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CFD analysis of natural convection heat transfer in a square cavity with partitions utilizing Al₂O₃ nanofluid

ABSTRACT

H. Sayehvand
A. Habibzadeh[*]
A. Mekanik

*Mechanical Engineering
Department, Engineering
Faculty, Bu-Ali Sina University,
Hamedan, Iran.*

In the present study, natural convective heat transfer in a partitioned square cavity utilizing nanofluids is studied. The vertical left and right walls are considered as the hot and cold walls, respectively and the partitions assumed to be adiabatic. The nanofluid used in this study is Al₂O₃ with the volume fraction of 20%. It is assumed that nanofluid is a single phase fluid. FLUENT 6.3.26 is used to simulate the problem. The influence of different parameters such as Rayleigh number (Ra=10^5 and 10^7), height of partition (h=0.1, 0.3, 0.5H) at a fixed distance from the walls (d=0.3H) are studied. According to the results, Rayleigh number and height of the partition are important factors that extremely affect the streamlines and isotherms. At Ra=10^7, the flow is confined in the distance between walls and partitions. Furthermore, at high partitions, the isotherms are horizontal between two partitions. For a fixed amount of the partition height, Nusselt number increases as the Rayleigh number rises. On the other hand, for a fixed Rayleigh, with the increasing partition height, Nusselt number decreases along the hot wall.

Keywords: *Nanofluid; Natural convection; Cavity; Partition; Rayleigh number; CFD.*

INTRODUCTION

Nanofluids are defined as the new solid-liquid composite materials with nanometer-sized solid-particles, typically 1-100 nm, suspended in the base fluid. The term of nanofluid was first used by Choi[1]. Nanofluids have attracted great interest recently because the suspended metallic or nonmetallic nanoparticles not only enhance the transport properties and heat transfer characteristics of the base fluids and make the suspension more stable, but also solve the problems of the heterogeneous solid/liquid mixture with millimeter or micrometer particles that suffer from sedimentation, cohesion, corrosion and pressure drop. Nanofluids are used in different engineering applications such as microelectronics, microfluidics, transportation, biomedical, solid-state lighting and manufacturing.

* Corresponding author:
Amin Habibzadeh
Mechanical Engineering
Department, Engineering Faculty,
Bu-Ali Sina University, Hamedan,
Iran.
Tel +98 9143475671
Fax +98 4412253619
Email *amin.habibzadeh@yahoo.com*

Different studies have been already conducted to investigate the performance of the nanofluids. Patel et al. [2] concluded that adding just 0.00026 vol% of Ag particles to the base fluid, leads to 5–21% increase in the thermal conductivity of the nanofluid. In case of adding 0.011% of Au particles, this amount is 7–14%. Zhu et al.[3] studied the dispersion behaviors and thermal conductivity of Al_2O_3–H_2O nanofluids in water under different pH values and different sodium decylbenzenesulfonate (SDBS) concentration. They showed that the stability and thermal conductivity enhancements of Al_2O_3–H_2O nanofluids are highly dependent on pH values and different SDBS dispersant concentration of nano-suspensions. Anoop et al. [4] investigated two nanofluids according to their particle sizes. It was observed that both nanofluids showed higher heat transfer characteristics than the base fluid and the nanofluid with 45 nm particles showed a higher heat transfer coefficient than that with 150 nm particles. Masuda et al. [5] proved that adding 4.3 % TiO_2 and g-Al_2O_3, increases the thermal conductivity 11 and 32%, respectively. Eastmann et al. [6] showed that Cu–ethylene glycol with φ=0.3% causes a 40% increase in thermal conductivity. Sivasankaran et al. [7] proved that the type of nanoparticles considered is very important on the convective heat transfer application. A 100% enhancement in the thermal conductivity of the base fluid was achieved by Grimm [8] for using aluminum particles with a volume fraction varying between 0.5–10%.

On the other hand, heat transfer in the field of the nanotechnology is the meeting point of the thermal engineering and nanoscale science. Furthermore, the study of natural convection in cavities has attracted great interest among researchers. Khanafer et al. [9] studied heat transfer enhancement in a two-dimensional enclosure utilizing nanofluids for various pertinent parameters. They found that the suspended nanoparticles substantially increase the heat transfer rate at any given Grashof number. In addition, the results illustrated that the nanofluid heat transfer rate increases with an increase in the nanoparticles volume fraction. The thermal characteristics of natural convection in a rectangular cavity heated from below with Al_2O_3 nanofluids with Jang and Choi's model for predicting the effective thermal conductivity of nanofluids and various models for the effective viscosity was investigated by Hwang

et al. [10]. The results showed that water-based Al_2O_3 nanofluids is more stable than base fluid in a rectangular cavity heated from below as the volume fraction of nanoparticles increases, the size of nanoparticles decreases, or the average temperature of nanofluids increases. Abu-nada and chamkha [11] studied the natural convection heat transfer characteristics in a differentially heated enclosure filled with a CuO-EG-Water nanofluid for different variable thermal conductivity and variable viscosity models. According to the results, the effects, the viscosity models are predicted to be more predominant on the behavior of the average Nusselt number than the influence of the thermal conductivity models. In another study, Abu-neda and Oztop [12] numerically analyzed the effect of the inclination angle on the natural convection heat transfer and fluid flow in a two-dimensional enclosure filled with Cu nanofluid. They showed that at high Rayleigh numbers, the percentage of the heat transfer enhancement decreased. Furthermore, they proved that the inclination angle can be a control parameter for nanofluid filled enclosure.

Although a lot of studies have been carried out to investigate the role of nanofluids in cavities, most of them have considered cavities without partitions. To our knowledge, very little work has been done on partitioned cavities utilizing nanofluids. Anilkumar and Jilani [13] studied the natural convective heat transfer in a partitioned cavity utilizing nano fluids for various pertinent parameters like solid volume fraction, partition height, Rayleigh numbers and aspect ratio of the cavity. The results illustrated that the nano particle solid volume fraction, leads to the increase in nanofluid heat transfer rate.

Therefore, studying the performance of the nanofluid in partitioned cavities needs to be investigated more. The aim of the present paper is to study the Al_2O_3 nanofluid-filled partitioned square cavity. The effects of different heights of the partition are investigated at a fixed nanoparticles volume fraction. In addition, the effects of Rayleigh number and partitions height on the Nusselt number are studied.

EXPERIMENTAL

Problem description and mathematical formulation

A schematic of the two-dimensional cavity is shown in Figure 1. It is a differentially heated square cavity in which two adiabatic vertical partitions are attached to. The hot wall is at T_h at X =0, and the cold wall is at T_c at X =1 and the other walls are adiabatic. The fluid in the enclosure is a water-based nanofluid containing Al_2O_3 nanoparticles. It is assumed that the nanofluid is Newtonian, incompressible and laminar and the base fluid and the nanoparticles are in a thermal equilibrium state. It is considered that nanofluid is a single phase fluid. The thermo-physical properties of the base fluid and the nanoparticles are given in Table 1. Except for the density of the nanofluid which is approximated by the Boussinesq model, the properties of the nanofluid are considered constant.

According to the above assumptions, the following formulas are obtained:

Continuity equation:

$$\frac{\partial u^*}{\partial x^*} + \frac{\partial v^*}{\partial y^*} = 0 \tag{1}$$

X-momentum equation:

$$u^* \frac{\partial u^*}{\partial x^*} + v^* \frac{\partial u^*}{\partial y^*} = -\frac{\partial p}{\partial x^*} + \Pr_f \left(\frac{C^*_{p,nf} \mu^*_{nf}}{k^*_{nf}} \right) \left(\frac{\partial^2 u^*}{\partial x^{*2}} + \frac{\partial^2 u^*}{\partial y^{*2}} \right) \tag{2}$$

Y-momentum equation:

$$u^* \frac{\partial v^*}{\partial x^*} + v^* \frac{\partial v^*}{\partial y^*} = -\frac{\partial p}{\partial y^*} + \Pr_f \left(\frac{C^*_{p,nf} \mu^*_{nf}}{k^*_{nf}} \right) \left(\frac{\partial^2 v^*}{\partial x^{*2}} + \frac{\partial^2 v^*}{\partial y^{*2}} \right) + Ra_f \, \Pr_f \, \beta^*_{nf} \left(\frac{\rho^*_{nf} C^*_{p,nf}}{k^*_{nf}} \right) \tag{3}$$

Energy equation:

$$u^* \frac{\partial T^*}{\partial x^*} + v^* \frac{\partial T^*}{\partial y^*} = \alpha_{nf} \left(\frac{\partial^2 T^*}{\partial x^{*2}} + \frac{\partial^2 T^*}{\partial y^{*2}} \right) \tag{4}$$

The effective density of the nanofluid is given by:

$$\rho_{nf} = (1-\phi)\rho_f + \phi\rho_p \tag{5}$$

The heat capacitance of the nanofluid is expressed as:

$$\left(\rho c_p \right)_{nf} = (1-\phi)\left(\rho c_p \right)_f + \phi \left(\rho c_p \right)_p \tag{6}$$

The effective thermal conductivity of nanofluid is:

$$\frac{k_{nf}}{k_f} = \frac{k_p + 2k_f - 2\phi\left(k_f - k_p\right)}{k_p + 2k_f + \phi\left(k_f - k_p\right)} \tag{7}$$

The dynamic viscosity of the nanofluid can be given as:

$$\mu_{nf} = \frac{\mu_f}{\left(1 - \phi\right)^{2.5}} \tag{8}$$

The thermal expansion coefficient of the nanofluid is expressed by:

$$\left(\rho\beta\right)_{nf} = (1 - \phi)\left(\rho\beta\right)_f + \phi\left(\rho\beta\right)_p \tag{9}$$
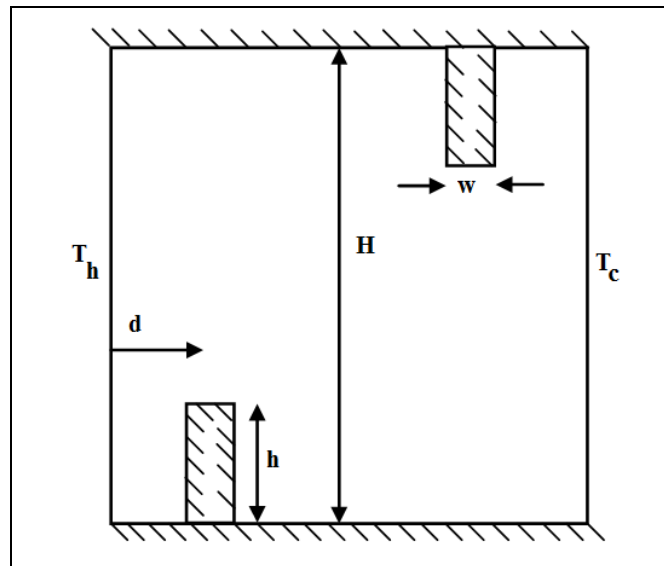

Fig. 1. Schematic of the partitioned square cavity

Table 1. Thermo-physical properties of fluid and nanoparticles

Properties	Fluid phase (water)	Solid phase (Al$_2$O$_3$)
ρ (kg/m^3)	997.1	3970
c_p (J/kg K)	4179	765
β (K^{-1})	2.1×10^{-4}	0.85×10^{-5}

Numerical procedure

The governing equations are solved by using a CFD software FLUENT 6.3.26. The SIMPLE algorithm was used for handling the pressure velocity coupling and PRESTO was used for pressure as well as laminar model to simulate the natural convection in the cavity. Second order discretization scheme was used for all simulations. Different grids, including 71×71, 81×81, 91×91 and 101×101 were tested. It is observed that a 91×91 grid, is accurate enough to be chosen as the grid for all calculations. For validation, the results of the numerical results for average Nusselt number in a square cavity are compared with the results of others. The comparison is shown in Table 2 which shows a very good agreement.

Table 2. Comparison between present work and other published data

	10^4	10^5	10^6
Present work	2.241	4.526	8.919
de Vahl Davis [14]	2.243	4.519	8.8
House et a.l [15]	2.254	4.561	8.923
Merrikh and Lage [16]	2.244	4.536	8.86
Kalita et al.[17]	2.245	4.522	8.829
Braga et al. [18]	2.249	4.575	8.918
Tric et al. [19]	2.245	4.522	8.825

RESULTS AND DISCUSSION

A numerical study is performed to investigate the natural convection in a nanofluid-filled (Al_2O_3-water) partitioned square cavity with isothermal vertical walls and adiabatic horizontal walls. All the simulations are performed for Ra=10^5 and 10^7, φ=20%, d=0.3H, w=0.1H and different partition height (h=0.1, 0.3, 0.5H). In all cases, the bottom baffle is placed near the hot wall, and the top baffle is placed near the cold wall. The isotherms and streamlines of the studied partitioned cavity for Al_2O_3-water (φ=20%) and different partition heights, is shown in Figures 2 and 3. In Figure 2, as the considered Rayleigh number (Ra=10^5) is moderate, both convection and conduction mechanisms are effective. The streamlines show large clockwise circulations.

When the height is little, elliptical vortex is seen, and the streamlines are uniform but near the partitions, a deflection occurs to pass them. However, as the height increases, the single vortex divides into two different vortexes, and the centers move toward the hot and cold walls. Moreover, the deflection of flow is more obvious in higher heights and intensely affects the circulation. In general, it is found that, partition height increasing, restricts the fluid flow and the temperature gradient does decrease.

For lower heights, the isotherms near the hot and cold walls are near vertical, but they are horizontal at the other parts. By increasing partition height, the isotherms tend to be more skewed. Nevertheless, they are still horizontal between the two partitions. The reason is the natural convection which is vigorous at the top left and bottom right of the square cavity but between the partitions, this effect is not strong enough therefore horizontal lines are seen.

At Ra=10^7, as the partition height rises, heat transfer occurs mostly because of the convection, and the primary circulation is divided into two circulations, the circulation on the hot wall and the circulation on the cold wall. Two vortexes are formed that move towards the walls. The flow is compacted at the distance between partitions and the walls.

Figure 3 (b) shows how the predominance of the convection influences the isotherms as Rayleigh number increases. Once more, it is clear that for low partition height, almost vertical isotherms appear only inside the very thin boundary layers and isotherms at the centre of the cavity are horizontal. As the height increases, the horizontal isotherms become packed between the two partitions and the density of the isotherms near the boundary layer reduces.

Figure 4 shows the variation between Nusselt number and Rayleigh number for different heights of the partitions. According to the graphs, for a fixed height of the partition, increasing Rayleigh number leads to an increase in the Nusselt number. By the Rayleigh number rising, heat transfer through convection overcomes the conduction and therefore, Nusselt number increases. As the height of the partition increases, Nusselt number decreases. The reason for this reduction is that heat transfer through conduction is greater than the convection.
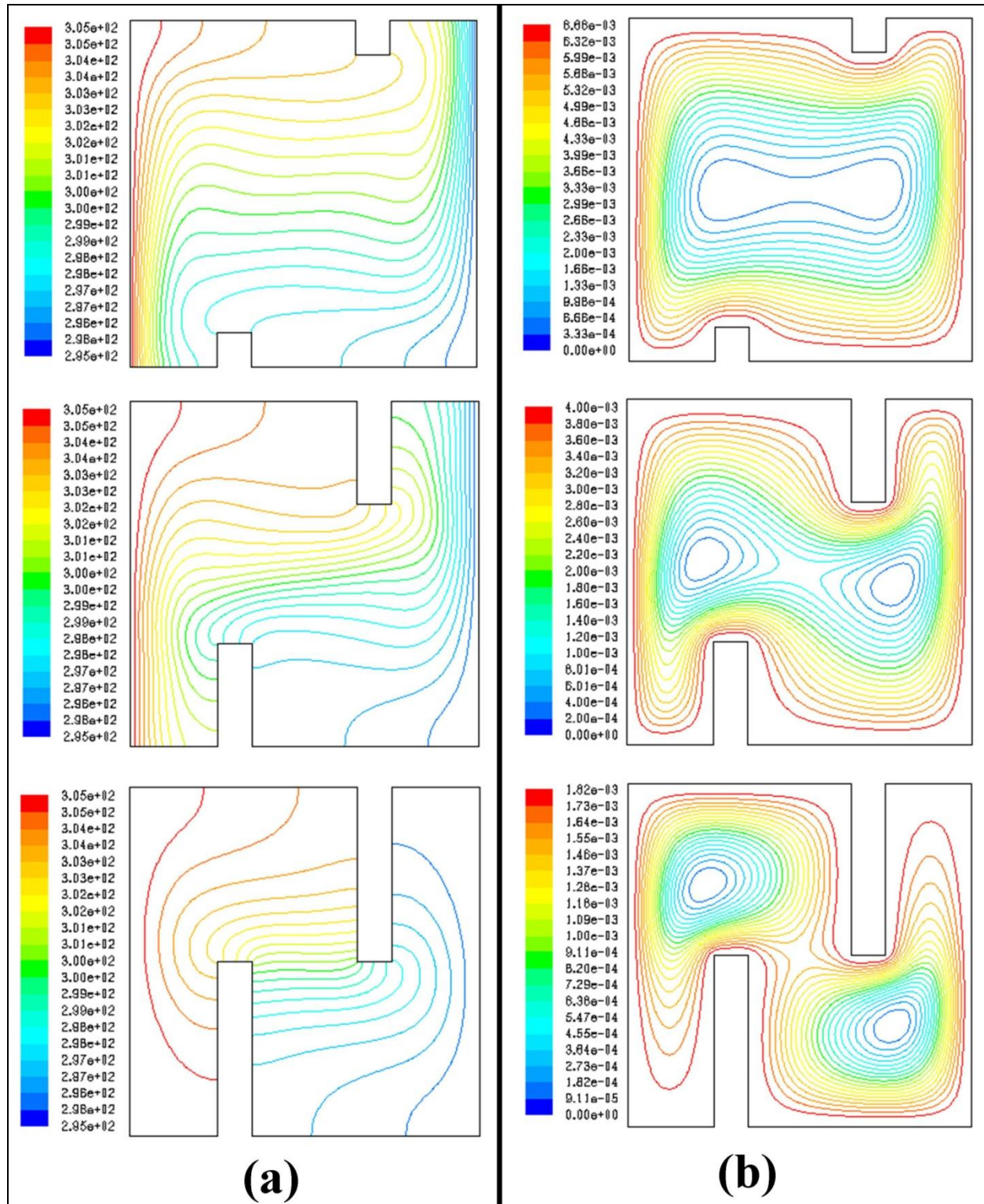
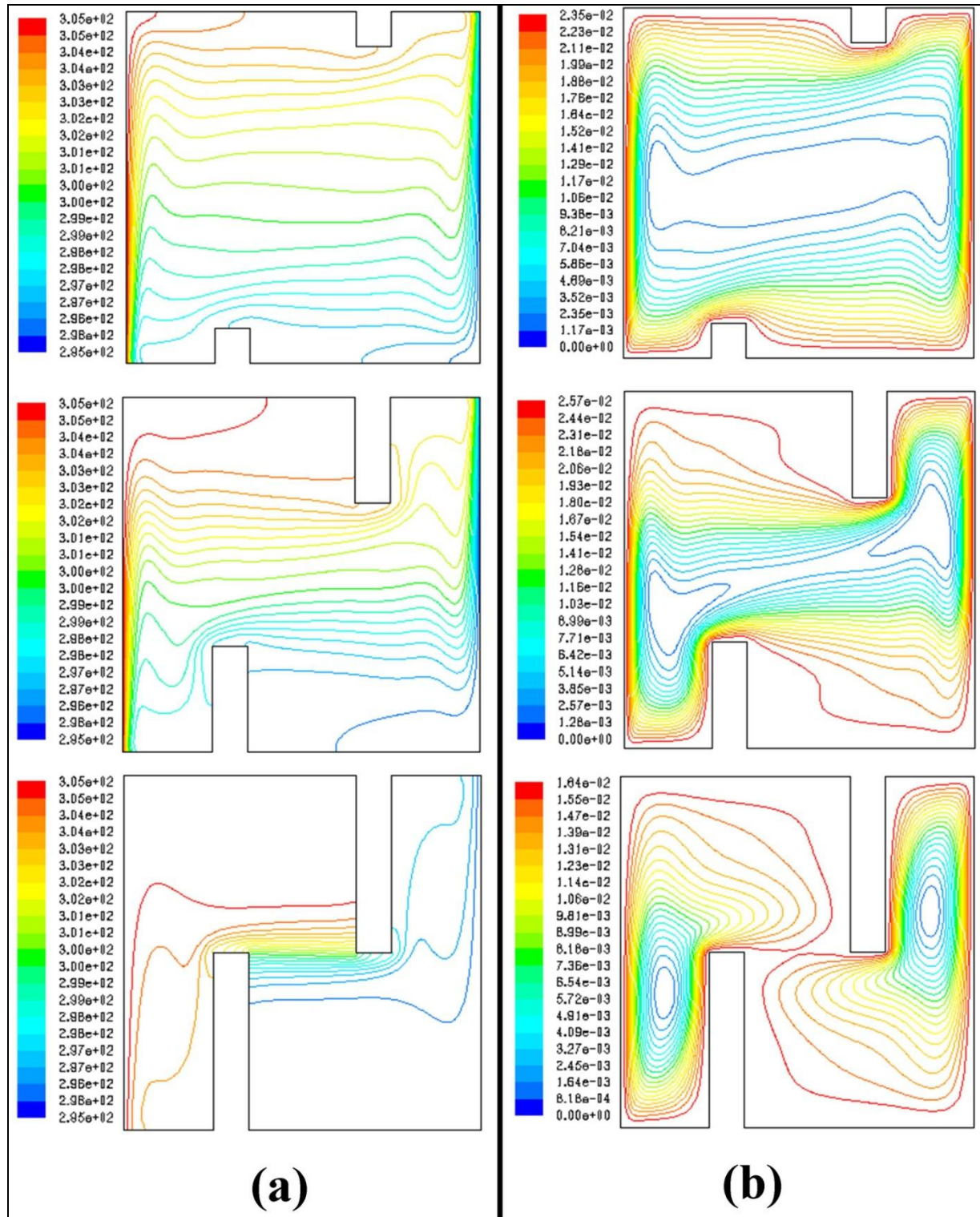**Fig.2.** Effect of partition height at Ra=10^5, φ=20% and d=0.3 (a) isotherms, (b) streamlines

Fig. 3. effect of partition height at Ra=10^7, φ=20% and d=0.3 (a) isotherms, (b) streamlines
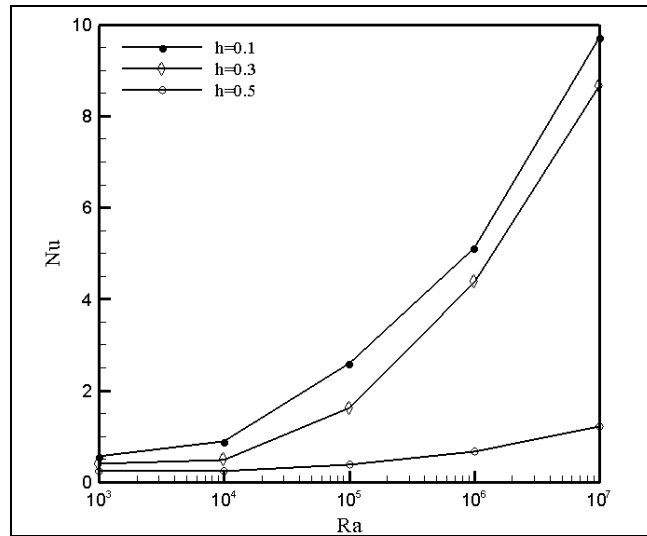
Fig. 4. variation of Nu with Ra at different partition heights

Figure 5 indicates the midplane temperature variation with partition height. As it was concluded before, the increasing partition height leads to a decrease in the temperature gradient. At h=0.1, gradient increase is not very clear but the highest amount of the decrease is seen at h=0.5. It should be noted that the gap which occurs at h=0.5, is because of the partition's adiabatic surface.

Figure 6 shows the variation of the Nusselt number on the hot wall of the cavity. It can be seen that by increasing partition height, Nusselt number along the hot wall decreases. It is because; the partition limits the fluid flow in the cavity.
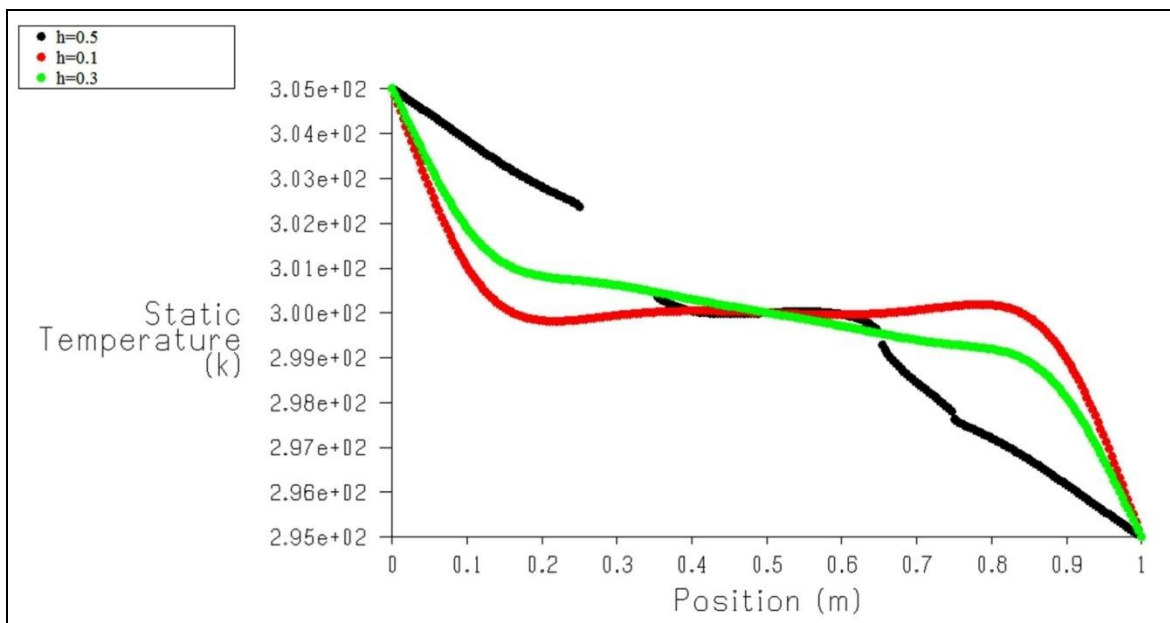

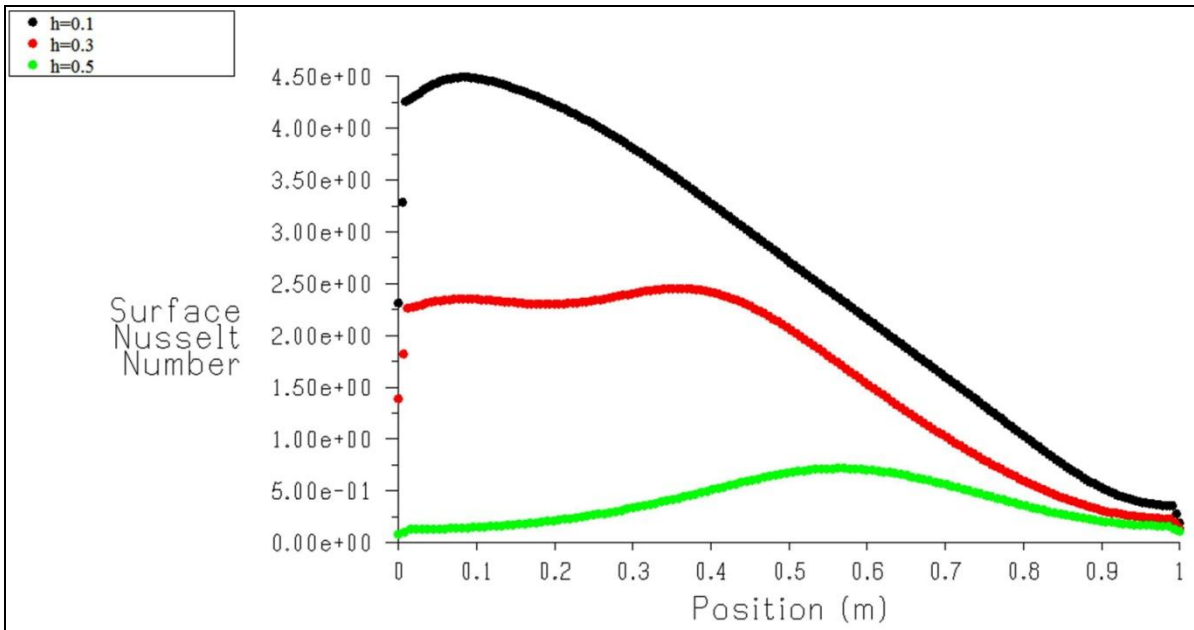**Fig. 5.** variation in mid-plane temperature with partition height at Ra=10^5

Fig. 6. Nusselt number variation along the hot wall for different partition heights at Ra=10⁵

CONCLUSION

Natural convection heat transfer is studied in a partitioned square cavity using computational fluid dynamics approach. Simulation is performed for Ra=10^5 and 10^7, φ=20% and for different heights of the Al_2O_3 nanofluid-filled cavity. It is assumed that nanofluid is a single phase fluid. The results show that by increasing partition height, vortexes move towards the hot and cold walls. According to the results, Rayleigh number and height of the partition are important factors that extremely affect the streamlines and isotherms. At Ra=10^7 the flow is confined in the distance between walls and partitions. Furthermore, at high partitions, the isotherms are horizontal between two partitions. For a fixed amount of the partition height, Nusselt number increases as the Rayleigh number goes up. On the other hand, for a fixed Rayleigh, with the increasing partition height, Nusselt number decreases along the hot wall.

NOMENCLATURE

Cp: specific heat at constant pressure (J/kg K)
d: distance of partition from hot wall (m)
g: gravitational acceleration (m/s^2)

H: cavity hight (m)
h: partition height (m)
k: thermal conductivity (W/m K)
p: pressure (N/m^2)
Pr: Prandtl number = υ_f/α_f
Ra: Rayleigh number = $g\beta\Delta TH^3/\alpha\upsilon$
T: temperature (K)
u,v: x and y components of velocity (m/s)
w: partition width (m)
x,y: Cartesian coordinates (m)

Greek symbols
α: thermal diffusivity (m^2/s)
β: thermal expansion coefficient (K^{-1})
φ: nanoparticle volume fraction
υ: kinematic viscosity (m^2/s)
ρ: density (kg/m^3)
μ: dynamic viscosity (m^2/s)

Subscripts
c: cold
f: fluid
h: hot
nf: nanofluid
p: particle

Subscript
* non-dimensional form

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