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Induced Buoyancy In Inclined Solar Chimney For Natural Ventilation

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Abstract

A 2-D plane, steady, incompressible, turbulent flow field developed by natural convection inside inclined solar chimney at different inclination angles ranging from (30^o to 90^o), heat fluxes from (100 W/m² to 500 W/m²) and chimney thickness(0.1, 0.2 m) chimney is investigated numerically. It is found that maximum air temperature and maximum volume flow rate was 101.7°C, 306.3 m³/h respectively at heat flux,500 W/m^2; inclination angle; 90^o and chimney thickness; 0.2m. Maximum outlet air velocity was 0.488 m/s at chimney thickness; 0.1m, heat flux; 500 W/m^2; and inclination angle; 90^o. Increase in heat flux, inclination angle and chimney thickness leads to increasing of volume flow rate. Increase in chimney cross-sectional area leads to decrease in air velocity and increase in volume flow rate.

Keywords: induced flow, natural convection, solar chimney

الطفو المستحث في المدخنة الشمسية المميلة للتهوية الطبيعية

الخلاصة

تـم اختبـار الاداء النظـري للمدخنـة الشمسـية المميلـة عـدديا خـلال حقـل جريـان مسـتوي، لا انظغـاطي واضـطرابي لتيـارات الحمـل الطبيعـي عنـد زوايـا مـيلان مختلفـة تراوحـت مـن (30^o to 90^o) وفيض حرارة من (100 W/m² to 500 W/m²) وسمك مدخنة (0.1, 0.2 m). بينـت النتـائج ان اقصـى درجـة حـرارة و اقصـى نسـبة جريـان الحجـم كانـت علـى التـوالي, (306.3 m³/h (101.7°C عند جريـان حـرارة(500 W/m^2) وزاويـة مـيلان (90^o) وسـمك مدخنـة(0.2 m). اقصـى سـرعة كانـت(0.488 m/s) عنـد سـمك مدخنـة (0.1m) جريـان حـرارة(500W/m²) وزاويـة مـيلان (90^o). كمـا وجـد ان زيـادة جريـان الحـرارة وزاويـة المـيلان وسـمك مدخنـة تـؤدي الـى زيـادة نسـبة الجريـان الحجمـي وان زيـادة مساحة المدخنة تؤدي الى نقصان السرعة وزيادة نسبة الجريان الحجمي.

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Nomenclature

G	Kinetic energy generation by shear	J
Gr^*	Modified Grashof number=$g\beta q x^4/k/\upsilon$	
q	Heat flux	J/m^2
x, y	Cartesian coordinate	m
S_u, S_v, S_T, S_k, S_p	Coefficients of lineairzed source expression	
S_ϕ	General source term	
S	thickness	m
t_o	Ambient temperature	^oC
u, v	Velocity components in (x&y) directions	m/s
u^*, v^*	guessed Velocities in equation (3-23)	m/s
u', v'	Fluctuation of mean velocities in equations(3-26),(3-27)	m/s
k	Turbulent kinetic energy	m^2/s^2
y^+	Dimensionless distance to wall	
y_p	Distance from near-wall node to the wall	m
Δx , Δy	Physical cell dimensions(i. e. distance between cell-faces in Cartesian coordinate)	m
ε	Rate of dissipation of kinetic energy	m^2/s^2
ρ	Fluid density	kg/m^3
ϕ	General dependent variable	
μ	Dynamic viscosity	$N.s/m^2$
υ	viscosity	
μ_t	Turbulent viscosity	$N.s/m^2$
μ_{eff}	Effective kinematics viscosity	$N.s/m^2$
Γ	Diffusion coefficient, =μ/d Γ	$N.s/m^2$
Γ_{eff}	Effective diffusion coefficient	$N.s/m^2$
τ_i	Shear stress in inertial sub layer	N/m^2
τ_{wall}	Wall shear stress	N/m^2
β	Volume coefficient of expansion	1/K
θ	Inclination angle	degree
g	Acceleration of gravity	m/s^2
eff	effective	
o	Ambient	

1-Introduction

The solar chimney is a simple channel glazed on one side with a collector wall on the other, during the day solar energy heats the chimney and the air within it creates an up draft of air in the chimney. Thesuction created at the chimney's base can be used to ventilate, cool and warm the building (Figure 1). Maad and Belghith [1] analyzed numerically the natural convection flow between two heated vertical platestodesign and realize a and Abdrabboh [4] investigated a combined wall roof solar chimney to improve night-time ventilation in building and reported that a roof solar chimney alone can induce airflow rate of 0.81m³/s when the average solar radiation is 850w/m².The maximum air velocity induced was 1.1m/s when the 25° inclined chimney plates were 0.25m apart. Chen [5] carried out experiments using an experimental solar chimney model with uniform heat flux on one chimney wall with variable chimney gap to height ratio from 1:15 to 2:05,different heat flux and inclination angles. Their results show maximum airflow rate at an inclination angle around 45° for a 200mm gap and 1.5m height of chimney. Jyotirmay, et al. [6] investigated the effect of inclination of absorber on the airflow rate in a solar induced ventilation system using Roof Solar Chimney (RSC) concept. Mathur S., et al. [7] reported an experimental investigation on four different configurations of solar chimneys. The results showed that the rate of ventilation increases when the solar chimney. Bansal and Mathur [2] studied the inclined solar chimney for enhanced stack ventilation in India. A steady state mathematical model wasdeveloped for a solar chimney. La Pica [3] recorded data from a channel 2.6m high. The channel was heated from one side using an electrical heating mat(theabsorberplate'in terms of a Trombe wall), and the other surface (the'cover') was silvered to reduce heat losses. Aboulnag flat absorber is inclined at an angle of 45º. Highest rate of ventilation induced with the help of inclined solar chimney was 273.5 kg/hr in comparison of 261.4 kg/hr for flat absorber chimney at solar radiation of 1000 W/m². J. Halldorsson, et al. [8] made experiments to study a full scale solar chimney as a ventilation device. The results showed that by changing the chimney gap while maintaining all the other conditions, the air flow rate increased continuously with increasing chimney gap. Andrew W. Woods [9] investigated the effect of a solar chimney on the effectiveness of natural ventilation in a large open building. It was shown that in regimes of low internal heat load, the additional solar drive can lead to much enhanced natural ventilation flow. Sakonidou E.P. and Karapantisios T.D. [10] developed a mathematical model to determine the tilt that maximizes natural airflow inside a solar chimney using daily solar irradiance data on horizontal plane at a site. Zoltan Adam, et al. [11] Mathematical model and Experimental study of airflow in solar chimneys", this research was done in Osaka University / Japan, the study aims to produce a mathematical simulation and experimental investigation of airflow in solar chimney which was a simple channel glazed on one with a collector wall on the other, used to calculate the mass flow rate of many chimneys, that of these models used average temperatures and transfer coefficients to calculate the temperature distribution inside the chimney. Cuohui Gan [12] studied solar heated open cavities including solar chimneys and double facades for enhancing natural ventilation of buildings. A commercial CFD package was used to predict buoyant air flow and flow rates in the cavities.

The present work is a study using computational fluid dynamics with finite–volume to solve the continuity, momentum and energy with 2D, conduction equations with rectangular coordinates is conducted. The study investigates the effects of induced natural convection due to incident solar radiation on temperature distribution and air flow velocity inside the chimney is investigated. The effect of different boundary conditions and effective parameters (inclination angle, heat flux and chimney thickness) on flow field and heat transfer was investigated to complete thermal analysis.

2-Problem Description

The computational domain with boundary conditions is shown in Figure 1. The aim of the study is to calculate the induce velocity inside the solar chimney. Solar flux is dropped in the glass cover the chimney then into the base of the solar chimney. The heating base will induce velocity due to natural convection. The induce velocity will depends mainly on the angle of the solar chimney. Zero induce velocity was expected when angle = 0, while 90 degree angle will induce maximum velocity.

3-Numerical Technique e and Mathematical Model

The basic equations that describe the flow and heat are continuity, momentum and energy equations. These equations describe plane, turbulent and incompressible flow. The values of modified Grashof number are between 2E+7 to 2E+9, so the equations are written with turbulent form and take the following forms:

$$\frac{\partial}{\partial x}(\rho u\varepsilon)+\frac{\partial}{\partial y}(\rho v\varepsilon)=\frac{\partial}{\partial x}\left(\Gamma_{\varepsilon}\frac{\partial\varepsilon}{\partial x}\right)+\frac{\partial}{\partial y}\left(\Gamma_{\varepsilon}\frac{\partial\varepsilon}{\partial y}\right)+C_1\frac{\varepsilon}{k}G-C_2\rho\frac{\varepsilon^2}{k}$$

i- Continuity equation (mass conservation)

$$\frac{\partial}{\partial x}(\rho u)+\frac{\partial}{\partial y}(\rho v)=0 \qquad \ldots(3\text{-}1)$$

ii - Momentum equations:

u-Momentum (x-direction)

$$\frac{\partial}{\partial x}(\rho uu)+\frac{\partial}{\partial y}(\rho vu)=-\frac{\partial p}{\partial x}+\frac{\partial}{\partial x}\left(\mu_{eff}\frac{\partial u}{\partial x}\right)+\frac{\partial}{\partial y}\left(\mu_{eff}\frac{\partial u}{\partial y}\right)+S_u \qquad \ldots(3\text{-}2)$$

v-Momentum (y-direction)

$$\frac{\partial}{\partial x}(\rho uv)+\frac{\partial}{\partial y}(\rho vv)=-\frac{\partial p}{\partial y}+\frac{\partial}{\partial x}\left(\mu_{eff}\frac{\partial v}{\partial x}\right)+\frac{\partial}{\partial y}\left(\mu_{eff}\frac{\partial v}{\partial y}\right)+S_V \qquad \ldots(3\text{-}3)$$

iii - Energy Equation

$$\frac{\partial}{\partial x}(\rho uT)+\frac{\partial}{\partial y}(\rho vT)=\frac{\partial}{\partial x}\left(\Gamma_{eff}\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(\Gamma_{eff}\frac{\partial T}{\partial y}\right)+S_T \qquad \ldots(3\text{-}4)$$

Where:

$$S_v = \frac{\partial}{\partial x}\left(\mu_{eff}\frac{\partial u}{\partial y}\right) + \frac{\partial}{\partial y}\left(\mu_{eff}\frac{\partial v}{\partial y}\right) + buoyanc$$

…(3-5)

$$S_v = \frac{\partial}{\partial x}\left(\mu_{eff}\frac{\partial u}{\partial y}\right) + \frac{\partial}{\partial y}\left(\mu_{eff}\frac{\partial v}{\partial y}\right) + buoyancy$$

….(3-6)

$S_T = 0$

Where:

μ_{eff} = effective viscosity coefficient as in equation (3-7) below:

$\mu_{eff} = \mu + \mu_t$ ….(3-7)

Γ_{eff} = effective diffusion coefficient as in equation (3-8) below:

$$\Gamma_{eff} = \frac{\mu_{eff}}{\delta_{eff}} + \frac{\mu_t}{\delta_t} \quad ….(3\text{-}8)$$

$$buoyancy \ \ (for \ \ u) = \rho g \beta (T_f - T_{in}) \sin\theta$$

….(3-9)

$$buoyancy(for \ v) = \rho g \beta (T_f - T_{in}) \cos\theta$$

….(3-10)

Where δ_{eff} is the effective Prandtl number including the turbulent dynamic viscosity and turbulent diffusion coefficient.

The turbulence according to Launder and Spalding [13] is assumed to be characterized by its kinetic energy and dissipation rate (ε). This model relates the turbulent viscosity to the local values of ρ, k and ε by the expression.

$$\mu_t = \rho C_\mu k^2 / \varepsilon \quad ….(3\text{-}10)$$

Where C_μ is an empirical "constant" value for high Rayleigh number. The turbulence parameters k and ε are derived from their respective transport equations. The modeled forms of these equations, steady are as follows:

i - Turbulence kinetic energy (k):

$$\frac{\partial}{\partial x}(\rho uk) + \frac{\partial}{\partial y}(\rho vk) = \frac{\partial}{\partial x}\left(\Gamma_k \frac{\partial k}{\partial x}\right)$$
$$\frac{\partial}{\partial y}\left(\Gamma_k \frac{\partial k}{\partial y}\right) + S_k$$

…. (3-11)

(Convection transport of k) (Diffusion transport of k due to velocity and pressure fluctuation)

Here:

$$\Gamma_k = \mu_{eff} / \delta_k \quad …..(3\text{-}12)$$

$$S_k = G - C_D \rho \varepsilon \quad … (3\text{-}13)$$

ii - Dissipation rate (ε):

$$\frac{\partial}{\partial x}(\rho u\varepsilon) + \frac{\partial}{\partial y}(\rho v\varepsilon) = \frac{\partial}{\partial x}\left(\Gamma_\varepsilon \frac{\partial \varepsilon}{\partial x}\right) + \frac{\partial}{\partial y}\left(\Gamma_\varepsilon \frac{\partial \varepsilon}{\partial y}\right) + C_1 \frac{\varepsilon}{k} G - C_2 \rho \frac{\varepsilon^2}{k}$$

….(3-14)

Here:

$$\Gamma_\varepsilon = \mu_{eff} / \delta_\varepsilon \quad ….(3\text{-}15)$$

Where:

$$G = \mu_t \left(2\left[\left(\frac{\partial u}{\partial x}\right)^2 + \left(\frac{\partial v}{\partial y}\right)^2\right] + \left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x}\right)^2 \right)$$

…(3-16)

= kinetic energy generation by shear

The values of the empirical constant used here are given in Table 1. At outlets of the computation domains, and at large Ra, the usual practice is to set normal gradients to zero. The conservation equation of mass, momentum and energy are solved by the SIMPLE algorithm with hybrid difference scheme.

Uniform grids were employed, with 56×36 mesh.

4- Heat Conduction

Conduction equation in the solid is:

$$\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial Y^2} = 0 \quad \ldots (3\text{-}17)$$

Three nodes are used for conduction in upper class, and three nodes are used for the base in y-direction while same number of nodes is used in x-direction (56) as in the fluid.

5- Results and Discussion

Build in Fortran F90 program was used to apply Finite volume for fluid calculation and finite difference for conduction in solid. Conduction subroutine was inserted with main finite volume program to exchange data between solid and fluid. Figure 2 at (S=0.2m), (q=300W/m²) and ($\theta=60^{\circ}$) shows that the air velocity reaches its maximum at the outlet of the chimney's cross section (since the heat accumulated by the absorber tends to accelerate the air over it). The velocity decreases upward until it reaches its minimum value near the glass cover but it does not reach zero value because the glass cover still keeps some heat. The maximum air velocity is 0.33 m/s. Thermal distribution in Figure 2 shows that the temperature reaches its maximum value at the center of the absorbing wall (since the absorbing wall absorbed heat, its temperature will increase till its length center, then the air velocity increase to the exit section it cools the absorbing wall from the wall center to the exit) and along the absorbing wall and it decreases until it reaches its minimum value near the glass cover which is, at 23.2 ºC. The maximum temperature at the center is 69.07 ºC.

Figure 3 shows the variation in volume flow rate with inclination angle at five heat fluxes (from 100 W/m² to 500 W/m²) and chimney thicknesses 0.1m, the figures show that the volume flow rate increases linearly with the increase in inclination angle, the increase in heat fluxes and chimney thicknesses were found to have the maximum volume flow rate at inclination angle 90°, heat flux 500 W/m² and chimney thickness 0.2.

Figure 4 shows the variation in volume flow rate with inclination angle at two chimney thicknesses (0.1m, 0.2m) and heat flux 500 W/m². The figure shows that the volume flow rate increases linearly with increase in chimney thickness and with the heat flux.

Figure 5 shows the variation in volume flow rate with the heat fluxes at five inclination angles (from 30° to 90°) and chimney thicknesses 0.2 m. The figure shows that the volume flow rate increases linearly with the increase in heat fluxes, the increase in inclination angles and chimney thicknesses.

Figure 6 shows the variation in volume rate with heat flux at two chimney thicknesses (0.1m and 0.2m) and inclination angle 30°. The figure shows that the volume flow rate increases linearly with increase in chimney thickness and with the inclination angle.

All previous figures show that the volume flow rate increases with the increase in chimney thickness and reaches its maximum value at chimney thickness 0.2m, inclination angle 90° and heat flux 500 W/m² while the minimum at chimney thickness 0.1m , inclination angle 30° and heat flux 100 W/m².

From the results and the figures we conclude that the volume flow rate increases with the increase in inclination angle, heat flux and chimney thickness and the air velocity increases with increase in heat flux and inclination angle while it decreases with the increase in chimney thickness. The air temperature increases with increase in heat flux only and it has the same value at different inclination angles and chimney thicknesses.

6- Conclusions

The following conclusions have been drawn:

1- The numerical results and figures in this study have a good agreement with the experimental results under the same conditions.

2- Maximum air temperature was 101.7C^o at heat flux; 500 W/m^2 maximum outlet air velocity; 0.488 m/s, at chimney thickness; 0.1m.

3- Maximum volume flow rate at heat flux was; 500 W/m^2, inclination angle; 90^o and chimney thickness; 0.2m.

4- Increasing heat flux, inclination angle and chimney thickness leads to increasing in volume flow rate.

5- The Increase in chimney thickness leads to decrease in air velocity and increasing in volume flow rate.

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Table (1) Values of constants in the $(k-\varepsilon)$ model

C_μ	C_D	C_1	C_2	δ_k	δ_ε
0.09	1.00	1.44	1.92	1.0	1.3

Table (2) Verification of the values of volume flow rate

Heat flux(W/m²)	**Chimny thickness (m)**	**Angle (degree)**	**Q(m³/h)**		**Deviation%**
			Present Study	**Zoltan and Toshio[11]**	
100	0.2	60	191.0224	189.3554	0.833055
200	0.2	60	219.5053	---	---
300	0.2	60	242.0304	242.1745	0.0019639
400	0.2	60	272.9298	---	---
500	0.2	60	300.9745	300.40045	0.191094

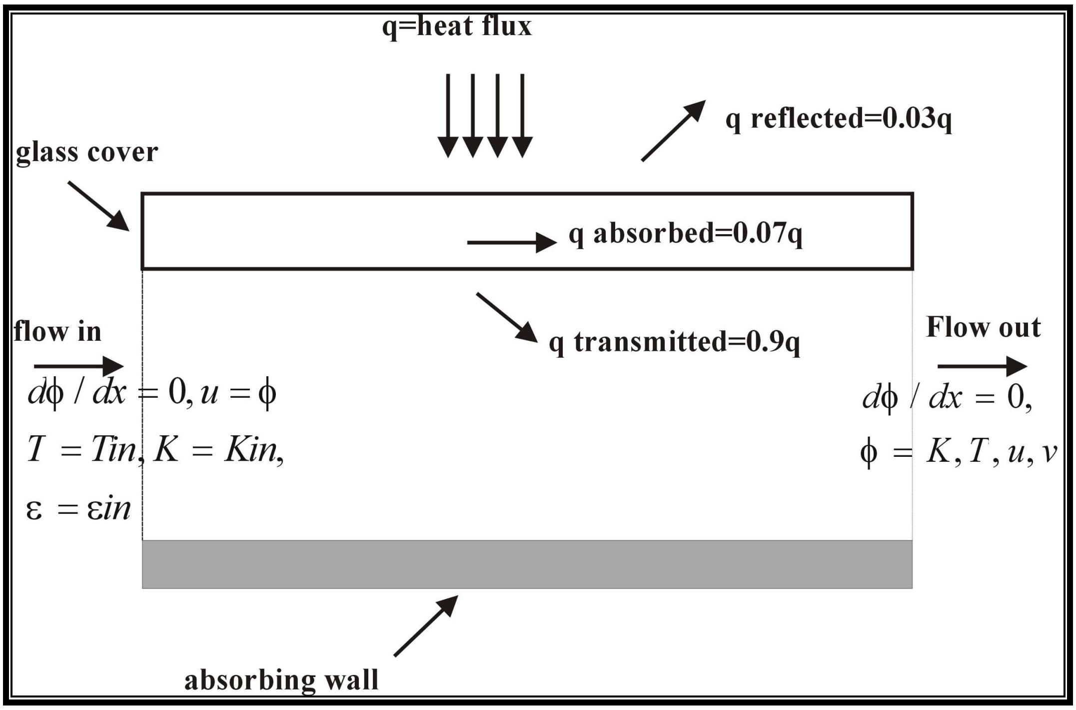

Figure (1) Solar chimney with Boundary conditions

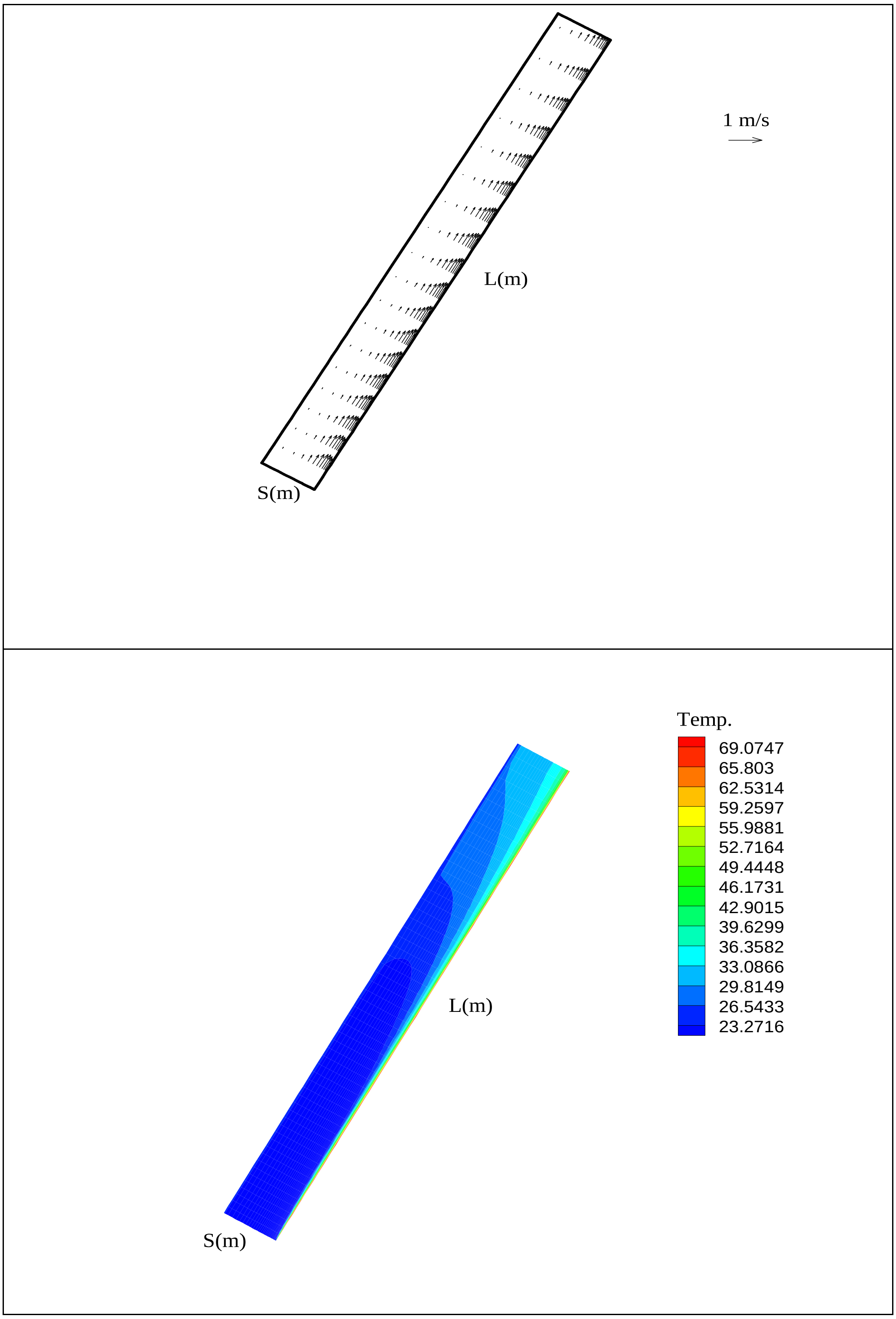

Figure (2) Flow field and isothermal at heat flux; q=300 W/m², angle; θ=60º and chimney's thickness; S=0.2m

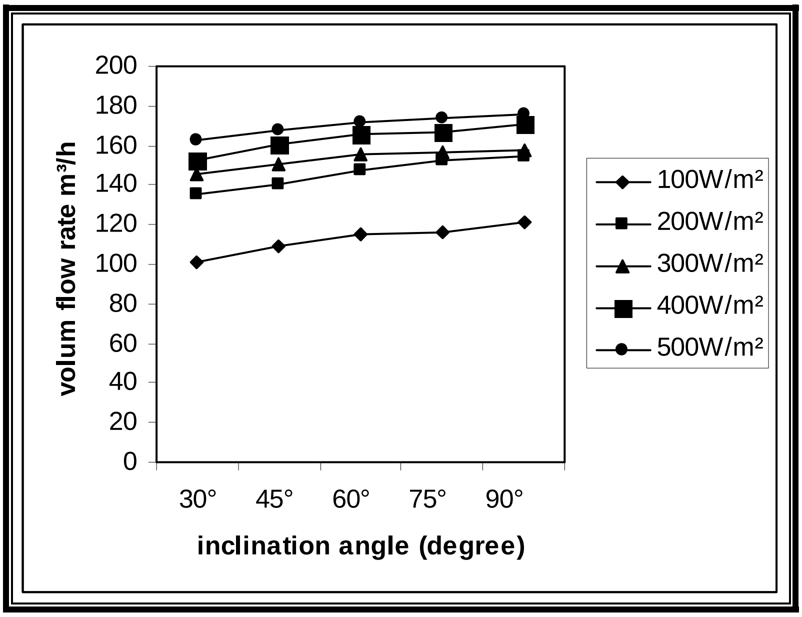

Figure (3) Variation in volume flow rate with inclination angle at chimney thickness; 0.1m and heat fluxes; 100, 200, 300, 400, 500 W/m².

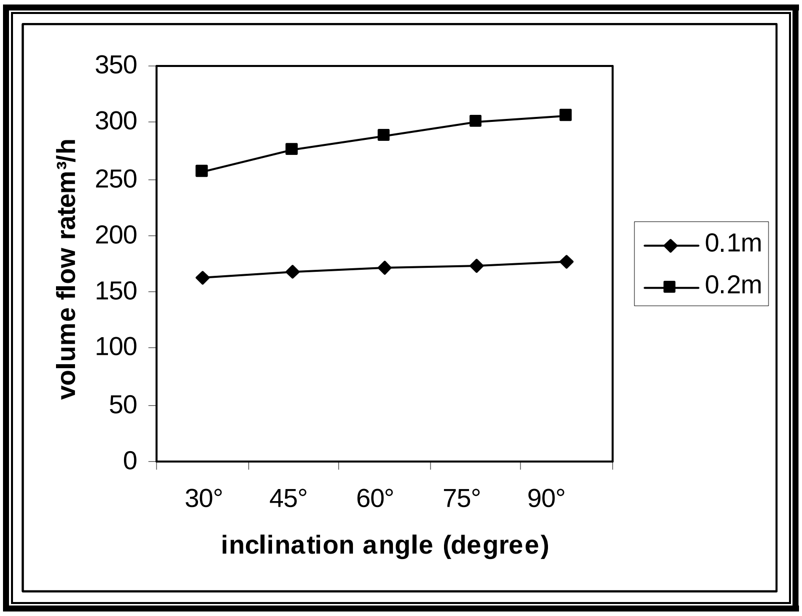

Figure (4) Variation in volume flow rate with inclination angle at heat flux; 500 W/m² and chimney thicknesses; 0.1, 0.2 m.

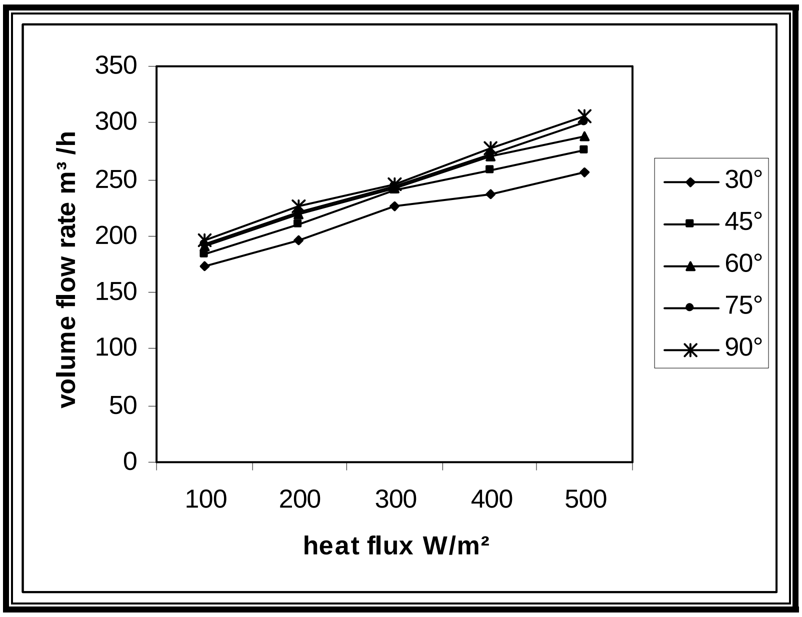

Figure (5) Variation in volume flow rate with heat flux at chimney thickness; 0.2 m and inclination angles; 30° , 45°, 60°, 75°, 90°.

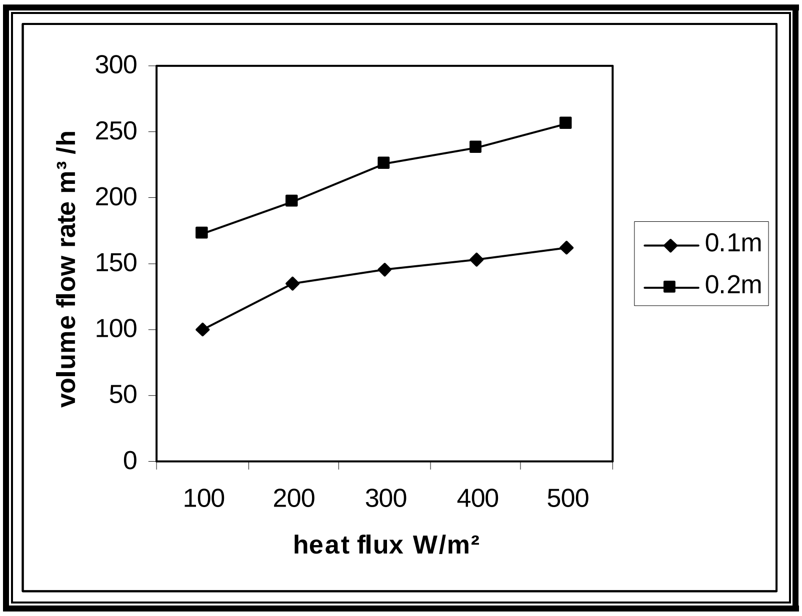

Figure (6) Variation in volume flow rate with heat flux at inclination angle; 30° and chimney thicknesses; 0.1, 0.2 m.