MODELING OF NANOFLUID MIXED CONVECTION IN A VENTED ENCLOSURE WITH PERIODIC HEATING

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Abstract

A numerical study is carried out for mixed convection heat transfer in a ventilated cavity with injection or suction of Al_2O_3-water Nanofluid. The bottom wall is subjected to a sinusoidal hot temperature profile whereas the other boundaries are assumed to be thermally insulated. The effects of various design parameters such as Reynolds number $200 \le Re \le 5000$, nanoparticles concentration, $\phi \le 0.1$, and mode of imposed external flow (injection and suction) on the fluid flow and heat transfer inside the cavity are investigated.

Keywords: *Mixed convection, vented cavity, nanofluid, sinusoidal heating, injection, suction.*

1. Introduction

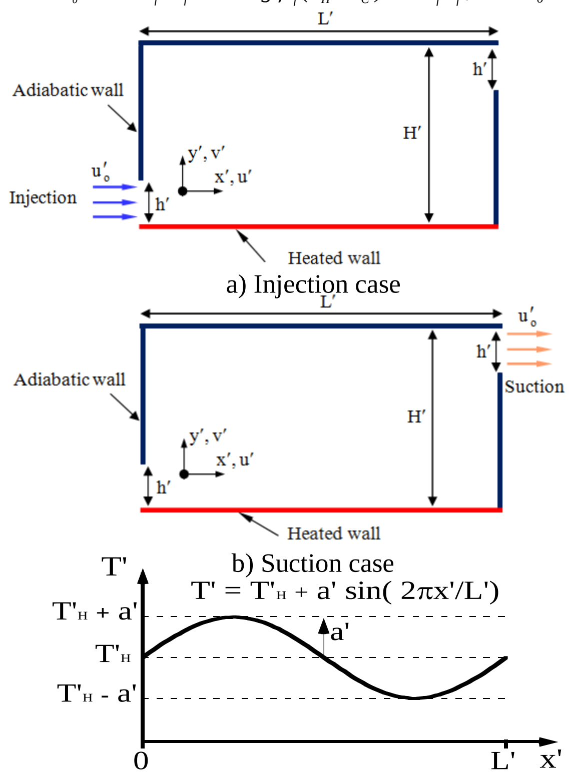
The primary limitation, in heat transfer, of conventional fluids such as water, ethylene glycol or oil, is their low thermal conductivity. Therefore in recent years, nanofluids have attracted more attention for cooling in various applications such as heat exchangers, lubrication technology, chemical processing equipments and solar energy collectors. Use of metallic nanoparticles with high thermal conductivity increases the effective thermal conductivity of these types of fluid remarkably [1] and eventually increases heat transfer performances [2]. Mixed convection heat transfer is one of the most important mechanism in many industrial applications. Over the past recently years, the mixed convection problems of nanofluid with varying heating temperature profile are mostly related to lid-driven cavities [3, 4]. Due to practical importance, the heat transfer characteristics of nanofluids mixed convection in vented cavities with inlet and outlet ports have been subjects of some other studies [5, 6 and 7].

The objective of this work is to study the effects of nanoparticles volume fraction, Reynolds number and the modes of imposed external flow on the heat transfer characteristics for steady mixed convection in a vented rectangular enclosure filled with a nanofluid.

2. Problem definition

The schematic diagram of the geometry considered in this work is displayed in Fig. 1. It consists of a vented rectangular enclosure with an aspect ratio A = 2. The physical system is subjected to an external cold flow which forced through the cavity by injection (Fig. 1a) or suction (Fig. 1b). The cavity is heated from its bottom wall by a sinusoidal varying hot temperature (Fig. 1c) while the remaining boundary parts are kept insulated. The nanofluid is assumed Newtonian and incompressible and the flow is laminar and two-dimensional.

Therefore, using the following dimensionless variables: $A = L'/H'$, $B = h'/H'$, $x = x'/H'$, $y = y'/H'$, $u = u'/u'_o$, $v = v'/u'_o$, $t = t'u'_o/H'$, $T = (T' - T'_C)/(T'_H - T'_C)$, $\Psi = \Psi'/u'_o H'$, $\Omega = \Omega' H'/u'_o$, $Pr = \nu_f/\alpha_f$, $Ra = g\,\beta_f (T'_H - T'_C) H'^3/\alpha_f \nu_f$, $Re = u'_o H'/\nu_f$.



c) Sinusoidal temperature profiles on the heated wall

Fig. 1: Geometry and coordinates system a) Injection case, b) Suction case and c) Heating temperature profile.

3. Mathematical modeling

The non-dimensional governing equations that describe the system behavior can be written, in terms of Ψ-Ω formulation, as follows:

$$\left\{\begin{array}{l}\dfrac{\partial\Omega}{\partial t}+u\dfrac{\partial\Omega}{\partial x}+v\dfrac{\partial\Omega}{\partial y}=\dfrac{Ra}{Re^2\,Pr}\left[\left(\dfrac{\phi}{\left((1-\phi)\dfrac{\rho_f}{\rho_s}+\phi\right)}\right)\dfrac{\beta_s}{\beta_f}+\dfrac{1}{\left(\dfrac{\phi}{(1-\phi)}\dfrac{\rho_s}{\rho_f}+1\right)}\right]\dfrac{\partial T}{\partial x}\\ +\dfrac{1}{Re}\left[\dfrac{1}{(1-\phi)^{2.5}\left(\phi\dfrac{\rho_s}{\rho_f}+(1-\phi)\right)}\right]\left(\dfrac{\partial^2\Omega}{\partial x^2}+\dfrac{\partial^2\Omega}{\partial y^2}\right)\end{array}\right\} \quad (1)$$

$$\frac{\partial T}{\partial t}+u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}=\frac{1}{Re\,Pr}\left(\frac{\dfrac{\lambda_{nf}}{\lambda_f}}{(1-\phi)+\phi\dfrac{(\rho c_p)_s}{(\rho c_p)_f}}\right)\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}\right) \quad (2)$$

$$\frac{\partial^2\Psi}{\partial x^2}+\frac{\partial^2\Psi}{\partial y^2}=-\Omega \quad (3)$$

Nanofluid effective density, thermal expansion coefficient, effective thermal conductivity, thermal diffusivity and heat capacity are, respectively, calculated as follow:

$$\rho_{nf}=\phi\rho_s+(1-\phi)\rho_f \quad (4) \qquad (\rho\beta)_{nf}=\phi\rho_s\,\beta_s+(1-\phi)\rho_f\beta_f \quad (5)$$

$$\frac{\lambda_{nf}}{\lambda_f}=\frac{\lambda_s+2\lambda_f-2\phi(\lambda_f-\lambda_s)}{\lambda_s+2\lambda_f+\phi(\lambda_f-\lambda_s)} \quad (6) \qquad \alpha_{nf}=\frac{\lambda_{nf}}{(\rho c_p)_{nf}} \quad (7)$$

$$(\rho c_p)_{nf}=\phi(\rho c_p)_s+(1-\phi)(\rho c_p)_f \quad (8)$$

Where "*f* ", "*s* " and "*nf* " indicate fluid, solid particles and nanofluid respectively.

The estimation of the heat transfer enhancement is based on the average Nusselt number, Nu, calculated on the heated bottom wall of the cavity such as:

$$Nu=-\frac{1}{A}\left(\frac{\lambda_{nf}}{\lambda_f}\right)\int_0^A\left.\frac{\partial T}{\partial y}\right|_{y=0}dx \quad (9)$$

4. Results and discussion

In this study, the Rayleigh number was kept fixed at Ra = 10^6 so that this value simulates mixed convection and forced convection dominating regimes.

Streamlines and isotherms plots illustrating the effect of Re on the dynamical and thermal fields, in the injection case, are shown in Figs. 2a-2b in both ϕ = 0 (solid line —) and ϕ = 0.1 (dashed line - - -). The streamlines show the presence of two closed convective cells separated by the open lines of the forced flow (Fig. 2a) for moderate Reynolds number (Re = 800). More precisely, a big trigonometric cell, due to shear effect, is positioned in the upper part of the cavity while the small clockwise one, due to free convection and shear effect is located below the open lines in the right corner of the cavity. This latter cell is far from the left corner because the forced convection is dominant in the entrance region of the enclosure. The corresponding isotherms, at the level of the heated horizontal wall, are very tightened from the inlet to the middle of the hot wall indicating a good convective heat exchange between the heating surface and the nanofluid in accordance with the imposed temperature profile. According to the Fig. 2b obtained for a great value of Re (Re = 3000), the streamlines obtained show that the more increase of Re from 800 to 3000 contributes to promote the lower cell, in terms of size, to the detriment of the space allowed in the lower part of the cavity, while the upper cell is divided into two others ones due to the large shear effect resulting from the growing forced convection. Furthermore, the shape of the flow is characterized by open parallel straight lines joining the two openings. Also, as expected, dynamical structure is insensitive to the addition of nanoparticles concentration. The corresponding isotherms illustrate that all isotherms are condensed near the hot wall, which justifies that the heat provided by the isothermal wall is carried by the forced flow to the outlet without passing through the remainder space of the cavity.

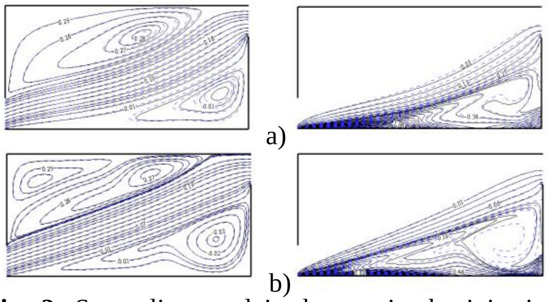


Fig. 2: Streamlines and isotherms, in the injection mode, for ϕ = 0 (—) or nanofluid ϕ = 0.1 (- - -) for different values of Re: a) Re = 800 and b) Re = 3000.

In the case of the suction mode, the effect of Re on the streamlines and temperatures contours is presented in Figs. 3a-3b in both pure water and Al_2O_3-water nanofluid situations. When Re = 800, as shown in Fig. 3a, the flow structure shows a big and a secondary closed cells, due to shear effect, occupying almost the upper half part of the cavity and surmounting the forced flow lines. Below these latter, a small clockwise cell is located in the lower right corner of the cavity whose formation is due to the buoyancy forces effects. The corresponding isotherms indicate that the thermal boundary layer thickness, reduced at the inlet, increases progressively towards to the right wall. Also, a big part of the cavity is at a uniform cold temperature. A further increase of Re up to 3000, as shown in Fig. 3b, the dynamical structure shows that the highest value of Re favors the closed natural convection cell located in right bottom corner due to the growing assisting effect of natural and forced convections. Also, the forced convection amplifies the closed cell localized in left top corner to the detriment of the main one surmounting the open lines.

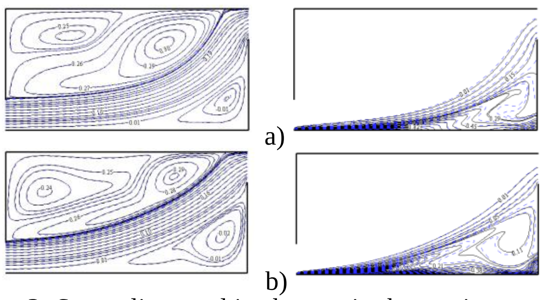


Fig. 3: Streamlines and isotherms, in the suction mode, for ϕ = 0 (—) or nanofluid ϕ = 0.1 (- - -) for two values of Re: a) Re = 800 and b) Re = 3000.

In order to illustrate the performance of the injection and suction modes in the heat removal, variations versus Re of the mean Nusselt number, Nu, along the heated wall are presented in Fig. 4 for various values of ϕ. Globally, a monotonous increase of Nu with Re is observed for both suction and injection modes. This tendency is justified by the flow intensification promoted by the increase of Re. For a fixed value of Re, the increase of the solid volume fraction ϕ up to 0.1 leads to a noticeable growing effect of the convection either for injection or suction case. This is due to the increase in effective thermal conductivity of the nanofluid with the increase in ϕ. It should be noted that, in comparison with the injection mode, the suction mode enhances more the heat transfer and consequently permits a better cooling within the cavity. Moreover, this thermal performance of the suction mode is more important in mixed convection mode (moderate values of Re).

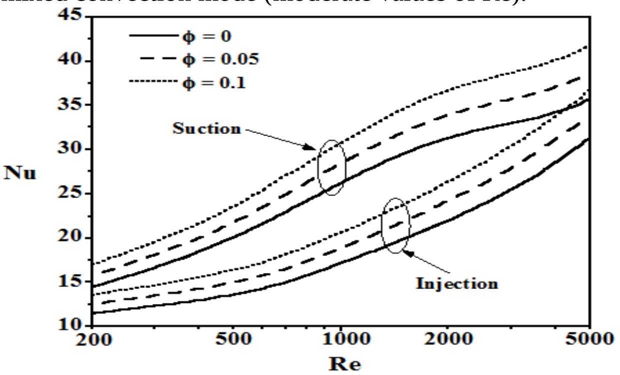


Fig. 4: Variations, with Re, of the average Nusselt number ″Nu″ evaluated on the heated wall, in both injection and suction modes for various values of ϕ.

Variations of mean temperature of the nanofluid with Re are plotted in Fig. 5 for different values of ϕ in both injection and suction modes. Particularly, in the injection case, the average temperature $\overline{T}$ increases by increasing Re up to a critical value ranging in [500-600] which strongly depends on ϕ. Then, this tendency is reversed because the growing of Re is marked by a decrease of $\overline{T}$; this behavior is due to the forced convection predominant effect which drives out the heat towards the outside and thereafter contributes to the cooling of the cavity.

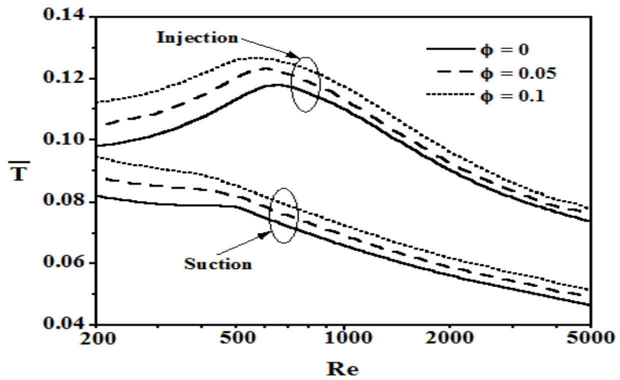


Fig. 5: Variations, with Re, of the mean temperature, $\overline{T}$, in both injection and suction modes for various values of ϕ.

For the other case (suction), the evolution of mean temperature $\overline{T}$ with Re is characterized by a notable decrease as long as Re is higher almost than 500. Below this threshold, the decrease of this parameter with Re remains weak. For a given value of Re, it is observed that when solid concentration increases, the average temperature increases. Also, it is obvious from this figure that the suction mode leads to a better cooling of the cavity.

5. Conclusion

This study investigates the mixed convection of nanofluids in a two-dimensional ventilated cavity heated by sinusoidal temperature profile. The obtained results show that the presence of nanoparticles enhances the heat transfer across the cavity and increases the mean temperature within the enclosure. The volume fraction of nanoparticles has a negligible effect on flow pattern and thermal structure. Also, the results indicate that the suction mode gives a better thermal efficiency and better cooling of the cavity than the injection one.

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