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Second law analysis in Cu-water nanofluid in a cavity with semicircular isothermal walls

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Abstract This work focuses on the influence of different parameters on the entropy generation and the Bejan number in a cavity filled with a Cu-Water nanofluid, with two semicircular isothermal walls associated to the vertical sides. This investigation was divided in two parts. The first concerned the case where the centers of the two isothermal semicircular walls are in the middle of the vertical sides. Related to this configuration, the influence of the Rayleigh number, the nanoparticles volume fraction, the nanoparticles size on entropy generation and Bejan number were studied. The second part concerned the minimization of entropy generation when the semicircular isotherm walls were translated along the vertical sides. Nine combinations related to the location of the two isothermal semicircles were considered. In this context, the variations with the location of the active walls of the thermal irreversibility, the viscous irreversibility, the Bejan number and the ratio (Ri) were calculated, for two fixed values of both, Rayleigh number and volume fraction.

Keywords *entropy generation, nanofluid, natural convection, Bejan number, heat transfer*

1. Introduction

Many studies concerning nanofluid flow have been published. Abu-Nada and Ozotop [1] studied the effects of inclination angle on natural convection in enclosures filled with Cu-water nanofluid. Results indicate that the addition of copper nanoparticles has produced important enhancement on heat transfer compared to pure fluid. Heat transfer is enhanced with increasing Rayleigh number almost linearly but the effect of nanoparticles concentration on Nusselt Number is more pronounced at low Rayleigh number than at high Rayleigh number. The inclination angle of enclosure is a good control parameter for both pure water and nanofluid filled enclosures. Mahmoudi et al., [2] studied entropy generation due to natural convection in partially open cavity where the nanofluid is exposed to a thin heat source. They specified that when the open boundary is situated upwards, the fluid flow augments and hence the heat transfer and Nusselt number increase but the total entropy generation decreases. El Bouihi and Sehaqui [3] Studied natural convection in a two dimensional enclosure numerically with a sinusoidal boundary thermal condition using nanofluid. They determined that, the heat transfer rate increases when nanoparticles volume fraction increases and that, the pure water and the nanofluid have the same velocity profiles. Chen et al., [4] examined the total irreversibility in mixed convection flow of Al_2O_3-Water nanofluid within a vertical channel. They showed that, for a lower Brinkman number the local Nusselt number of the nanofluid on the hot wall is greater than that of pure water and increases with an increasing nanoparticle concentration. Khorasanizadeh et al, [5] investigated the entropy generation of Cu-Water nanofluid mixed convection in cavity. They concluded that, the increase of Rayleigh number results in increasing total entropy generation. Maiga et al., [6] numerically studied the heat transfer enhancement by using nanofluids in forced convection flow. They showed that, the heat transfer enhancement increases considerably with an augmentation of the flow Reynolds number. They concluded that, both the Reynolds number and the distance separating the disks do not seem to considerably affect in one way or another heat transfer enhancement of the nanofluid. Haddad et al., [7] conducted a review for recent numerical and experimental studies including single phase and two phases flow in different geometric configurations. They found that, natural convection heat transfer enhancement using nanofluidis still controversial. They found that numerical results showed that nanofluids significantly improve the heat transfer capability of conventional heat transfer in fluids; whereas experimental results showed that the presence of nanofluids deteriorates the heat transfer systematically. Pavin et al., [8] studied a laminar natural convection and entropy generation in a nanofluid filled complex cavity with horizontal and vertical portion. They showed that the use of nanofluid increases the Nusselt number, entropy generation and the Bejan number. Singh et al., [9] theoretically studied the entropy generation in a tube containing Al_2O_3-Water nanofluid for different tube diameters. They observed that there is an optimum diameter at which the total entropy generation is minimal for both turbulent and laminar flow. Shahi et al., [10] analyzed natural convection heat transfer and entropy generation in a square cavity protruding heat source. They observed that increasing nanoparticles volume fraction can reduce the entropy generation and increase theNusselt number. Alipanah et al., [11] observed the effect of adding ultrafine metallic nanoparticles to a pure fluid on the entropy generation in a square cavity. They found that the addition of nanoparticles has a larger effect on the total irreversibility at the highest Rayleigh number, whereas its efficiency decreases as the Rayleigh number goes up. Oliveski et al., [12] studied numerically the entropy generation on natural convection in rectangular cavities. They observed that the total entropy increases exponentially with the Rayleigh number and increases linearly with the aspect ratio and the irreversibility coefficient. Sheikhzadeh [12] studied the laminar natural convection and entropy generation in a square cavity with an obstacle. They observed that, using nanofluid especially at high Rayleigh number; generally induce the increase of the flow strength, Nusselt number and entropy generation and the decreases of Bejan number. Patel et al.[13] studied a micro-convection model for thermal conductivity of nanofluids. They remarked a slight heat transfer enhancement of 0.8% with alumina particles suspended in water compared to Hamilton- crosser model. They supposed that an increase in a specific surface area as well as Brownian motion were the most significant reasons for anomalous enhancement in thermal conductivity of nanofluids.

To our knowledge, the use of the thermal conductivity model involving the micro-convection phenomenon to calculate the entropy generation of nanofluid flow in a cavity with two semicircular isothermal walls has not yet been encountered. The present paper reports a numerical study related to the effects of the Rayleigh number, the volume fraction, the powder size and the location of the active walls on the entropy generation, the Bejan number the thermal entropy generation ratio in steady state of natural convection.

2. Problem Statement

The studied system consists in a square cavity filled with Cu-Water nanofluid, with two isothermal semicircular walls linked to the vertical sides. The first one, maintained at high temperature, was associated to the left side. The second, maintained at cold temperature was associated to the right side. The remaining walls were insulated and adiabatic. The base fluid (water) and the copper nanoparticles (Cu) were supposed to be in thermal equilibrium. All physical properties of the nanofluid were assumed to be constant, except the density which satisfied the Boussinesq approximation. The characteristics of the base fluid and the solid nanoparticles are listed in Table 1.

Table 1: Physical properties of water and Cu

	P **($Kg.m^{-3}$)**	**Cp** **($J.Kg^{-1}.K^{-1}$)**	**K** **($W.m^{-1}.K^{-1}$)**	**B** **(k^{-1})**
water	997.1	4179	0.613	$2.1*10^{-4}$
Cu	8933	385	400	$1.67*10^{-5}$

3. Mathematical formulation

The governing equations related to the natural convection flow are the following:

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

$$\rho_{nf}\left(\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}\right)=-\frac{\partial p}{\partial x}+\mu_{nf}\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}\right) \quad (2)$$

$$\rho_{nf}\left(\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}\right)=-\frac{\partial p}{\partial y}+\mu_{nf}\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}\right)+\rho_{nf}\beta_{nf}g(T-T_c) \quad (3)$$

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

The following parameters were used to convert the governing equation from the dimensional to the dimensionless form:

$$X=\frac{x}{H}\ ;Y=\frac{y}{H}\ ;U=\frac{u}{u_0}\ ;\ V=\frac{v}{u_0}\ \ T=\frac{T'-T_c'}{T_h'-T_c'}\ ;\ Ra_f=\frac{g\beta_f(T_h'-T_c')H^3}{\nu_f\alpha_f}\ ;\ \Pr_f=\frac{\nu_f}{\alpha_f};$$

$$\Delta T'=T_h'-T_c'\ ;u_0=\frac{\alpha_f}{H}$$

Hence, in steady state and in two-dimensional Cartesian coordinate system, the dimensionless equations of continuity, momentum and energy are written as:

$$\frac{\partial U}{\partial X}+\frac{\partial V}{\partial Y}=0 \quad (5)$$

$$U\frac{\partial U}{\partial X}+V\frac{\partial U}{\partial Y}=-\frac{\partial P}{\partial X}+\frac{\mu_{nf}}{\rho_{nf}\alpha_f}\left(\frac{\partial^2 U}{\partial X^2}+\frac{\partial^2 U}{\partial Y^2}\right) \quad (6)$$

$$U\frac{\partial V}{\partial X}+V\frac{\partial V}{\partial Y}=-\frac{\partial P}{\partial Y}+\frac{\mu_{nf}}{\rho_{nf}\alpha_f}\left(\frac{\partial^2 V}{\partial X^2}+\frac{\partial^2 V}{\partial Y^2}\right)+\frac{(\rho\beta)_{nf}}{\rho_{nf}\beta_f}Ra_f\ \Pr_f\ T \quad (7)$$

$$U\frac{\partial T}{\partial X}+V\frac{\partial T}{\partial Y}=\frac{\alpha_{nf}}{\alpha_f}\left(\frac{\partial^2 T}{\partial X^2}+\frac{\partial^2 T}{\partial Y^2}\right) \quad (8)$$

The expressions of density, thermal expansion, specific heat coefficient and dynamic viscosity of the nanofluid are given as follows [15]:

$$\rho_{nf}=(1-\varepsilon)\rho_f+\varepsilon\rho_s \quad (9)$$

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

$$(\rho c_p)_{nf}=(1-\varepsilon)(\rho c_p)_f+\varepsilon(\rho c_p)_s \quad (11)$$

$$\frac{\mu_{nf}}{\mu_f}=\frac{1}{(1-\varepsilon)^{2,5}} \quad (12)$$

Many theoretical and experimental studies, related to the heat conduction mechanism in nanofluids, were conducted. In this context, researchers have proposed many thermal conductivity expressions fornanofluids.These expressions were based on different parameters such as, nature, shape, size, nanoparticle volume fraction, and effects such as, nanolayer, Brownian motion, aggregation or clustering, nanoconvection(Lee et al. [16]; Das et al. [17]). The conductivity model of Patel et al. [14] was used in this work. This model predicts the nanofluid thermal conductivity for nanoparticle size, volume fraction and temperature variation ranging from 10 to 100 nm, from 1% to 8% and from 25°C to 50°C, respectively. This model can be used for metal particles as well as metal oxides and for water and ethylene glycol as a base fluid. This model presents a semi-empirical approach for the enhancement in thermal conductivity by emphasizing the increase in the specific area as well as the Brownian motion through the micro-convection. Based on this model, nanofluid thermal conductivity is written as:

$$k_{nf} = k_f \left(1 + \frac{k_s A_s}{k_f A_f} + C k_p Pe \frac{A_s}{k_f A_f} \right) \quad (13)$$

The parameter C is fixed and equal to25000. The parametersPe and (A_s/A_f) are defined as:

$$P_e = \frac{u_s d_s}{\alpha_f} ; \frac{A_s}{A_f} = \frac{d_f}{d_s} \frac{\varepsilon}{1-\varepsilon} \quad (14)$$

In Eq.(14), $d_f$is the molecular size of water, which is taken as 2A° and $d_s$is the diameter of solid particles. The variableu_s, which depends on the temperature, is the Brownian motion velocity of particles and is given by [18]:

$$u_s = \frac{2 k_b T}{\Pi \mu_f d_s^2}$$

Where k_b is the Boltzmann constant.

The appropriate boundary conditions and initial of the problem are:

- Along the left isothermal semicircular wall (C_1) the dimensionless temperature was T=1.
- Along the right isothermal semicircular wall (C_2), the dimensionless temperature was T=0.
- Along the horizontal insulator walls: $\frac{\partial T}{\partial y} = 0$
- Along the vertical insulator walls: $\frac{\partial T}{\partial x} = 0$
- Along the isothermal and insulator walls U=V=0.
- At dimensionless time equal to zero, T=0 and U=V=0 in the whole cavity.

4. Entropy generation

The entropy generation is given by the sum of conjugate fluxes and forces products. In natural convection process, it is given by Bejan [12]:

$$s_{gen} = \frac{k_{nf}}{T_0^2} \left[\left(\frac{\partial T'}{\partial x} \right)^2 + \left(\frac{\partial T'}{\partial y} \right)^2 \right] + \frac{\mu_{nf}}{T_0} \left[2\left(\frac{\partial u}{\partial x} \right)^2 + 2\left(\frac{\partial v}{\partial y} \right)^2 + \left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} \right)^2 \right] \quad (15)$$

Where T_0 is the average temperature equal to $(T'_h+T'_c)/2$

On the right side of Eq. (15), the first term represents the heat transfer irreversibility, while the second is the viscous effect irreversibility. Using the dimensionless parameters listed above, the dimensionless entropy generation expression becomes:

$$S_{gen} = \frac{k_{nf}}{k_f} \left[\left(\frac{\partial T}{\partial X} \right)^2 + \left(\frac{\partial T}{\partial Y} \right)^2 \right] + \phi \left[2\left(\frac{\partial U}{\partial X} \right)^2 + 2\left(\frac{\partial V}{\partial Y} \right)^2 + \left(\frac{\partial U}{\partial Y} + \frac{\partial V}{\partial X} \right)^2 \right] \quad (16)$$

According to the expressions of the Raleigh number and the physical properties of the nanofluid mentioned above, the distribution irreversibility ratio can be written as:

$$\phi = \frac{\mu_{nf} T_0}{k_f} \left(\frac{\alpha_f}{H \Delta T} \right)^2 \tag{17}$$

5. Numerical Procedure and Validation

In the dimensionless form and taking into account the initial and the boundary conditions, the flow governing equations were solved using COMSOL software. Results given by COMSOL calculations were validated with the works of Magherbi et al. [19] in terms of isentropic lines related to a pure fluid (air) and of Ozotop et al., [20] in terms of streamlines and isotherms related to a nanofluid (Cu-water). It was verified that the numerical results obtained by COMSOL are in good agreement with those obtained from the works.

6. Results and Discussion

Results were carried out for Rayleigh number, nanoparticle volume fraction and nanoparticle size, ranging from 500 to 10^6, from 0 to 8% and from 10 to 100nm, respectively. Particular interest is given to the impact of the active walls location on the entropy generation, the Bejan number and the flow structure. In this study the Prandtl number and the distribution irreversibility ratio were fixed at 6.02 and 10^{-5}, respectively.

6.1. *Effects of Rayleigh number and volume fraction on the entropy generation ratio*

The study of the influence of the Rayleigh number and the volume fraction on the entropy generation ratio concerns the geometric configuration of Figure 1.

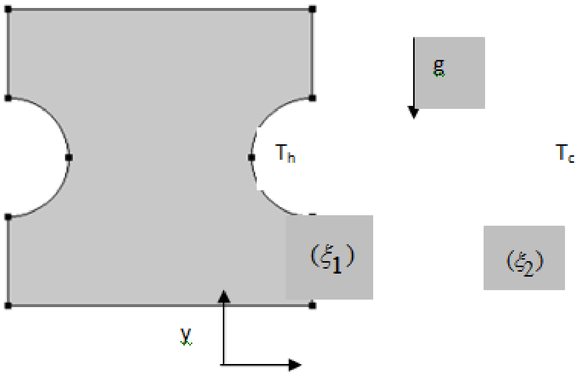


Figure 1: Schematic view of the system under study

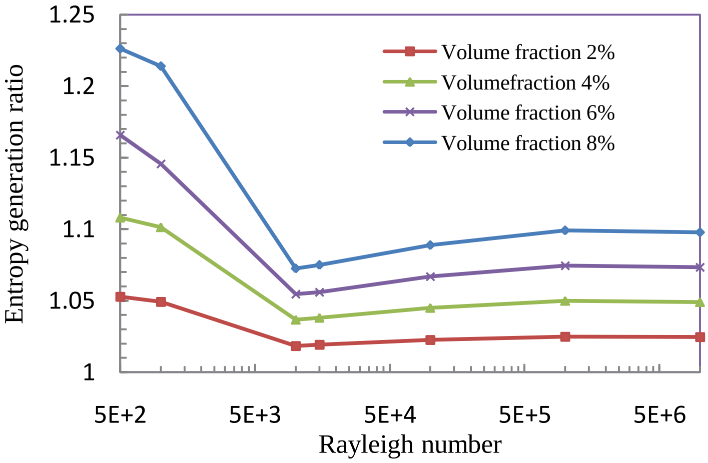


Figure 2: Rayleigh number effect on the entropy generation ratio for different Volume fraction

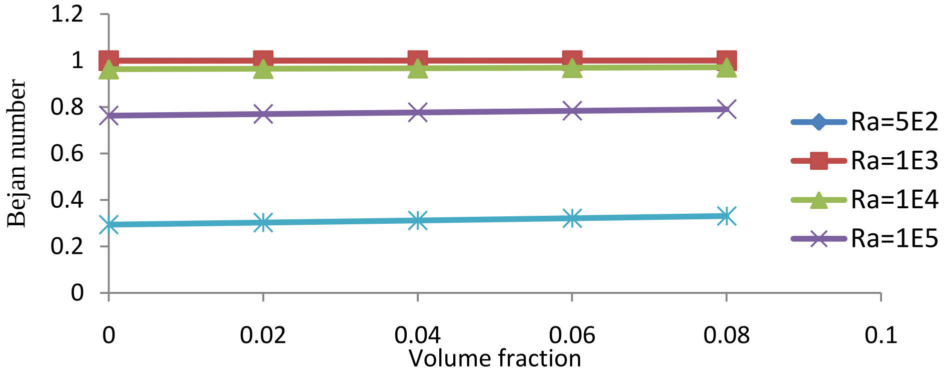
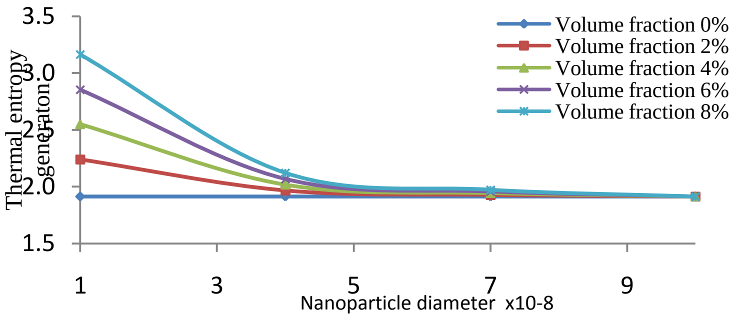
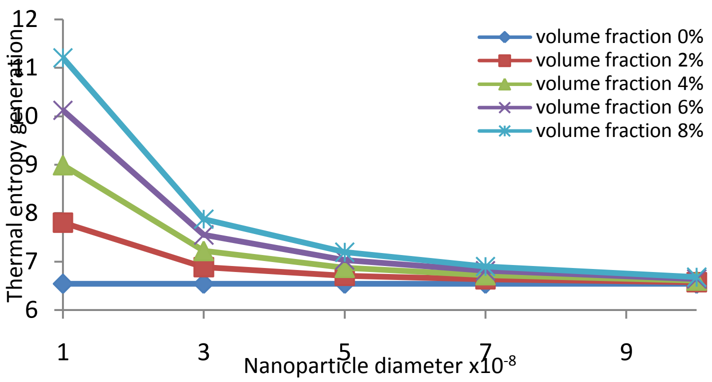


Figure3: Bejan number effect on the entropy generation ratio for different Volume fraction



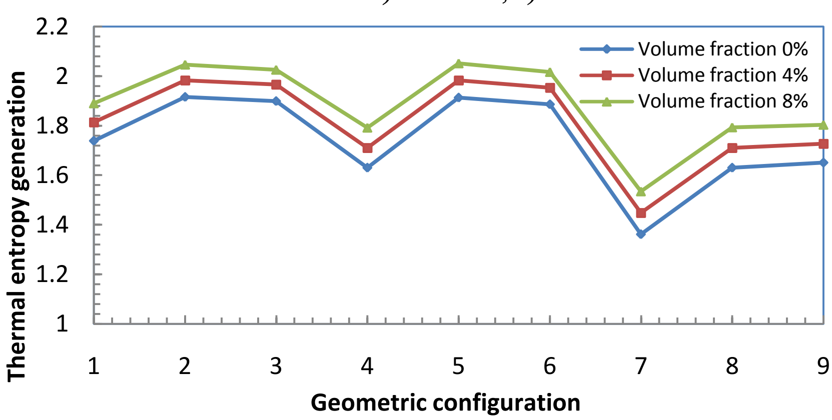
(a)



(b)

Figure 4: Thermal entropy generation versus particle size fordifferent volume fraction:

a) $Ra=10^4$, b) $Ra=10^6$



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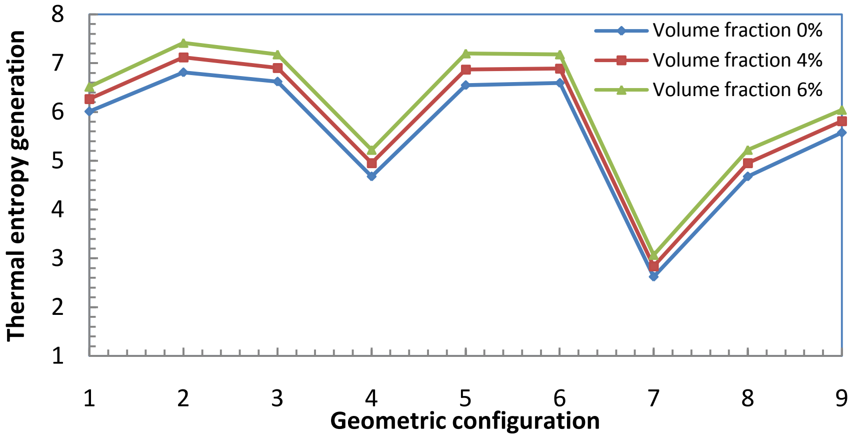
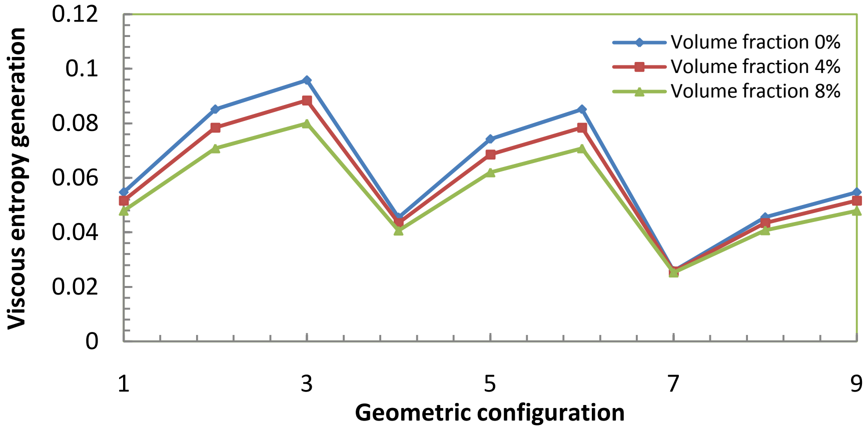


(b)

Figure 7: Thermal entropy generation variation with the location of the isothermal semicircular walls for different volume fraction: a) Ra=10^4, b) Ra=10^6



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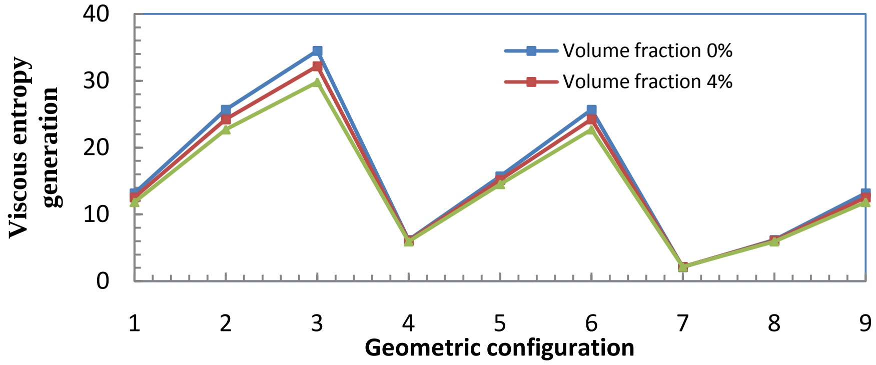
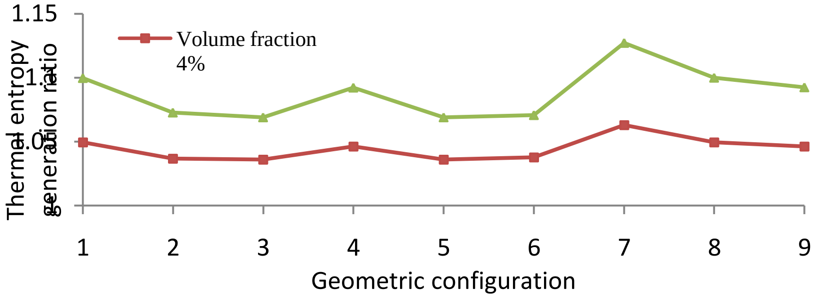


(b)

Figure 8: Viscous entropy generation variation with the location of the isothermal semicircular walls for different volume fraction: a) Ra=10^4, b) Ra=10^6

The entropy generation ratio, denoted by (Ri), is defined as the quotient at the same Rayleigh number of the thermal entropy generation of the nanofluid by that of the base fluid. Figure 9 depicts the variation of (Ri) with the Rayleigh number for different nanoparticle volume fraction. As can be seen from this figure, (Ri) decreases rapidly at relatively small Rayleigh number, reaches a minimum at critical Rayleigh number (Ra_c) equal to 10^4, then it slightly increases and practically tends towards a constant value at a relatively high Rayleigh number. The decrease int he entropy generation ratio (Ri) at a Rayleigh number smaller than Ra_c can be explained by the fact that the developed convection in the cavity is less important in the nanofluid than that in the base fluid.



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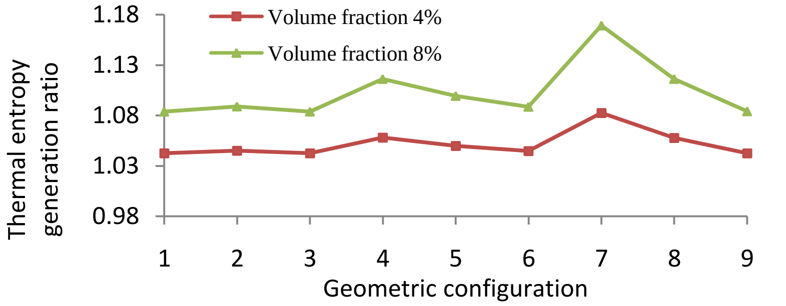
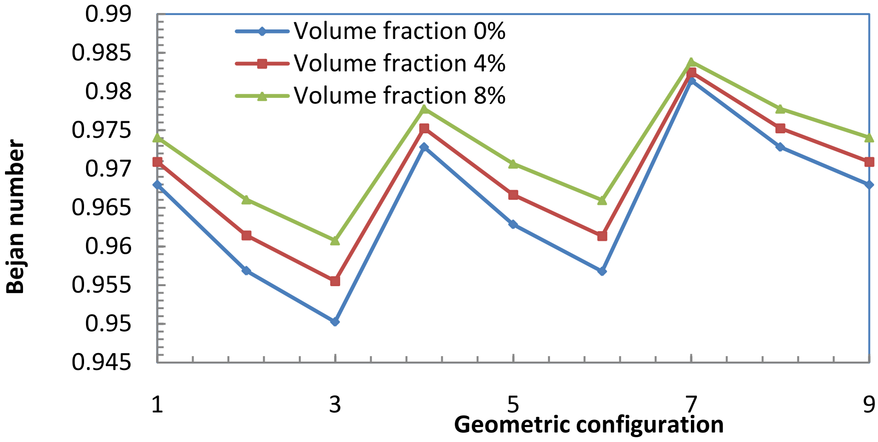
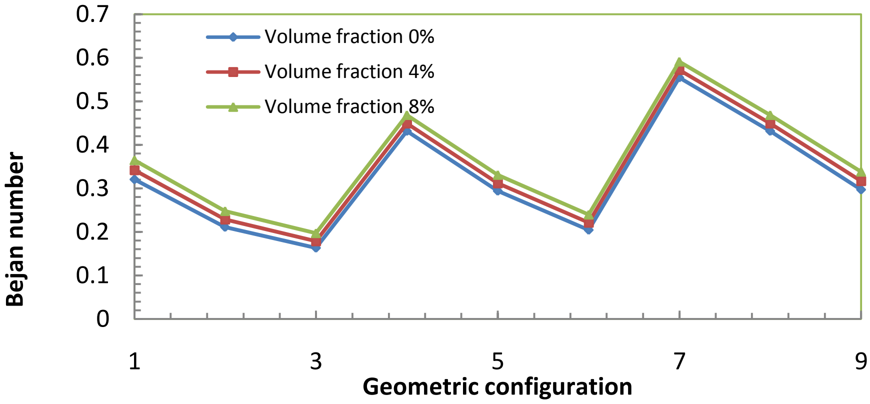


(b)

Figure 9: Variation of the thermal irreversibility ratio (Ri) with the location of the isothermal walls for different volume fraction: a) Ra=10^4; b) Ra=10^6



(a)



(b)

Figure 10: Bejan number as function of the location of the isothermal walls for different volume fraction: a) Ra=10^4; b) Ra=10^6

Hence, the conductive regime persists in the nanofluid and its entropy generation remains almost constant whereas the convective regime is well developed in the base fluid and its entropy generation increases. It is obvious that when solid nanoparticles are added to the fluid, both the nanofluid thermal conductivity and the nanofluid dynamic viscosity increase. Hence, we are in front of a cause (add of nanoparticles) with two opposite effects. The first concerns the increase in the heat transfer which may enhance the convective phenomenon and the second is related to the increase of the viscous friction force thereby lowering the fluid motion. The amplitude of the two effects depends on the geometry, size, volume fraction, nature of the solid nanoparticles and possibly on the character of the fluid-nanoparticle and nanoparticle-nanoparticle interactions. It can be noticed that the decrease of (Ri) is more important when the volume fraction is higher. At a critical Rayleigh number (Ra_c=10000) the convective regime in the nanofluid, begins to appear. As the Rayleigh number increases, thermal entropy generation ratio increases and tends toward a constant value, which indicates that the convection regime is more developed in the nanofluid than in the base fluid. Therefore, thermal irreversibility is more important in the nanofluid than that in the base fluid. As seen in Figure 2, the ratio (Ri) tends toward a constant value at high Ra, which indicates that the Rayleigh number becomes without effect on the entropy generation ratio (Ri) and consequently the irreversibility variations with the Rayleigh number in both nanofluid and base fluid are proportional. It is important to observe that both the minimum and constant values of the thermal entropy generation ratio (Ri) are more higher when the volume fraction is higher. Moreover, the minimum values of (Ri) were reached at the same critical Rayleigh number (Ra_c=10000) for all volume fraction, whereas the Rayleigh number from which (Ri) becomes constant depends on the volume fraction.

6.2. *Effects of Rayleigh number, volume fraction and nanoparticle size on irreversibility*

The Bejan number (Be) is defined as the quotient of the thermal entropy generation by the total entropy generation. When the Bejan number is strictly greater than 0.5 the irreversibility due to heat transfer dominates. While, if the Bejan number is strictly smaller than 0.5, the irreversibility due to viscous effects dominates. The thermal and viscous irreversibility's are equal when the Bejan number takes the value 0.5.

Figure 3 gives the nanoparticle volume fraction effect on the Bejan number, for Rayleigh number ranging from 10^3 to 10^6. Fig.3 shows that, for Rayleigh number smaller than 10^5 heat transfer irreversibility dominates, whereas when Rayleigh number reaches 10^6, the Bejan number becomes smaller than 0.5 and consequently fluid friction irreversibility dominates for all the selected volume fraction. It is noticeable that, at fixed Rayleigh number, the Bejan number increases with the volume fraction. This increase, which is essentially due to the attenuation of the viscous entropy generation, is more important when the Rayleigh number is higher.

The influence of the particle size on thermal irreversibility is given in Fig.4, for volume fraction nanoparticle ranging from 2% to 8% and for Rayleigh numbers equal to 10^4 and 10^6. Fig.4 shows that, at a given volume fraction and when nanoparticle diameter increases, the thermal entropy generation decreases and tends asymptotically toward the constant values of 6.6 and 1.9,corresponding to the entropy generation values of the base fluid related to the two Rayleigh numbers 10^6 and 10^4, respectively. This implies that, at a relatively high powder size (higher than 50nm), the nanofluid may be assimilated to the base fluid and thus nanoparticles are without effect on both, the thermal irreversibility and the thermal conductivity enhancement. This may be the consequence of the decrease in the Brownian motion velocity of nanoparticles, when the particle size increases. This decrease of the Brownian motion induces a decrease of the heat transfer, which in turn reduces the heat transfer irreversibility. This result is consistent with that of Chon and Kihm [20], who measured the thermal conductivity and found that the enhancement is negligible if the powder size exceeds 38.4 to 80nm. It is important to observe that, the diminution in the thermal entropy generation, with the nanoparticle diameter, is accentuated when the volume fraction is important. For example, at Ra equal to 10^6 and at volume fractions 8%and 2%, the thermal entropy generation decreases by 40.4% and 15%, respectively, when particle diameter passes from 10 to 100 nm.

6.4. *Effects of the location of the isothermal semicircle walls on irreversibility*

In this section the effects of the position of the hot and the cold semicircular walls on their reversibility, the entropy generation ratio (Ri), the Bejan number and the flow structure were studied. We denote by Y_{c1} and Y_{c2} the dimensionless y-coordinate of the centers of the two semicircular active walls. The dimensionless x-coordinate of the centers of the two semicircular active walls X_{c1} and X_{c2} are equal to 0 and 1, respectively. Each one of the two dimensionless coordinates Y_{c1} and Y_{c2}may take three dimensionless values (0.25, 0.5, 0.75), so that the pair ($Y_{c1,}Y_{c2}$) has nine possible combinations and consequently nine possible geometric configurations of the cavity (Figure 5). To each pair of position ($Y_{c1,}Y_{c2}$) was assigned a number n (n from 1 to 9),which characterizes the associated geometric configuration. Figure 6 shows the thermal entropy generation variation with the position of the semicircular walls, for two values of both the Rayleigh number and the volume fraction. Figure 6 demonstrates that, the location of the isothermal semicircular walls affects the irreversibility in the cavity considerably. Figure 6 shows that, for Rayleigh number equal to 10^4, the thermal entropy generation is maximum for the geometric configurations 5, whereas it is minimum at configuration 7. We remark that the effect of the volume fraction on the entropy generation is observable for all the geometric configurations. A Rayleigh number Ra=10^6, the minimum irreversibility remains related to configuration 7, but the maximum of thermal irreversibility is associated to configuration 2. It is important to note that, the volume fraction effect is more significant for the configuration where the irreversibility is maximum than for that where irreversibility is minimum. For example, at configuration 2 where irreversibility is maximum and for Ra=10^6, the entropy generation undergoes an increase of 14% when volume fraction increases from 0 to 8%. Whereas it undergoes an increase of 8.1% related to configuration7, where the irreversibility is minimum. The viscous irreversibility was plotted in Figure 7, for Ra=10^4 and 10^6 and for volume fraction equal to 0%, 4% and 8%. As seen from Figure 7, the viscous irreversibility is maximum for configuration 3 and minimum for configuration 7. It is noticeable that, the effect of the volume fraction is considerable for the configuration where the viscous irreversibility is maximum, whereas it is nearly absent for the configurations where the viscous irreversibility is minimum. As important result, the impact of the nanoparticle volume fraction on the irreversibility and the flow structure is closely linked to the location of the isothermal semicircular walls. The variation of the thermal entropy generation ratio (Ri) with the location of the active semicircle walls is plotted in Fig.8. As can be seen from this figure, at fixed Rayleigh number, the ratio (Ri) is higher than the unity for all configurations, which implies that the heat transfer irreversibility in the nanofluid is greater than that in the base fluid for all the studied configurations and for the two concerned volume fractions. It is important to note that the ratio (Ri) is maximum for configuration 7, for which the thermal irreversibility in the base fluid is minimum. This leads to believe in the important impact of nanoparticles adding on the thermal irreversibility for this geometric configuration.

The variation of the Bejan number with the location of the active semicircle walls is given in Figure 9. As seen from the Figure 9a, for Rayleigh number equal to10^4, the Bejan number is higher than 0.9 and therefore thermal irreversibility strongly dominates for all the considered locations of the two semicircles. It is noticeable that, although its variation is small, the Bejan number presents a maximum and a minimum for configurations 7 and 3, respectively. For the Rayleigh number equal to 10^6 the Bejan number takes a value greater than 0.5 for configuration 7 only (Figure 9b). Consequently, for this geometric configuration, the thermal irreversibility dominates. Otherwise, the viscous irreversibility is the most dominant for all the remaining configurations. Itis important to notice from Fig.9b that, when the volume fraction increases,the thermal and the viscous irreversibilities are nearly identical for configurations 4 and 8, since the Bejan number approaches the value of 0.5.

7. Conclusion

The entropy generation investigation in laminar convection in a cavity, with semicircular isothermal walls associated to the vertical sides, filled with the nanofluid Cu-water was studied numerically from direct solutions of complete Navier–Stokes and energy equations. Nine cavity geometric configurations corresponding to nine positions of the active semicircular walls were considered. The Patel model for the thermal conductivity, which involves the Brownian motion, was used. The calculations were carried out for Rayleigh number, volume fraction and nanoparticle size varying from 500 to 10^5, from zero to 8% and from 10 to 100nm, respectively. Based on this study, the following results can be drawn:

1. The entropy generation ratio (Ri) decreased rapidly at relatively small Rayleigh number, reached a minimum at a critical Rayleigh number Ra_c=10000, then it slightly increased and tended toward a

constant value at a relatively high Rayleigh number. The critical Rayleigh number (Ra_c) is independent of thenanofluid volume fraction.

2. The Bejan number is greater than 0.5 at Rayleigh number smaller than 10^5 and the heat transfer irreversibility dominated. Whereas, the Bejan number becomes smaller than 0.5 when the Rayleigh number reaches 10^6 and fluid friction irreversibility dominated.
3. When nanoparticle diameter increased, the thermal entropy generation of the nanofluid decreased, and tended asymptotically towards the constant value corresponding to the thermal entropy generation of the base fluid.
4. The minimum thermal irreversibility corresponds to the geometric configuration 7 for all Rayleigh number. The maximum thermal irreversibility corresponds to configurations 5 and 2 for Ra=10^4 and 10^6, respectively.
5. For Rayleigh number equal to10^4, the thermal irreversibility strongly dominates for all the considered configurations. For the Rayleigh number equal to 10^6, the thermal irreversibility dominates only for configuration 7.

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