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CONVECTIVE HEAT TRANSFER FROM HEATED OBJECT IN A SQUARE ENCLOSURE

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ABSTRACT

This paper presents, the computational analysis of natural convection heat transfer from a heated object in an square enclosure. The enclosure has two ventilators at the top of the vertical side walls. An isothermally heated object is placed at the middle of the bottom of the container and all walls are assumed to be adiabatic The SUR method is used to solve discritized two dimensional continuity, Navier-Stokes and energy equation on the basis of stream function-vorticity formulation by the finite difference method. Uniform grids are used throughout the computational domain. The fluid flow characteristics and temperature behavior is investigated throughout the enclosure. The fluid from the surrounding entrains into the enclosure and fills up the empty space. Rayleigh numbers in the range from $1.0x10^2$ to $1.0x10^4$ is considered for the investigation. The heating efficiency of the enclosure is increases with the decrease of Rayleigh numbers.

Keywords: Free Convection, Heating efficiency, Enclosure, Recirculation, Separating Stream line.

1. INTRODUCTION

Natural convection heat transfer plays important role in the industrial application. Investigation about buoyancy dominated flow is carrying out for long time by the researchers. The investigation about heat transfer characteristics of a submerged heated object in fluid such as electrical winding in transformers, crops in green house, human body in atmosphere and electronic parts in enclosure etc. have attracted the researcher. The study of natural heat transfer characteristics is very important in engineering applications.

The cooling of mechanical or electronic devices is increasing in almost every branch of industry due to their continuous application. Introduction of microelectronics together with increasing demands on cryogenic engineering, especially in the field of refrigeration with micro fins is growing up. The ever increasing miniaturization, packaging density, quality demands and reduction in life costs will put ever-increasing pressure on the solutions of these problems.

The solution of such heat transfer depends on successful and accurate solution of the nonlinear Navier-Stokes equation along with the energy equation. Various attempts have been made in obtaining approximate solutions based on simplified Navier-Stokes equations. With the advent of high speed computers, numerical modeling of complex free convective heat transfer solutions has become simpler. The specific problem dealt with here is dependent on a number of parameters, an optimization of which is necessary to yield reasonably accurate results.

The demand of high performance heat exchanger having spatial dimensions is increasing due to their need in applications such as transformer cooling, comfortableness of human body, electronic equipments and so on. Enhancement technique that improves over all heat transfer characteristics, are important to heat exchanger designers. However, it is important to have knowledge of the characteristics of laminar free convection heat transfer from isothermal surface of objects in order to exercise a proper control over the performance of the heat exchanger and to economize the process.

Natural air ventilation in partially open cavities is encountered in many practical applications such as energy conservation in buildings and the heating or cooling of environmental systems. In this work, natural convection heat transfer in a partially open cavity is investigated. A vertical isothermal object is placed inside the middle of the enclosure, acts as the thermal source which is responsible for the buoyant force of the inside fluid and the lighter fluid exits from the enclosure through the ventilators. At the same time, cold surrounding fluids enter into the container through the lower portion of the same openings and becomes hot and exit through the openings again.

Chu and Churchill [1] have studied the natural convection caused by a heat-generating conducting body located inside an enclosure. Numerical studies of natural convection heat transfer and flow in closed enclosures without a local heat source are reported in the literature;

it can be cited the work of Davis [2]. Numerous studies on natural convection caused only by external heating in partially open enclosures have been conducted by Chan and Tien [3]. Nara [4] was one of the first researchers to perform numerical simulations of air circulation within Greenhouse. He used the vortices and stream functions as field variables to solve the finite difference scheme of the Navier-stokes equation for a two dimensional cross-section on a mono span greenhouse with a fixed temperature difference between a worm soil and a colder roof to simulate soil surface heated by solar radiation. Aubinet and Deltour [5] who studied natural convection for heating pipes in greenhouse tomato canopy and characterized the plume generated by the heating pipes in the crop rows. However, few results have been reported for natural convection caused by an internal local heat source, although problems of this type are frequently important and their study is necessary for understanding the performance of complex natural convection flow and heat transfer.

2.MODEL DESCRIPTION

The geometry for the consideration is shown in Fig. 1. The model considered here is a rectangular enclosure with two side openings on two side walls with an object, isothermally heated is placed on the bottom surface at the middle of the enclosure. The enclosure dimensions is L=6 and H=6 and opening width W=1. All walls of the enclosure are assumed to be adiabatic. The out flow openings are located on the top of left and right vertical walls as shown in the Fig. 1.

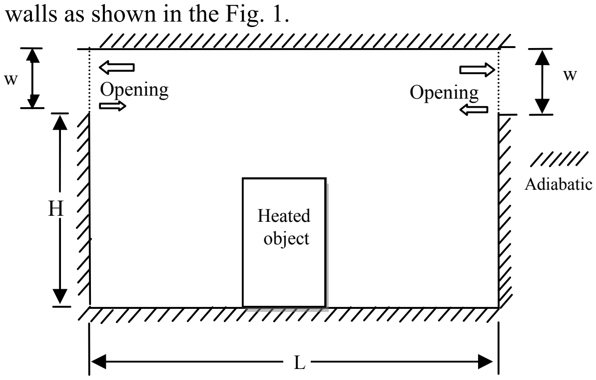

Fig 1. Schematic diagram of the problem considered and coordinate system.

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3. MATHMATICAL FORMULATION

Thermo physical properties of the fluid in the flow model are assumed to be constant except the density variations causing a body force term in the momentum equation. The Boussinesq approximation is invoked for the fluid properties to relative density changes to temperature changes and to couple in this way the temperature field to the flow field. The governing equations for laminar, steady, free convection flow using conservation of mass, momentum and energy equation can be used. The two dimensional, steady, incompressible, constant properties laminar flow from the heated object in a container with two side ventilators has been investigated.

4.GOVERNING EQUATIONS

Now for incompressible fluid and for two dimensional flow, steady flow the Navier-Stokes equation and continuity equation can be written as follows,

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0$$

$$u\frac{\partial u}{\partial x} + v\frac{\partial v}{\partial y} = -\frac{1}{\rho}\frac{\partial p}{\partial x} + \nu\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2}\right)$$

$$u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} = -\frac{1}{\rho}\frac{\partial p}{\partial y} + \nu\left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2}\right) + g\beta\,(T_{obj} - T_\infty)$$

The two dimensional energy equations is,

$$u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y} = \alpha\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2}\right)$$

Now, to make this above equation in non dimensional form, the width of two equal opening sides W is considered as the characteristic length, maximum velocity, u_∞ as the characteristic velocity and initial pressure p_0 as the characteristic pressure

$$X = \frac{x}{W}\ ;\quad Y = \frac{y}{W}\ ;\quad U^* = \frac{u}{u_\infty}\ ;\quad P^* = \frac{p}{p_0} = \frac{p}{\frac{1}{2}\rho u_\infty^2}$$

$$\theta = \frac{T(x,y) - T_\infty}{T_{obj} - T_\infty}$$

Now, putting these values in the above equations, the final non-dimensional form will appear,

$$\frac{\partial U}{\partial X} + \frac{\partial V}{\partial Y} = 0$$

$$U\frac{\partial U}{\partial X} + V\frac{\partial V}{\partial Y} = -\frac{1}{2}\frac{\partial P}{\partial X} + \Pr\left(\frac{\partial^2 U}{\partial X^2} + \frac{\partial^2 U}{\partial Y^2}\right)$$

Similarly ,

$$U\frac{\partial V}{\partial X} + V\frac{\partial V}{\partial Y} = -\frac{1}{2}\frac{\partial P}{\partial Y} + \Pr\left(\frac{\partial^2 U}{\partial X^2} + \frac{\partial^2 U}{\partial Y^2}\right) + Ra\,.\Pr\,.\theta$$

and

$$U\frac{\partial \theta}{\partial x} + V\frac{\partial \theta}{\partial y} = \left(\frac{\partial^2 \theta}{\partial x^2} + \frac{\partial^2 \theta}{\partial y^2}\right)$$

5. BOUNDARY CONDITIONS

At all walls: Since the Velocity Component, u and v both are zero at the walls and applying no-slip conditions, u=0 and v=0, then stream function ψ=c and ω=c

the wall are considered as adiabatic.

At the object: Since the velocity component, u and v both are zero at the walls and applying no-slip conditions, u=0 and v=0 then, stream function ψ=c and ω=c. The object is assumed to be heated. So, the dimensionless temperature T=1.0

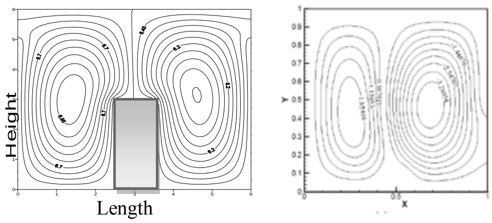
Boundary Conditions at both openings:

Velocity gradients are assumed to be zero for the flow variables as:

$$\frac{\partial u}{\partial x} = 0; \frac{\partial v}{\partial x} = 0; \frac{\partial \psi}{\partial x} = 0; \frac{\partial \omega}{\partial x} = 0; \frac{\partial T}{\partial x} = 0$$

6. RESULTS AND DISCUSSION

The grid independency test has been performed. It is observed that more than 120×120 grid size does not give more accurate result, but increases the computational time only. The maximum error is obtained as 10^{-11}. Fig.2 shows the comparison between present investigation and the published work of V.C. Mariani and L.S. Coelho[6]. It is observed that there is good agreement between two results.



Present investigation — V.C. Mariani and L.S. Coelho[6]

Fig 2. Comparison between present work and V.C. Mariani and L.S. Coelho[6].

Figure 3, shows the stream function pattern at Ra= $1.0\text{x}10^2$. It is observed that there forms two recirculation on both sides of the heated object and it extended up to the exit openings.

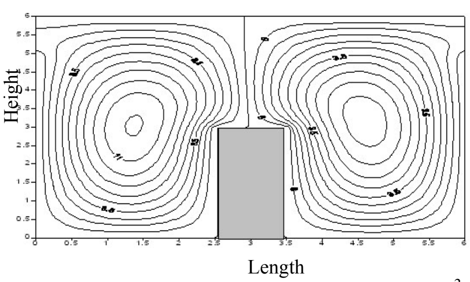


Fig 3. Stream function at Ra=1.0×10^3.

The fluid becomes heated as it comes to contact with the heated object and becomes lighter and goes up due to buoyancy force and exit from the openings. As a result a vacuum is created inside the enclosure and fluid comes from the surrounding through the opening to fill up that vacuum inside the enclosure.

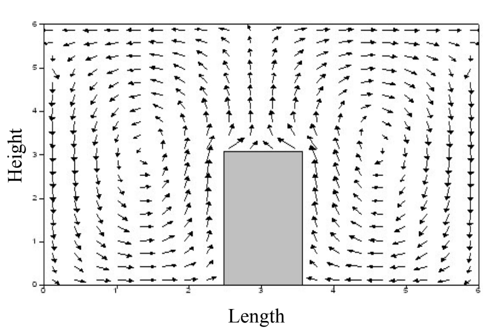


Fig 4. Velocity Vector for Ra=$1.0\text{x}10^3$.

Figure 4 shows the velocity vector for Ra=$1.0\text{x}10^3$ as the heated object placed at the middle of the enclosure. The velocity vector shows the two recirculation region on two sides of the heated object and the separating stream line is shown at the middle plane of the object. The eye of the recirculation created at the same distance on either sides of the object. The direction of the recirculation is opposite in direction. On the left side of the object the fluid is rotating counter clockwise and on the right side of the object the fluid is rotating clockwise direction.

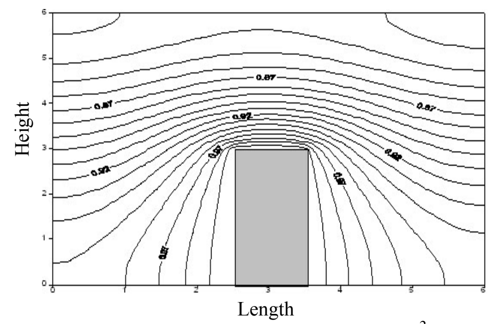


Fig 5. Isotherm at Ra =$1.0\text{ x}10^3$.

Figure 5 shows the isothermal lines at Ra =$1.0\text{ x}10^3$. The cold fluid comes into contact with the heated object and becomes heated and goes up to the top insulated surface.

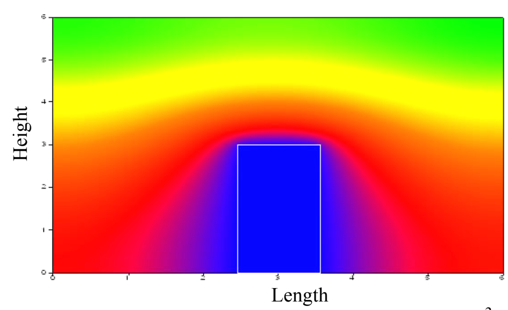


Fig 6. Temperature contour at Ra =$1.0\text{ x}10^3$.

Figure 6 shows the color contour of the flow field at Ra =$1.0\text{ x}10^3$. It is observed that the temperature of the fluid is varying in the whole domain. The blue color predicts the highest temperature, whereas the green color predicts the lower temperature in the domain.

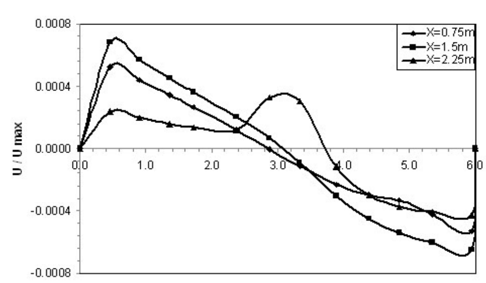


Fig 7. Velocity profile at the left side of the object at

different axial locations from the left vertical side wall for Ra =100.

Figure 7 shows that the velocity varies positive to negative from bottom to top of the enclosure, which is due to the recirculation of the fluid in the enclosure. It is observed that the velocity at the left side of the object increases and then decreases with vertical height and goes to negative value because of recirculation near the object. Very close to the object the magnitude of the velocity is less than the velocity profile at the far distance from the object. Similar trend is observed at the right side of the object, but negative value starts near the bottom of the square enclosure.

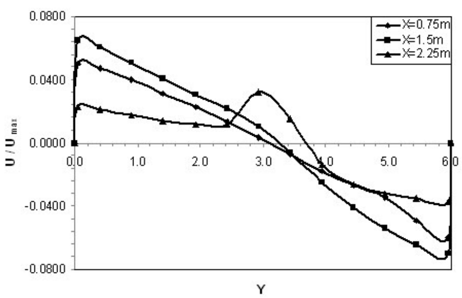


Fig 8. Velocity profile at the left side of the object at different axial locations from the left vertical side wall for Ra =1.0x10^4.

Comparing Fig. 7 and Fig. 8, it is observed the same trends follows for higher Rayleigh no. but the magnitude of the velocity is increased.

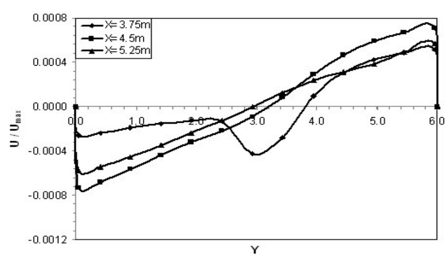


Fig 9. Velocity profile at the right side of the object at different axial locations from the left vertical side wall for Ra =100.

Figure 9 shows the variation of velocity along vertical height at different axial locations from the left vertical side wall. The velocity varies negative to positive value from bottom to the top of the enclosure surface due to the clockwise recirculation.

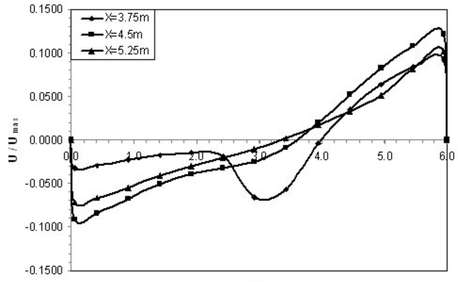


Fig 10. Velocity profile at the right side of the object at different axial locations from the left vertical side wall for Ra =1.0x10^4.

Comparing Fig. 9 and Fig. 10, it is observed the same trends follows for higher Rayleigh no. but the magnitude of the velocity is increased.

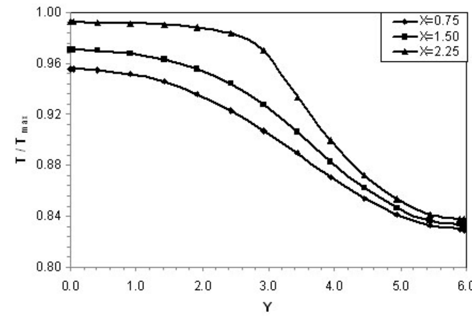


Fig 11. Temperature profile at the left side of the object at different axial locations from the left vertical side wall for Ra =1.0x10^3.

Figure 11 shows that the temperature of the fluid decreases with the increase of vertical height. The fluid very close to the object remains hot up to the height Y=2 and then starts decayed. The fluid far from the heated object starts it decay from the beginning. The temperature profile predicts that the temperature decreases with vertical distance and also decreases with the axial distance far from the object.

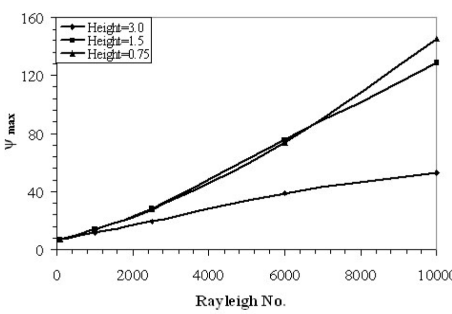


Fig 12. Maximum value of stream function with Rayleigh no. for different object heights.

Figure 12 shows that the maximum value of stream function increases with the increase of Rayleigh no. The maximum value of stream function increases with the increase of Rayleigh number. Also, the value of maximum stream function increases with the decrease of height of the object.

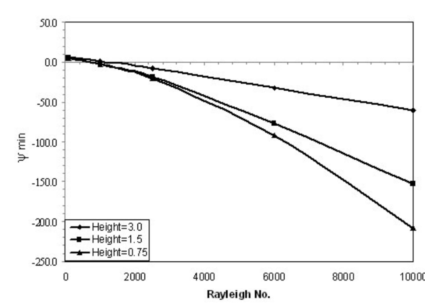


Fig 13. Minimum value of stream function with Rayleigh no. for different object heights

Figure 13 shows that the minimum value of stream function decreases with the increase of Rayleigh no. The minimum value of stream function decreases with the increase of the Rayleigh number. It is observed that the value of Rayleigh number more than 900 predicts the negative value of minimum stream function.

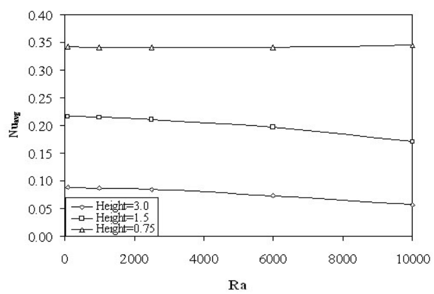


Fig 14. Variations of average Nusselt no. at different Ra & different heights.

Figure14 shows the variation of average nusselt no. with Rayliegh no. for different object heights. It is observed that the average nusselt no. decreases with the increasing of Rayleigh no., but for object height =0.75 the average nusselt no. remains more or less constant for all values of Rayleigh no. The average value of Nusselt number decreases with the increase of Rayleigh number.

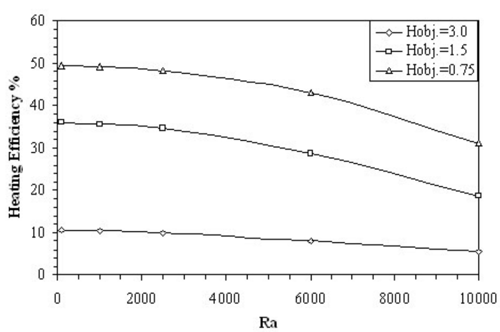


Fig 15. Variation of heating efficiency with Rayleigh no. for different object heights.

The heating efficiency is calculated according to the way described in Singh, S. and Sharif, M.A.R. [7]. The heating efficiency of the enclosure increases with the decrease of Rayleigh numbers. The heating efficiency is higher for the small object size.

7. CONCLUSION

Finite difference numerical method was used for laminar free convection flow in a square container with adiabatic side walls and heated object placed on bottom. The considered range of Rayleigh Number form $1.0x10^2$ to $1.0x10^4$.

This investigation led the following conclusions.

Higher recirculation zones are formed at the two sides of object. The average value of Nusselt number decreases with the increase of Rayleigh number. The heating efficiency decreases with the increase of Rayleigh number and heating efficiency is higher for the small object size.

8. NOMENCLATURE

Symbols	Descriptions
B	The length of space between object surface & container's wall
C_p	Specific heat of fluid at constant pressure
H	Height of the container
H_{obj}	Height of the object
I, J	Index along the X-axis and Y- axis respectively
K	Thermal conductivity
L	Length of the container
L_{obj}	Length of the object
P	Pressure of the flowing fluid
Pr	Prandtl Number
p_0	Initial pressure
P^*	Pressure in the dimension less form, $\frac{p}{\frac{1}{2}\rho u_\alpha^2}$
Re	Reynolds number = $\frac{u_\infty w}{\upsilon}$
Ra	Rayleigh Number, Gr.Pr
T(x,y)	Local fluid temperature
T_{obj}	Temperature of the object.
T_∞,	Fluid temperature
u_∞	Free stream velocity
u, v	Velocity components
U^*, V^*	Dimensionless velocity component, $\frac{u}{u_\alpha} . \frac{v}{u_\alpha}$
W	Outlet opening of the container
x, y	Cartesian coordinates
X, Y	Dimensionless Cartesian coordinates, $\frac{x}{W}, \frac{y}{W}$
ρ	Density of fluid
ω	Vorticity
ω^*	Dimensionless Vortices $\omega^* = \frac{\omega}{\omega_0}$
υ	Kinematics viscosity of fluid
θ(x,y)	Dimensionless temperature, $\frac{T(x,y)-T_\infty}{T_{obj}-T_\infty}$
ψ	Stream function
ψ_0	Initial value of Stream function
ψ^*	Dimensionless Stream function , $\psi^* = \frac{\psi}{\psi_0}$

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