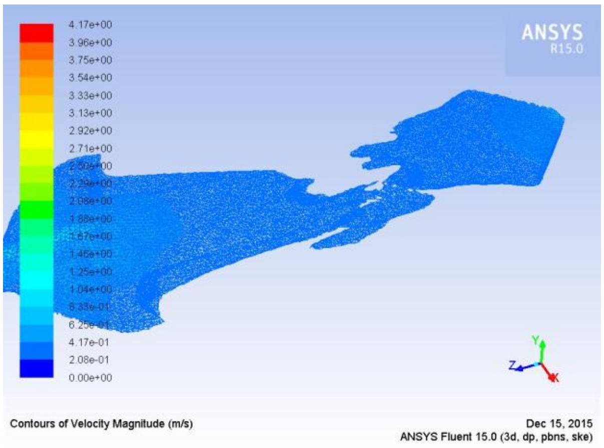

Fig.7 Velocity distribution over the absorber plate of air.

Findings from CFD modeling –

- Discrete Transfer Solar Radiation model gives robust predictions on the temperature variation of the air inside Solar Air flat plate Collector.
- Corrugation is given on the Absorber plate so as to increase the air molecules turbulence; k-έ model predicts the Air motion with moderate tolerance.
- Solar ray tracing when is included gives commendable depiction of the temperature profile followed by inside solar air heater.

III. FABRICATION OF SOLAR AIR COLLECTOR

A. Description of Solar air collector

The sole purpose of this experimental was to setup an efficient solar air heater. The solar air heater is used to dry spices , vegetables, fruits, and many more other objects which need moisture control to avoid addling. The solar air heater is 1m in length and is 1m wide. The absorbing area of the air heater is 1.1177m^2. Solar air heater is constructed at Thapar University in Patiala, India (30.3568° N latitude, 76.3688° E longitude). The top of the air heater is covered with double glass cover to minimize the radiation losses. The bottom covering of the solar air heater is insulated with expanded polystyrene sheets of 25mm thickness to minimize conduction as well convection losses. The absorbing section of the air heater is made of stainless steel (204 grades) and is painted with dull black board color to increase its absorptivity. Higher the absorptivity, higher will be the temperature of the plate and higher will be the heat flow from absorbing plate to the working fluid (Air). First, the materials are procured for making the solar air heater. The frame of the solar heater which takes the weight of the device is made from iron angles of 0.75inch width and 32 feet in length. The frame is made and the stainless steel sheet after bending it in mechanical press is moved in the frame. The absorbing plate and glass cover rests on the iron frame. Glazed iron sheets are used to make the bottom plate of the solar air heater and its side walls and solar heaters inlet as well outlet section. Glazed sheet of 12*8 feet size was used as per design considerations. The glasses used at top have transmissivity of 0.95. Two glasses have a gap of 5 mm in between them to curb the conduction losses by top glass cover. The stand which is inclined as per inclination

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angle specific to place is made from iron angles of 0.75inch width to cope-up with the weight of the setup.

Fig.8 Solar air collector with multi-pass arrangement made from transparent glass.

B. Preparation of various parts of solar air collector

Ducts of collector - Inlet cover of the solar air heater. It allows air inside the experimental setup. It is cut out from glazed iron sheets. The thickness of the sheet is enough to support the weight of the whole cover hence no support is given to inlet and outlet cover of solar sir heater.

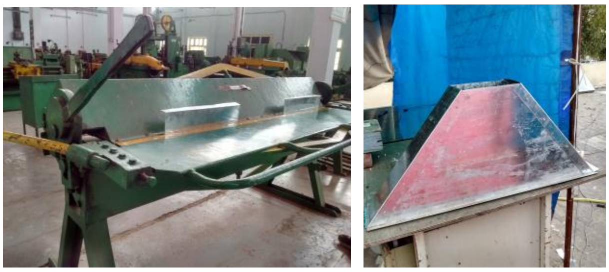

Fig.9 Inlet/Outlet covers of solar air collector.

Insulation of solar air collector - The bottom plate of the solar air heater is filled with insulating material; EP sheet to minimize the conduction losses.

Fig.10 Insulation of the solar air collector.

Variable speed fan –

Fan is a 12V powered DC fan whose RPM can be controlled by connecting it with a rotary switch containing different ohm resistors to manipulate speed as per requirement. The fan speed could go from 0.8 to 5 m/s.

Fig.11 Variable speed 12V DC Fan.

Multi-Pass arrangement –

The multi-passing is done with mirrors only. Multi-passing with metal sheet is avoided as it introduces shading on the metal absorber plate which affects the performance of the solar air heater. The glass strips allow all sun rays to hit the absorber plate and does not introduces shading on the absorber plate. Air contact with metal sheet is sacrificed in order to curb the shading losses.

Fig.12 Multi-Pass arrangement of solar air collector.

C. Instrumentation and Measurement

Temperature readings were taken with 9 pt-100 temperature sensors accurate with range of $\pm$ 0.5 °C. The radiation intensity is measured with pyranometer. The thermocouples could determine temperature from -50 °C to 200 °C with ease and minimum error. The thermocouples are placed on absorber sheet and 5 are hung in air by attaching them with mirror placed on absorber section.

Distance between the thermocouples is equal on the absorber plate while the thermocouples which are hung in air are placed at irregular distances corresponding to the channels made on the absorber plate.

Pyranometer - The intensity of solar radiations is measured with the help of Pyranometer. Pyranometer measures the direct solar beam and diffused radiations coming from the sun. This pyranometer takes the reading after every 10minutes and data logger is attached which is further connected to the computer to log the values of solar intensity. The pyranometer by Kipp & Zonen (CMP 11) is used with operational irradiance 4000 W/m^2. Operating and storage temperature range 40 °C to + 80 °C and Sensitivity7 to 14µV/W/m^2.

Temperature Sensing Board –
The board is compatible with the p-type thermocouples. The maximum capacity of thermocouples which can be installed in it is 10. The resistance offered is less as found from thermocouples calibration thus the actual temperature result is not much affected.

Velocity measurement –
Velocity meter was used to gauze the velocity of the variable speed fan. Accurate up to ± 0.3m/s. The fan is made to rotate just next variable speed fan rpm's converted to linear speed of air is displayed on the screen of the instrument.

D. Equations used
Calculations were done to estimate the solar irradiation absorbed by the solar air collector corresponding to the mass flow rate inside the collector. Energy absorbed by collector is useful energy and Energy consumed by fan for propelling air inside collector is energy squandered thus effective efficiency is major concern while designing solar air collector.

The angle of refraction, as the sun rays passes through air to glass cover, is calculated by Snell' law as:

$$qrf1 = \sin^{-1}\left[(2/3)\sin\theta_i\right] \quad (1)$$

Where θ_i is angle of refraction.

The incidence angle is equal to zenith angle which is evaluated as:

$$\theta_z = \cos^{-1}\left[\cos(\delta_d)\cos(\varphi)\cos(\theta_h) + \sin(\delta_d)\sin(\varphi)\right] \quad (2)$$

Where δ_d is declination angle, φ is latitude angle, θ_h is hour angle.

Declination angle is defined as (n is day of the year) :

$$\delta_d = 23.45\left(\frac{360(284+n)}{360.25}\right) \quad (3)$$

Hour angle as: $$\theta_h = \left(\frac{(h-12)}{15}\right) \quad (4)$$

Quseful= m.cp.(T_o - T_{in}) where T_o is air temperature at exit and T_{in} is inlet temperature of air.

The value of heat transfer coefficient (h) be increased by active and passive improving techniques. It is represented in non-dimensional form of Nusselt number (Nu). Where

$$\overline{Nu} = \left(\frac{hl}{k}\right) \quad (5)$$

Hydraulic performance = Hydraulic performance of solar air heater concerns pressure drop (ΔP) in duct of solar air heater. Pressure drop accounts energy consumption by blower to propel air through duct. Pressure drop can be represented in a non-dimensional form using following relationship of fanning friction factor (f). $$f = \left(\frac{\Delta P.D}{2.L.v^2}\right) \quad (6)$$

Effective efficiency = $$n_{eff} = \left(q_u - \frac{P_m}{C}\right)/I_b.A_b \quad (7)$$

P_m is the mechanical power consumed by Fan.

The value of C is conversion efficiency taken as 0.34 defined as:

C= η_{th} (34%) (Thermal power plant efficiency) .η_{tr} (90%) (Transmission eff) .η_m (90%) (Motor eff) .η_p (75%) (Pump eff)

Instantaneous efficiency = $$\left(\frac{m.cp.\Delta T}{I_b.A_b}\right) \quad (8)$$

Where $m.cp.\Delta T$ = Q_{useful} = q_u (9)

And $I_b.A_b$ is the irradiation (Absorber area of collector 1.1177m^2 and irradiation observed with pyranometer).

IV.RESULTS AND DISCUSSIONS

Experiments were performed on solar air heater and temperature readings were recorded with RTD (Resistance Temperature Detector) Pt-100 sensors. Temperature profiles were recorded on natural convection mode, forced convection mode, natural convection multi-pass mode, forced convection multi-pass mode and forced convection induced turbulence mode. The data were taken in month of May and June because of less incidence angle of irradiation.

Performance analysis in case with natural convection of air
Air in the solar air heater under natural convection mode has been analysed under 9 different spots. The temperature profile is plotted and efficiency of the solar air heater is plotted. Max efficiency is seen during peak irradiation hours; 12 NOON to 3 PM. Mass flow rate inside the collector depends upon the temperature of air inside the solar air collector as higher the temperature higher will be the suction rate of air from inlet duct. Fig.16 gives the collector efficiency pertaining to natural convection without multi-pass data collected on 14/05/2016 and Natural convection with multi-pass on 5/06/2016.

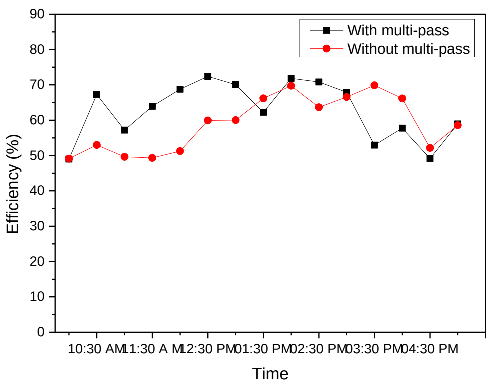

Fig.13 Solar air collector performance comparison with and without multi-pass in natural convection mode.

Performance analysis in case with forced convection of air
Under forced convection with different mass flow rate of 36.144 kg/hr and 72.188 kg/hr with multi-pass of air over absorber plate and comparison of collector efficiency and thermo-hydraulic efficiency is made in Fig.17. The Mechanical power consumed by fan is 1.2 and 2 Watts

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respectively. Experiments were performed on 08/06/2016 and 10/06/2016. Blue lines correspond to data collected on 10/06/2016 and Red lines correspond to data collected on 08/06/2016.

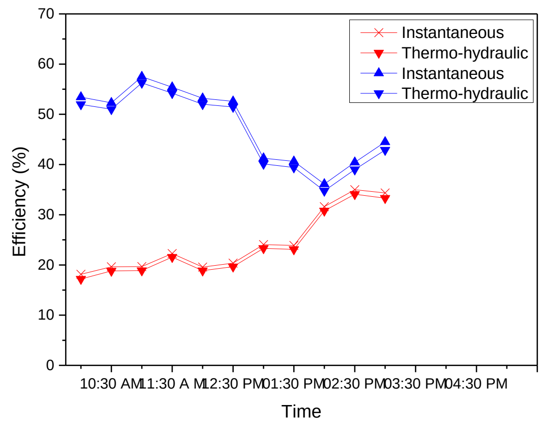

Fig.14 Comparison of collector efficiency and thermos-hydraulic efficiency under forced convection of air with mass flow rate of 36.144 and 72.288 kg/hr respectively.

Performance analysis in case with forced convection and induced turbulence with coiled wires

The performance of solar air collector with mass flow rate of 36.144 and 72.288 kg/hr is monitored when the air is given turbulence while flowing over the absorber plate to increase the heat transfer rate to the air from absorber. Fig.18 represents the performance of the collector with turbulence on and Fig.19 compares the collector performance with and without turbulence. Blue line links to 72.288 kg/hr and Red lines corresponds to 36.144 kg/hr mass flow rate of air.

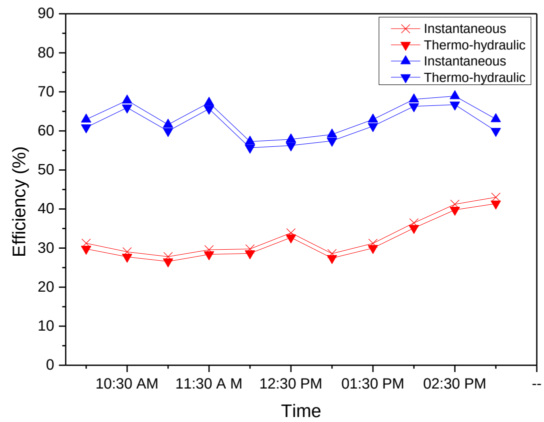

Fig.15 Comparison of solar air collector under forced convection and with induced turbulence mode.

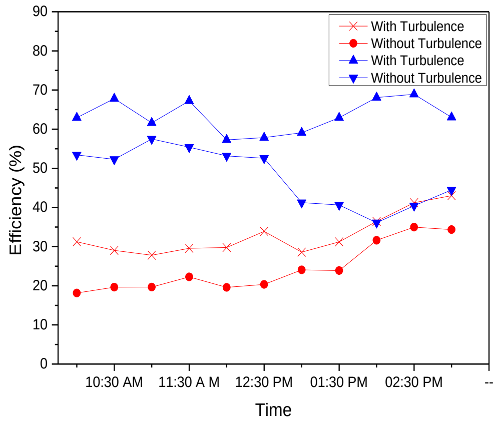

Fig.16 Comparison of solar air collector with and without turbulence under forced convection of air.

This study analysis the solar air heater performance under various configurations. Natural convection yields maximum rise in air temperature but sacrifices on the mass flow rate of air which is not beneficial to drying industry processes. The air flow rate under the influence of turbulence yields better balance [10] between temperature rise in air and mass flow rate of air. Thermo-hydraulic efficiency is major concern in case of artificially induced turbulence configuration of solar air heater. Performance of solar air collector depends upon mercy of weather conditions. CFD modeling was done with clear sky model under fair weather conditions. Power consumed by DC motor fan is compensated under mathematical analysis from Heat energy absorbed by absorber plate to accentuate the thermos-hydraulic performance of solar air heaters making it a very cardinal parameter in selection criteria of solar air flat plate collectors.

CONCLUSIONS

Solar energy is readily available and has the latent potential to provide many times the energy consumed by industry worldwide. In this report the analysis of solar air collector which was fabricated in Thapar University, Patiala, Punjab, India is represented. Solar air heater was studied under Natural with and without Multi-Pass arrangement and Forced convection with and without turbulence mode.

The performance of solar air heater in Natural mode yielded maximum efficiency of 69.879 % whereas in case of Natural convection mode but with multi-pass arrangement made with glass yielded maximum efficiency of 72.422 %.

Performance under forced convection with turbulence yielded maximum efficiency of 66.712 % and without turbulence yielded efficiency of 56.26 %. It was observed that under artificial turbulence induced by coiled wired placed on absorber plate gives better results in terms of air temperature rise and efficiency which is decisive in solar drying processes.

Collector has been made as per opinions of research faculty assistance to analyze the performance aspects under forced and natural convection with and without multi-pass and with and without turbulence induced inside solar air collector. Meanwhile, for the first time transparent glass has been used to make multi-pass arrangement which losses on the area of contact available to air but gains the edge over shading losses on absorber plate. However, much more research is needed in

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the proposed collector to depict more advantageous parameters corresponding to the configuration used in this collector. Turbulence induced could be made with help of twisted glass partitions in order to reduce the losses arising because of high friction offered by metal contact with air.

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