# NUMERICAL INVESTIGATION OF NATURAL CONVECTION HEAT TRANSFER IN AN INCLINED RECTANGULAR ENCLOSURE WITH SINUSOIDAL CORRUGATION

**Md. Anisuzzaman, C.M. Feroz and A.K.M. Sadrul Islam**
Department of Mechanical Engineering
Bangladesh University of Engineering and Technology(BUET), Dhaka
Bangladesh

**Abstract** Natural convection heat transfer phenomena and flow characteristics in an inclined rectangular enclosure consisting of a hot sinusoidal corrugated plate and a cold flat upper plate with plane and adiabatic vertical side walls are investigated numerically for different angles of inclination. The results obtained from numerical investigation are compared with the experimental results. In the numerical analysis the integral form of the governing equations are descretized to linear equations by control volume based finite volume method with collocated variable arrangement. SIMPLE algorithm is used and TDMA solver is applied for solutions of the system of the equations. Average Nusselt number ($Nu_{ave}$ ) and fluid flow patterns are investigated at different angle of inclination of the enclosure and for different aspect ratios. The result reveals that the natural convection heat transfer in a rectangular enclosure, where heat is transferred from a lower hot sinusoidal corrugated plate to a cold flat upper plate decreases with the increase of the angle of inclination(θ) of the enclosure but increases with the increase of aspect ratio(asp).

*Keywords: Natural convection, Nusselt number.*

## INTRODUCTION

The fluid flow in natural convection arises as a result of density variation caused by the thermal expansion of the fluid in a non-uniform temperature field. The flow and heat transfer occurred in the enclosure is the result of the complex interaction between the finite size fluid system in thermal communication into combined walls. In the case of fluid layers inclined with the horizontal, for very small Rayleigh number, the fluid motion consists of one large cell which is known as the 'base flow'. This flow is characterized as ascending fluid layer near the hot surface and descending near the cold surface with streamlines parallel to the boundary surfaces, except at the ends where the fluid turns as long as the inclination angle of the fluid layer is not exactly zero. In this flow regime the heat transfer is purely conductive except at extreme ends, where there is some convective heat transfer associated with the fluid turning. In this paper numerical investigation is done for the prediction of natural heat transfer phenomena and fluid flow pattern in an inclined rectangular cavity where heat is transferred from an inclined lower sinusoidal hot plate to a upper cold flat plate.Vertical sidewalls of the enclosure are plane and adiabatic.

Randall investigated V–corrugated surfaces and correlated the data in terms of the Nusselt number and Rayleigh number. Elsherbiny et al. reported a correlation for wide range of variables: aspect ratio asp = 1 to 4, inclination angle, $0 \le \theta \le 60^0$ and Rayleigh number, $10 \le Ra_L \le 4\times10^6$. In another work Chinnappa reported measurements of heat transfer rates for the horizontal air layers only for a narrow range of Rayleigh number, $7x\ 10^3 \le Ra_L \le 7\times10^5$. Feroz reported results on natural convection heat transfer from hot trapezoidal and rectangular corrugated plate to cold flat plate for different aspect ratios and different angles of inclination including the horizontal. Latifa reported results on natural heat transfer from a hot V-corrugated plate to a cold flat plate for different aspect ratios and different angles of inclination including horizontal. From above it is seen that many researchers have worked on free convection heat transfer in an enclosure bounded by a hot flat or corrugated plate and a cold flat plate. But a very few numerical investigations are reported on natural convection from an inclined hot sinusoidal plate to a cold flat plate. So in this paper an effort has been made to investigate the natural convection numerically from an inclined hot sinusoidal corrugated plate to a cold flat plate and the numerically obtained results are compared with the experimental results of Kabir. Average Nusselt number and flow pattern are investigated for different angles of inclination. Also the investigation is carried out for different aspect ratio of the investigated enclosure.

## MATHEMATICAL MODELING

For laminar, incompressible buoyancy-driven flow of a Newtonian fluid, the governing equations of mass, momentum and energy take the form:

$$\partial u/\partial x + \partial v/\partial y = 0 \qquad (1)$$

$$\partial u/\partial t + u\partial u/\partial x + v\partial u/\partial y = -(1/\rho)\partial p/\partial x + \nu(\partial^2 u/\partial x^2 + \partial^2 u/\partial y^2) + \rho g \cos\theta \qquad (2)$$

$$\partial v/\partial t + u\partial v/\partial x + v\partial v/\partial y = -(1/\rho)\partial p/\partial y + \nu(\partial^2 v/\partial x^2 + \partial^2 v/\partial y^2) + g\beta(T-T_\infty) + \rho g \sin\theta \qquad (3)$$

$$\partial T/\partial t + u\partial T/\partial x + v\partial T/\partial y = \alpha(\partial^2 T/\partial x^2 + \partial^2 T/\partial y^2) \qquad (4)$$

In the mathematical modeling Differential Equations have been solved with the standard Finite-Volume (FV) method using the SIMPLE algorithm. The FV method starts from the conservation equation in integral form. The integral forms of governing equations are descretized using control volume based Finite Volume method (Ferziger et al.).

The final descretized forms of governing equations are solved iteratively using TDMA solver. Iteration is continued until difference between two consecutive field values of variables is less than or equal to $10^{-5}$. For further stabilazation of numerical algorithm, under relaxation factors of 0.2-0.6 are used.

## RESULTS AND DISCUSSION

Figure 1 shows the investigated enclosure with numerical grid. Computations are carried out in the range of Rayleigh number $8.3\times10^4 \leq Ra_L \leq 5.97\times10^5$ and for the angle of inclination $0\leq\theta\leq45^0$. Average Nusselt numbers are computed for different Rayleigh numbers and aspect ratios at different angle of inclination. Aspect ratio is defined here as the ratio of the distance between the hot and cold plates and the amplitude of the sinusoidal corrugation. Computations are carried out for the grid size 240x 80.

Figure 2 shows the comparison of present prediction with the experimental data of Kabir. It is observed that the Natural convection heat transfer rate decreases with the increase of the angle of inclination and also with the increase of aspect ratio.

Figure 3 shows the effects of inclination angle(θ) on Nusselt number ($Nu_L$) for different aspect ratios(asp) and Rayleigh number($Ra_L$). From this figures it is observed that at constant aspect ratio and Rayleigh number, Nusselt number decreases with increasing of inclination angle. For a constant Rayleigh number, Nusselt number is found to be maximum at inclination angle $\theta=0^0$. This trend agrees with the experimental results [Kabir]. This is due to the beginning of the interference of the hydrodynamic instabilities with the motion induced by thermal instabilities as θ increases. The thermal instabilities are dominant at lower angle of inclination.

Isotherms and streamlines at the aspect ratio, asp=3.10 and Rayleigh number, $Ra_L=0.16\times10^6$ are plotted for increasing angle of inclination ($\theta=0^0,15^0,30^0,45^0$) At the angle $\theta=0^0$, four identical vortices are formed. With the increase of angle (at $\theta=15^0,30^0,45^0$) the vortices merges to be one vortex and tend to attain the single cell convection. As a result of this the heat transfer rate decreases.

## CONCLUSION

Natural convection heat transfer characteristics are investigated numerically for three different aspect ratio (2.5,3.10 and 3.65) and various Rayleigh Numbers for different angle of inclination ($\theta=0^0$, $15^0$, $30^0$, $45^0$). The results reveal that the Average Nusselt number decreases with the increase of inclination angle for a constant Rayleigh number and aspect ratio. The average Nusselt numbers are found to be maximum for horizontal layers ($\theta=0^0$) for all aspect ratios and Rayleigh numbers investigated.

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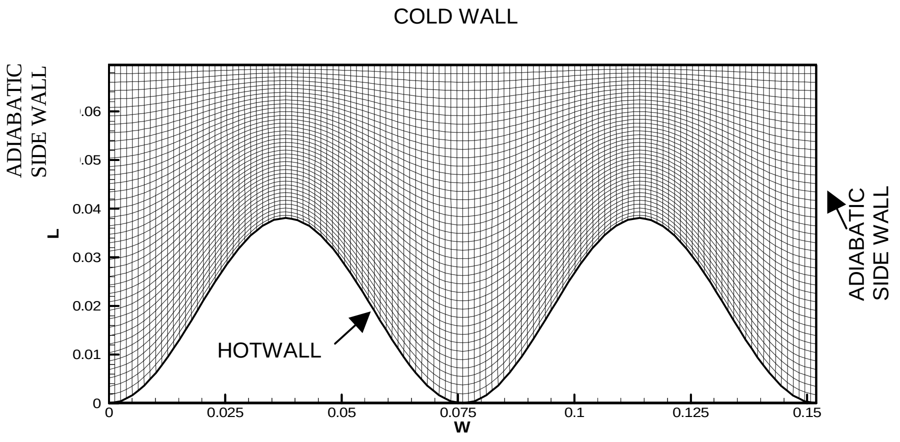


Fig. 1 Investigated rectangular enclosure with numerical grid

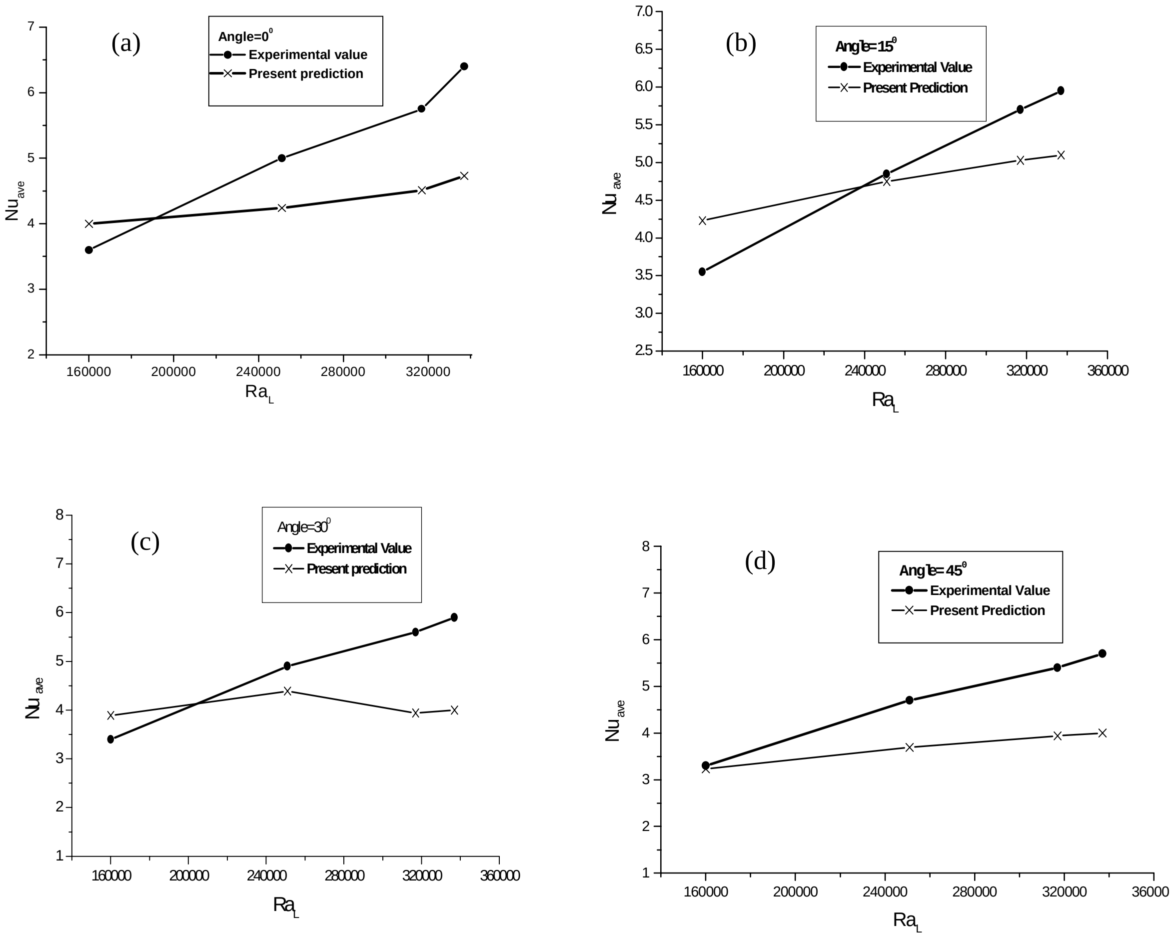
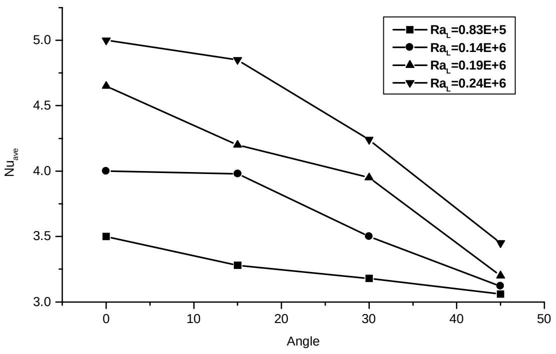
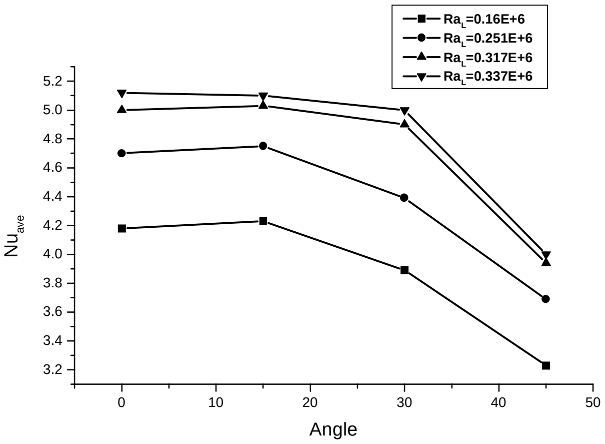


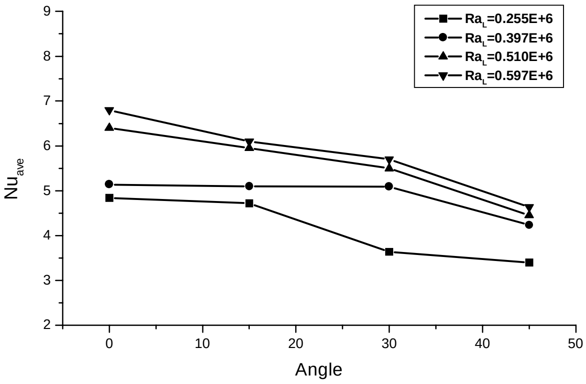
Fig. 2 Average Nusselt number at different Rayleigh numbers for different angles of inclination (θ)



(a) For asp=2.5

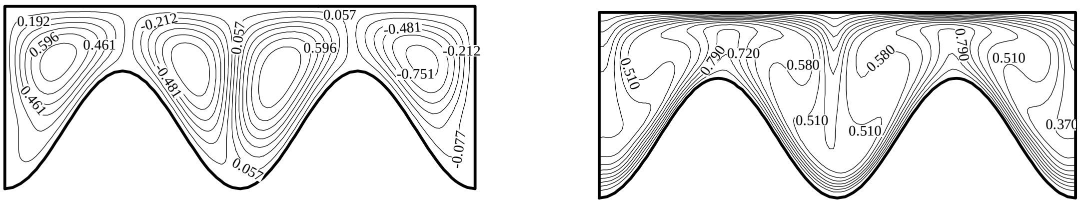


(b) For asp=3.1

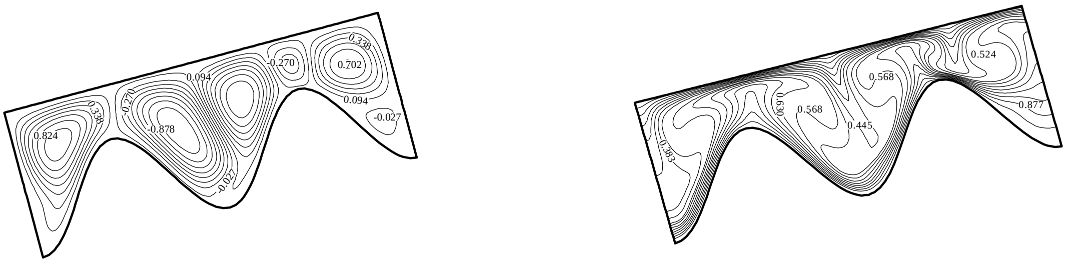


(c) For asp=3.65

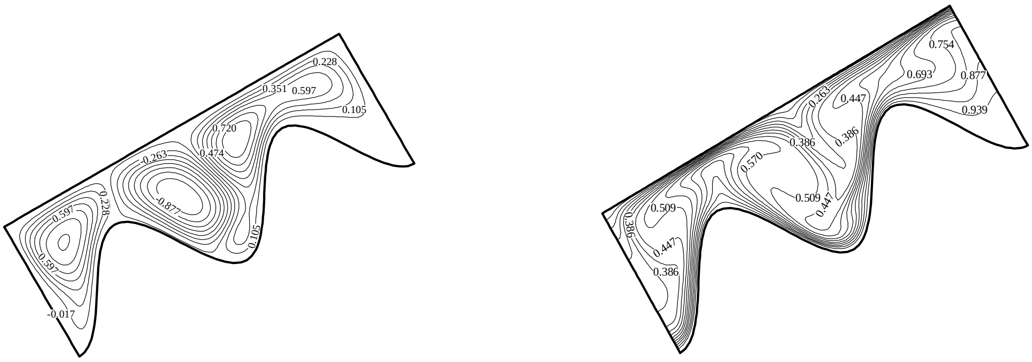
Fig. 3 Change of Average Nusselt number for different aspect ratio and Rayleigh number with the change ogf the angle of inclination



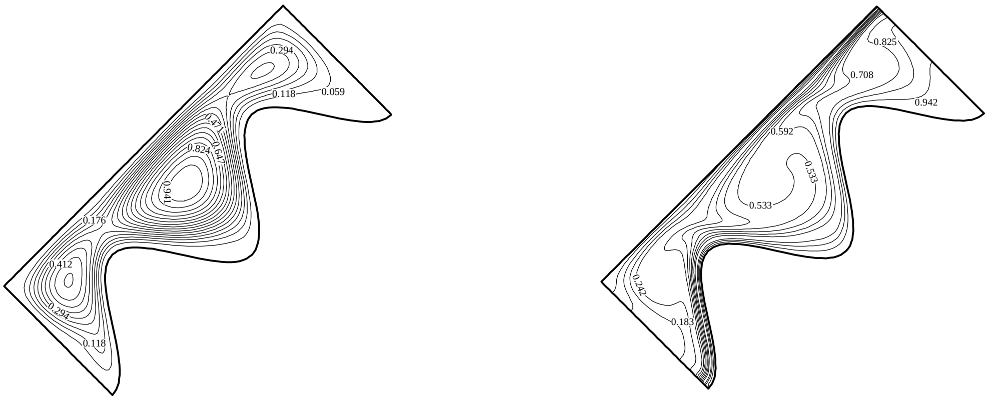
(a) Streamlines at θ=$0^0$ (e) Isotherms at θ=$0^0$



(b) Streamlines at θ=$15^0$ (f) Isotherms at θ=$15^0$



(c) Streamlines at θ=$30^0$ (g) Isotherms at θ=$30^0$



(d) Streamlines at θ=$45^0$ (h) Isotherms at θ=$45^0$

Fig.4 Streamlines and Isotherms at different angle of inclination (asp=3.1, $Ra_L=0.16\times10^6$)