CFD ANALYSIS OF HEAT TRANSFER AND FLUID FLOW IN FLAT PLATE NATURAL CONVECTION SOLAR AIR HEATER

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Abstract

A parametric study of flat plate natural convection solar air heater was conducted using CFD Analysis. A solar air heater with single glass cover flat plate solar collector with air gap is selected for the study under the climatic condition of Addis Ababa, Ethiopia. The study aims at finding optimum inclination angles taking into account the seasonal variation, finding optimum air gap depth, and characterizing the effect of incident radiation magnitude and ambient temperature on the collector output. For modeling the system, the governing continuity, momentum and energy equations were considered in multi dimensions. The coupled governing equations were simplified by neglecting effect of density in the continuity equation and by approximating the density difference in momentum equation as a linear function of temperature. The modeling was conducted by the CFD Software Fluent. By varying the inclination angle, it was found that the optimum inclination angle that gives maximum energy gain with better mass flow rate and temperature rise was 45^0 for November while it was 15^0 for May. The two angles of inclinations represent the two extreme seasons of the year. It was also found that a collector with 50mm channel depth yields better exit velocity and temperature and maximum energy gain but comparable with 60 mm and 70mm depth for 2 m long collector. The outputs of the simulation are comparable with the already available reported experimental results found in literatures.

1. Introduction

It is apparent that solar energy has got two major advantages over fossil fuels. The first is in the fact that it is renewable and the second is it does not emit green house gases and any other pollutants to the environment.

Solar heating of outdoor air is considered as cost effective alternative to meet process heat demand of drying (Duffie, and Beckman, 1991) This paper focuses on parametric study of natural convection flat plate solar air heater. Natural convection flat plate solar air heater is a heater where by the flow of air through the rectangular air channel is derived by the buoyancy force, which in turn comes from the temperature difference between the heated absorber plate and the ambient temperature. Even though the main problem of such heater is the low induced mass flow rate, it has got acceptance in the application of small scale food drying. Moreover, the maintenance requirement and operating cost of the collector is almost nil as there are no moving mechanical devices such as a fan. In this heater, the flow rate and collector outlet temperature are dependent on different parameters such as inclination angle, air gap, incident radiation flux, material properties, absorber type and others.

The objective of this work is to find optimum inclination angles taking into account the seasonal variation, find optimum air gap depths, and study the effect of the magnitude of incident radiation and ambient temperature on collector output.

Several works have been done and published on solar air heaters with little emphasis on multidimensional computational analysis of natural convection solar air heaters (Varun and Siddhartha, 2010; Varun et al. 2009; Pakdaman et al., 2011; Tiris et al., 1994; Choudhury et al, 1985; Macedo, 1978). Most of the works focus on either experimental investigation of specific type of solar air heater or dyer or optimization of forced convection air heater using one dimensional model and optimization algorithm. Gao et al. (2001) studied using computational model natural convection between sine wave absorber and glass cover and determined the convective heat transfer coefficient by varying temperature difference between the absorber and glass cover for different geometric configurations. The rare literature that reports optimum channel depth (air gap) for maximizing heat transfer of a natural convection solar air heater is that of Bansal et. al. (1999). The near optimum duct depths of 50-75mm were recommended for maximum solar energy collection for air heater of about 1m length.

An optimization of a fixed collector tilt angles, with respect to maximum amount of total isolation on south facing collector surface has been done by several researchers (Kern and Harris, 1974; Manes, and Lanetz, 1983; Pericle and Koronakis,1986) for different places. Kern and Harris (1974) recommended that for small installation, the very simple relationship that the tilt should be equal to the latitude holds. Although, it may deviate from the latitude up to $\pm 15^{0}$ without significant loss in total solar gain (Soponronnarit,1 995). However information regarding collector tilt angle optimization for natural convection solar air heaters is not available in literatures. For such heaters, not only the radiation incident on the absorber and exit air temperature are dependent on inclination angle, but also the flow rate that is induced by buoyancy effect.

Although the effect of turbulence as the fluid passes through the channel is important, In case of natural convection through a channel, for with heated surface facing downwards, the flow remains laminar throughout (Bansal et. al. 1999), which is the case of the present study.

2. Mathematical Model

The heat transfer and air flow in solar air heater is described by flow and energy equations. The general basic governing equations in 3D for natural convection problem are:

Continuity equation:

$$\frac{\partial \rho}{\partial t}+\nabla \cdot (\rho \vec{v})=0 \qquad \text{(eqn. 1)}$$

Naiver Stokes equations:

$$\frac{\partial}{\partial t}(\rho \vec{v})+(\vec{v}\cdot\nabla)\rho\vec{v}=-\nabla p+\mu\nabla^{2}\vec{v}+\frac{\mu}{3}\nabla(\nabla\cdot\vec{v})+\rho\,\bar{\vec{g}} \qquad \text{(eqn. 2)}$$

Energy equation:

$$\frac{\partial}{\partial t}(\rho E)+\nabla\cdot(\rho E+p)\vec{v}=\nabla\cdot k_{eff}\nabla T+S_{h} \qquad \text{(eqn. 3)}$$

S_h in the energy equation also includes radiation source terms.

The radiative transfer equation for an absorbing, emitting, and scattering medium at position $\vec{r}$ in the direction $\vec{s}$ using the Discrete Ordinate method is given as

$$\nabla\cdot\left(\left(\vec{r},\vec{s}\right)\vec{s}\right)+\left(a+\sigma_{s}\right)I\left(\vec{r},\vec{s}\right)=an^{2}\frac{\sigma T^{4}}{\pi}+\frac{\sigma_{s}}{4\pi}\int_{0}^{4\pi}I(\vec{r},\vec{s}\,')\,\Phi(\vec{s}\cdot\vec{s}\,')\,d\Omega' \qquad \text{(eqn. 4)}$$

In case of the natural convection, it is the variation of density (ρ) that gives rise to the flow. The temperature field is dependent on the flow and all the above equation are coupled through the variation of density(ρ).The

Boussinesq approximation simplifies the coupled governing equations with the following two important conclusions.

- The effect density variation in the continuity equations may be neglected.
- The density difference, which causes the flow due to an interaction between the gravitational body force and the hydrostatic pressure gradient, can be approximated as a linear function of temperature.

The instantaneous thermal efficiency of the collector is

$$\eta_{th,i} = \frac{\dot{Q}_u}{A_a I} \qquad \text{(eqn. 5)}$$

Where the useful net energy gain by the air is defined as

$$\dot{Q}_u = c_p \dot{m} (T_e - T_i) \qquad \text{(eqn.6)}$$

The cumulative efficiency of the collector can be expressed as:

$$\eta_{th,c} = \frac{\int_0^t \dot{Q}_u \, dt}{A_a \int_0^t I \, dt} \qquad \text{(eqn.7)}$$

3. Computational Model

FLUENT uses finite volume method for the discretization of the governing equations. Finite volume method is a discretization technique based on the conservation of a specific physical quantity, such as mass, momentum or energy. The integral form of the continuity, momentum and energy equations over the domain for laminar steady state natural convection gives:

$$\int_\Omega \nabla \cdot \vec{v} d\Omega = 0 \qquad \text{(eqn. 8)}$$

$$\int_\Omega (-(\vec{v} \cdot \nabla) \rho \vec{v} - \nabla p + \mu \nabla^2 \vec{v} + \frac{\mu}{3} \nabla(\nabla \cdot \vec{v}) + \rho \vec{g}) d\Omega = 0 \qquad \text{(eqn. 9)}$$

$$\int_\Omega \left(-\nabla \cdot (\rho E + p)\vec{v} + \nabla \cdot k \nabla T + S_h\right) d\Omega = 0 \qquad \text{(eqn. 10)}$$

By discretizing the domain into finite volumes and approximating the integrals numerically over the finite volumes, sets of systems of algebraic equation are generated.

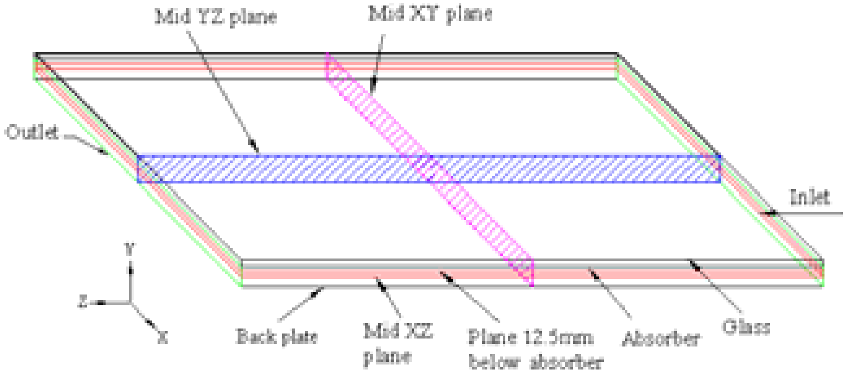

Fig. 1. Geometry of flat plate collector for air heating

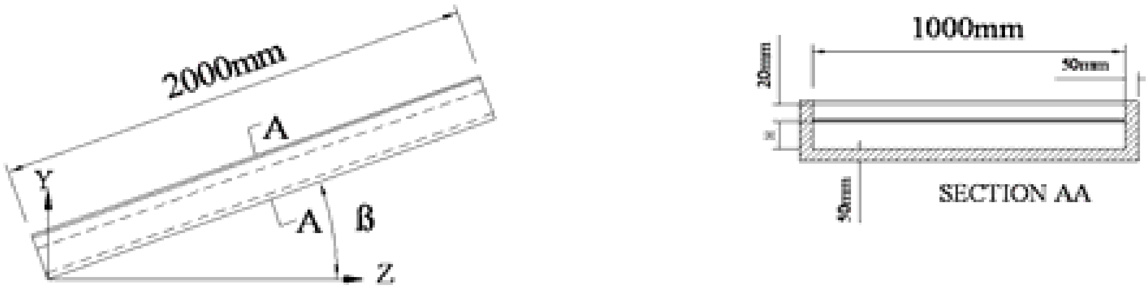

Fig. 2. Collector orientation and dimensions considered for simulation

A three dimensional flat plate solar air heater is modeled with the help of FLUENT to obtain realistic results by accounting side effects. The collector model used for parametric investigation is the flat plate solar air heater with still air gap and transparent cover shown in Fig. 1. 2mx1m collector geometry was considered, as it is the most common dimension for flat plate collectors. Different models were generated by varying the air channel depth. The model is composed of three linked domains: glass domain, enclosed air between glass and absorber, the air in the absorber channel. The two fluid domains are separated by a surface of finite thickness. For the air passage, air gap depths of 30mm, 50mm, 60mm, 70mm and 100mm were considered. The absorber considered in the model was an aluminum sheet of l mm thickness with its sun-facing surface painted black. The single glass cover of the collector has a thickness of 4mm. The collector was insulated with 50mm thick fiber glass insulation material at the side and from beneath. Addis Ababa, (9.02^0 latitude, 38.42^0 longitude) was selected for inputting the climate data for the simulation

5. Results and Discussion

The steady state simulation were conducted on May at solar noon thinking that May can be a representative for six months of the year namely, March, April, June, July, August, and September. The incident radiation on collector surface Vs inclination angle for the above months shows nearly the same pattern with the peak value in the range of 0 to 10^0 inclinations from the horizontal as shown in Fig. 2. To account for the seasonal variation, simulations were conducted for the month of November varying the inclination angle, which is thought to be representative of four months namely, October, December, January and February. For the above five months, the incident radiation is maximum in the range of 200-35^0 from the horizontal.

Transient analysis was conducted for the representative day of May for a total duration of nine hours with reasonable heat gain (8:30.-17:30) for three air gap depths of 50mm, 60mm and 70mm based on the results of the steady state analysis to select the optimum air gap depth.

5.1 Inclination Angle Optimization

Two representative months were selected to see the effect of inclination angles on collector performance for Addis Ababa, and the results are presented. The simulations for May were done for 8 different inclinations angles from the horizontal.

Fig. 3 shows that a sharp increase in mass flow for inclination angles up to 15^o due to an increase of the component of buoyancy in the direction of the channel as inclination increases. The flow rate decreases beyond 45 ^{o}, because of a very low incident radiation at high inclination angles. Fig. 4 shows a sharp decrease in temperature as inclination increases up to 20 ^{o} because of a decrease in incident radiation on the collector surface and an increase in mass flow rate as inclination increases.

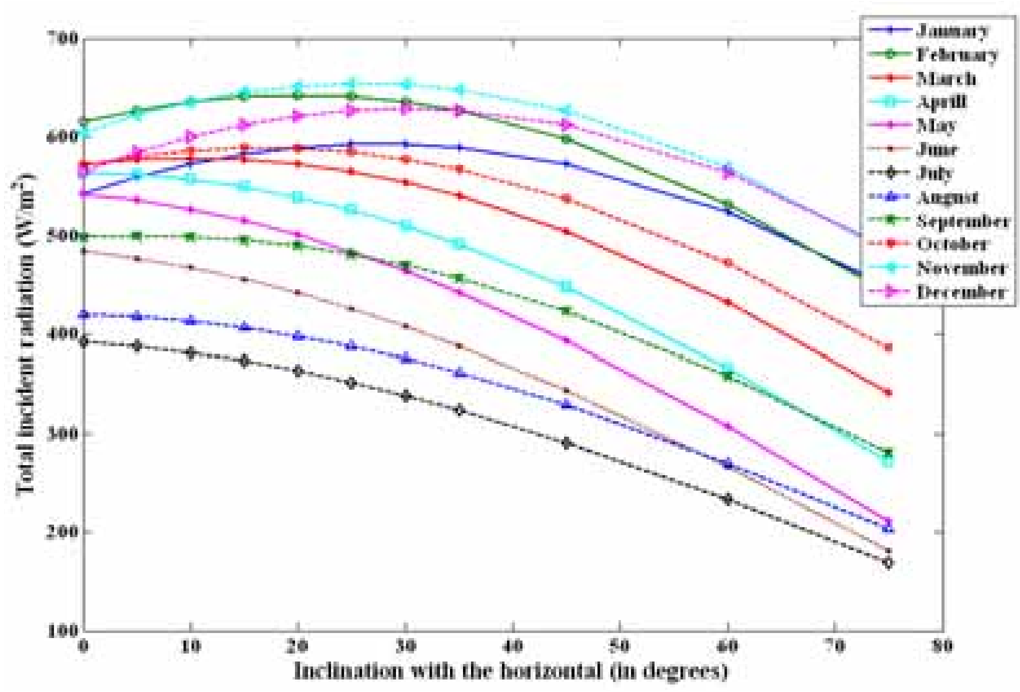

Fig. 2. : Variation of incident radiation on surfaces with inclination angles for different months at noon (for south facing collector, Addis Ababa)

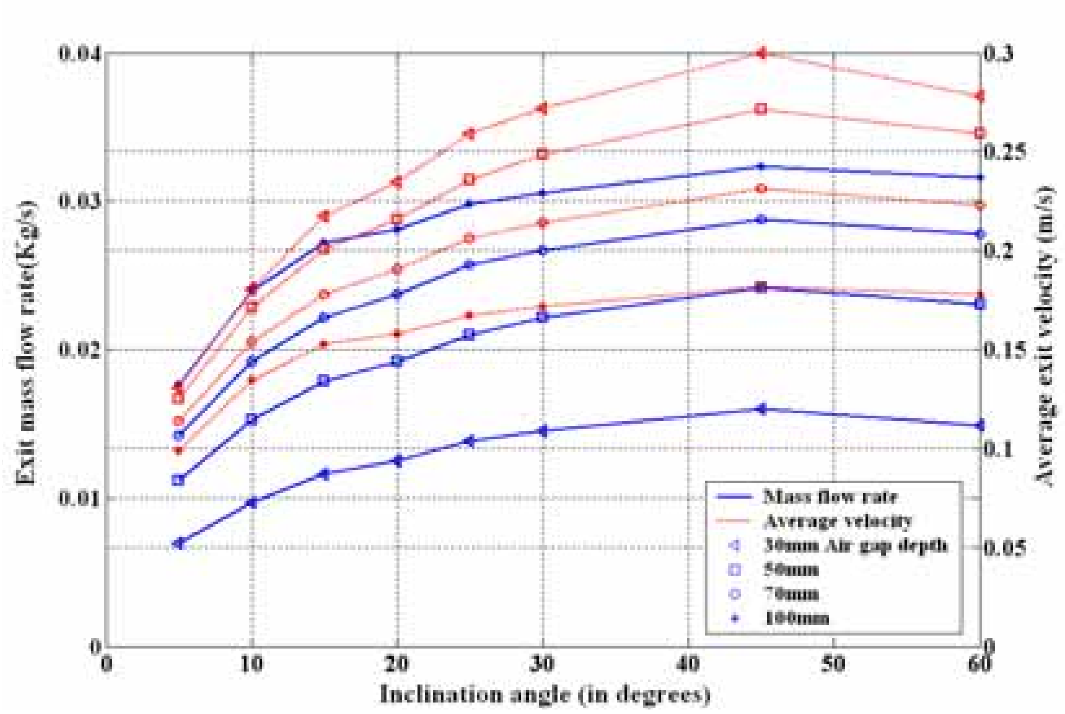

Fig. 3. Variation of exit mass flow rate and exit average velocity of air with inclination angle for different channel depths. (May) (For south facing collector, Addis Ababa).

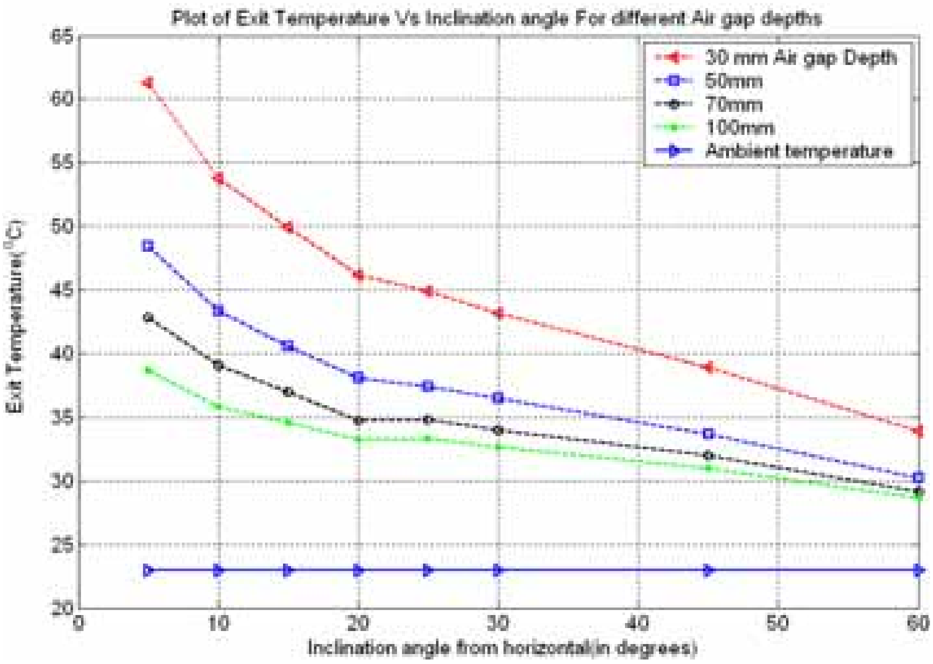

Fig. 4. Variation of exit temperature of air with inclination angle for different channel depths. (May) (For south facing collector, Addis Ababa).

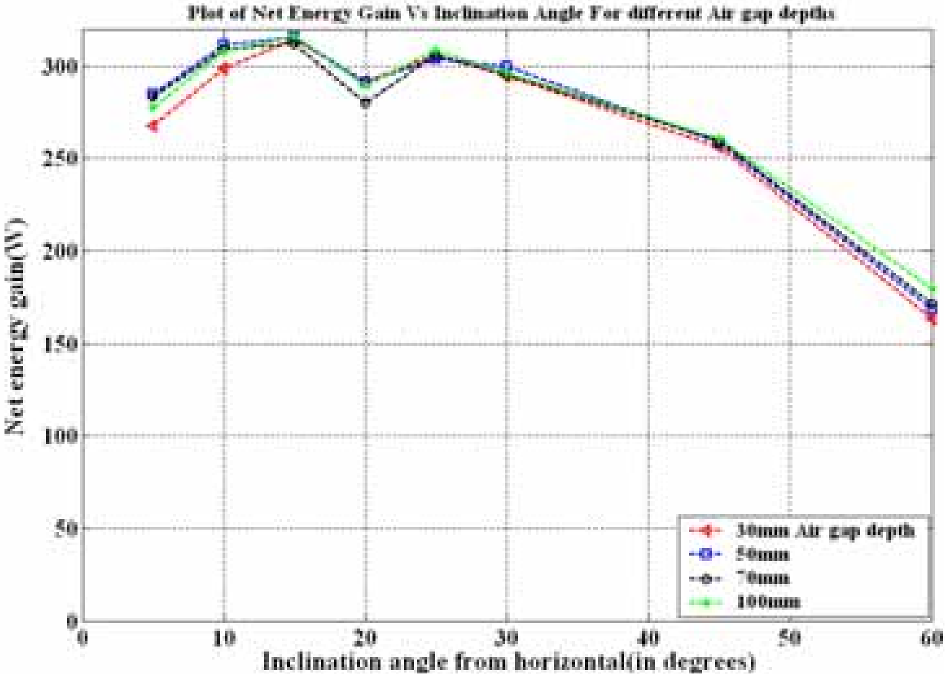

Fig. 5. Variation of net energy gain with inclination angle for different channel depths. (May) (For south facing collector, Addis Ababa).

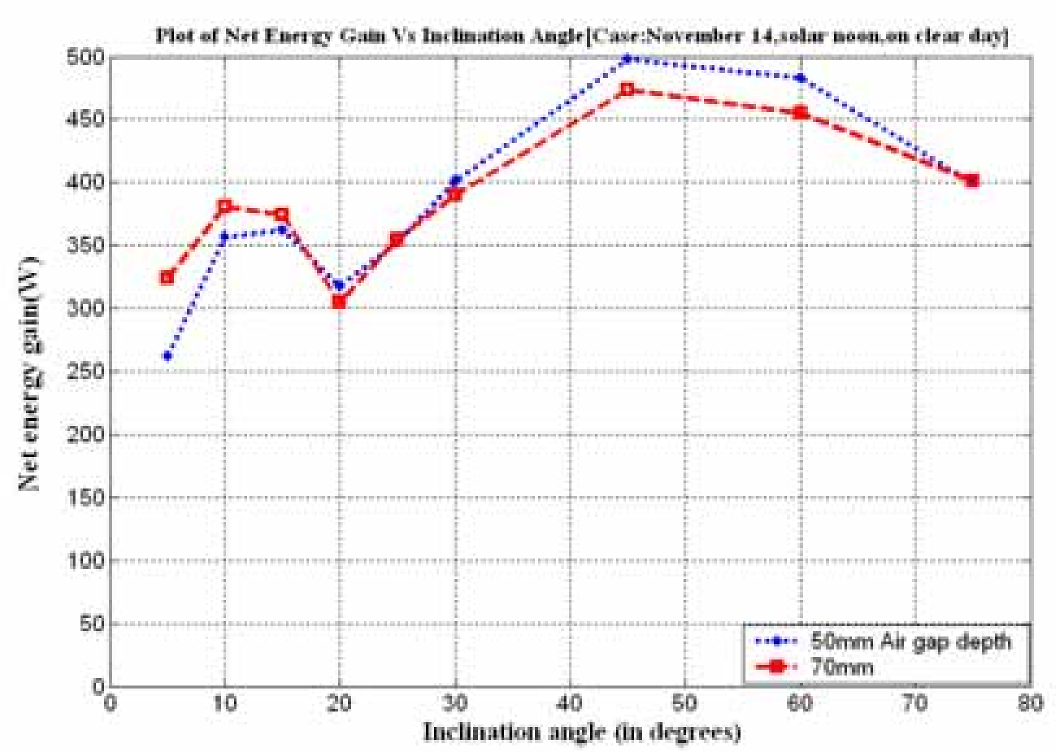

Fig. 6. Variation of net energy gain with inclination angle for different channel depths. (November) (For south facing collector at Addis Ababa).

Fig. 5 displays that the net energy gains at 15° and 25° inclination become maximum. It also shows that the net energy gain in drops at 20° inclination, which has been caused by pockets of reverse flows at the outlet boundary as shown in Fig. 7. The possible existence of such phenomena for a one sided heated channel was found out experimentally on vertical channels by Sparrow et. al.(1984) and on inclined channels by Azevedo and Sparrow (1985). Beyond inclination of 20°, the reverse flow vanishes increasing the effective flow area. As a result the velocity and mass flow rate increase. Comparing the energy gain at 15 ° and 25 ° inclination, the energy gain at 15° inclination is accompanied with significant temperature change. For simulations done on November, 45 ° inclination angle gives maximum energy gain as shown in Fig. 6.

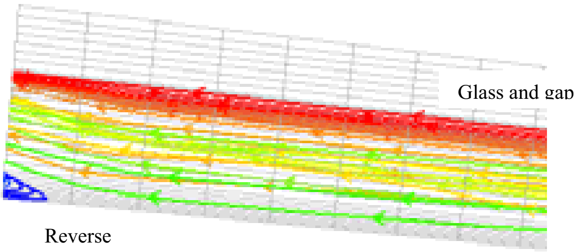

Fig. 7. Reverse Flow at outlet for 5° inclination

5.2 Channel Depth Optimization

The objective of optimizing the channel depth is to maximize the overall outputs of the collector or conditions necessary for specific applications, which are in the case of drying: the exit air temperature, exit velocity and net energy gain. Hence, the channel depth was optimized considering transient analysis of solar heaters of 50mm, 60mm and 70mm depth on a representative day of May for a total duration of nine hours (local time starts from 8:30-17:30), so that the simulation results can correspond to actual drying conditions. The ambient air temperature and global radiation data were taken from metrological data for May 18.The diffuse radiation is predicted using empirical relations.

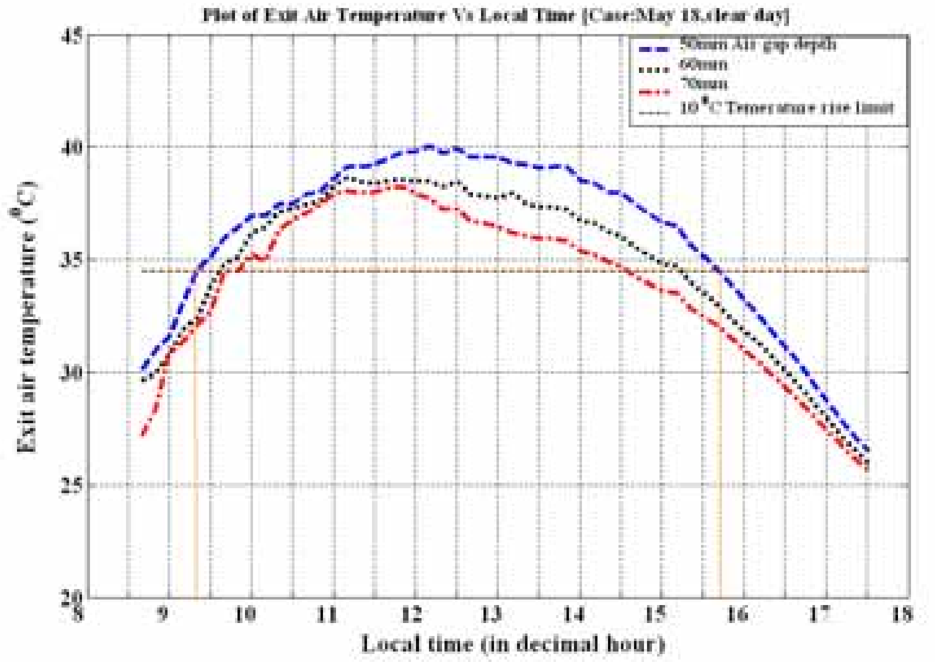

Fig. 8. Variation of exit temperature of natural convection air heater (2mx1m) for different channel depth during the day obtained by transient CFD analysis (For south facing collector at Addis Ababa in May).

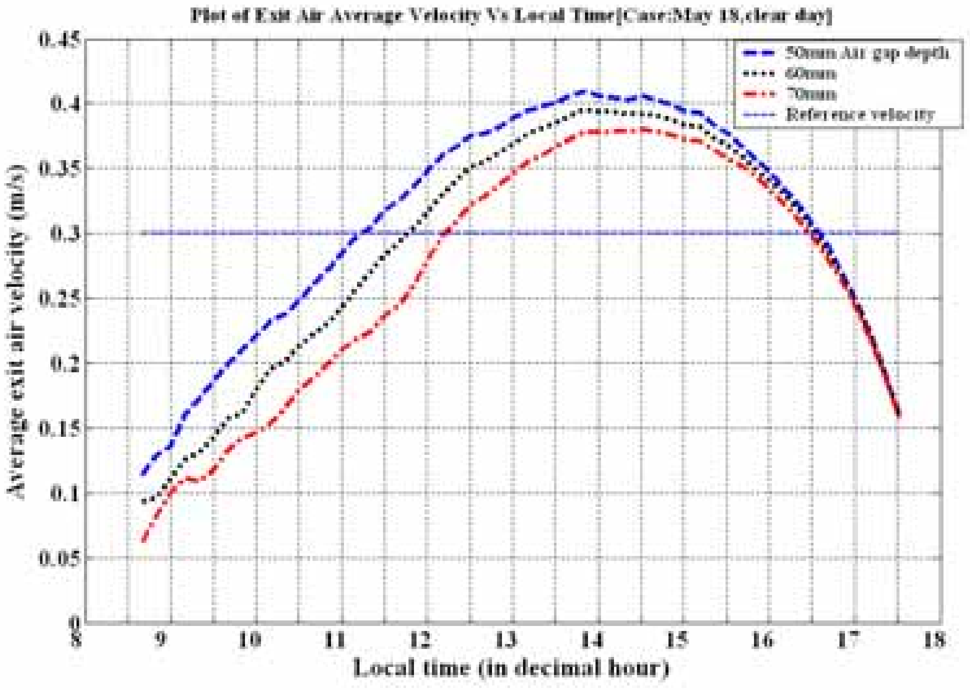

Fig. 9. Variation of exit average velocity of natural convection air heater (2mx1m) for different channel depth during the day. obtained by transient CFD analysis (For south facing collector at Addis Ababa in May).

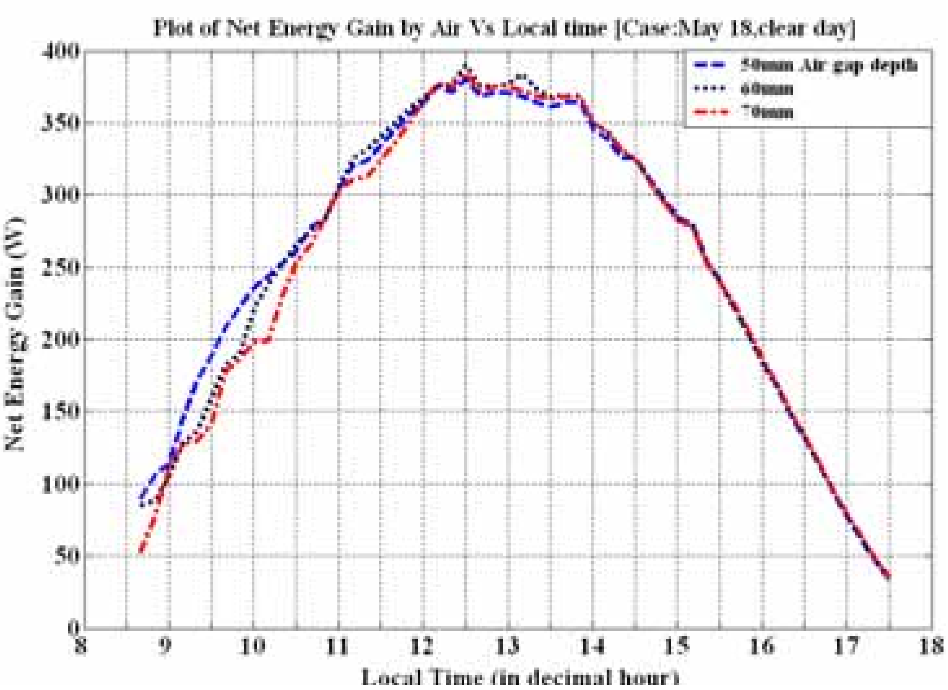

Fig. 10. Variation of net energy gain for different channel depth during the day obtained by transient CFD analysis (For south facing collector at Addis Ababa in May)

The results shown in Fig. 8 indicate that, 50mm channel depth can yield 10^0C temperature rise from maximum ambient temperature (T_{max}=24.5^0C) for about 6 and1/2 hours with a relatively large average velocity of exit air above 0.3m/s. The average velocity at the outlet of the collector is shown in Fig, 9. The net heat gain that can be achieved by the collector with the three channel depths is comparable as shown in Fig. 10. Therefore, it can be concluded that a collector depth of 50mm is preferable in the applications like drying, as it meets temperature and velocity requirements over wide range of time while yielding slightly higher heat gain. The cumulative efficiency for the total period of this collector was 21.3 %.

6. Conclusion

A parametric study was done on natural convection flat plate solar air heater with aid of three dimensional CFD model for steady state and transient analysis, and it is found that inclination angles at or around 15^0 are recommended in summer month and higher inclination angles around 45^0 are recommended in winter month for areas around Addis Ababa**.** The air gap depth of 50mm is found to give better outputs in terms of high temperature rise, average velocity, and net energy gain.

Nomenclature

A_a - Absorber or cover area

c_p - Specific heat of air at constant pressure

E - Energy

$\vec{g}$ - Gravitational force per unit mass of the fluid

I - Radiation intensity,
k_{eff} - Effective thermal conductivity.
$\dot{m}$ - Mass flow rate of air
n - Refractive index
p - Static pressure
Q_u - Useful thermal energy gain
$\vec{r}$ - Position vector
s - Path length
$\vec{s}$ - Direction vector
$\vec{s}\,'$ - Scattering direction vector
S_h - Volumetric heat source
T - Temperature
T_e - Exit temperature of air
T_i - Inlet temperature of air
$\vec{v}$ - Velocity vector ($v_x i + v_y j + v_z k$, *in Cartesian coordinates*)

Greek

α - Absorption coefficient
$\alpha + \sigma_s$ - Opacity of a medium
β - Inclination angle from horizontal
Φ - Phase function
$\eta_{th,i}$ - Instantaneous thermal efficiency of the collector
$\eta_{th,cu}$ - Cumulative thermal efficiency of the collector
μ - Dynamic viscosity
ρ - Density
σ_s - scattering coefficient
σ - Stefan-Boltzmann constant
Ω - Solid angle
Ω - Domain

REFERENCES

1. Azevedo, L.F.A. and Sparrow E.M. ,1985, Natural Convection in an Open Ended Inclined Channels, Transaction of ASME, J. Heat Transfer, Vol.107, PP. 893-901.

2. Bansal, Amit, Anil Kumar et al. ,1999, Experimental Investigation of Thermal Performance of Natural Convection Solar Air Heater, Seminar on Solar Technologies, India.

3. Choudhury, C., Andersen, S.L. and Rekstad, J., 1985, A Solar Air Heater for Low Temperature Applications, Solar Energy, Vol.40, No.4, PP.335-343, 1985.

4. Duffie, J. A. and Beckman, W. A, 1991, Solar Engineering of Thermal Processes. 2nd edition, J. Wiley and Sons.

5. Gao, Wenfeng, Lin ,Wenxian , Lu, Enrong ,2001, Numerical study on natural convection inside the channel between the flat-plate cover and sine-wave absorber of a cross-corrugated solar air heater, Energy Conversion & Management , 41, pp. 145-151.

6. Kern, J. and Harris I., 1974, On the Optimum Tilt of Solar Collector. Solar Energy, Vol.17, No.2B, PP.77-102.

7. Macedo, I. C. and Altemani, C. A. C., 1978, Experimental evaluation of natural convection solar air heaters, Energy, Volume 20, Issue 5, 1978.
8. Manes, A., and Lanetz, A., 1983, On the Optimum Exposure of Flat Plate Fixed Solar Collectors. Solar Energy, Vol.31, No.1, pp. 21-27.
9. Pakdaman, M. Fakoor Lashkari, M. Fakoor, Tabrizi, H. Basirat and Hosseini, R., 2011, Performance evaluation of a natural-convection solar air-heater with a rectangular-finned absorber plate, Management, Volume.
10. Pericle and Koronakis S. , 1986, On The Choice of the Angle of Tilt for South Facing Solar Collectors in the Athens Basin Area, Solar Energy, Vol.36, No.3, PP.217-225.
11. Soponronnarit, Somchart, 1995, Solar Drying in Thailand, Energy for Sustainable Development, Vol. II, No.2, pp.19-25.
12. Sparrow, E.M., Chrysler G.M., and Azevedo L.F., 1984, Observed Flow Reversals and Measured Predicted Nusselt Numbers for Natural Convection in a One Sided Heated Vertical Channels. ASME, J. Heat Transfer, Vol. 106, May, PP. 325-332.
13. Tiris, Cigdem, Ozbalta, Necdet, Tiris, Mustafa and Dincer, Ibrahim, 1994, Performance of a solar dryer, Energy, Volume 19, Issue 9.
14. Varun, Sharma, Naveen, Bhat, I.K. and Grover, D., 2011 , Optimization of a smooth flat plate solar air heater using stochastic iterative perturbation technique, Solar Energy, Volume 85, Issue 9.
15. Varun, and Siddhartha, 2010, Thermal performance optimization of a flat plate solar air heater using genetic algorithm, Applied Energy, Volume 87, Issue 5.