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Heat transfer by natural convection of Al_2O_3-water nanofluid

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***Abstract*— In this paper, we present a numerical study of heat transfer by Al_2O_3 water nanofluid in differentially heated square cavity. Natural convection is induced by temperature gradient imposed on cavity walls. In this study, two cases are numerically simulated; horizontal and a vertical temperature gradients. The objective is to compare the performance of two systems working under these conditions. Numerical tools used for this work are Gambit as mesh generator and Fluent as numerical solver. The results indicate that the average Nusselt number increases with the increase of Rayleigh number and concentration of nanoparticles. The improved rate of heat transfer increases from the horizontal to the vertical gradient.**

***Keywords*— nanofluids, heat transfer, natural convection, concentration**

I. Introduction

Most traditional fluids such as water, ethylene glycol and oil, are of limited thermal conductivities, which can impose severe restrictions in many thermal applications. So we must look for new strategies to improve the thermal behaviour of these fluids. With advances in nanotechnology and thermal engineering, many efforts have been made for the improvement of heat transfer. On the other hand, most of the solids, in particular metals, have much higher thermal conductivities compared to traditional fluids. Another approach to improve the thermal properties of a fluid involves adding nanosolides whose size is around 30 µm and then obtains the famous nanofluid. In this study, we used Al_2O_3 -water as nanofluid.

II. Problem statement

This work presents a comparison of the effects of horizontal and vertical temperature gradients on the heat transfer by Al_2O_3-water nanofluid considered as Newtonian and incompressible fluid le flow is supposed to be laminar and two dimensional. Natural convection is confined in a square cavity of side L (Fig.1). The thermo physical properties of the nanofluid are assumed to be constant except density, which obeys the Boussinesq approximation.

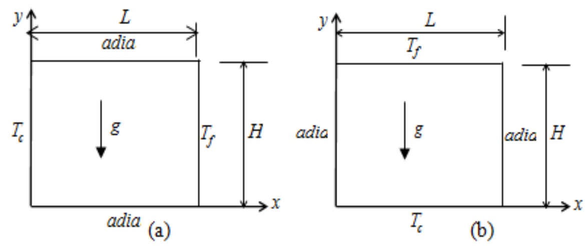

Fig.1 thermal Configurations differentially heated cavity
(a): horizontal gradient, (b) vertical gradient

III. *Governing equations*

The dimensionless variables used to convert the equations are:

$$X=\frac{x}{L};Y=\frac{y}{L};U=\frac{uL}{\alpha_f};V=\frac{vL}{\alpha_f};P=\frac{pL^2}{\rho_{nf}\alpha_f^2};\theta=\frac{(T-T_f)}{(T_c-T_f)}$$

The dimensionless equations for continuity, momentum, and energy are expressed in the following form:

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

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

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

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

Ra and *Pr*, are the traditional dimensionless Rayleigh and Prandtl numbers respectively.

The density of nanofluid in previous equations is calculated from the following relations:

$$\rho_{nf}=(1-\varphi)\rho_f+\varphi\rho_s \quad (5)$$

φ represent the solid volume fraction defined as the ratio of solid volume phase by the volume of the base liquid.

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Thermal expansion coefficient, specific heat, dynamic viscosity and thermal conductivity of the nanofluid are expressed as [1-4]:

$$\beta_{nf} = (1-\varphi)\beta_f + \varphi\beta_s \quad (6)$$

$$Cp_{nf} = \frac{1}{\rho_{nf}}(1-\varphi)(\rho Cp)_f + \varphi(\rho Cp)_s \quad (7)$$

$$\mu_{nf} = \frac{\mu_f}{(1-\varphi)^{2.5}} \quad (8)$$

$$k_{nf} = \frac{(k_p-k_{lr})\varphi k_{lr}\left[2\beta_1^3-\beta^3+1\right]+(k_p+2k_{lr})\beta_1^3\left[\varphi\beta^3(k_{lr}-k_f)+k_f\right]}{\beta_1^3(k_p+2k_{lr})-(k_p-k_{lr})\varphi\left[\beta_1^3+\beta^3-1\right]}$$

(9)

Where β and β_1 are characteristics of the nanofluid:

The Nusselt number *Nu* is one of the most important dimensionless parameters in describing the convective heat transfer. The local Nusselt number in the case of horizontal temperature gradient is given as follows:

- $Nu = -\frac{k_{nf}}{k_f}\left(\frac{\partial\theta}{\partial X}\right)_{x=0}$ (10) in the case of horizontal temperature gradient
- $Nu = -\frac{k_{nf}}{k_f}\left(\frac{\partial\theta}{\partial Y}\right)_{y=0}$ (11) in the case of vertical temperature gradient

The space averaged Nusselt number *Nu* is calculated by integrating the last expression over the vertical wall x=0. In the case of vertical temperature gradient, Nu is calculated by the same expressions but by permitting *x* to *y*.

Table 1: Thermophysical properties of water and aluminum oxide (Al_2O_3) and nanofluid (Al_2O_3 + water)

	k_{nf} (wm⁻k¹)	ρ_{nf} ($kg\ m^{-3}$)	μ_{nf} ($kg^{-1}m^{-1}s^{-1}$)	C_{pnf} ($J\ kg^{-1}\ k^{-1}$)	β_{nf} (k^{-1})	$\alpha_{nf}\ 10^{-7}$ ($m^2\ s^{-1}$)
Water	0.613	997	$85*10^{-5}$	4179	$21*10^{-5}$	1.47
Al_2O_3	40 [5]	3970	--	761.55	$85*10^{-7}$	--
1 %	0.66375	1027.72	$1.027*10^{-3}$	4046.98	$2.082*10^{-4}$	1.5958
2 %	0.71556	1057.44	$1.053*10^{-3}$	3922.39	$2.064*10^{-4}$	1.7252
3 %	0.76847	1087.16	$1.081*10^{-3}$	3804.61	$2.047*10^{-4}$	1.857
4 %	0.82252	1116.88	$1.109*10^{-3}$	3693.10	$2.029*10^{-4}$	1.9941
5 %	0.87774	1146.60	$1.139*10^{-3}$	3587.36	$2.011*10^{-4}$	2.1339

IV. RESULTS AND DISCUSSION

IV.1- Square cavity under a horizontal temperature gradient

In this work, numerical simulations are performed with a uniform mesh of 81 x 81. The Rayleigh numbers considered are in range of 10^4 to 10^6. Concentrations of nanoparticle are from 1 to 5%.

Table 2: Comparison of the results of Nusselt numbers with those Kahveci [6] with φ=0%

Ra	This workrs	Kahveci [6]
10^4	2.2004	2.274
10^5	4.6932	4.722
10^6	9.2859	9.230

Table 2 shows a comparison between the present study and the results of Kahveci [6] for different Rayleigh numbers. The results found are in good agreement with those found by Kahveci.

a) *Influence of the Rayleigh number on the flow*

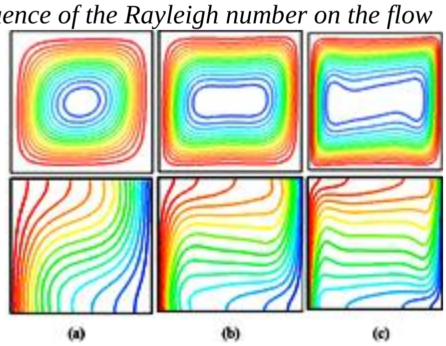


Fig.2 Streamlines (at the top) and isotherms (at bottom) for nanofluid (φ = 5%) (a): $Ra = 10^4$, (b): $Ra = 10^5$, (c): $Ra = 10^6$

Fig.2 shows as the flow values for all monocellular are of the number of Rayleigh. At low Rayleigh number $Ra = 10^4$ At low Rayleigh number $Ra = 10^4$ isotherms are perpendicular to the adiabatic walls and parallel to the walls differentially heated. At high Rayleigh number $Ra = 10^6$, the isotherms are very tight near the two walls hot and cold which proves the formation of a thermal boundary layer.

In the middle of the cavity isotherms are parallel to the adiabatic walls. This shows that the transfer is mainly by convection.

b) *Effect of the concentration of nanoparticles on the heat transfer*

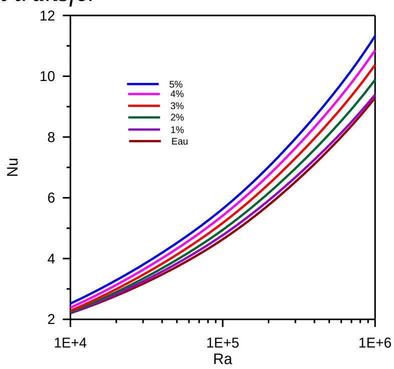


Fig.3 Variation of Nusselt number with solid volume fraction for different Rayleigh number

Fig.3 illustrates the variation of the average Nusselt number through the hot wall of the cavity for different Rayleigh number; the results are shown for different concentrations of the nanoparticles. It is noted that the Nusselt number increases with increasing volume fraction of the nanoparticles. This increase is due to the improvement of the effective thermal conductivity of the fluid after the addition of the nanoparticles. These results are in good agreement with numerical results [2, 13]. For $Ra = 10^4$, the improvement in heat transfer rate from φ = 0% to 5% affected 14% for $Ra = 10^4$, 20% for $Ra = 10^5$ and 22% for $Ra = 10^6$.

IV.2- Square cavity under a vertical temperature gradient

In this case we studied the case of a closed cavity with two horizontal walls are maintained at constant temperatures and uniform Tc and Tf at y = 0 and y = L, respectively. Both vertical walls are adiabatic.

a) Influence of the Rayleigh number on the flow

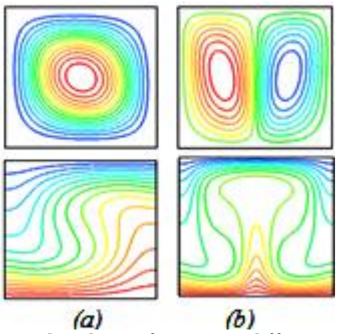


Fig.4 Streamlines and isotherms for a cavity differentially heated from below (a) $Ra = 10^4$, (b) $Ra = 10^5$

Fig.4 shows $Ra = 10^4$, the flow is unicellular. It is characterized by a great cell occupying the entire cavity. In this case, the isothermal are perpendicular the adiabatic walls and parallel to the vertical walls. For $Ra = 10^5$, the flow becomes celled. Both cells are symmetric with respect to the center of the cavity. In this case the cells circulate in opposite direction, the fluid flows from the middle of the cavity upwardly and down from left and right sides. The isotherms are also symmetrical relative to the vertical plane of the cavity. By increasing from $Ra=10^5$. Revenue is when the value $2.8 * 10^5$, periodic oscillations appears. The flow passes a steady bicellular a periodic flow characterized by a periodic sequence of appearance and disappearance of vortex cells.

b) periodic regime

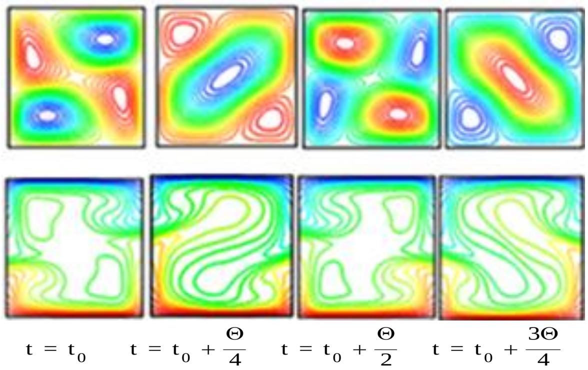
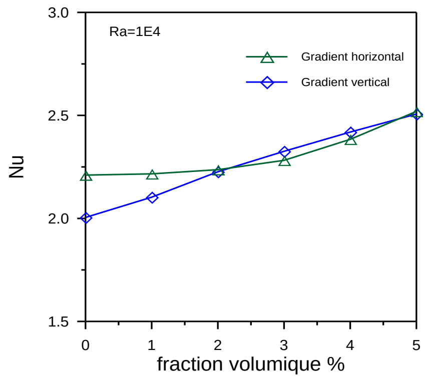


Fig.5: Periodic Regime

Fig.5 shows the streamlines and isotherms of a periodic regime to $Ra = 4.3 * 10^5$. This figure clearly shows the formation of four cells which evolve toward a three cells of a predominant and two other small cells circulating in the corners of the cavity. This oscillatory regime occurs in a period of time equal to Θ= 15 seconds

IV.3- Comparison of the heat transfer in the two cases studied

(a)



(b)

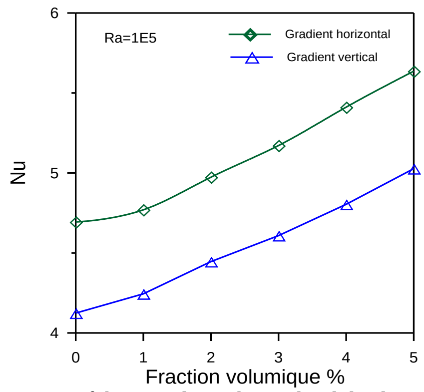


Fig.6: Variation of the Nusselt number with solid volume fraction (a): $Ra = 10^4$, (b): $Ra = 10^5$.

The effect of temperature gradient on the natural convection is shown in fig.6 for Rayleigh number equal to 10^4 and 10^5. To $Ra = 10^4$ and a low concentration of heat transfer nanoparticle is almost constant in the case of horizontal gradient but increases when the concentration of the nanoparticle increases from Ø=3%. By cons in the case of vertical gradient Nusselt number believed almost linearly with the concentration of nanoparticles. In Fig.6 (a), it is noted the presence of two regions. The first where the volume fraction is less than 2%, in the region of the Nusselt number to a horizontal temperature gradient is greater than the vertical gradient. This is due to the low concentration of nanoparticles added to the base fluid. But for the second region where the volume fraction is greater than 2% the situation is reversed. This increase is due to the high thermal conductivity observed after the addition of a large amount of nanoparticles. In this case the thermal conductivity dominates viscosity. So we can conclude that the influence of the addition of nanoparticles is more important in the case of vertical gradient.

Fig.6 (b) shows that for $Ra = 10^5$, and in the case of the horizontal gradient Nusselt number is greater than the vertical gradient. Note also that the amelioration heat transfer rate between 0% and 5% at 20% in the case of horizontal gradient and 22% to the vertical gradient.

V. References

Khanafer and al. [7] studied numerically the effect of the suspension of ultrafine metal nanoparticles on fluid flow and heat transfer. It was revealed that the heat transfer rate increases with the increase of particle fraction at any given Grashof number. Jou and al. [8] presented a numerical study of heat transfer of nanofluid Al_2O_3-water. They found that the rate of heat transfer increases with the addition of the nanoparticles. Ho and al [9] have observed that low concentrations of the dispersion of nanoparticles in water Al_2O_3 can effectively improve the intrinsic characteristics compared to pure water. Hakan Oztopa and al [10] performed a numerical study of natural convection in a partially heated enclosure filled with nanofluid. This study is done for different types of nanofluid Al_2O_3, CuO and TiO_2. The results show that the heat transfer increases with the volume fractions of nanoparticles. Feng-Hsiang Lai and al. [11] presented numerical simulations by natural convection of nanofluid Al_2O_3-water. They found that the average Nusselt number increases with the increase of the volume fraction and Rayleigh nanoparticle. A.G.A.Nnanna [12] studied numerically the heat transfer nanofluid Al_2O_3-water in a rectangular enclosure. He showed that the Nusselt number is improved at low concentrations nanofluid ($0.2 \leqslant \phi \leqslant 2\%$). But for $\phi > 2\%$ of the Nusselt number decreased because of the increase in kinematic viscosity. B. Ghasemi and al. [13] studied numerically heat transfer by natural convection in an enclosure filled with an inclined nanofluid CuO / water.

The results show that the heat transfer depends on the Rayleigh number, the angle of inclination and the volume fraction of the nanoparticles. And the Nusselt number increases with the Rayleigh.

V. Conclusions

The present work consist in comparing the heat transfer convection in two cases: cavities subjected to horizontal temperature gradient to a cavity then subjected to a vertical temperature gradient in a closed cavity filled with a nanofluid Al_2O_3 - water. The numerical results show that:

1 - The effect in the case of nanofluid convection occurs in particular in the case of the horizontal gradient $Ra = 10^4$.

2 - The increase of the volume fraction of for nanofluid increases heat transfer in the case of the $Ra = 10^5$.

3 - The addition of the nanoparticles in the case of vertical gradient improves the rate of heat transfer of a larger manner as in the case of the horizontal gradient.

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