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A Numerical Study of Turbulent Natural Convection in a Rectangular Enclosure with Localised Heating and Cooling

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Abstract: ***This study models natural turbulent convection in a rectangular enclosure with localized heating and cooling. The equations used in modeling the flow are the equation of continuity, momentum equation and the energy equation. The model that is considered is a rectangular enclosure with one side wall being heated and the other side wall being cooled. The other walls of the enclosure are adiabatic. The non – linear differential equations obtained by using the k - turbulence model are solved using the finite difference technique and a computer program called FLUENT 6.3.26 is used in the presentation of results in form of contours. The results of the study show that with increase in the Rayleigh Number, there is increase in the number of contours and vortices. With regard to the velocity magnitude, it is found that an increase in the Rayleigh number results in increase in the turbulence hence implying that there is an increase in the velocity magnitude.***

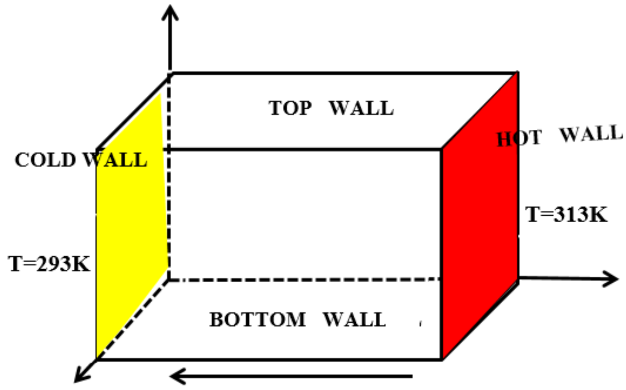
Keyword: Turbulent, Natural Convection, Localised heating, model, Rayleigh number, turbulent intensity.

1. Introduction

There have been studies on modelling of natural turbulent convection flow of fluids in an enclosure by different researchers. Zimmermann [6] is known to have done a numerical study of a turbulent natural convection problem with a compressible Large - Eddy Simulation. Nzomo and Awuor [5] carried out a numerical investigation of turbulent natural convection in a rectangular enclosure using a two equation turbulence model. Most recently Nafula and Awuor [4] studied Numerical Simulation of Turbulent Natural Convective Heat Transfer in a Rectangular Enclosure using the model. However, the determination of fluid quantities such as velocity, temperature and kinetic energy is challenging due to the presence of unknown turbulent correlations in the equations governing turbulent flows. This is attributed to the fact that the terms are nonlinear.

2. Mathematical Model

The geometry of the problem is as illustrated in figure below. The heating and cooling of the rectangular enclosure is done on the face – wall. The lower part of the face – wall is heated (painted red) while the upper half of the face – wall is cooled. The Ampofo and Karayiannis [1] measurements were used because they carried out the experiment under high accuracy. The cold and the hot parts of the enclosure were isothermal at 313k and 293k respectively. All boundaries of the rectangular enclosure are rigid, non - permeable, and have no slip. The other walls of the enclosure are adiabatic.



3. Governing Equations

The set of leading equations in two- dimensional rectangular coordinates which are continuity, momentum and energy equations are derived by Anderson *et al* 1984 [2]

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0 \quad (1)$$

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=-\frac{\partial p}{\partial x}+\mu\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}\right) \quad (2)$$

$$\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}=F_Y-\frac{\partial p}{\partial y}+\mu\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}\right) \quad (3)$$

$$\rho C_p\left(\frac{\partial T}{\partial t}+u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}\right)=k\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}\right)+\Phi \quad (4)$$

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

The above equations were non-dimensionalised to reduce the number of parameters. The resulting equations in general form become;

$$\frac{\partial U}{\partial X}+\frac{\partial V}{\partial Y}=0 \quad (5)$$

$$U\frac{\partial U}{\partial x}+V\frac{\partial U}{\partial Y}+\frac{\partial U}{\partial \tau}=-\frac{\partial P}{\partial x}+Pr\left(\frac{\partial^2 U}{\partial x^2}+\frac{\partial^2 U}{\partial Y^2}\right) \quad (6)$$

$$U\frac{\partial V}{\partial x}+V\frac{\partial V}{\partial Y}+\frac{\partial V}{\partial \tau}=-\frac{\partial P}{\partial Y}+Pr\left(\frac{\partial^2 V}{\partial x^2}+\frac{\partial^2 V}{\partial Y^2}\right)+Ra.Pr.\theta_f \quad (7)$$

$$\frac{\partial \theta_f}{\partial \tau}+u\frac{\partial \theta_f}{\partial x}+v\frac{\partial \theta_f}{\partial Y}=k\left(\frac{\partial^2 \theta_f}{\partial x^2}+\frac{\partial^2 \theta_f}{\partial Y^2}\right)+\Phi \quad (8)$$

4. Temperature and Boundary Conditions

$$\theta_f=\frac{T_f-T_c}{T_h-T_c}=constant\ ,\ \frac{\partial \theta_f}{\partial n}=0,\ \theta_{hot}=1,$$

$$\theta_{cold}=0,\ v=u=0,\ \psi=0,\ \frac{\partial \psi}{\partial n}=0$$

The following constants were also used;
Density of air = 1.1649kg/m^3, Dynamic Viscosity = 1.868E - 5kg/m - s,
Cp= 1.0065E+3J/ Kg/ K, conductivity K= 0.026341W/m/k, Pr = 0.71,

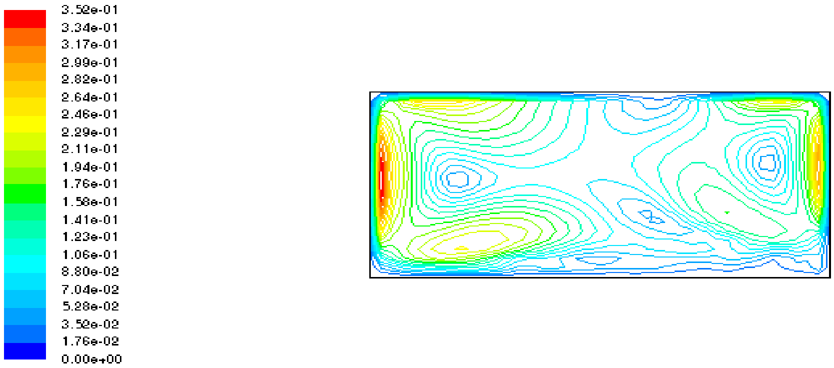
Thermal Expansion Coefficient = 3.2987E - 3

5. Results and Discussion

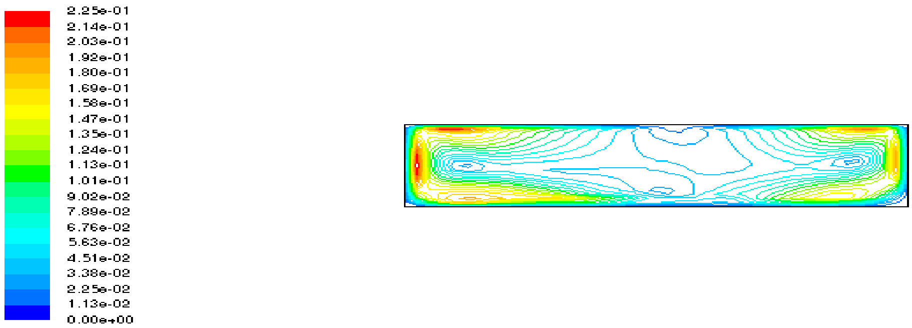
Contours of velocity magnitudes (m/s)

As Rayleigh number rises, it is observed that there is an increase in the number of vortices and increase in the number of streamlines on the hot wall. It can also be noted that there is an increase in turbulence with increase in the Rayleigh number since the flow becomes more chaotic with the increase in the Rayleigh number leading to an increase in the velocity magnitude. The results obtained are in line with the experimental results by Doğan and Doğan (2017) [3 [who pointed out that an increase in the Rayleigh number results in the increase in velocity magnitude. The results are clearly shown in the figures below.

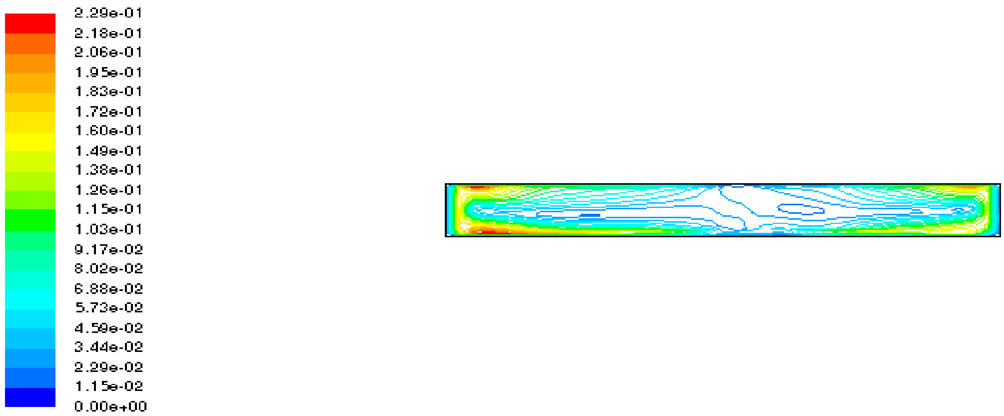
a) Contours of velocity magnitude (m/s) of aspect ratio 2 and Ra = 7.1859×10^{9}



b) Contours of velocity magnitude (m/s) of aspect ratio 4 and Ra = 2.8744×10^{10}



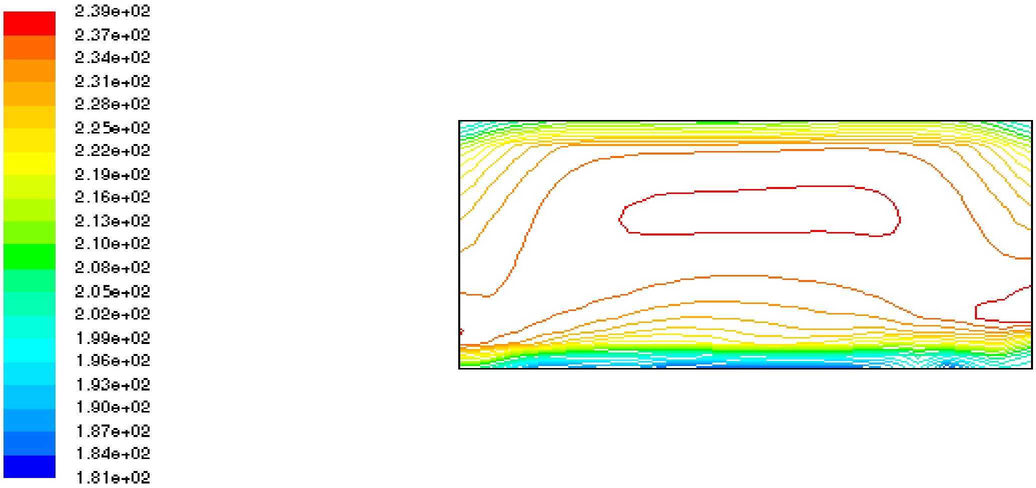
c) Contours of velocity magnitude (m/s) of aspect ratio 8 and Ra = 1.1498×10^{11}



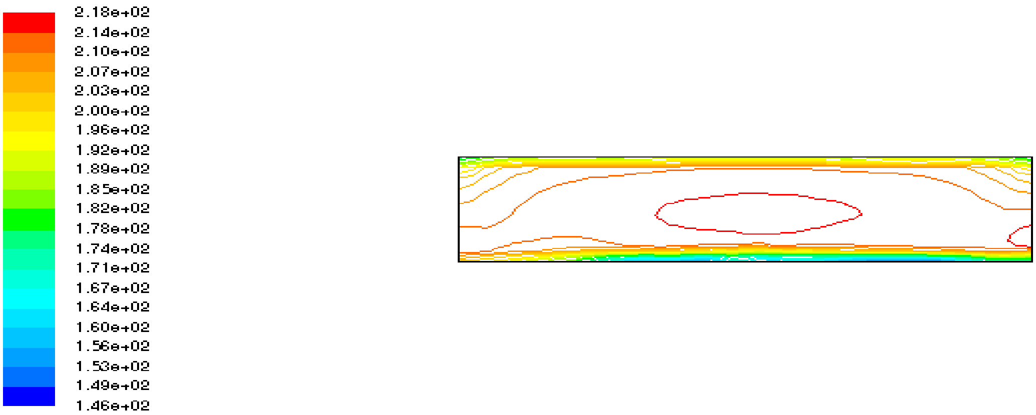
Contours of total temperature

As the Rayleigh number increases, the role of convection in heat transfer becomes more significant. It can be seen that an increase in Rayleigh number makes the distribution of contours to increases. Contours emanate from the hot wall and end on the cold wall illustrating the path of heat flow. The domination of conduction of heat transfer in low Rayleigh number can be observed from the heat line patterns since no passive area exists as shown in figure (a). The increase in Rayleigh number causes clustering of contours from hot to the cold wall and generates passive heat transfer area in which heat is rotated without having significant effect on heat transfer between the walls as shown in figure (c). Also it can be noted that as the Rayleigh number increases, the buoyancy forces increase and in turn the thermal boundary layer thickness near the hot wall decreases and high temperatures tend to concentrate at the centre. The variation of the Rayleigh number in comparison to total temperature is clearly illustrated in figures below;

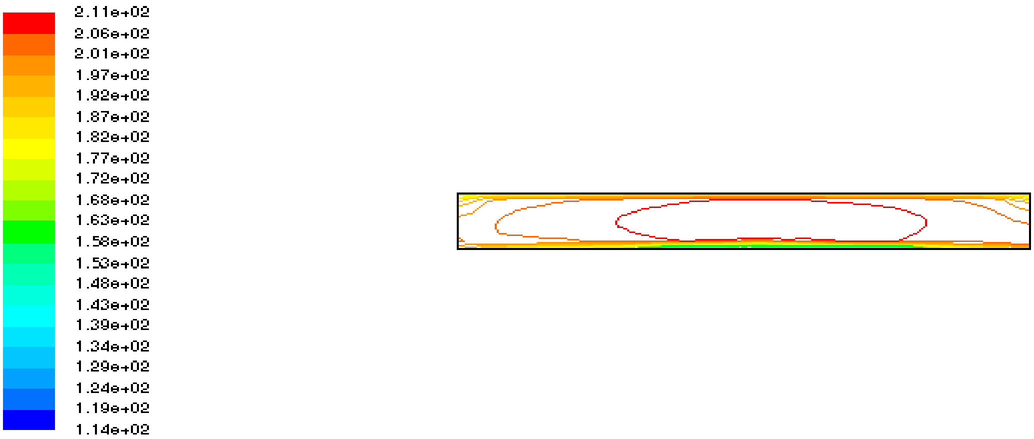
a) Contours of total temperature of aspect ratio 2 and Ra = 7.1859×10^{9}



b) Contours of total temperature of aspect ratio 4 and Ra = 2.8744×10^{10}



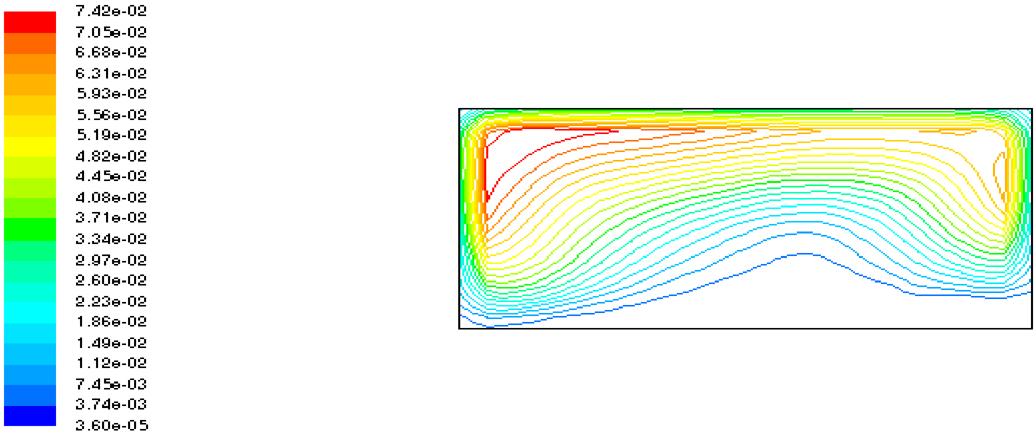
c) Contours of total temperature of aspect ratio 8 and Ra = 1.1498×10^{11}



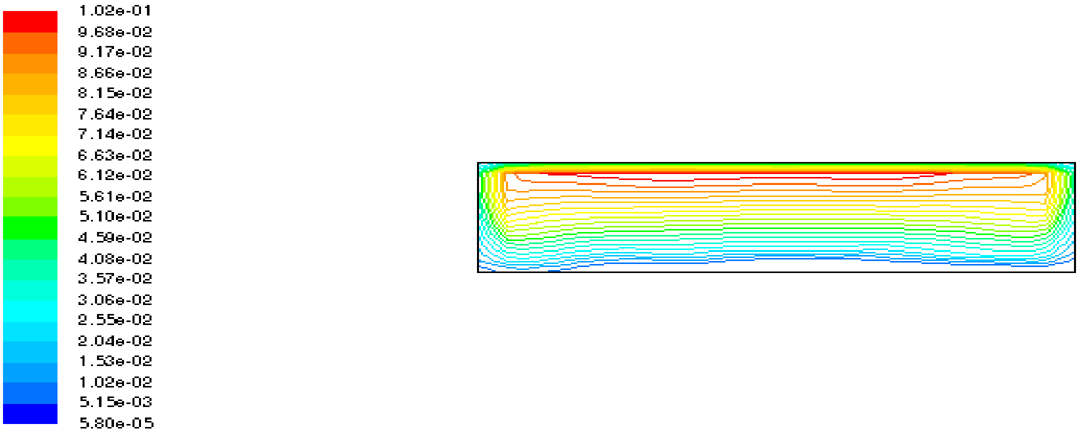
Contours turbulent kinetic energy

Increase in Rayleigh number causes an increase in kinetic energy. The results below show that by increasing the Rayleigh number leads to enhanced turbulent kinetic energy of the fluid in the domain. The results show that improved value of Rayleigh number leads to the enhancement in the fluctuation of kinetic energy, which is the reason of increasing the value of fluid velocity within the enclosure. It is observed that Rayleigh number has a considerable effect on the flow structure and the turbulent kinetic energy, especially with the high speed regimes near the heated wall. There is high kinetic energy at the left part wall compared to the right part wall

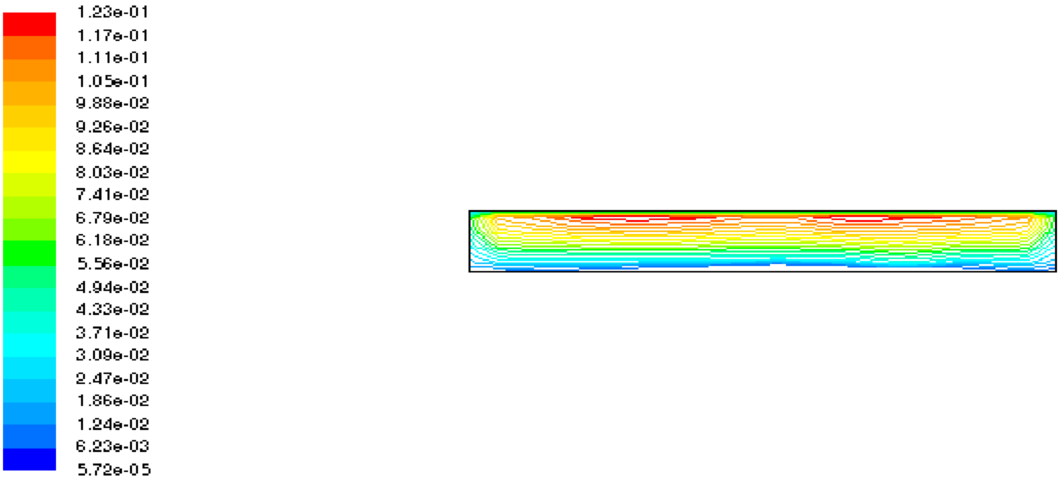
a) Contours of turbulent kinetic energy of aspect ratio 2 and Ra = 7.1859×10^{9}



b) Contours of turbulent kinetic energy of aspect ratio 4 and Ra = 2.8744×10^{10}



c) Contours of turbulent kinetic energy of aspect ratio 8 and Ra = 1.1498×10^{11}



6. Conclusion

The results obtained above indicate that a variation in the Rayleigh number affects the fluid properties such as velocity and temperature. As such, the velocity magnitude rises with the increase in the Rayleigh number. It is found that increase in Rayleigh numbers results in the increase in the size of vortices.

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In relation to the temperature distribution in different parts of the enclosure, it is found that the temperature of the enclosure is higher at the right part of the enclosure and the temperature decreases with the increase in the Rayleigh number. The increase in the Rayleigh number as well is seen to result in an increase in the turbulence and hence the flow becomes more chaotic.

The results also show that by increasing the Rayleigh number turbulent kinetic energy of the fluid in the domain is enhanced. Also, improved value of Rayleigh number leads to the enhancement in the fluctuation of kinetic energy, which is the reason of increasing the value of fluid velocity within the enclosure. It is observed that Rayleigh number has a considerable effect on the flow structure and the turbulent kinetic energy, especially with the high speed regimes near the heated wall.

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