Intensification of heat transfer in cavity partially heated and filled with nanofluid (cu-water)

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ABSTRACT. Natural convection in a rectangular cavity with aspect ratio (A_x), partially heated and filled with a nanofluid (Cu-Water) has been studied numerically. Two heat sources with length (B) are placed on the opposite vertical walls; the remainder of the walls is maintained adiabatic while the horizontal walls are brought to a cold temperature. The equations governing the flow are solved using a finite volume home code using a multigrid technique. Among the parameters governing the flow, a detailed study on the effects of the aspect ratio (A_x) and the length of the source (B) on flow and heat transfer rate is given. The results are shown in terms of streamlines and isotherms. It was found that the transfer of heat significantly increases with the aspect ratio (A_x) and the length of the source (B). A correlation expressing the Nusselt number as a function of (A_x) and d is established.

1 INTRODUCTION

Natural convection heat transfer is an important phenomenon in engineering and industry with widespread applications in diverse fields, such as, geophysics, solar energy, electronic cooling, microelectromechanical systems, and nuclear energy to mention a few. A major limitation against increasing the heat transfer in such engineering systems is the inherently low thermal conductivity of the commonly used fluids, such as, air, water, and oil. The idea is to insert within the fluid, metallic particles of nanometer size hope to increase the effective thermal conductivity of the mixture. In fact, the presence of the nanoparticles in the fluids increases appreciably the effective thermal conductivity of the fluid and consequently enhances the heat transfer characteristics [1-2]. The term nanofluid was then introduced by Choi et al. [1] and is commonly used to characterize this type of colloidal suspension. Because the prospect of nanofluids is very promising, several studies of convective heat transfer in nanofluids have been reported in recent years. Most of the studies considering the heat transfer performance using nanofluids in natural convection were investigated based on rectangular enclosures in the last decades [3–5]. Nithyadevi et al. [6] performed a numerical study to investigate the effect of aspect ratio, Grashof number and active sources locations (the left active source is at a higher temperature than that of the right side wall) on the flow, temperature fields, and heat transfer rate within the enclosure. Nine different relative positions of the active sources are considered. The results show that the heat transfer rate is high for the bottom–top thermally active locations while the heat transfer rate is poor in the top–bottom case. The heat transfer rate is found to increase with an increase in the aspect ratio and also when a cooling source location is in the top of the enclosure. Oztop and Abu-Nada [7] studied heat transfer and fluid flow due to buoyancy forces in a partially heated enclosure. They used three types of nanofluids as coolant. The heat source being located at the left vertical wall and the temperature of the right vertical wall is lower than that of heater while other walls are insulated. The authors have shown an increase in mean Nusselt number with the volume fraction of nanoparticles for the investigated Rayleigh number. They found that the heater location and heater height affect the flow and temperature fields by using nanofluids.

Natural convection in a partially heated enclosure from below and filled with different types of nanofluids has been numerically investigated by Aminossadati and Ghasemi [8]. The heat source is located at the bottom wall; the remaining walls of the enclosure are cooled. The influence of pertinent parameters such as Rayleigh number, location and geometry of the heat source, the type of nanofluid and solid volume fraction of nanoparticles on the cooling performance studied. These authors have shown that the maximum temperature of the heat source decreases notably with increasing volume fraction of solid nanoparticles and especially at low Rayleigh number, where the conduction is the main heat transfer mechanism.

This present work is a continuation of our last work [9], in which we always seek benefit conditions leading to an optimal thermal transfer in partially heated enclosure filled with nanofluids. The active parts of the vertical left and right side walls are maintained at a constant heat flux q'' well the inactive parts are kept insulated; however, the enclosure's top and bottom walls are cooled. Among the nine investigated cases, we keep one configurations, namely case MM (Middle-Middle). The main aim of this work is to study the effects of the aspect ratio ($A X = L/H$) and the sources length (B) on heat transfert rate, flow field and temperature distribution.

2 PROBLEM DESCRIPTION

A schematic diagram of the considered model is shown in Fig.1 with coordinates. It is a two-dimensional square enclosure of height H , and filled with Cu-water nanofluid. A two heat sources with constant heat flux q'' and dimensionless length B ($B=H/2$) are embedded in the two sidewalls. The top and bottom walls are kept at a maintained constant temperature T_c . The remaining boundary parts of the enclosure are adiabatic. The Cu-water nanofluid is assumed to be Newtonian, in thermal equilibrium, and the nanoparticles are kept uniform in shape and size.

Fig.1: Physical model and boundary conditions for square cavity with active side walls

3 FORMULATION

The thermo-physical properties of the cu-water nanofluid, presented in Table 1, are considered to be constant with the exception of its density which varies according to the Boussinesq approximation. Using the following dimensionless variables:

$$X = \frac{x}{L}, \quad Y = \frac{y}{L}, \quad U = \frac{uL}{\alpha_f}, \quad V = \frac{vL}{\alpha_f}$$

$$P = \frac{(p + \rho_0 gy)L^2}{\rho_{nf}\alpha_f^2}, \quad \theta = \frac{T - T_C}{\Delta T}$$

$$Ra = \frac{g\beta_f \Delta T L^3}{\alpha_f \nu_f}, \quad \Delta T = \frac{q'' L}{k_f} \quad \text{and} \quad Pr = \frac{\nu_f}{\alpha_f}$$

the dimensionless form of the governing equations for unsteady nanofluid flow can be written as [9],

$$\frac{\partial U}{\partial X} + \frac{\partial V}{\partial Y} = 0 \quad (1)$$

$$\frac{\partial U}{\partial t} + U \frac{\partial U}{\partial X} + V \frac{\partial U}{\partial Y} = -\frac{\partial P}{\partial X} + \frac{\mu_{nf}}{\alpha_f \rho_{nf}} \left(\frac{\partial^2 U}{\partial X^2} + \frac{\partial^2 U}{\partial Y^2} \right) \quad (2)$$

$$\frac{\partial V}{\partial t} + U \frac{\partial V}{\partial X} + V \frac{\partial V}{\partial Y} = -\frac{\partial P}{\partial Y} + \frac{\mu_{nf}}{\alpha_f \rho_{nf}} \left(\frac{\partial^2 V}{\partial X^2} + \frac{\partial^2 V}{\partial Y^2} \right) + \frac{(\rho\beta)_{nf}}{\rho_{nf}\beta_f} \quad (3)$$

$$\frac{\partial \theta}{\partial t} + U \frac{\partial \theta}{\partial X} + V \frac{\partial \theta}{\partial Y} = \frac{\alpha_{nf}}{\alpha_f} \left(\frac{\partial^2 \theta}{\partial X^2} + \frac{\partial^2 \theta}{\partial Y^2} \right) \quad (4)$$

Table1: Thermo-physical properties of water and copper nanoparticles.

	Pur water	Copper (Cu)
$\rho(kgm^{-3})$	997.1	8933
$\beta(K^{-1})$	21×10^{-5}	1.67×10^{-5}
$k(Wm^{-1}K^{-1})$	0.613	401
$C_p(Jkg^{-1}K^{-1})$	4179	385

where the Rayleigh number Ra , and the Prandtl number Pr are defined as follows:

$$Ra = \frac{\overline{g\rho_f}\beta_f\Delta TL^3}{\mu_f\alpha_f}, \text{ and } Pr = \frac{\nu_f}{\alpha_f}$$

The boundary conditions consist of:

- $U = V = 0$ on all four walls.
- $\theta = 0$ for $Y = 0, 1$ and $0 \leq X \leq 1$
- $\frac{\partial \theta}{\partial Y} = 0$
for $X = 0, 1$ and $0 \leq Y \leq (D - 0.5B)$ and $1 \geq Y \geq (D + 0.5B)$
- $\frac{\partial \theta}{\partial Y} = -\frac{k_f}{k_{nf}}$
for $X = 0, 1$ and $(D - 0.5B) \leq Y \leq (D + 0.5B)$

The local Nusselt numbers on the heat source surface can be defined as:

$$Nu_s = \frac{hL}{k_f} \quad (5)$$

where h is the convection heat transfer coefficient:

$$h = \frac{q''}{T_s - T_c} \quad (6)$$

Rewrite the local Nusselt number by using the dimensionless parameters:

$$Nu_s(Y) = \frac{1}{\theta_s(Y)} \quad (7)$$

where θ_s is the dimensionless heat source temperature. The average Nusselt number (Nu_m) is determined by integrating Nu_s along the heat source:

$$Nu_m = \frac{1}{B} \int_{D-0.5B}^{D+0.5B} Nu_s(Y) dY$$

4 NUMERICAL APPROACH

The governing equations (1) - (4) were numerically solved using the classical projection method [10]. A finite volume method on a staggered grid system have been implemented to discretise the dimensionless equations and the QUICK scheme of Hayase et al. [11] is employed to minimize the numerical diffusion for the advective terms. The Poisson equation with homogeneous boundary conditions is solved with the help of an accelerated full multigrid method [12] whoever, the momentum equations are computed by a red black successive over-relaxation method.

Finally, the convergence of the numerical 2D velocity field is established at each time step by controlling the L2-residuals norm of all equations to be solved by setting its variation to less than 10^{-8} . In order to secure the steady state conditions, the following criterion has to be satisfied:

$$\sqrt{\sum (x_{i,j}^n - x_{i,j}^{n-1})^2} < 10^{-8}_{i,j}$$

Here the superscript n indicates the iteration number and the subscript sequence (i, j) represents the space coordinates x and y . This numerical method was implemented in a FORTRAN home code named «NASIM» [13].

Fig.2: Vertical velocity profiles along the mid-section of the enclosure (Cu–Water, $\phi = 0.1$, $Ra=10^5$, $D=0.5$ and $B=0.4$).

The present numerical code was validated against the results of other natural convection studies in enclosures filled with nanofluid developed by Aminossadati et al. [8] in terms of computational data (see Table 3 in Reference [9]) and v - velocity component profile as shown in Fig.2 (Cu–Water, $\phi = 0.1$, $Ra=10^5$, $D = 0.5$ and $B=0.4$). Our results are in excellent agreement with those of [8].

5 RESULTS AND DISCUSSION

Fig. 2 show the presence of two contrarotating cells for all investigated aspect ratio, these cells become large and $|\psi_{\max}|$ increases with increasing the aspect ratio contrary to $\theta_{\max}$ that reduces both by increasing of the aspect ratio and by the addition of the nanoparticles, this may be explained by increasing the cold surface both with the aspect ratio and by increasing the heat transfer using the nanofluid. Isotherms are also sensible to aspect ratio and to add of the nanoparticles. The variation

of average Nusselt number as function of the source length (B) and the aspect ratio (A_x) is presented in **Fig. 3**. A comparison between the numerical results and those obtained by correlation is shown too in this figure. It is noted that the average Nusselt number increases monotonically with the length of source regardless of the aspect ratio owing to the increase of the heating surface.

Fig.3: Streamlines (1st line) and isotherms (2nd line) for different aspect ratio of the cavity partially heated and filled with Cu/water nanofluid $\phi = 0.1$ (—), water $\phi = 0$ (- - -) at $Ra = 10^5$ ($B = 0.5$ and $D = 0.5$).

Similarly, the Nusselt number increases with the increase of aspect ratio (A_x) due to the increase of the cold surface.

Fig. 4: Variation of average Nusselt number as function of the source length (B) and the aspect ratio (A_x); comparison between the numerical results and those obtained by correlation.

The comparison between the numerical results and those obtained by the correlation is reported in Fig.4 where we see a good agreement between these results.

6. CONCLUSION

The effect of the length of the heat source and the effect of the aspect ratio on unsteady natural convection in a rectangular cavity heated and partially filled with a water-based nanofluid (Cu-Water) has been studied numerically. We Note that $\psi_{\max}$ increases with increasing the aspect ratio

contrary to $\theta_{\max}$ that reduces both by increasing of the aspect ratio and by the addition of the nanoparticles. The average Nusselt number increases monotonically with the length of the source and the aspect ratio independently one from another.

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