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Performance analysis of solar chimney for passive cooling of the building

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Abstract: The solar chimney is a passive device that is applied to enhance room ventilation. The chimney could be vertical or inclined. The chimney inclination angle and air inlet opening position are important parameters that greatly affects flow pattern and ventilation rate inside the room. In this study, the effect of air inlet opening position and chimney inclination angle on air change per hour and air flow pattern inside the room was numerically investigated. A numerical simulation using CFD code was used to predict flow pattern. Then the results were compared with published experimental measurements. Find out the effect of air inlet opening position and inclination angle of chimney on mass flow rate at outlet of the chimney.

Keywords: Solar chimney, natural ventilation, air inlet position, inclination angle, CFD

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1 **Introduction:** The equipment, materials or human activity increase the pollutant concentration inside the building, which affects to the indoor air quality. Pollutant concentration can affect human health and productivity, which makes necessary their removal. Traditionally the ventilation replaces the indoor air for outdoor air, which has better quality. The different modes of promoting air exchange are mechanical ventilation, which allows controlling the flow rate all the moment, their quality and temperature; and natural ventilation, which has less maintenance, makes less noise and does not use electric energy to move the air. The solar chimney is a simple and practical idea that is applied to enhance space natural ventilation. The solar chimney is a system that uses the solar radiation to move the air, improving the natural ventilation and providing fresh air for the building.

Solar chimney: Solar chimney (SC) is a passive element that makes use of the solar energy to induce buoyancy-driven airflow and naturally ventilate the building. It enables heating of air in the tower. As air heated in the tower, it rises up and creates upward draught.

Working principle of solar chimney: The system uses the solar energy. The temperature difference between the outdoor temperature air in the chimney and the air temperature in the attached room promotes movement of air. The rate at which air is drawn through the room depends upon the buoyancy-force experienced, (i.e. dependent upon the temperature differential), the resistance to flow through the chimney, and the resistance to the entry of fresh air into the room.Figure (1) shows a schematic diagram for a solar chimney with glass cover. The glass cover is exposed to solar radiation and transmits most of the solar radiation inside the channel which falls on the absorber surface. The absorber surface absorbs the heat from solar radiation and heats up the air through radiation and convection. The inside air temperature of the channel becomes higher than temperature of ambient air outside it. Due to the difference between ambient air and air inside the channel, a natural convection flow is induced inside the room.

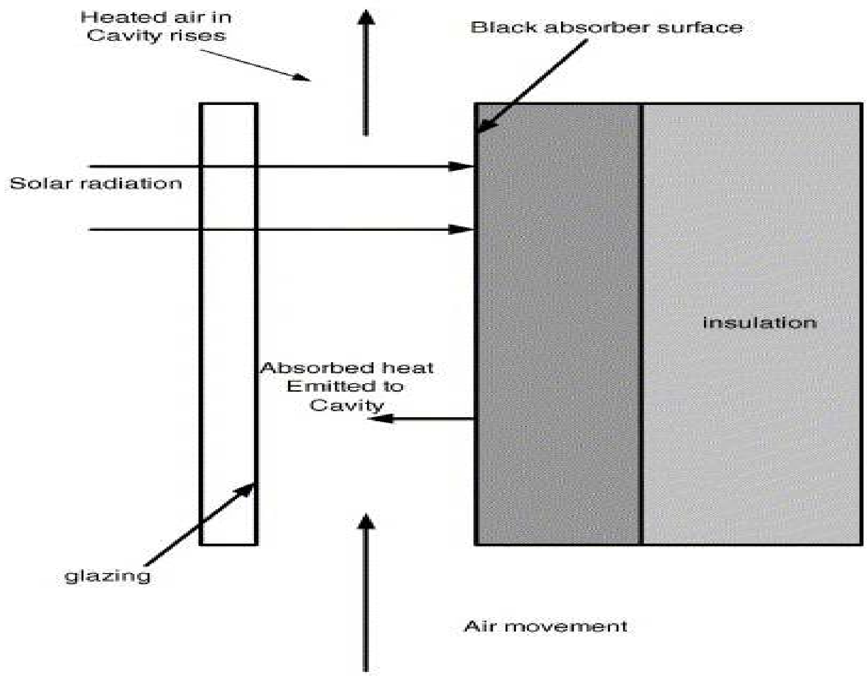

Figure (1): Schematic of solar chimney.

Nomenclature: Following symbols are defined for the physical quantities and are used in the manuscript. The first letter in the bracket indicates the symbol used while second one is its corresponding unit.

Aspect ratio (A, Ha/w); Grasof number (Gr); Gravitational Acceleration (g , m/s^2); Ventilated space height (H, m); Height of the absorber (Ha, m); Length of ventilated space (L, m); Mass flow rate (m , kg/s); Prandtl Number (Pr); Rayleigh Number (Ra); Nusselt Number (Nu); Local fluid Temperature (T, k); Reference fluid temperature (T0, K); Horizontal velocity component (u, m/s); Vertical velocity component (v, m/s); Volume (V, m^3); and Exit air gap width (w, m)

2 Numerical Simulations

2.1 Introduction: In this work a two dimensional numerical study has been undertaken to study the effect of inclination angle on air change per hour and indoor air flow rate and also the effect of air in let position on air flow rate at the exit of solar chimney.

2.2 Numerical modeling: Figure (2) displays a schematic of an empty room with attached inclined solar chimney with important dimensions. Here air flow and temperature distribution within the solar chimney is governed by the mass, momentum and energy conservation laws. The mathematical modeling of flow and velocities inside the domain involves solving the Renormalization Group (RNG)K-E model the energy equation. Boussinesq approximation is applied since the difference in the temperature of the air at the inlet and outlet of the solar chimney system is not expected to be high; assuming thermo-physical properties of the air remains constant (except for the density variation in the buoyancy term of the vertical momentum equation)

Under this assumptions governing equations to be solved for two-dimensional steady-state turbulent flow (since $Ra > 10^9$) with RNG K-E turbulence.

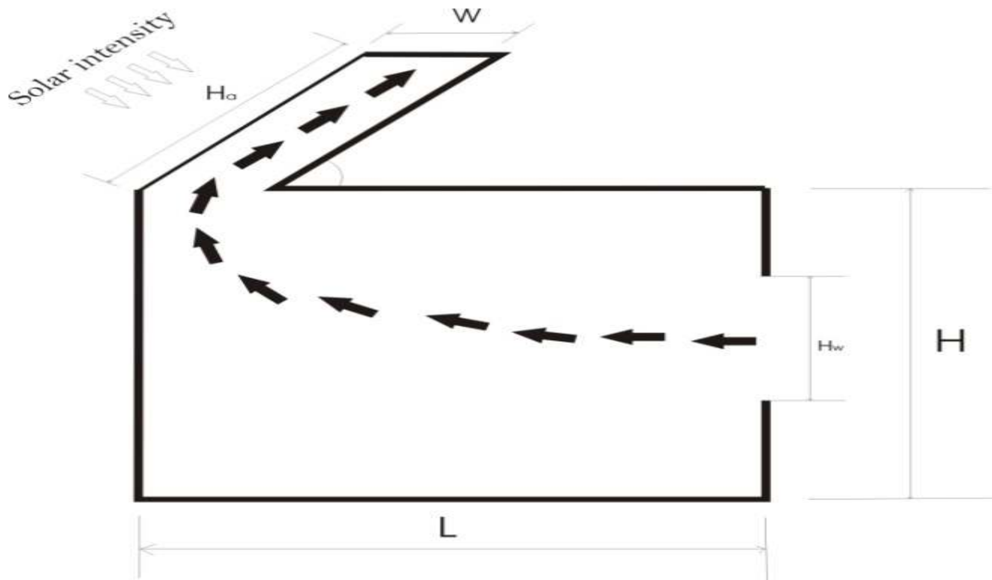

Figure (2): Room attached with inclined solar chimney.

Here, Length of room (L) = 3 m; Height of room (H) = 3 m; Air gap width (w) = 0.35 m; and Absorber Height (Ha) = 1 m.

The present work is mainly concerned with the effect of inclination angle and position of air inlet path on flow rate so here we change only the inclination angle and air inlet position without changing chimney and room dimension. Here constant heat flux condition is applied on the absorber plate.

The natural convection flow inside a solar chimney channel can be characterized by three non-dimensional parameters i.e. Ra, Pr, and Ar, which are defined as follows:

$$Ra = \frac{g\beta q Ha^{4}}{\alpha k \nu} \qquad \text{………………………1}$$

$$Pr = \frac{\nu}{\alpha} \qquad \text{…………………….2}$$

$$Ar = \frac{Ha}{w} \qquad \text{……………………3}$$

2.3 Methodology: The methodology can be divided into four parts i.e. geometry modeling, geometry meshing, computational simulation and data reduction. Geometry modeling and meshing constitute the pre-processor section. Computational simulation is the solver section. The data-reduction is the post-processor section in which we formulate the obtained data into more conceivable forms like graph or contour plot.

Pre-Processor

⇩

Solver

⇩

Post-Processor

2.3.1 Geometry Modeling: The modeling software used here is Ansys Design Modular 15.0. Here two-dimensional solar chimney with room has been drawn.

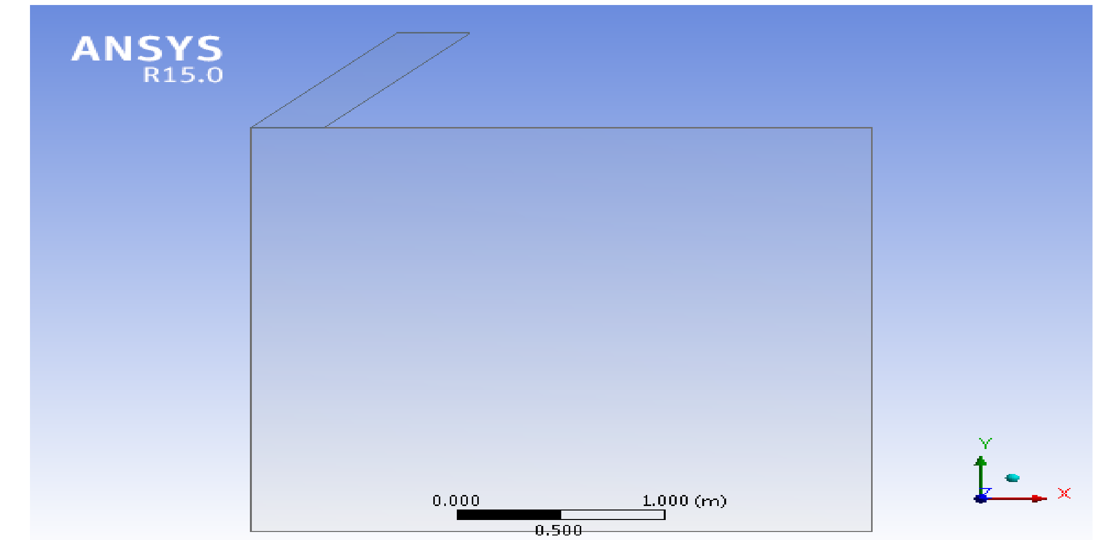

Figure (3): Geometry of room attached with chimney in Design modular.

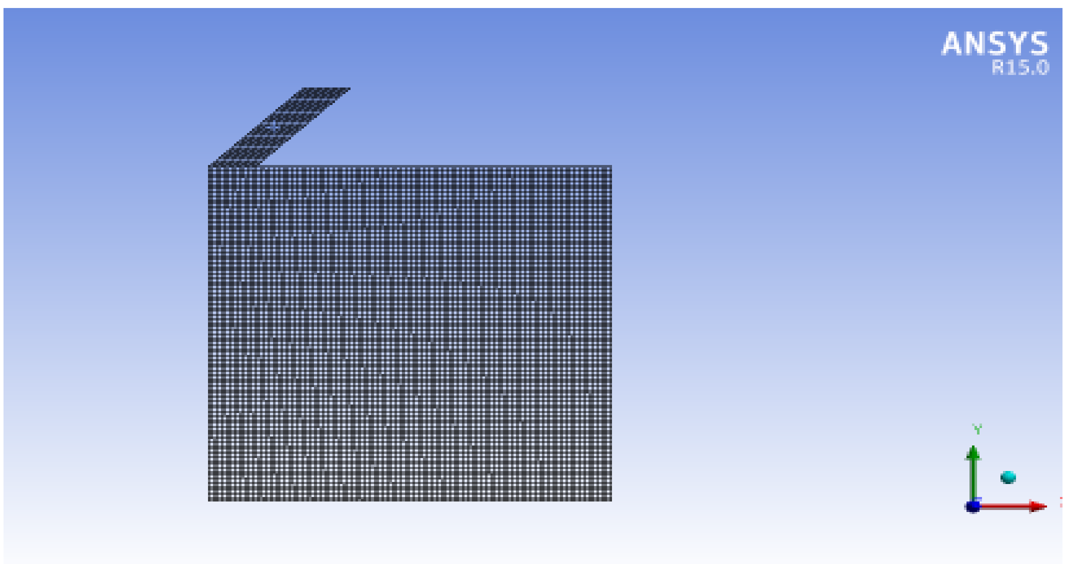

Figure (4): Geometry meshing of Computational Domain.

2.3.2 Geometry Meshing: The meshing software used here is ANSYS ICEMTM 15.0. To obtain better results the entire fluid flow zone is sub-divided into many zones and a structured mapped mesh and refinement mesh were created for the fluid domain.

3 Results and discussion:

3.1 Introduction: Natural convection in room with solar chimney attachment enclosure filled with air is subjected to end-to-end temperature difference on side vertical walls is characterized by four dimensionless parameters Ra, Pr, Ar, θ. Solution is obtained on CFD Software Ansys FLUENT 15.0, for Ra = $4.567*10^{10}$, Pr =0.7045, $\theta = 45^0$

3.2 Boundary conditions: Absorber plate the boundary condition was taken as constant heat flux condition and the other surfaces were taken as adiabatic wall. For the inlet to the room, a pressure inlet boundary condition is prescribed where the total (gauge) pressure is set to zero and the inflow is assumed to be normal to the inlet. The incoming air is at the reference temperature T_0 (T_0= 300 K in the present investigation). The turbulence properties at the inlet are specified by the turbulent intensity and turbulent length scale with the turbulent intensity set to 3%. All the thermo physical properties of air is taken at reference temperature (T_0). Pressure outlet boundary condition is prescribed for the outgoing air from the chimney in where the fluid pressure is presumed to be the same as the ambient pressure and the stream wise variations of the velocity components, temperature, turbulent kinetic energy and dissipation rate are negligible. In the case with a backflow (air entering the channel through the chimney exit), the backflow is assumed to be normal to the exit boundary and is at the reference temperature (300 K).

3.3 Grid independence test: First, a mesh independence test was conducted to ensure that we have mesh-independent solution. The accuracy of the numerical result is ascertained by a grid independence study, which is performed on two meshes with 8460 and 18560 elements in total for the Rayleigh number (Ra = 4.567 x 10^{10}) considered in this study. Since the mass flow rate is the parameter of interest which quantifies the effectiveness of the solar chimney system, it is chosen for comparison. From the results of the mesh test, it is found that the variation of the calculated mass flow rates between these two meshes is less than 2 %. Based on the numerical test, the coarser mesh is chosen for the present study as it can provide sufficient spatial resolution and requires much less computational time than the finer mesh.

3.4 Validation of CFD analysis: Numerical values of average mass flow rate obtain in the present study for $\theta = 45^0$ and Ar = 2.85 compared with the values reported in the experimental study by Mathur et al. [12]. Comparison of present value with the values reported in the experimental study below Table (1).

Table (1): Comparing the air flow rate at different solar intensities.

Intensity of radiation on absorber (w/m^2)	Air flow rate (kg/min) at an inclination angle 45^0	
	Exp. [12]	Present
500	4.275	3.493
550	4.521	3.605
600	4.521	3.706
650	4.865	3.806
700	5.233	3.904
750	5.405	4.016

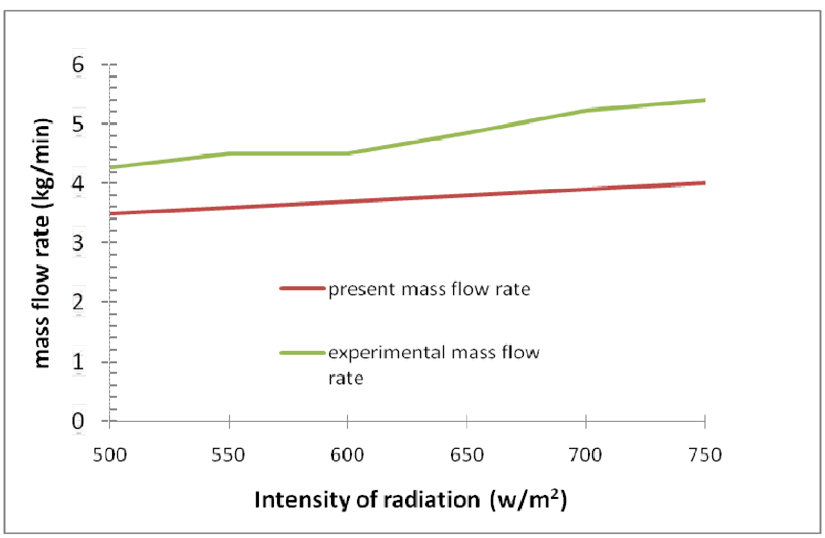

Figure (5): Variation of mass flow rate (Kg/min) vs. intensity of radiation (W/m^2).

Velocity stream function for different radiation ranging from 500-750 w/m^2 given below.

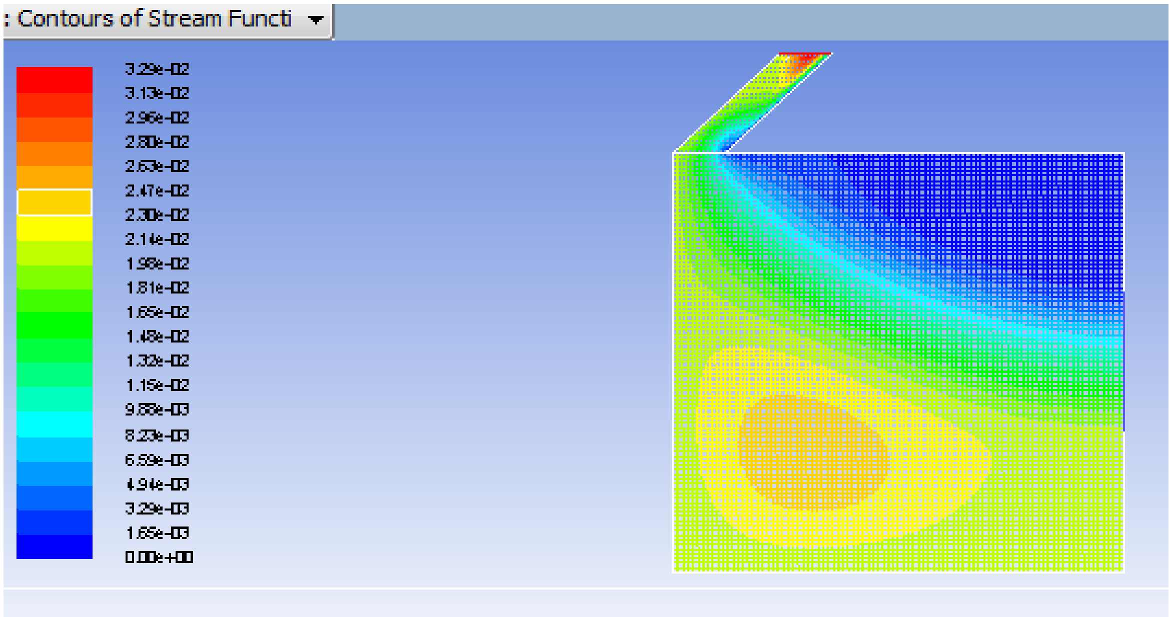

Figure (6): Contours of steam function for q=500 w/m^2.

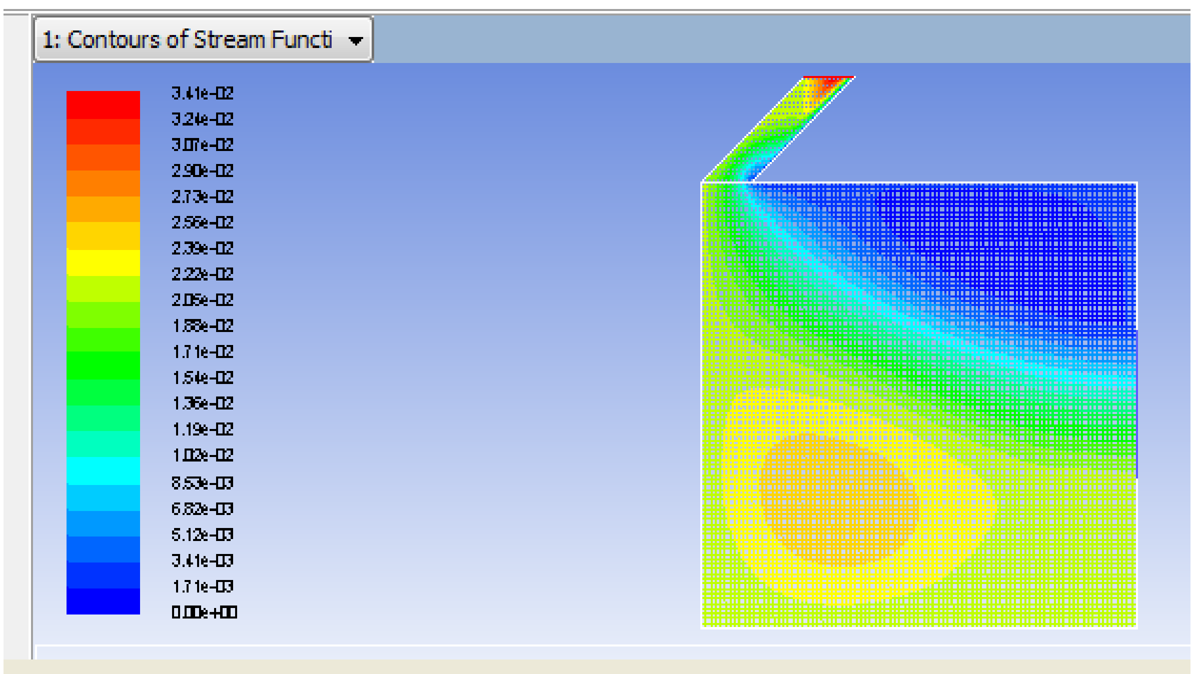

Figure (7): Contours of steam function for q=550 w/m^2.

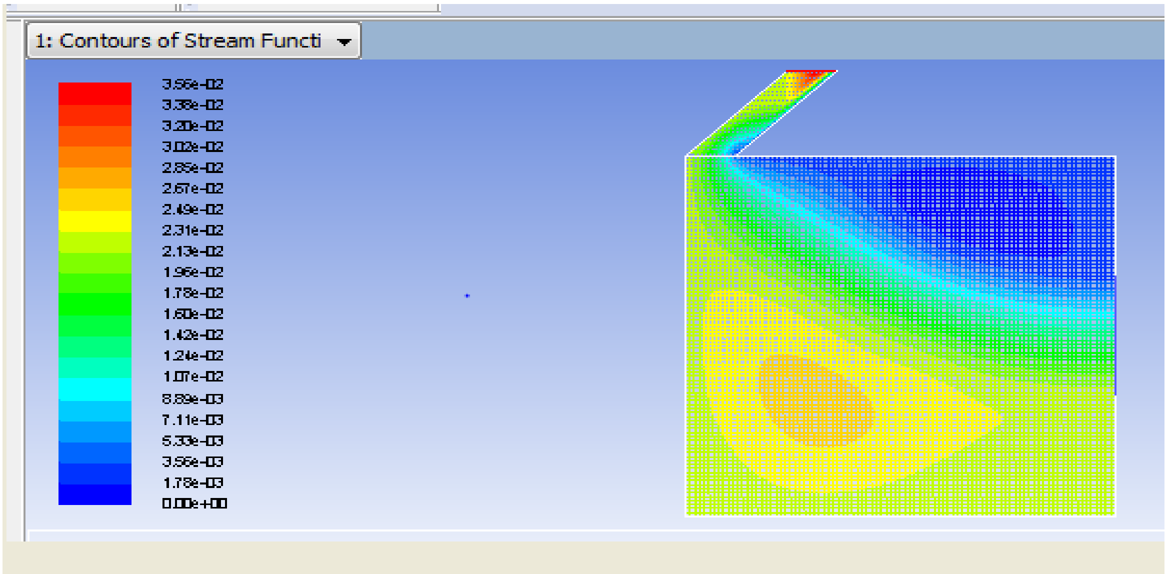

Figure (8): Contours of steam function for q=600 w/m^2.

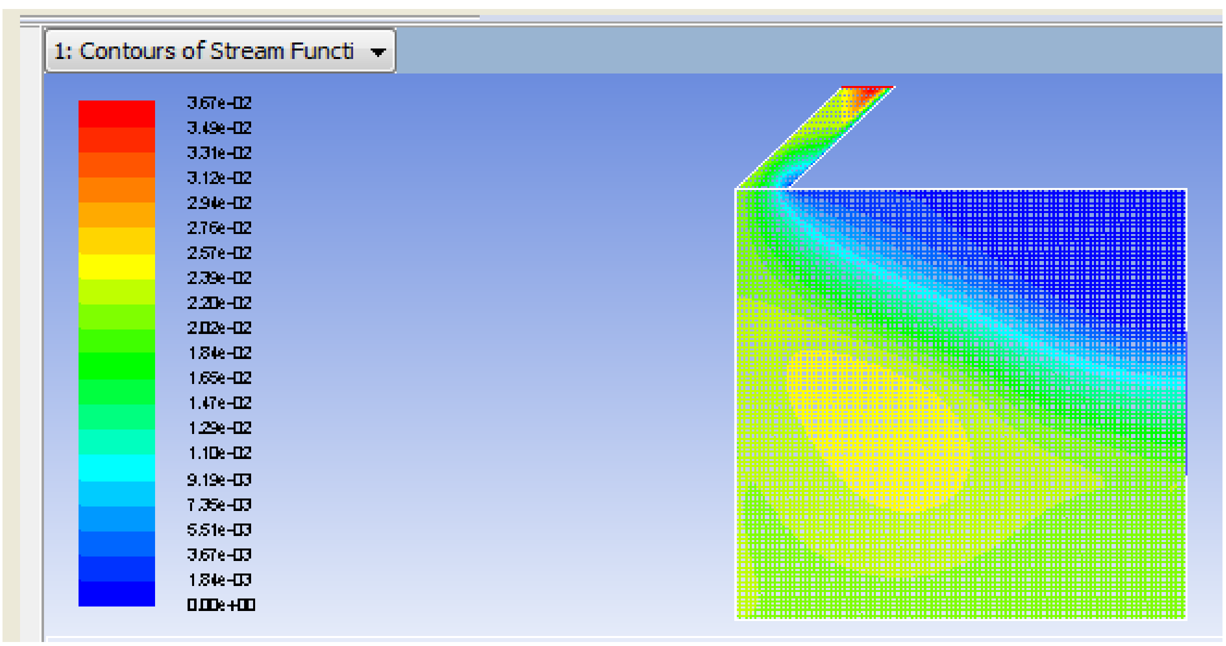

Figure (9): Contours of steam function for q=650 w/m^2.

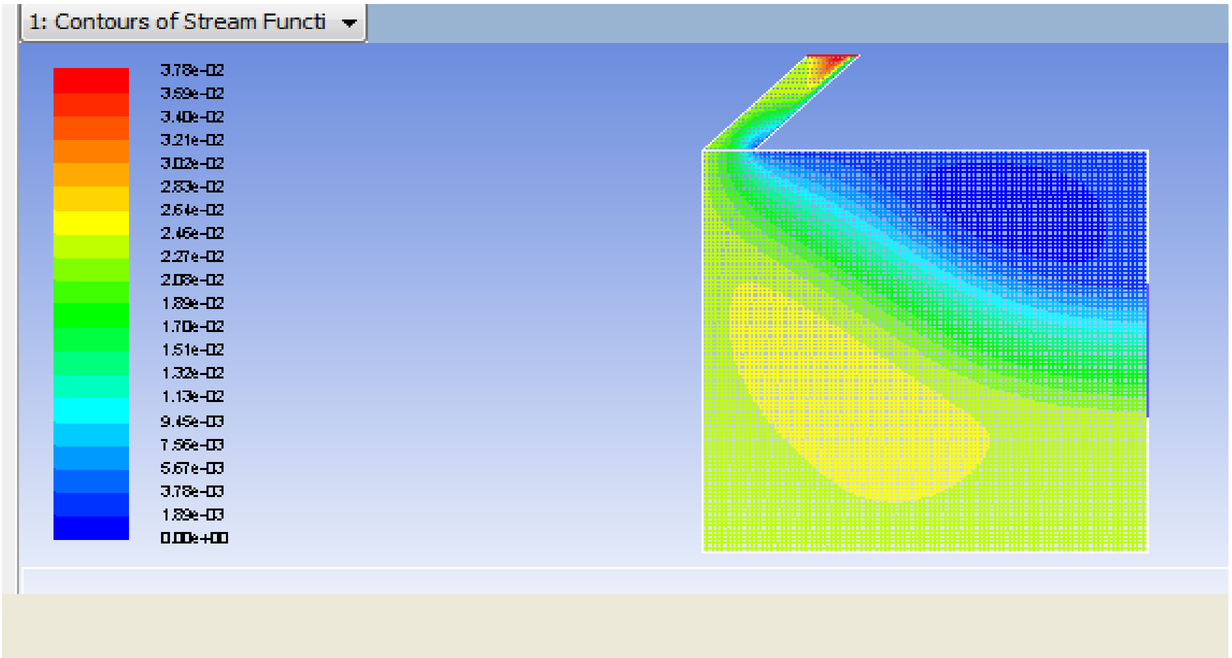

Figure (10): Contours of steam function for q=700 w/m^2.

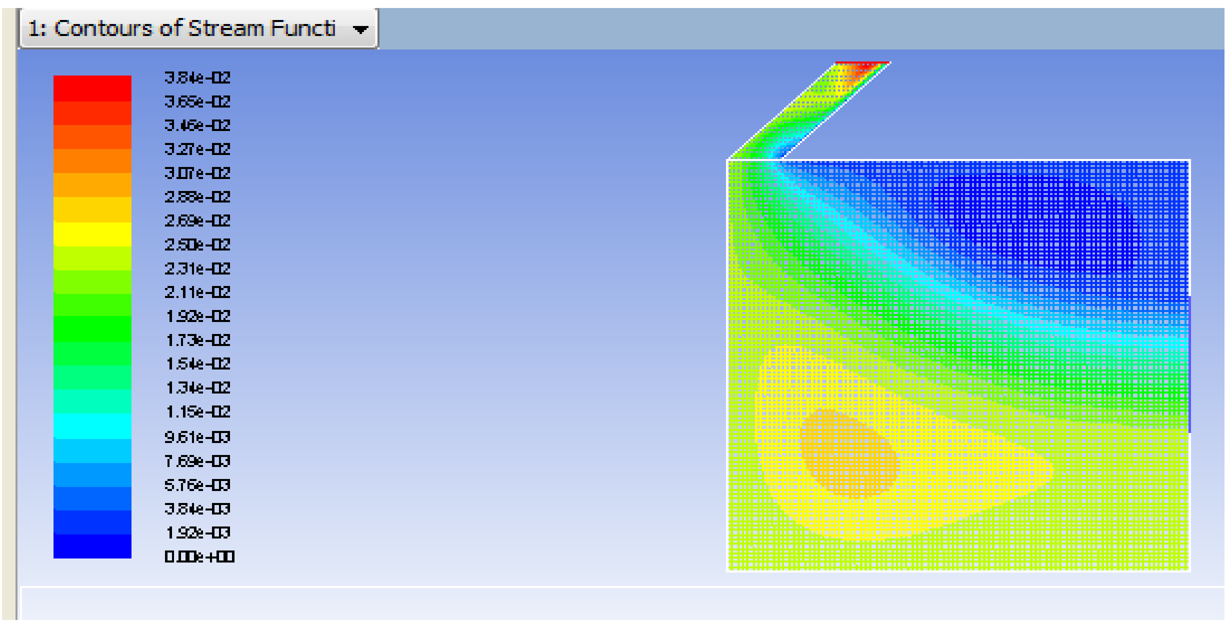

Figure (11): Contours of steam function for q=750 w/m^2.

From the above stream functions for various heat flux ranging from 500-750 w/m^2 shown in Figures (6-11) it is clear there is not much variation in stream function but mass flow rate increases when heat flux increases. It shows that when there is more heat flux on the absorber plate then temperature difference between inside room and solar chimney more which increases the buoyancy driven flow i.e. rate ventilation increases inside the room.

3.5 Results: Result were obtained for $\theta = 45^0$, Ar = 2.85, q = 750 w/m^2, changing the position of air inlet and comparison when the chimney was placed vertical and make an angle 45 degree with vertical.

Case-1 (When changing the inlet position)

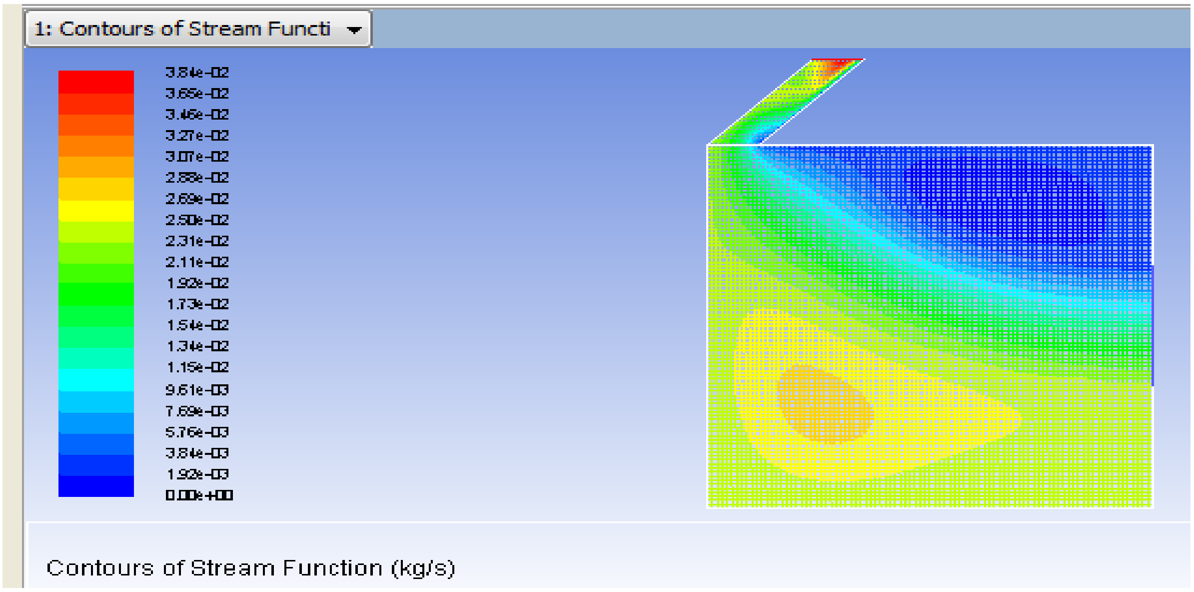

Figure (12a): Inlet at middle of the wall; Mass flow rate = 4.2158 kg/min.

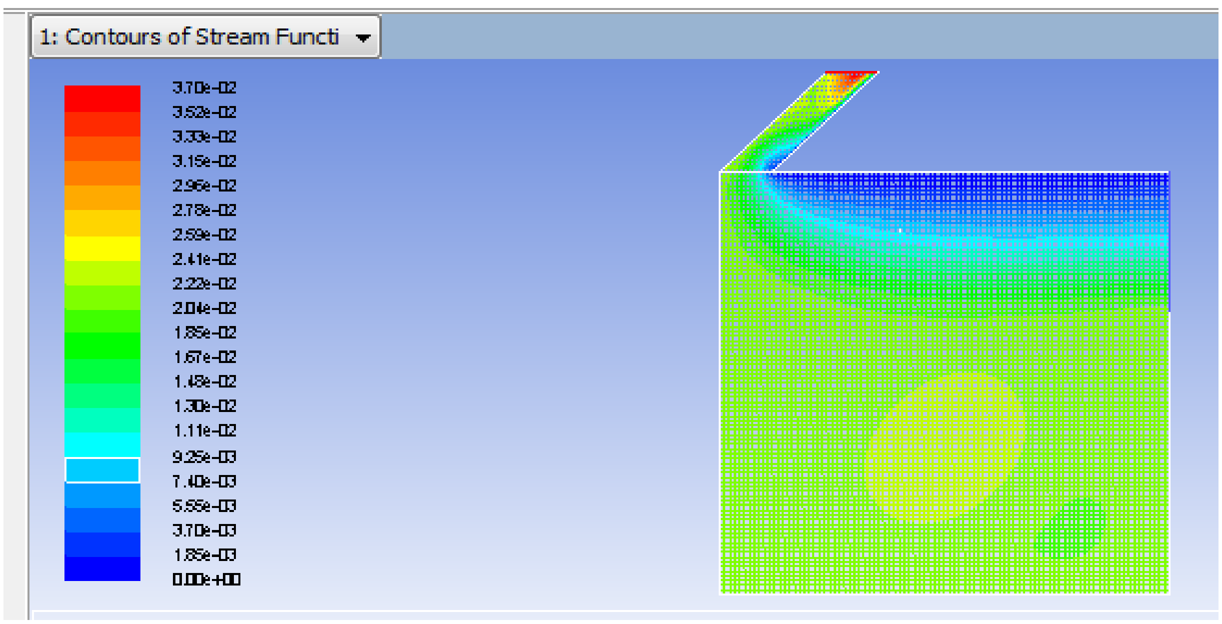

Figure (12b): Inlet at top of the wall; Mass flow rate=3.9641 kg/min.

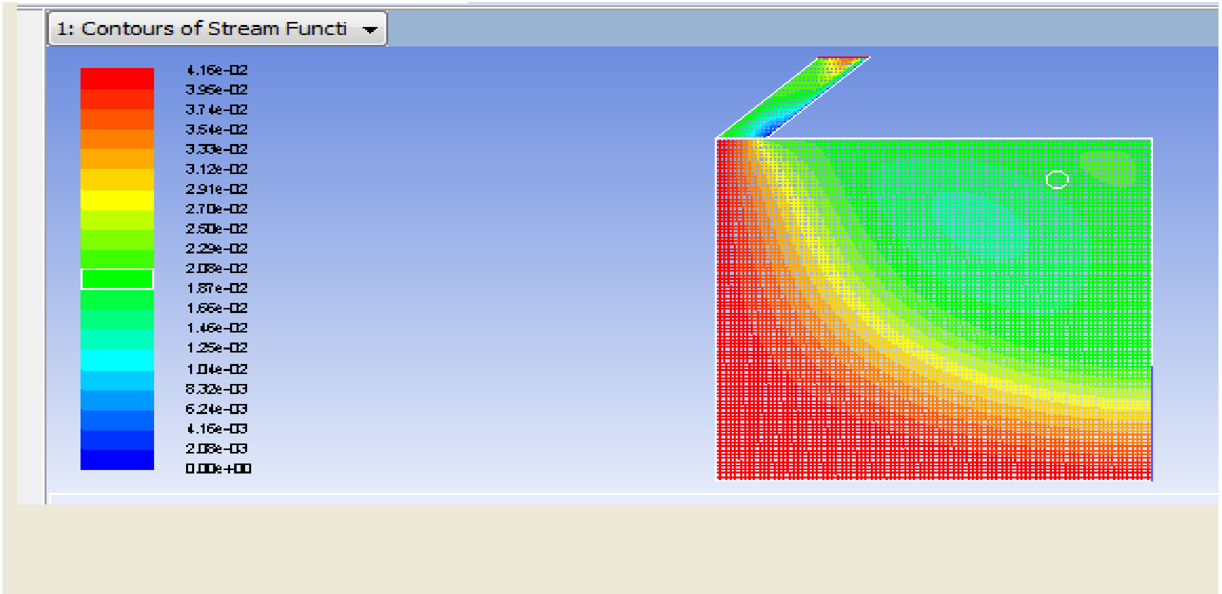

Figure (12c): Inlet at bottom of the wall; Mass flow rate=4.00 kg/min.

As can be noticed in Figure (12a, b, & c) effect of inlet position on the mass flow rate from the Solar-chimney outlet. When the inlet position is at the middle as shown in Fig-a mass flow rate is 4.2158 kg/min where as when inlet is at top and bottom (as shown in Figure 12b and Figure 12c) mass flow rates are 3.9641 kg/min and 4.00 kg/min. It shows that middle position for air inlet to the room is suitable for room ventilation which increases the rate ventilation. So window opening for air inlet to the room should be positioned in such a way that it increases the ventilation rate inside the room.

<u>Case-2 (when θ=0^0 and θ=45^0)</u>

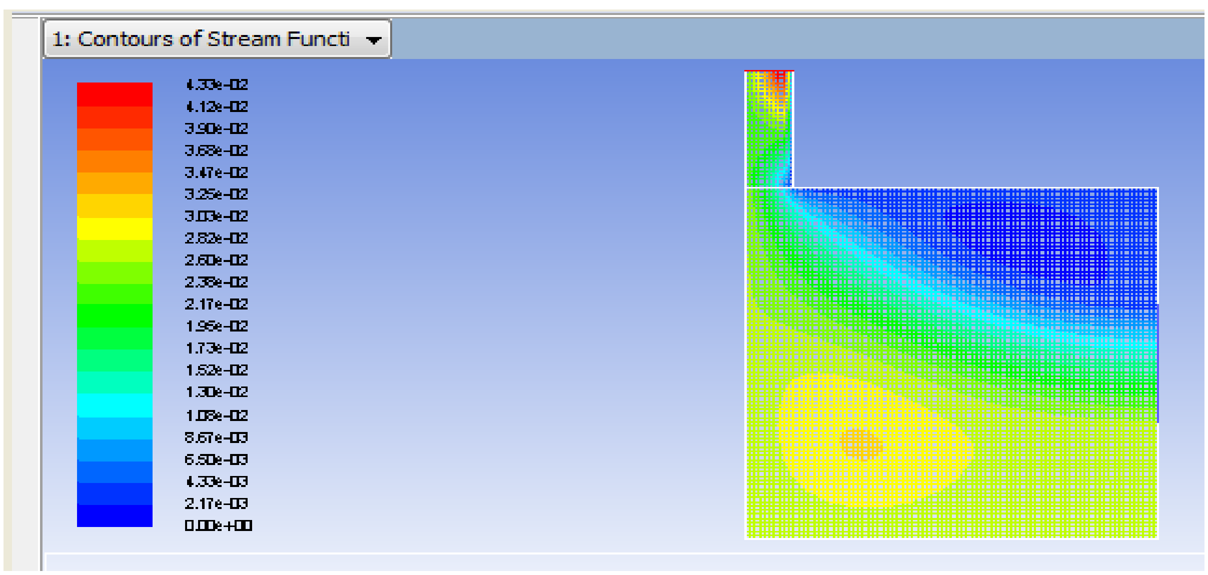

Figure (12d): When θ=0^0, mass flow rate=3.8602 kg/min.

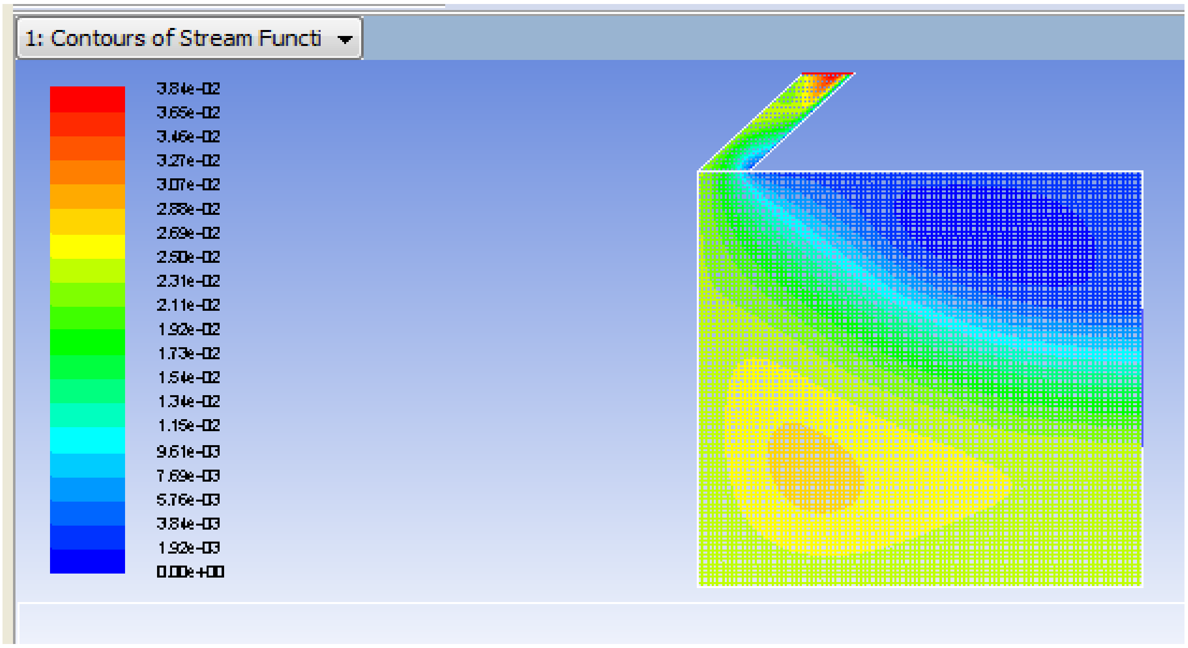

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Figure (12e): At $\theta=45^0$, mass flow rate=4.2158 kg/min.

Figure (12d) and Figure (12e) show that there is a noticeable effect of the solar chimney inclination angle on the air exit flow rate. Here we take two angles with respect to vertical are 0^0 and 45^0. From figure it is clear that when inclination angle increase with respect to vertical the rate of flow of air increases and get a optimum value at 45^0 after that the rate of flow decrease as there is more resistance to flow inside the chimney due to large angle with respect to vertical direction.

So from above two cases it is clear that the inlet position and inclination angle largely affect the mass flow rate out of the chimney.

4 Conclusions: The present study aimed at investing the effect of air inlet position and solar chimney inclination angle on mass flow rate i.e. ventilation rate and drawing the stream functions for various flow pattern. Out of the results, following can be drawn:

- The numerical visualization show that with increase in heat flux there is increase in mass flow rate at the outlet of the solar chimney.
- Air inlet at the middle of the wall is best position for better air flow inside the room.
- With increase in inclination angle of solar chimney with vertical direction mass flow rate increases.

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