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ORIGINAL ARTICLE

IMPACT OF RAYLEIGH NUMBER ON A CAVITY CONTAINING A HEATED CIRCULAR CYLINDER FILLED WITH BASE FLUID AND NANOFLUID

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ABSTRACT: Application of nanofluids inside the cavities has been investigated by many researchers, due to importance of using nanofluids to enhance heat transfer and therefore effects of different nanofluids parameters such as type of nanofluid, volume fraction of nanofluid, and its temperature on heat transfer and stream characteristics has been studied. A hot cylinder with radius r and different positions at a high constant temperature (T_h) is considered to be located inside the cavity and the side lids are remained at a low constant temperature (T_c). The upper and lower lids are also insulated. Nanofluids used in this problem are considered to be incompressible and Newtonian and the stream is laminar and steady in all areas of the cavity. In a general sense contour and stream pattern, temperature and stream contours in a cavity containing base fluid and a cavity containing nanoparticles are approximately the same for different values of Rayleigh number. In other words, phenomenon such as formation of parallel isotherms at Ra = 104 and formation of Thermal Stratification in higher values of Rayleigh number can be seen in a similar way in all of the contours. Based on present study can be conclude that addition of nanoparticles to the base fluid increases the amount of heat transfer in all points of the lid and amount of this increase is more at upper areas of the lids. Also, increasing Ra number caused a noticeable enhancement in the rate of heat transfer.

KEYWORDS: Nanofluid, Natural Convection, Circular Cylinder, Heat Transfer.

INTRODUCTION

Research and study about free convection is an essential issue because of its applications in industry. Some of important applications of free convection include the following: Radioactive waste materials disposal (Bilgen, 2005) and nuclear reactors cooling (Bilgen, 2002).

Application of nanofluids inside the cavities has been investigated by many researchers, due to importance of using nanofluids to enhance heat transfer and therefore effects of different nanofluids parameters such as type of nanofluid, volume fraction of nanofluid, and its temperature on heat transfer and stream characteristics has been studied. Free convection fluid flow and heat transfer of various water based nanofluids in a square cavity with an inside thin heater has been investigated numerically by Mahmoodi, (2011). Due to lack of extensive research on nanofluids heat transfer inside a cavity with a hot square cylinder, and also considering application this geometry in industrial application, purpose of this study is to investigate this geometry with respect to different effective factors like strength and weakness of buoyancy force, type of suspended particles, and volume fraction of nanoparticles. Results of this study are presented in the form of temperature and stream contours and different figures.

NUMERICAL MODELING

Schematic of the problem is shown in Figure 1. A hot cylinder with radius r and different positions at a high constant temperature (T_h) is considered to be located inside the cavity and the side lids are remained at a low constant temperature (T_c). The upper and lower lids are also insulated.

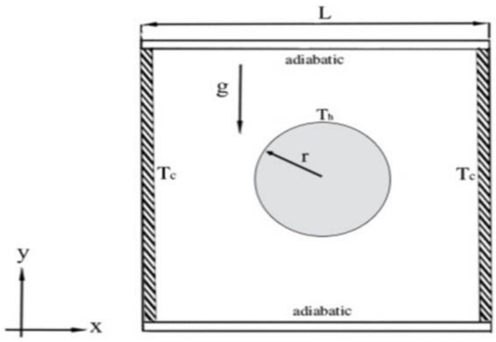

Figure 1: Schematic of the problem.

Nanofluids used in this problem are considered to be incompressible and Newtonian and the stream is laminar and steady in all areas of the cavity. Except for the density which varies according to the Boussinesq approximation, other thermophysical properties of water and

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nanofluid are assumed to be constant.
Continuum, momentum and energy equations for a laminar and steady free convective stream of nanofluid in a 2-D square cavity can be written as:

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

$$u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=-\frac{1}{\rho_{nf}}\frac{\partial p}{\partial x}+\upsilon_{nf}\nabla^2 u \quad (2)$$

$$u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}=-\frac{1}{\rho_{nf}}\frac{\partial p}{\partial y}+\upsilon_{nf}\nabla^2 v+(\rho\beta)_{nf}\,g(T-T_c) \quad (3)$$

$$u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}=\alpha_{nf}\nabla^2 T \quad (4)$$

Non-dimensionalized form of the governing equations is obtained using dimensionless parameters:

$$X=\frac{x}{L},\ Y=\frac{y}{L},\ R=\frac{r}{L},\ U=\frac{uH}{\alpha_f},\ V=\frac{vH}{\alpha_f}$$

$$\theta=\frac{T-T_c}{T_h-T_c} \qquad P=\frac{pL^2}{\rho_{nf}\,\alpha_f^2} \quad (5)$$

$$Ra=\frac{g\beta_f\,\Delta TL^3}{\upsilon_f\alpha_f},\quad Pr=\frac{\upsilon_f}{\alpha_f} \quad (6)$$

Nanofluid effective density, thermal diffusivity, specific heat capacity and dynamic viscosity are calculated by the following equations:
Maxwell equation is used to calculate nanofluid.

$$\rho_{nf}=(1-\varphi)\rho_f+\varphi\rho_s \quad (7)$$

$$\alpha_{nf}=k_{nf}/(\rho c_p)_{nf} \quad (8)$$

$$(\rho c_p)_{nf}=(1-\varphi)(\rho c_p)_f+\varphi(\rho c_p)_s \quad (9)$$

$$(\rho\beta)_{nf}=(1-\varphi)(\rho\beta)_f+\varphi(\rho\beta)_s \quad (10)$$

$$\frac{\mu_{nf}}{\mu_f}=\frac{1}{(1-\varphi)^{2.5}} \quad (11)$$

heat conduction coefficient:

$$\frac{k_{nf}}{k_f}=\frac{(k_s+2k_f)-2\varphi(k_f-k_s)}{(k_f+2k_s)+\varphi(k_f-k_s)} \quad (12)$$

Where, k_p and k_f are nanoparticles thermal coefficient and base fluid thermal coefficient, respectively.

NUMERICAL APPROACH

In this study the governing equations (mass, momentum and energy) have been discretized using the finite volume method and the SIMPLE algorithm has been used to couple velocity and pressure fields.

RESULTS AND DISCUSSION

4.1. Effect of Rayleigh Number on a Cavity Filled With Fluid and Nanofluid

In a general sense contour and stream pattern, temperature and stream contours in a cavity containing base fluid and a cavity containing nanoparticles are approximately the same for different values of Rayleigh number. In other words, phenomenon such as formation of parallel isotherms at *Ra* = 104 and formation of Thermal Stratification in higher values of Rayleigh number can be seen in a similar way in all of the contours.
In order to investigate stream and temperature fields in these cases, which are not very different with respect to the geometry, the value for ψ_{max} in all cases and its difference with the corresponding case of base fluid are presented in percentage.

$(\psi_{\max})_{nf}=1.68, (\psi_{\max})_f=1.66$

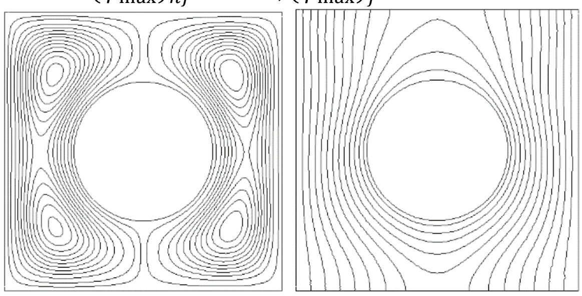

Figure 2: Temperature lines (right) and streamlines (left) of the water-copper nanofluid in 6% of volume fraction, $Ra=10^4, r=0.25$, $c(x,y)=(0.5,0.5)$.

As can be seen in the Fig. 2, which is related to streamlines and temperature lines of the water-copper nanofluid at *Ra* = 10^4, isotherms are formed in the cavity and especially in the vicinity of the lids which shows the dominance of conduction heat transfer.

$(\psi_{\max})_{nf} = 13.29, (\psi_{\max})_{f} = 11.15$

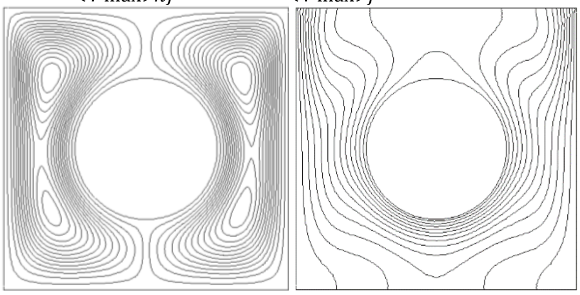

Figure 3: Temperature lines (right) and streamlines (left) of the water (base fluid) $Ra = 10^5, r = 0.25, c(x,y) = (0.5,0.5)$.

Streamlines also show that two separate vortices are formed in left and right sides of the hot circular cylinder which definitely are weak. The important point is the increase of stream strength in the cavity due to 6% increase of copper nanoparticles to water. Off course, this increase in strength of the stream resulted from increase in the amount of nanoparticles to the base fluid has previously been reported by other studies.

Anyhow, according to the figure above, in this study value of ψ_{max} for copper-water nanofluid at $Ra = 10^4$ for volume fraction equal to 6% has 16%increase which is not significant.

Figure 3 shows stream and temperature contours at $Ra = 10^5$ which are symmetrical due to the symmetry of geometry and boundary conditions.

In this case, value of temperature gradient in the vicinity of the vertical lids in the upper section of the cavity considerably increases. For the higher values of Rayleigh number, temperature lines show that ratio of conduction heat transfer to total heat transfer is more than other forms of heat transfer. Density of isotherm in the lower section of the cavity significantly decreases which demonstrates that lesser heat exchanges in this area. As can be seen in the stream contour, in this case buoyancy force is developed and acts against temperature and density differences and moves the fluid in an upward direction. And this makes the streamlines of the upper section denser than the lower section.

Flow intensity in the cavity filled with nanofluid is also stronger than the cavity filled with base fluid and this increase in intensity is even higher for the value of ψ_{max} at $Ra = 10^4$. In this case, value of ψ_{max} increases by 19.19% in cavity filled with nanofluid.

CONCLUSION

Numerical simulation was carried out and the following results were extracted:

1) In addition of nanoparticles to the base fluid increases the amount of heat transfer in all points of the lid and amount of this increase is more at upper areas of the lids.

2) Increase in Ra number causes a noticeable enhancement in the rate of heat transfer.

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