Numerical Study of Natural Convection Flow inside Squared and Trapezoidal Cavities in Various Conditions

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***Abstract*— In this article, natural convection inside square and trapezoidal cavities is simulated numerically. The fluids inside these cavities are air and lubricating oil. Each of the cavities is studied in two different boundary conditions. In all simulations, the results are presented in variety of forms such as streamlines, isothermal lines, and velocity profiles. In all simulations, Rayleigh number ranges between 10^5 and 10^8. As a result, the flow is laminar in all cases. In these flows, various eddies are formed inside the cavity. Some of them are central and large whereas some others appear as tiny eddies in the corners.**

***Index Terms*— Cavity, Natural Convection, Numerical Method, Vortex.**

1) Introduction

Natural convection with the thermal buoyancy influence happens in many applications of science and technology. Natural convection flows are mainly complex concerning several parameters such as the geometry and thermophysical characteristics of the fluid. The study of this field is supported by experimental and numerical methods. Basak et al. [1] investigated natural convection in trapezoidal enclosures for uniformly heated bottom wall, linearly heated vertical wall(s) in presence of insulated top wall. Their method was numerical scheme with penalty finite element method. Parametric studies for the wide range of Rayleigh numbers and Prandtl numbers with various tilt angles of side walls had been performed. Adibi and Razavi [2, 3] in two different work, simulated natural and forced convection in three bench marks. Their bench marks was squared cavity, flow between two parallel plates, and flow over circular cylinder. They used a new numerical scheme that was proposed by themselves. Akbari[4] did a numerical and experimental research about heat transfer. He used finite difference method for numerical simulation. In this research, all kind of heat transfer was considered. The Obtained results indicated that heat absorption occurs 69 % through radiation, 28% convection and 3 % conduction.

In this paper, natural convection in squared and trapezoid cavities are simulated by numerical methods in different conditions and different Prandtl numbers. Four different state are considered in this research.

In the first case, natural condition in a squared cavity is simulated. The temperature of right wall is considered 300K, the left one's is considered 400K. The up and down walls is considered adiabatic. The fluid in cavity is considered air in this condition.

The second case is similar to first one unless, the fluid in cavity is engine oil.

The third case is trapezoid cavity. The boundary conditions in this case is like the first case.

In the fourth and last case, trapezoid cavity is simulated by different boundary conditions. In this case, the temperature of right and left walls is considered 300K and for up and down walls, constant heat rate is considered. This heat rate is equal 400W/m2 and -100W/m2 for up and down walls respectively.

2) Governing equations and Numerical method

In this section, the governing equations the flow are investigated. Given that the flow is assumed to be two-dimensional, the mentioned equations include the continuity equation, the momentum equation in X and Y directions, and the energy equation. The dimensionless form of the mentioned relationships is shown in equations (1) to (4).

$$\frac{\partial U}{\partial X}+\frac{\partial V}{\partial Y}=0 \tag{1}$$

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

$$U\frac{\partial U}{\partial X}+V\frac{\partial V}{\partial Y}=-\frac{\partial P}{\partial Y}+\Pr\left(\frac{\partial^2 V}{\partial X^2}+\frac{\partial^2 V}{\partial Y^2}\right)+Ra.Pr\theta \tag{3}$$

$$U\frac{\partial \theta}{\partial X}+V\frac{\partial \theta}{\partial Y}=\frac{\partial^2 \theta}{\partial X^2}+\frac{\partial^2 \theta}{\partial Y^2} \tag{4}$$

The dimensionless numbers are displayed in equation (5).

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$$X=\frac{x}{H},\ Y=\frac{y}{H},U=\frac{uH}{\alpha},V=\frac{vH}{\alpha},P=\frac{pH^2}{\rho\alpha^2},$$
$$\theta=\frac{T-T_c}{T_h-T_c},\ Pr=\frac{\vartheta}{\alpha},\ Ra=\frac{g\beta(T_h-T_c)}{\vartheta\alpha} \quad (5)$$

In above equation Pr is Prandtl number and Ra is Rayleigh number.

In order to solve the above-mentioned equations numerically, the finite volume method is used. The considered grids for the square and trapezoid is shown in Figure 1. Considering that formed boundary layers require computations with high accuracy, the grids along the walls is finer than the one at the points far from the walls.

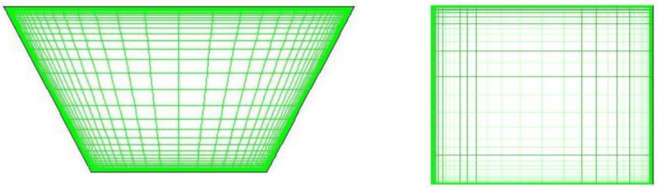

Figure 1. Grids for squared and trapezoid cavities

Then, the Rayleigh number is calculated for each condition ranging between 10^5 and 10^8; however, given that the Rayleigh number is less than 10^9, the flow is considered laminar.

3) Results and Discussions

After carrying out numerical analysis, the results are shown in Figures 2-24. Figure 2 shows the isotherm surfaces in the squared cavity. As Figure 2 indicates, the temperature of the fluid near the left wall is high which is due to the higher temperature of the left plate. The temperature of the fluid near the upper plate is higher than the temperature near the lower one that is because of the lower density of the warm air.

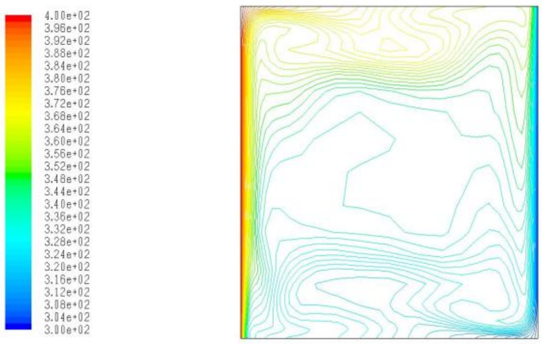

Figure 2. Contours of static temperature in the case 1

The changes in temperature, at five different vertical lines and five different horizontal lines, are shown in Figure 3, 4 respectively.

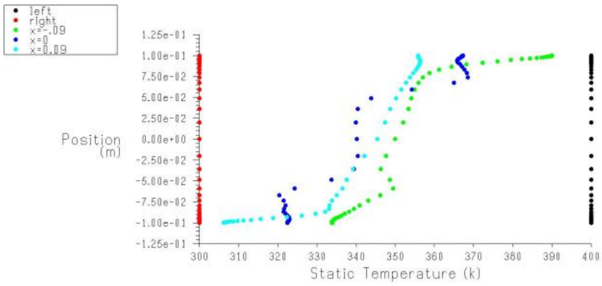

Figure 3. The temperature of fluid at different vertical lines in the case 1

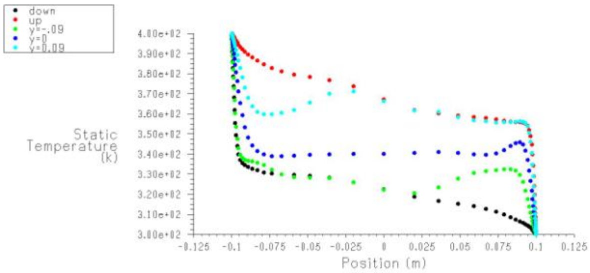

Figure 4. The temperature of fluid at different horizontal lines in the case 1

In Figure 5, the formation of the boundary layer can be easily seen which thickens upward near the left wall where the fluid is getting warmer and expands downward on the left wall where the fluid is getting colder. In Figure 6, the formation of the main vortex and small vortexes can be observed.

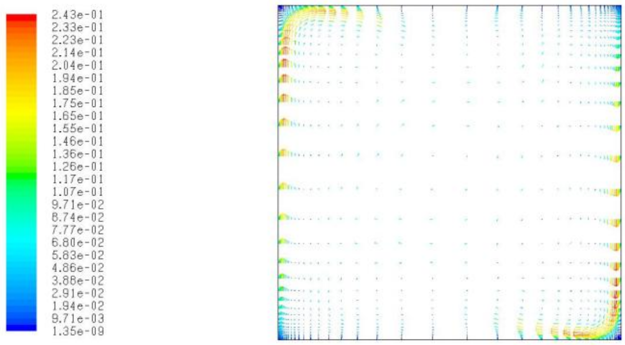

Figure 5. Velocity profiles in the case 1

Figure 6. Contours of stream function in the case 1

Figure 7 shows the value of the velocity at three horizontal plates, respectively. As shown in the Figure, the velocity is zero on the wall and near zero at the points far from the wall but it has the highest value at the parts near to the wall that is due to the nature of natural convection.

Moreover, at low elevation, the velocity is more on the left. Considering the formed boundary layers, logical results are obtained. Figure 8 shows the Nusselt number on the left and right wall. It is taken for granted because of the physics of the matter that the Nusselt number is negative on the right wall that means the heat transfer towards the wall. However, the Nusselt number is positive on the right wall that means the heat transfer from the wall towards the fluid.

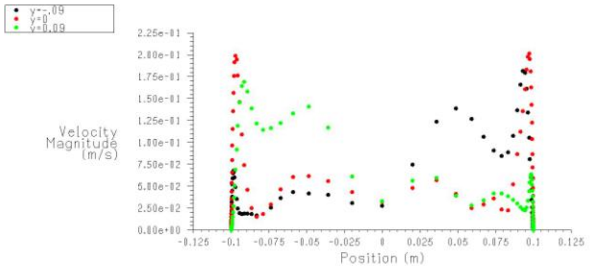

Figure 7. Velosity magnitude versus x-directon in different horizontal lines in case 1

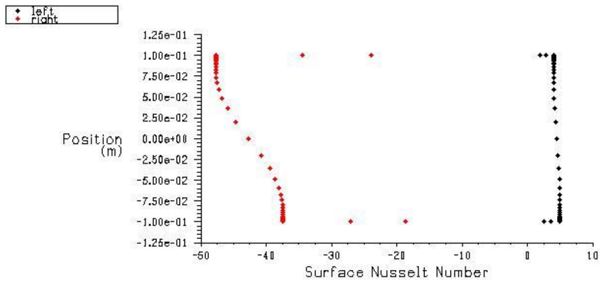

Figure 8. Local Nusselt number at the left and right walls in case 1

Figures 9-14 demonstrate above results for the second state. The differences between these two states are that the generated velocities in lubricating oil are much less than the generated velocities in air that can result from the higher velocity of the oil. Furthermore, the profiles of the velocity and flow lines become more regular which can also result from the higher viscosity of the oil. Only one main vortex can be seen, and free convection has a limited role in comparison with thermal conduction due to much lower generated velocities.

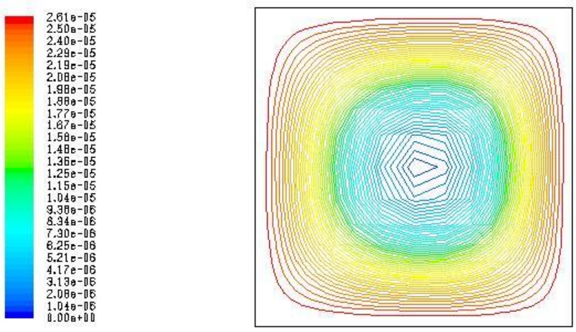

Figure 9. Stream lines in case 2

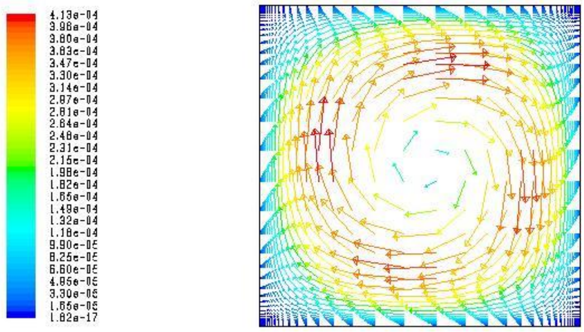

Figure 10. velocity profiles in case 2

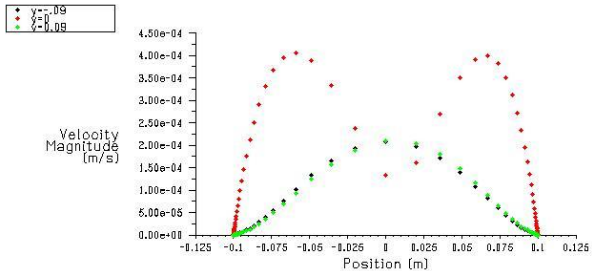

Figure 11. Velosity magnitude versus x-direction in different horizontal lines in case 2

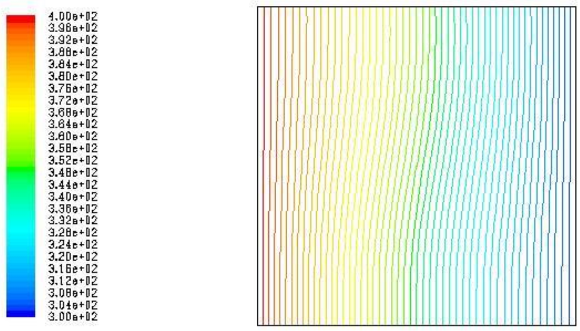

Figure 12. Isoterms in case 2

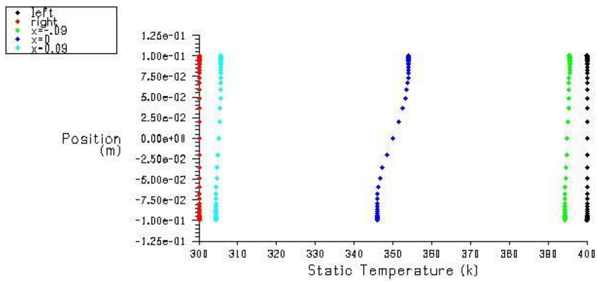

Figure 13. The temperature of fluid at different vertical lines in the case 2

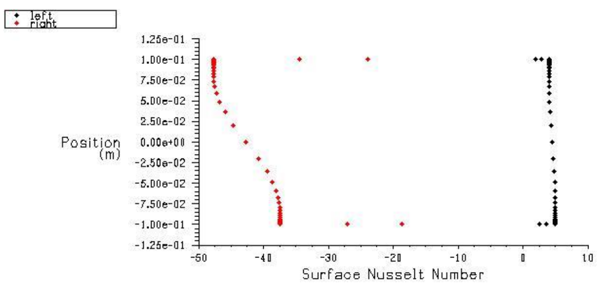

Figure 14. Local Nusselt number at the left and right walls in case 2

Figures 15-20 show the results for the case 3. The obvious differences of this condition with the first one lies in the formation of two main regular vortexes in two sides of the trapezoid and some small eddies in the corners. In addition, it seems that the corners present the proper formation of the boundary layer and mobility for the fluid so that, in this condition, the velocity lessens and the thermal convection resulting from the free convection will fade away.

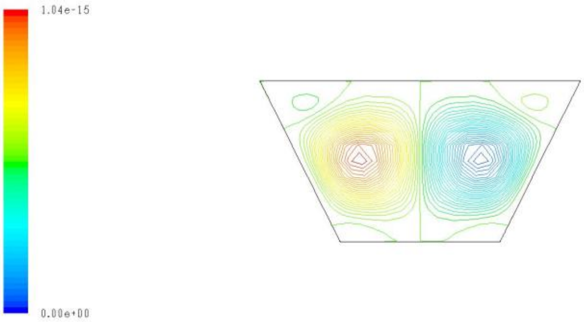

Figure 15. Stream lines at main vortexes in case 3

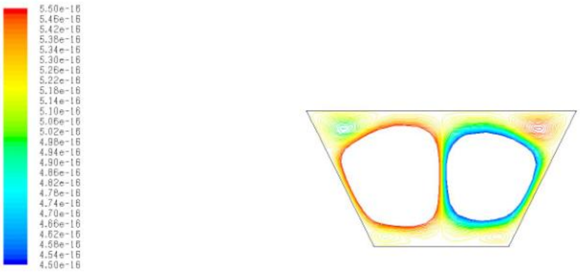

Figure 16. Stream lines at small vortexes in case 3

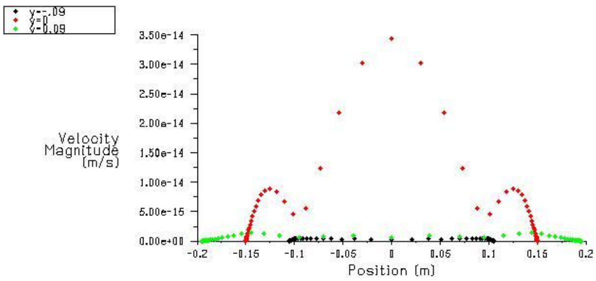

Figure 17. Velosity magnitude versus x-direction in different horizontal lines in case 3

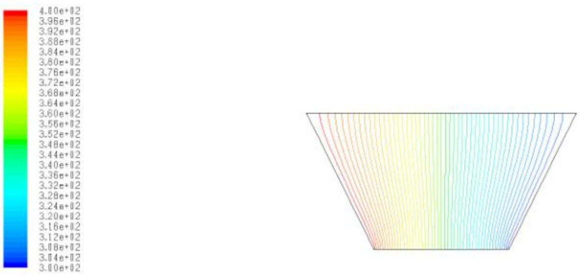

Figure 18. Isoterms in case 3

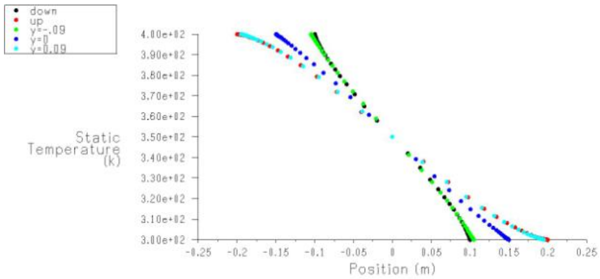

Figure 19. The temperature of fluid at different vertical lines in the case 3

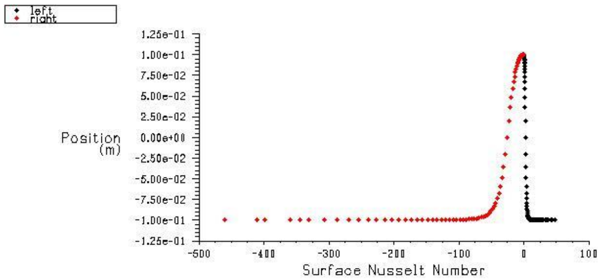

Figure 20. Local Nusselt number at the left and right walls in case 3

The obtained results from the fourth condition are shown in Figures 21-24. The main existing features of these forms are the symmetry of them that result from the symmetry of boundary conditions. Local Nusselt number is equal for left and right walls. The temperature at the center of the lower wall and upper one is higher than the side that is due to the heat transfer towards the left and right walls. Temperature changes on the lower wall are much more than the upper wall that can result from two factors: first, the thermal rate of the lower wall is more and the second, the surface of the lower wall is smaller.

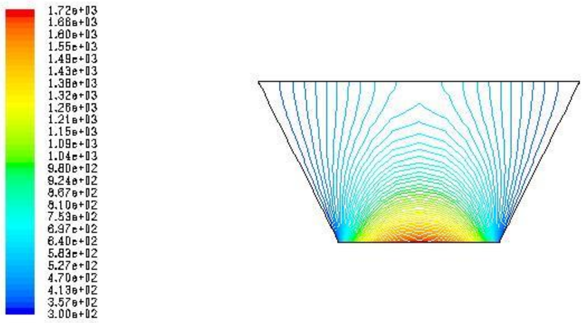

Figure 21. Isoterms in case 4

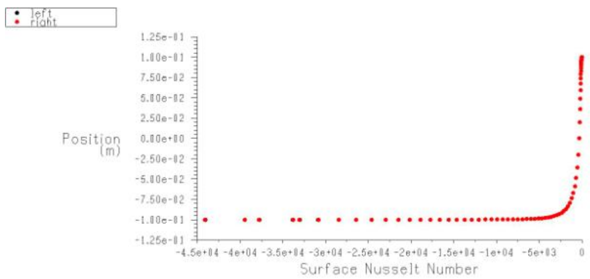

Figure 22. Local Nusselt number at the left and right walls in case 4

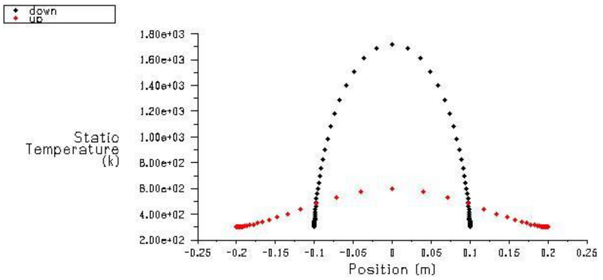

Figure 23. Temperature versus x-direction at the up and down walls in case 4

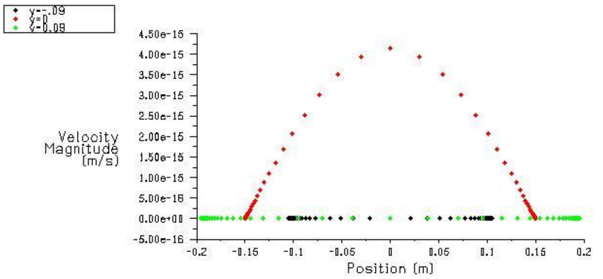

Figure 24. Velosity magnitude versus x-direction in different horizontal lines in case 4

4) CONCLUSION

In this article, four different cases with variable forms with different boundary layers as well as different fluids are studied, and the flow resulting from the free convection is investigated. Regarding the range of Rayleigh number in all simulations, the flow is laminar. Considering the obtained results, the generated flow in the air is stronger than the oil. Moreover, the generated flow in the squared cavity is more than the trapezoidal cavity. Given the obtained results, there are some vortexes in different forms, which all form a central vortex in the case 1and 3; overall, there are two central vortexes. In cases 1, 2, and 3 with the air fluid, there are small peripheral vortexes, too. In the case 2, there is only one observable eddy inside the square section.

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