

Do Nanofluids Really Enhance Heat Transfer?

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Abstract

Heat transfer by nanofluids is deeply influenced by two parameters; thermal conductivity and dynamic viscosity. In nanofluids these parameters play a contradictory role. The addition of nanosolids into basic fluid leads to an augmentation in thermal conductivity which leads to an augmentation in heat transfer but also causes to an increase of the dynamic viscosity which causes to a regression in heat transfer. This paper investigates the contradictory roles played by thermal conductivity and dynamic viscosity on heat transfer by some types of nanofluids. Tests are realized considering a flow of natural convection in a differentially heated cavity. Navier-Stokes and energy equations are solved by the computational fluid dynamics code FLUENT. The solid volume fraction of nanosolids is varied from 0% to 5% whereas their sizes are in the range of 15-140nm. Heat transfer is evaluated at temperatures ranging from 20°C to 70°C. The numerical results have shown that at room temperature, increasing the concentration of nanosolids reduces the heat transfer from the hot wall to the flow. This attitude is reversed when the system is at high temperatures. These effects on heat transfer and entropy generation are discussed in this work.

Keywords: nanofluid; heat transfer; entropy generation;

1. Introduction

Nanofluid is a type of liquid made by the addition of nanosolids of sizes less than ~100nm into a basic liquid. Choi [1] was the first researcher who has the idea to mix a liquid with solid nanoparticles in the hope to improve the thermo-physical properties of the resulting liquid. Choi [1] finds that even at low nanosolid concentration, thermophysical properties of the nanofluid are largely modified. Especially thermal conductivity and dynamic viscosity are increased with increasing the nanosolid concentration. The nanofluids have many important applications in scientific engineering such as solar collectors, electronic components cooling, energy storage systems and heat exchangers. Since the publication of Choi [1] in 1995, experimental studies as well as numerical investigations of nanofluids start around the world. Bouhalleb and Abbassi [2] analyzed heat transfer and fluid flow of natural convection in inclined cavity filled with CuO-water nanofluid and differentially heated. Parameters of the problem are aspect ratio from 0.5 to 4, solid volume fraction varied from 0% to 4%, and the inclination angle is varied from 0° to 90°. Numerical results show that the efficiency of heat transfer is improved by the addition of nanoparticles into base fluid. They observed also, that the heat transfer enhancement depends strongly on the diameter of solid particle. Results show then that the increasing and decreasing of inclination angle highlights a

hysteresis behavior of the flow. Ghasemi and Aminossadati [3] presented a numerical study of heat transfer by natural convection in inclined enclosure filled with CuO-water nanofluid. The results show that heat transfer depends on the Rayleigh number, the angle of inclination and the solid volume fraction of the nanoparticles and they show that adding nanoparticles in pure water improves its heat transfer performance. Hakan and Abu-Nada [4] performed a numerical study of natural convection in a partially heated enclosure filled with nanofluid. This study is done for nanofluids Al_2O_3 , CuO and TiO_2 . The results show that the mean Nusselt number increases with increasing the solid volume fraction of nanoparticles for the whole range of Rayleigh numbers. They noted that heat transfer at low aspect ratios is more pronounced than at high aspect ratios. Bouhalleb and Abbassi [5] reported a numerical investigation of the effect of solid volume fraction on heat transfer and fluid flow in the case of natural convection in inclined cavity filled with CuO-water nanofluid. Results show that the addition of CuO solid particle in water leads to enhancement of heat transfer. The average Nusselt number is influenced by the variation of the aspect ratio and inclination angle. Heat transfer enhancement utilizing Cu-water and Al_2O_3 -water nanofluids in a trapezoidal enclosure is achieved by Saleh et al. [6]. Parameters considered are inclination angles of the sloping

wall, solid volume fractions, and Grashof numbers. They showed that Cu nanoparticles with high volume fraction combined with acute angles are most effective in enhancing performance of heat transfer rate.

Many studies have been published concerning the entropy generation. Magherbi et al. [7] conducted a numerical study of the transient state of entropy generation for laminar natural convection in a square cavity with heated vertical walls. Results show that the total entropy generation has a maximum value at the onset of the transient state, which increases with the Rayleigh number and the irreversibility distribution ratio. Ilis et al. [8] studied the entropy generation due to natural convection in a square cavity filled with air. Results show that with high values of Rayleigh numbers, the total entropy generation due to fluid friction and total entropy generation increases with increasing aspect ratio, attain a maximum and then decreases. In recent years, the problem of entropy generation in nanofluids has also attracted significant attention for many researches [9]. Effects of different parameters, such as solid volume fraction and particle size on the entropy generation were studied.

Cho [10] realizes a numerical study of heat transfer characteristics and entropy generation of natural convection in a partially-heated wavy-wall cavity filled with Al_2O_3 -water nanofluid. Results show that the mean Nusselt number increases and total entropy generation decreases as the solid volume fraction of Al_2O_3 nanoparticles increases. They also show that the mean Nusselt number reduces and the total entropy generation increases as the amplitude and wavelength of the wavy-surface increases. Shahi et al. [11] investigated the natural convection heat transfer phenomenon in a square cavity containing Cu-water nanofluid and a protruding heat source. They observed that the Nusselt number increases and the entropy generation decrease as the solid volume fraction of nanoparticles increases. The results have shown that the maximum value of Nusselt number and minimum entropy generation are obtained when the heat source is mounted on the bottom horizontal wall.

The addition of nanosolids into basic liquid leads to an augmentation not only of thermal conductivity but also of the dynamic viscosity. The first effect causes to the enhancement of heat transfer whereas the second causes to a decrease in heat transfer via the slowing of the flow motion. According to the above bibliography, it appears that addition of nanosolids in basic fluid enhances heat transfer even at room temperature [2-6]. These studies used theoretical models for viscosity and thermal conductivity such as Brinkman [12], Batchelor [13] and Maxwell [14] models. Actually, many recent experimental measurements of nanofluid viscosity are available in literature [15-16]. It turns out that theoretical model underestimate the viscosity of the nanofluid especially at high concentrations of nanoparticles. Experimental measurements of Nguyen et al. [15] show that the dynamic viscosity of Al_2O_3 -water nanofluid is 0.002PI for 5% nanosolid concentration. For the same concentration, Brinkman model [12] gives a viscosity of only 0.0011PI, a deviation of 45% of the model compared to the

experiment is appears. This strong divergence between experimental and theoretical values makes us in doubt about the finding that the additions of nanosolids into basic fluid, leads to an increase in heat transfer. Purpose of the paper is to verify if the nanofluids leads really to heat transfer enhancement. For this raison, a numerical investigation of heat transfer by nanofluids Al_2O_3 , TiO_2 and CuO suspended in water or in ethylene glycol is presented, using more accurate models for dynamic viscosity and thermal conductivity, firstly at room temperature and secondly at high temperature.

2. Statement of the problem and governing equations

In the following, the influence of dispersion nanoparticles Al_2O_3 , TiO_2 and CuO in base fluid (water or ethylene glycol EG) on heat transfer by natural convection in square cavity heated from one vertical side as indicated in Figure 1 is discussed. The nanofluid is considered as Newtonian and incompressible. The flow is supposed to be laminar and bi-dimensional.

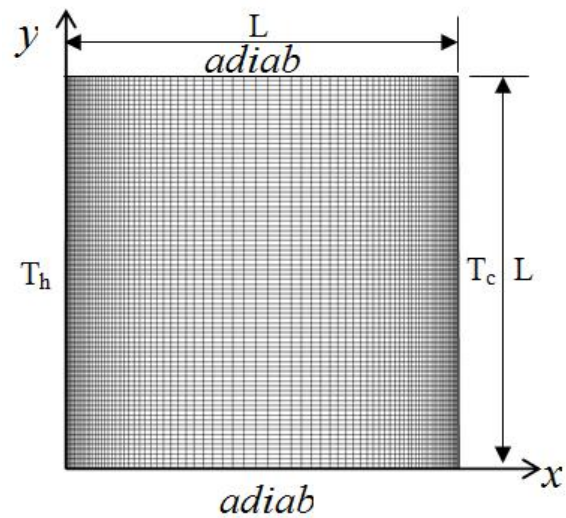


Figure 1. Square cavity with grid meshing and boundary conditions

The numerical solutions of momentum and energy equations were performed to simulate the amount of heat transferred from the hot wall to the flow. The resolution is obtained by FLUENT software.

The mathematical equations describing the nanofluid flow are the continuity, Navier-Stokes and energy equations:

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

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

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

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

These equations are normalized by the characteristic side length L of the square cavity and the specific velocity $\frac{\alpha_f}{L}$, where α_f is the thermal diffusivity of the basic fluid. The dimensionless temperature is defined as $\theta = (T - T_c)/(T_h - T_c)$.

The dimensionless numbers that appear in governing equations are the classic Prandtl and Rayleigh numbers designed by Pr and Ra respectively.

The density of nanofluid is calculated from the following relation:

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

Where ϕ represents the solid volume fraction of the nanoparticles, subscripts nf , f and s refer to the mixture nanofluid, the basic liquid and the solid particles respectively.

The expression of specific heat is given by Abu-Nada et al. [17] and thermal expansion coefficient is given by Ghasemi and Aminossadati [3]. These relations are inspired from Eq. 5:

$$(\rho C_p)_{nf} = (1 - \phi)(\rho C_p)_f + \phi(\rho C_p)_s \quad (6)$$

$$(\rho\beta)_{nf} = (1 - \phi)(\rho\beta)_f + \phi(\rho\beta)_s \quad (7)$$

From several experimental data available in the literature relative to nanofluids, Corcione [18] proposes models for thermal conductivity and dynamic viscosity for several nanofluids such as alumina (Al_2O_3), copper oxide (CuO), titanium (TiO_2) and copper (Cu) nanoparticles suspended in water or in ethylene glycol. Concentration is varied from 0.2% to 9%, and the nanoparticles diameters are ranging from 10 nm to 150 nm. Models developed by Corcione [18] are as following:

$$k_{nf} = k_f \left[1 + 4.4 Re^{0.4} Pr^{0.66} \left(\frac{T}{T_{fr}} \right)^{10} \left(\frac{k_s}{k_f} \right)^{0.03} \phi^{0.66} \right] \quad (8)$$

$$Re = \frac{2\rho_f k_b T}{\pi \mu_f^2 d_p}$$

$$\mu_{nf} = \mu_f \left[\frac{1}{1 - 34.87(d_p/d_f)^{-0.3} \phi^{1.03}} \right]; d_f = 0.1 \left(\frac{6M}{N\pi\rho_f} \right)^{1/3} \quad (9)$$

Where d_f , ρ_f and T_f are the molecule diameter, the density and the freezing point of the base fluid at room temperature respectively. It should be noted that, as mentioned by Corcione [18], the maximum deviations of these models from experimental values are 1.86% and 1.84% for thermal conductivity and dynamic viscosity respectively. It appears that these models are largely more accurate than old theoretical ones.

Figure 2 represents the variations of relative dynamic viscosity and relative thermal conductivity as functions of solid volume fraction respectively for various particle diameter dp . As can be seen, both, conductivity and viscosity increases with increasing the nanosolid concentration and decreasing diameter sizes of nanoparticles. Figure 2 shows also that for the same particle size, the increase in viscosity is largely higher than corresponding to thermal conductivity. For example, at $dp=30nm$, when ϕ passes from 0 to 5%, the enhancements of the relative viscosity and the relative thermal conductivity are 75.92% and 11.71% respectively. Thus a

question arises, is the addition of nanosolids into basic liquid really enhance heat transfer by the obtained nanofluid? The response to this question is the principal objective of this study.

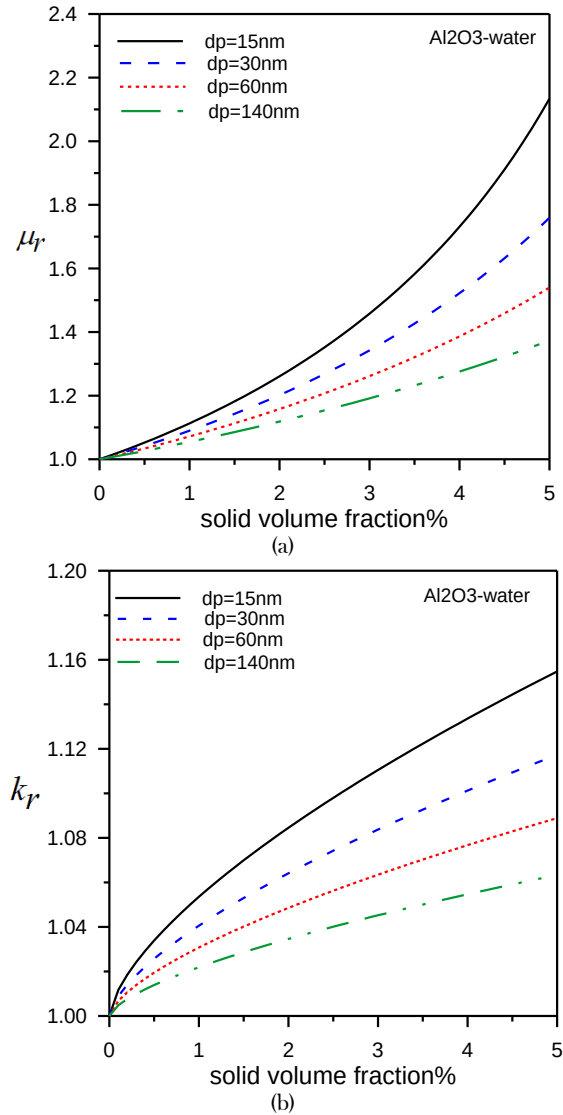


Figure 2. Variation of relative viscosity μ_r (a) and relative thermal conductivity k_r (b) as function of solid volume fraction for Al_2O_3 -water nanofluid for various diameters.

The amount of heat exchanged between the hot wall and the flow is evaluated by the space average Nusselt number and expressed as:

$$Nu = -\frac{k_{nf}}{k_f} \int_0^1 \frac{\partial \theta}{\partial x} dy \quad (10)$$

In natural convection, the entropy generation is due to heat transfer and frictions. According to Bejan [19], the local dimensional entropy generation s_{gen} is expressed as:

$$s_{gen} = \frac{k_{nf}}{T_0^2} \left[\left(\frac{\partial T}{\partial x} \right)^2 + \left(\frac{\partial T}{\partial y} \right)^2 \right] + \frac{\mu_{nf}}{T_0} \left[2 \left(\frac{\partial u}{\partial x} \right)^2 + 2 \left(\frac{\partial v}{\partial y} \right)^2 + \partial u \partial y + \partial v \partial x \right] \quad (11)$$

Where T_c is the mean temperature of the cavity and approximated by $(T_h + T_c)/2$

The first term between two brackets at the right side of Eq.11 represents the local entropy generation due to heat transfer, while the second term represents the local entropy generation due to the viscous effects. As previously, using the length and velocity characteristics, expression of the non-dimensional entropy generation, S_{gen} can be written as:

$$S_{gen} = \frac{k_{nf}}{k_f} \left[\left(\frac{\partial \theta}{\partial X} \right)^2 + \left(\frac{\partial \theta}{\partial Y} \right)^2 \right] + \frac{\mu_{nf}}{\mu_f} \delta \left[2 \left(\frac{\partial U}{\partial X} \right)^2 + 2 \left(\frac{\partial V}{\partial Y} \right)^2 + \partial U \partial Y + \partial V \partial X \right] \quad (12)$$

Where δ is the irreversibility coefficient and expressed as:

$$\delta = \frac{\mu_f T_0}{k_f} \left(\frac{\alpha_f^2}{(T_h - T_c)^2 L^2} \right) \quad (13)$$

S_{gen} is normalized by the reference entropy expressed as:

$$S_{ref} = \frac{k_f (T_h - T_c)^2}{T_0^2 L^2} \quad (14)$$

More discussions about δ and S_{ref} are reported later.

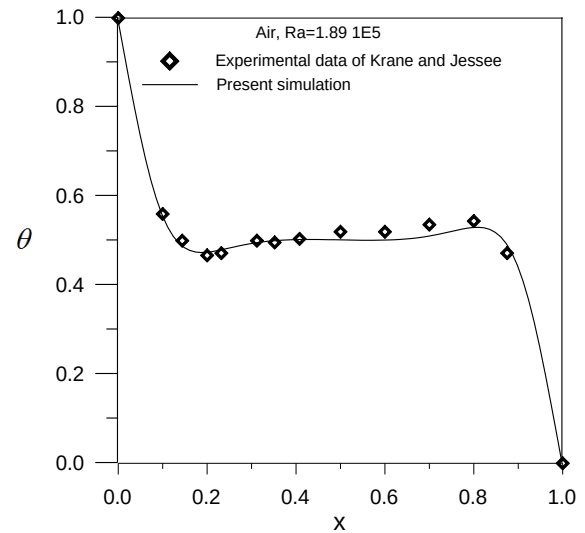
3. Grid refinement and test validation

To study the influence of the grid on numerical results, we calculated the average Nusselt number at the hot wall given by Eq. 10 for five non uniform grids. The results are related to pure water at $Ra = 10^5$ and the Prandtl number is equal to 6.83. Table.1 presents the Nusselt number for different grids. When we pass from the grid 71x71 to the grid 81x81, Nu undergoes a variation of 1.3%. When we pass to the grid 91x91, the variation of Nu is only 0.04%. We conclude that the grid of 81x81 gives a good compromise between precision and calculation time, it is sufficient to carry out a numerical study of this flow.

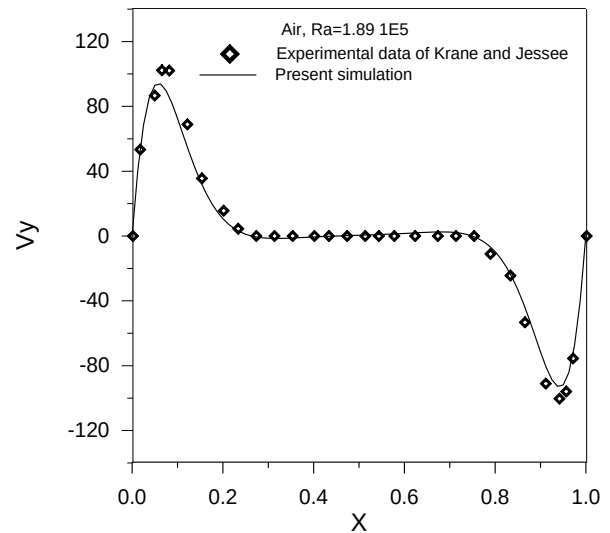
Table1. Variation of the Nusselt number versus grid mesh

Grid	51x51	61x61	71x71	81x81	91x91
Nu	4.7572	4.7501	4.7452	4.7388	4.7366

To compare our simulations with experimental results, the cavity is firstly filled with air ($Pr=0.72$). This comparison is shown in figure 3, where the temperature distribution (a) and the velocity profile (b) at the midplane cavity ($y=0.5$) are presented against the experimental results of Krane and Jessee [20]. It can be seen from these figures that our numerical simulations are in good agreement with experimental data of Krane and Jessee [20].



(a)



(b)

Figure 3. Validation of the present results against experimental results of Krane and Jessee [20] at $Pr=0.71$, $Ra= 1.89 \cdot 10^5$, $y=0.5$, (a) Temperature distribution, (b) Velocity profile.

Table 2 compares the Nusselt number Nu of the present simulations to the results of De Vahl David [21] and Barakos and Mitsoulis [22] and Khanafer et al [23]. This comparison indicates clearly that the present simulations give acceptable results.

Table 2. Validation tests: Nusselt numbers for various Rayleigh numbers

Ra	Present study	De Vahl Davis[21]	Barakos and Mitsoulis [22]	Khanafer et al.[23]	max erreur %
10^3	1.118	1.118	1.114	1.118	0.35
10^4	2.223	2.243	2.245	2.245	0.89
10^5	4.543	4.519	4.510	4.522	0.53
10^6	8.851	8.799	8.806	8.826	0.59

For more validations, the cavity is secondly filled by 1% Al_2O_3 -water nanofluid. The validation was performed for Rayleigh numbers ranging from 10^3 to 10^6 . Table 3 compares Nu of our simulations to the results of Lai and Yang [24] and Kahveci [25]. The maximum difference between our results and these references for pure water and 1% solid volume fraction of Al_2O_3 -water is less than 1.08% and 3.2% respectively. We conclude that our simulations give acceptable results also for the case of nanofluids.

Table 3: Validation tests

Ra		10^3	10^4	10^5	10^6
Pure water	Present study	1.121	2.285	4.738	9.271
	Lai and Yang [24]	1.128	2.286	4.729	9.173
	Kahveci [25]	—	2.274	4.722	9.230
Nanofluid $\phi = 1\%$	Present study	1.121	2.312	4.802	9.434
	Lai and Yang [24]	1.160	2.351	4.864	9.432

4. Results and discussions

4.1. Heat transfer at room temperature

In Figure 4, the variation of Nusselt number as a function of solid volume fraction for various nanofluids at $Ra=10^6$ and $dp=30\text{nm}$ is presented. This figure shows a general trend of decrease in the Nusselt number when the concentration increases. An exception can be seen at the vicinity of $\phi=1\%$ where Nu increases slightly. For this situation, effects of thermal conductivity enhancement of the nanofluid prevail over viscosity enhancement. In general, it appears that adding nanosolids into basic liquid lead to a nanofluid not efficient in heat transfer. This result seems to be surprising; we expect that, as in many findings in literature [2-6] the addition of nanosolids in basic liquid enhances heat transfer. But in this numerical work, and using models for dynamic viscosity and thermal conductivity based on experimental results, a clear reduction of the heat transfer especially when ϕ exceeds 1% is appears. This decrease is due to the predominant viscosity effects than the influence of the thermal conductivity enhancement when adding nanosolids. The increasing of viscosity leads to an increase in the boundary layer thickness, causing a decrease in the heat transfer performance.

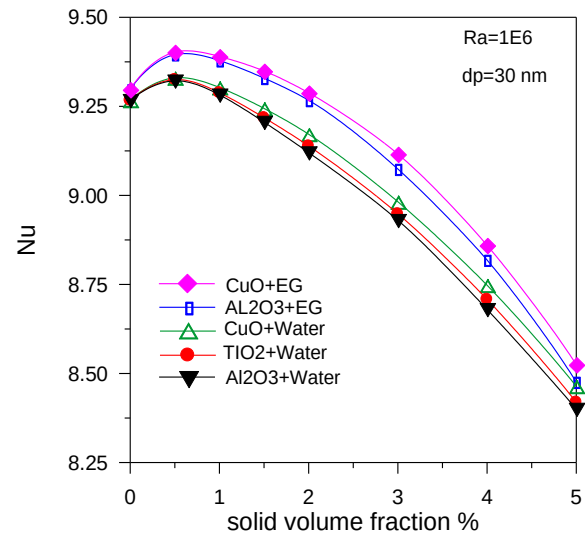


Figure 4. Nusselt number versus solid volume fraction for various nanofluids

For more credibility of these conclusions, we studied the effect of nanosolid sizes on heat transfer by choosing Al_2O_3 -water nanofluid as case test. In Figure.5 we present the variation of Nusselt number as a function of solid volume fraction for particle diameters varying from 15 to 140nm. Precedent conclusions are verified, a slight increase in heat transfer is observed for ϕ in the vicinity of 1% and a clear decrease when concentration increases, and this is true for all diameters in these computations. From Figure.5, two intervals of ϕ appeared; for $\phi \leq 2\%$, heat transfer increases as solid particles are smallest. When ϕ exceeds 2% the appearance is inversed, heat transfer increase when dp increase. As mentioned earlier, we think that this behavior is due to the opposing effects of viscosity and thermal conductivity enhancements.

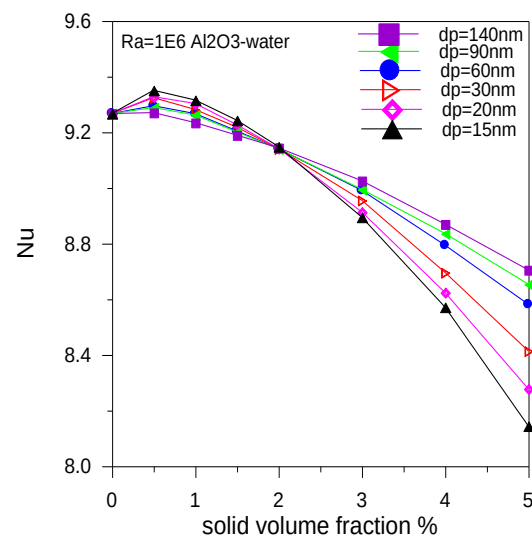
Figure 5. Nusselt number as a function of solid volume fraction for various solid particle diameters computed for Al_2O_3 at room temperature

Figure 6 shows the velocity profiles at the midplane of the cavity ($y=0.5$) at $Ra=10^6$ for $\phi = 5\%$ in comparison with pure water. This figure shows that the velocity profiles of

pure water are superior to that of nanofluid indicating that, addition of nanosolids into water leads to increases the fluid viscosity and slows the flow. At $\phi = 5\%$, and in the range of diameter sizes between 15 nm and 140 nm the velocity profile increases as dp increases. This behavior is explained by the significant decrease of viscosity when the particle size varies from 15 nm to 140 nm.

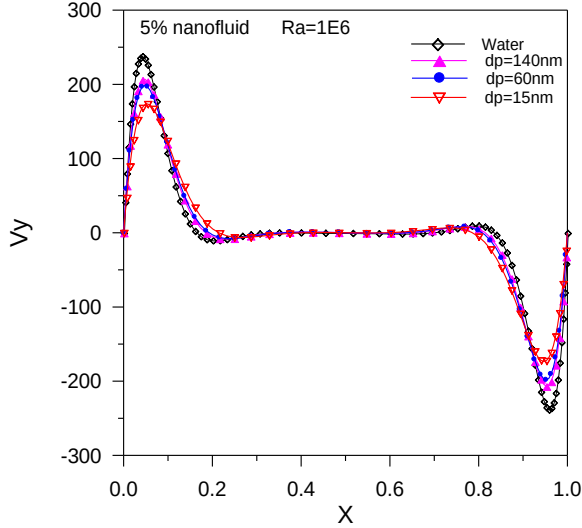


Figure 6. Velocity profile at midplane cavity at $Ra=10^6$ and 5%nanofluid, for various nanoparticles sizes

4.2. Effects of temperature on heat transfer

At the molecular viewpoint when the temperature increases, the intermolecular distance becomes larger, which leads to the decrease of the viscosity and the agitation in microscopic scale becomes stronger leading to an increase in thermal conductivity. In this context, we conducted a numerical study of the effects of temperature on viscosity and thermal conductivity in hope to find a situation where the addition of nanosolids improves thermo-physical properties of the nanofluid. We propose to use other models of thermal conductivity (Eq.15) and viscosity (Eq.16-17) which are expressed as functions of temperature and developed by Khanafer and Vafai [26] based on experimental measurements of Al_2O_3 -water nanofluid.

$$Kr = 0.9843 + 0.398 \phi^{0.7383} \left(\frac{1}{d_p (nm)} \right)^{0.2246} \left(\frac{\mu_{nf}}{\mu_f(T)} \right)^{0.0235} - 3.9517 \frac{\phi}{T} + 34.034 \frac{\phi^2}{T^3} + 32.509 \frac{\phi}{T^2} ; 20^\circ C \leq T \leq 70^\circ C \quad (15)$$

$$\mu_f(T) = 2.414 \cdot 10^{-5} 10^{247.8/(T-140)} \quad (16)$$

$$\mu_{nf} = -0.4491 + \frac{28.837}{T} + 0.5740\phi - 0.1634\phi^2 + 23.053 \frac{\phi^2}{T^2} + 0.0132\phi^3 - 2354.734 \frac{\phi}{T^3} + 23.498 \frac{\phi^2}{d_p^2} - 3.0185 \frac{\phi^3}{d_p^3} ; 20^\circ C \leq T \leq 70^\circ C \quad (17)$$

The temperature has a significant effect on relative thermal conductivity, equation (15-16) shows that, kr increases considerably with increasing temperature. At $\phi=5\%$, kr undergoes an increase of 20.65% when temperature passes from $20^\circ C$ to $70^\circ C$. At $T=70^\circ C$, a total increase of 20.10% in thermal conductivity ratio is recorded, when we pass from $\phi=1\%$ to $\phi=5\%$. Equation (17) describes the variation of the viscosity as a function of temperature, concentrations and diameter size of nanoparticles. The nanofluid viscosity decreases strongly with increasing temperature. At 5% solid volume fraction, viscosity is found to be decreased by 57.59% when the temperature passes from $20^\circ C$ to $70^\circ C$.

The decrease in viscosity and increase in thermal conductivity due to an increase of the temperature seems to be very promising regarding the enhancement of heat transfer by the nanofluid Al_2O_3 -water. In this regard, we computed the Nusselt number characterizing heat transfer as a function of temperature and results are presented in Figure 7. It appears that Nusselt number increases considerably with increasing the mean temperature of the nanofluid for all concentrations. For example, at $\phi=5\%$, when temperature passes from $20^\circ C$ to $70^\circ C$, the enhancements of Nu is 15.36%. On the other hand, two temperature intervals appear; $20^\circ C \leq T \leq 40^\circ C$ and $40^\circ C \leq T \leq 70^\circ C$. For the first interval, at a given temperature, the Nusselt number decreases when solid volume fraction increases meaning that the addition of nanosolids leads to a decrease in heat transfer. In this situation, the augmentation in viscosity prevails over the augmentation in thermal conductivity. For the second temperature interval, the Nusselt number increases when solid volume fraction increases and temperature increases, indicating that addition of nanosolids into water lead to an enhancement of heat transfer. Now the phenomenon is inversed, effects of increasing conductivity prevails over of the increase in viscosity when nanosolids Al_2O_3 are added into pure water.

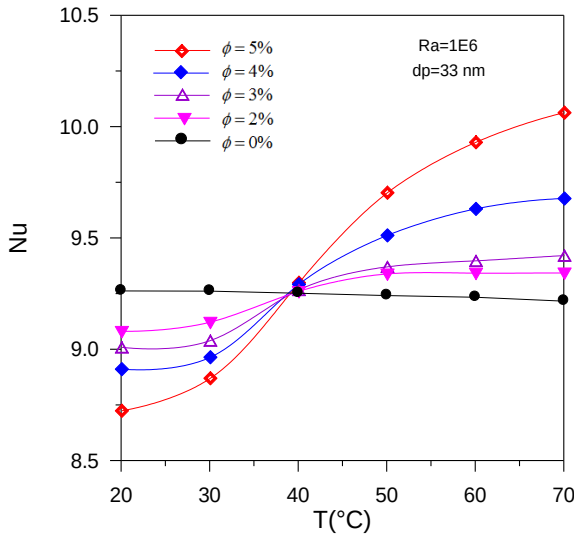


Figure 7. Variation of Nusselt number with temperature for different solid volume fraction of Al_2O_3 .

4.3. Effects of temperature on entropy generation

Generated entropy is an amount of energy degraded in the system, this energy is not recoverable, and it causes unnecessary heating and then reduces the system efficiency. The design of any thermal system should minimize the entropy generation. Dimensionless entropy generation computed in this work is given by Eq.12 as a function of the irreversibility coefficient δ and various gradients. The reference entropy S_{ref} that arises from the adimensionnalisation procedure is given by Eq.13. Table 3 presents δ and S_{ref} values for different Rayleigh numbers and lengths L values corresponding to pure water at ambient temperature. It is found that δ decreases by increasing Ra when L is fixed. We note also that, for a constant Ra , the irreversibility coefficient δ decreases when the length L of the cavity decreases. Moreover, this table shows that the reference entropy S_{ref} varies according to the Rayleigh number and length of the cavity. It is found that for a constant Ra , S_{ref} increases when the length of the cavity decreases. Whereas for a fixed length of the cavity S_{ref} increase by increasing Rayleigh number. In contrary to some findings in the literature [7, 27, 28] these results show that the irreversibility factor δ and the reference entropy S_{ref} are not constants, but they are functions of Rayleigh numbers and the cavity side length.

Table 3. Irreversibility coefficient δ and the reference entropy S_{ref} at different Rayleigh numbers and side length values

Ra	$L(m)$	δ	$S_{ref}(\text{JK}^{-1}\text{m}^3\text{s}^{-1})$
10^3	1	2.016	$3.6576 \cdot 10^{-20}$
	0.5	0.1260	$9.3634 \cdot 10^{-18}$
	0.02	$3.2263 \cdot 10^{-7}$	$1.4287 \cdot 10^{-6}$
10^4	1	0.0202	$3.6576 \cdot 10^{-18}$
	0.5	0.0013	$9.3634 \cdot 10^{-16}$

	0.02	$3.2267 \cdot 10^{-9}$	$1.4283 \cdot 10^{-4}$
10^5	1	$2.016 \cdot 10^{-4}$	$3.6576 \cdot 10^{-16}$
	0.5	$1.2602 \cdot 10^{-5}$	$9.3634 \cdot 10^{-14}$
	0.02	$3.2311 \cdot 10^{-11}$	0.0142
10^6	1	$2.016 \cdot 10^{-6}$	$3.6576 \cdot 10^{-14}$
	0.5	$1.2602 \cdot 10^{-7}$	$9.3634 \cdot 10^{-12}$
	0.02	$3.2755 \cdot 10^{-13}$	1.3861

In order to study the effect of adding nanosolids into basic liquid on entropy generation, we consider the case of natural convection of Al_2O_3 -water nanofluid in the cavity of Figure 1 with side $L=0.02\text{m}$ [24]. For this case, the irreversibility factor δ is very weak and varies from $3.22 \cdot 10^{-7}$ at $Ra=10^3$ to $3.27 \cdot 10^{-13}$ at $Ra=10^6$ (see table.3). Consequently, the entropy generation due to viscous effects can be neglected compared to that of heat transfer. In the following study, only entropy due to thermal conduction is computed.

Figure 8 summarizes the effects of solid volume fraction and temperature on the entropy generation at $Ra=10^6$. From this Figure, it is seen that at low temperatures (let's say less than 30°C), the entropy generation decreases when the concentration nanoparticle increases. For example, at $T=20^\circ\text{C}$, the total entropy generation is found to be decreased by 4.24% when the solid volume fraction passes from 1.5 to 5%. We can conclude that, at room temperature, adding nanosolids into pure water leads to a decrease in entropy generation. This is in harmony with last results indicating that addition of nanosolids reduces heat transfer which is the principal cause of entropy production. For high temperatures, the total entropy generation increases when the solid volume fraction increases. At $T=70^\circ\text{C}$, when the concentration varies from 1.5 to 5%, the increase is in the order of 5.57%.

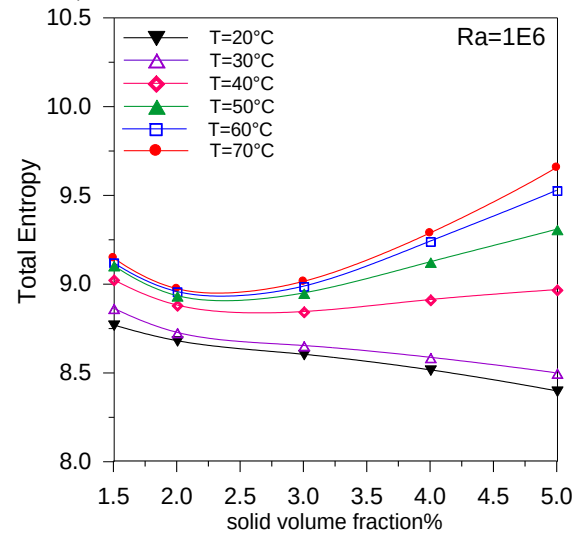


Figure 8. Total entropy generation as a function of solid volume fraction of Al_2O_3 for different temperatures

Entropy generation maps at $T=20^\circ\text{C}$ are depicted in Figure 9. The entropy contours are drawn for $\phi=0\%$ and $\phi=5\%$ together for two Rayleigh numbers, 10^5 and 10^6 . The solid and dashed lines indicate the pure water and 5% concentration respectively. It can be observed from these figures that the entropy generation is produced

essentially near the two working walls thanks to the existence of severe thermal boundary layer. Central area of the flow doesn't contribute to any significant entropy production. Also, we can observe that contours of entropy generation for pure water are more contracted compared to contours of nanofluid.

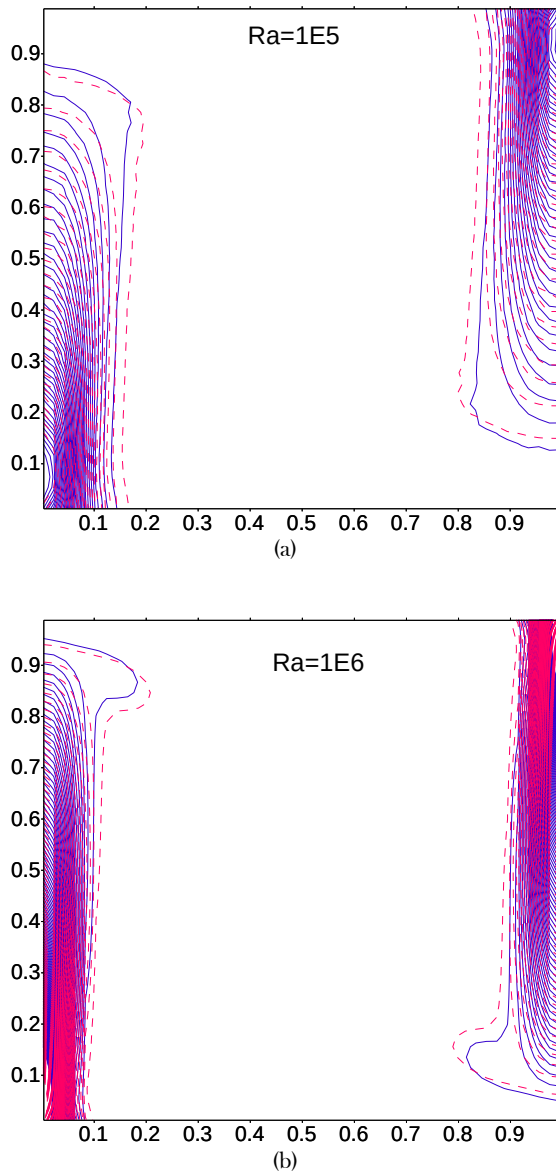


Figure 9. Contours of entropy generation for water (solid lines) and 5% nanofluid (dashed lines) at $T=20^{\circ}\text{C}$: (a) $Ra=10^5$, (b) $Ra=10^6$

5. Conclusion

In this paper, a numerical work is performed to study the effects of adding nanoparticles into basic liquid on heat transfer and entropy generation in the case of natural convection in a heated cavity. Tests are made for nanofluids Al_2O_3 -EG, CuO -EG, CuO -water, TiO_2 -water and Al_2O_3 -water to study the contradictory effects of thermal conductivity and dynamic viscosity. It appears that, at ambient temperature, dispersion of nanosolids in base fluid leads to decrease in heat transfer regardless particle sizes. In this case the enhancement of viscosity prevails over the thermal conductivity enhancement. Knowing that temperature has a strong effect on thermo-physical

properties of the nanofluid, we choose Al_2O_3 -water as test nanofluid. The reason is that a model of viscosity and thermal conductivity is established as a function of temperature. Results obtained show that at high temperature ($T>40^{\circ}\text{C}$), by adding Al_2O_3 nanoparticle into pure water, the heat transfer increases as the concentration increases. It can be interpreted that nanofluid is efficient regarding heat transfer only at high temperatures ($T>40^{\circ}\text{C}$). This situation is ideal, for example, for the operation of thermal solar systems such as solar water heater wherein the average water temperature is relatively high and can reach 80°C . Concerning entropy generation, it appears from this study that irreversibility factor is not constant, but depends on Rayleigh number and cavity side length. The addition of nanosolids into pure liquid leads to a decrease in entropy generation at low temperatures ($T<40^{\circ}\text{C}$), but for higher temperatures this behaviour is inverted.

Nomenclature

C_p	Specific heat at constant pressure ($\text{J.kg}^{-1}.\text{K}^{-1}$)
dp	Nanoparticles diameter (m)
df	The equivalent diameter of fluid molecule (m)
g	Gravitational acceleration (ms^{-2})
k	Thermal conductivity ($\text{Wm}^{-1}\text{K}^{-1}$)
kr	Relative thermal conductivity (k_{nf}/k_f)
kb	Boltzmann constant ($=1.38066 \cdot 10^{-23} \text{ J.K}^{-1}$)
L	Length of the cavity (m)
M	Molecular weight of the base fluid (kg.mol^{-1})
N	Avogadro number ($=6.022 \cdot 10^{23} \text{ mol}^{-1}$)
Nu	Space averaged Nusselt number
P	Dimensionless pressure
Pr	Prandtl number (ν_f / α_f)
Ra	Rayleigh number ($g\beta_f L^3 \Delta T / \nu_f \alpha_f$)
S_{gen}	Dimensional entropy generation ($\text{J.K}^{-1}.\text{m}^{-3}.\text{s}^{-1}$)
S_{gen}	Dimensionless entropy generation
T	Temperature (K)
U, V	Dimensionless velocity components (normalized by α/L)
X, Y	Dimensionless coordinates (normalized by L)

Greek symbols

α	Thermal diffusivity ($k / \rho C_p$) ($\text{m}^2.\text{s}^{-1}$)
β	Thermal expansion coefficient (K^{-1})
δ	Irreversibility coefficient
ϕ	Solid volume fraction
θ	Dimensionless temperature $(T - T_c) / (T_h - T_c)$
μ	Dynamic viscosity of the fluid ($\text{kg.m}^{-1}.\text{s}^{-1}$)
ν	Kinematic viscosity of the fluid (μ / ρ) ($\text{m}^2.\text{s}^{-1}$)
ρ	Density (kg.m^{-3})

Subscripts

c	cold
h	hot
f	fluid
nf	nanofluid
s	solid

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