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Research Paper

Heat Transfer Improvement in an Open Cubic Cavity using a Hybrid Nanofluid

Saliha Bellout , Rachid Bessaïh

LEAP Laboratory, Department of Mechanical Engineering, Faculty of Sciences Technology, University of Brothers Mentouri-Constantine 1,
Route de Ain El. Bey, 25000 Constantine, Algeria

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Corresponding author: S. Bellout (belloutsaliha@email.net)
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Abstract. Numerical simulation of convection heat transfer and entropy generation in an open cubic cavity filled with a hybrid nanofluid is carried out. This configuration is heated uniformly by a constant volumetric heat source q_v . All the walls are adiabatic. The hybrid nanofluid flow (Al_2O_3 -Cu/water) penetrates in the cavity at a uniform velocity U_0 and a temperature T_0 . To solve the mathematical equations, we used Ansys-Fluent 14.5 software. Results are validated with other works found in the literature. We present our results in terms of streamlines, isotherms, velocity, temperature, local and average Nusselt numbers profiles, and entropy generation for the Reynolds number ($300 < \text{Re} < 700$), the solid volume fraction ($0 < \phi < 0.08$), and heat source location ($1\text{cm} < d < 3\text{cm}$). Results indicate that by increasing Re , ϕ and d_h , the heat transfer is improved. Moreover, nanohybrid gives better heat transfer than nanofluid, and the use of nanoparticles contributes to the minimization of entropy generation. Compared with the vertical location of the heat source, the horizontal location gives an increase in heat transfer. The Nu_{av} correlations are determined for the nanofluid and hybrid nanofluid. This study may help to enhance the heat transfer of electronic equipment.

Keywords: Heat transfer, Entropy generation, Hybrid nanofluid, Heat source, Open cavity.

1. Introduction

One of the new strategies for optimizing heat exchange consists of modifying the nature of the basic fluid. The idea is then to insert solid particles of nanometric size into liquids to improve the mixture's thermal performance. This new fluid concept is called "nanofluid" Choi [1]. Nanofluids have many technological and industrial applications such as solar receivers, boilers, nuclear reactors, and power plants.

Experimental studies on nanofluids were realized by [2-4]. They found an improvement in heat transfer by using the nanofluid. Numerical simulation of forced convection flows in a triangular configuration filled with a nanofluid was made by Saeed et al. [5]. Results show that the addition of nanoparticles increases the Nusselt number. Ahmed et al. [6] studied the nanofluid flow numerically in a corrugated channel. They found that using nanofluid gives a higher heat transfer. Sourtiji et al. [7] studied heat transfer by mixed convection of Al_2O_3 -water nanofluid inside an open cavity with different outlet ports' positions. Increasing Re , Ri (Richardson number), and ϕ promote heat transfer.

The recent advances in nanotechnology have given birth to a new type of nanofluid, characterized by a significant heat transfer investigation. This type is called "hybrid nanofluid." It involves suspending two kinds of solid nanoparticles in a base liquid to improve the thermophysical properties of simple nanofluids. The research carried out so far on hybrid nanofluids is very limited experimental investigations [8-13] to estimate the thermophysical properties. The estimation of these results indicates that hybrid nanofluids' thermal characteristics are higher than the primary fluid and nanofluid. Surech et al. [14] examined heat transfer through a hybrid nanofluid-filled circular tube. Compared with the nanofluid, results show an increase in heat transfer. A numerical study on the hybrid nanofluid (CuO -Cu/water) in a cylinder was carried out by Balla et al. [15]. They found good improvement in the heat transfer coefficient. Takabi et al. [16] studied numerically forced convection in a hybrid nanofluid in a uniformly heated cylinder. Their results show that the hybrid nanofluid improves the heat transfer rate. The forced convection of a nanofluid and an hybridnanofluid was investigated numerically by Moghadassi et al. [17]. The results show that the hybrid nanofluid has a more important convective heat transfer coefficient. Hussain et al. [18] performed a computational analysis in a horizontal channel with an open cavity filled with hybrid nanofluid (Al_2O_3 -Cu/water). The results show that an enhancement in the rate of heat transfer when the Reynolds number and nanoparticle volume fraction increases.

In the work of Sameh et al. [19], the effects of thermal stratification and suction / injection on the production of entropy and heat transfer were discussed. The effects of thermal stratification and suction / injection on the production of entropy and heat transfer were discussed. In the injection case, the minimum values for the entropy generation are found to occur. The irreversibility of friction in free convection flow using a nanofluid was studied by Alipanah et al. [20]. It was entirely found that the nanofluid's heat transfer and entropy generation is more than the pure fluid and the minimum entropy generation, and the Nusselt number occurs at every Rayleigh number in the pure fluid.



The entropy generation minimization method were used in [21] for heat transfer and fluid flow optimization inside a wavy channel. The heat transfer and entropy generation skills of hybrid nanofluids were examined in [22]. The results indicated that for microtubes, the traditional approach to predicting the heat transfer coefficient was applicable. In [23], heat transfer and entropy production were investigated in a hybrid nanofluid flow caused by an elastic curved surface. As compared to hybrid nanofluid, it was found that less entropy is produced in a normal nanofluid. Chen et al. [24] conducted a numerical simulation of heat transfer and entropy generation of nanofluid (Al_2O_3 -water) in a vertical channel. The results indicate that in a lower Brinkman number, the Nusselt number of nanofluid is greater than pure water.

In a square cavity, the free convection of nanofluid cooled from two vertical and horizontal walls, heated to its horizontal bottom wall, was investigated by Aminossadati and Ghasemi [25]. It was found that the nature of nanoparticles, length, and location of the heat source had a major effect on the maximum temperature. The Lattice Boltzmann Method was used to model nanofluid flow in a three-dimensional porous cavity under the influence of the magnetic field [26]. Results indicate that with an increase in Re , Da , nanofluid kinetic energy increases. Convective flow decreases as the Hartmann number increases. Sheikholeslami et al. [27] examined a four-lobed pipe and swirl generator installed in a solar collector to achieve higher efficiency. The turbulent transport of nanoparticles was studied with helical tape installation in the solar system, as reported by Sheikholeslami et al. [28]. The main concept of using the turbulator is the rise in radial fluctuation, and the installation of the system induces secondary flow and creates thinner boundary layers. A numerical simulation on nanofluids were investigated by [29-31]. They found that an improvement in heat transfer by addition of nanoparticles.

A detailed review of the numerical and experimental studies performed by different researchers [32-34] to achieve improved heat transfer. Younes et al. [35] numerically studied heat and nanofluid mass transfer characteristics for various base fluids inside a rectangular channel created by detached and attached obstacles. A numerical simulation of forced convection in a rectangular Al_2O_3 - H_2O channel by adding basic geometry baffles and fins was investigated by Younes et al. [36]. The results indicated that there are important heat transfer effects from the presence of nanoparticles and baffle plates. The study of heat transfer indicated a quantitative increase in heat in all channels relative to those without obstacles [37].

The main objective is to analyze heat transfer and entropy production in an open cavity using a hybrid nanofluid, for different Reynolds numbers, solid volume fraction, and horizontal and vertical locations of the heat source. The effects of Re , ϕ and d (d_h and d_v) on the rate of heat transfer and the production of entropy are the motivation for this work. This work will help to improve the heat transfer of electronic equipment.

2. Geometry and Mathematical Model

The geometry considered is an open cubic cavity of $L=5\text{cm}$ (Figure 1). The volumetric heat generation (q_v) is placed on the lower wall of the cavity. All walls are adiabatic, and the flow enters at a velocity U_0 and a temperature T_0 .

The governing equations of three-dimensional laminar flow and heat transfer are written as:

Continuity:

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

x-momentum:

$$u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} + w \frac{\partial u}{\partial z} = \frac{1}{\rho_{\text{hnf}}} \left[-\frac{\partial p}{\partial x} + \mu_{\text{hnf}} \left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2} \right) \right] \quad (2)$$

y-momentum:

$$u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} + w \frac{\partial v}{\partial z} = \frac{1}{\rho_{\text{hnf}}} \left[-\frac{\partial p}{\partial y} + \mu_{\text{hnf}} \left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} + \frac{\partial^2 v}{\partial z^2} \right) \right] + (\rho\beta)_{\text{hnf}} g(T - T_0) \quad (3)$$

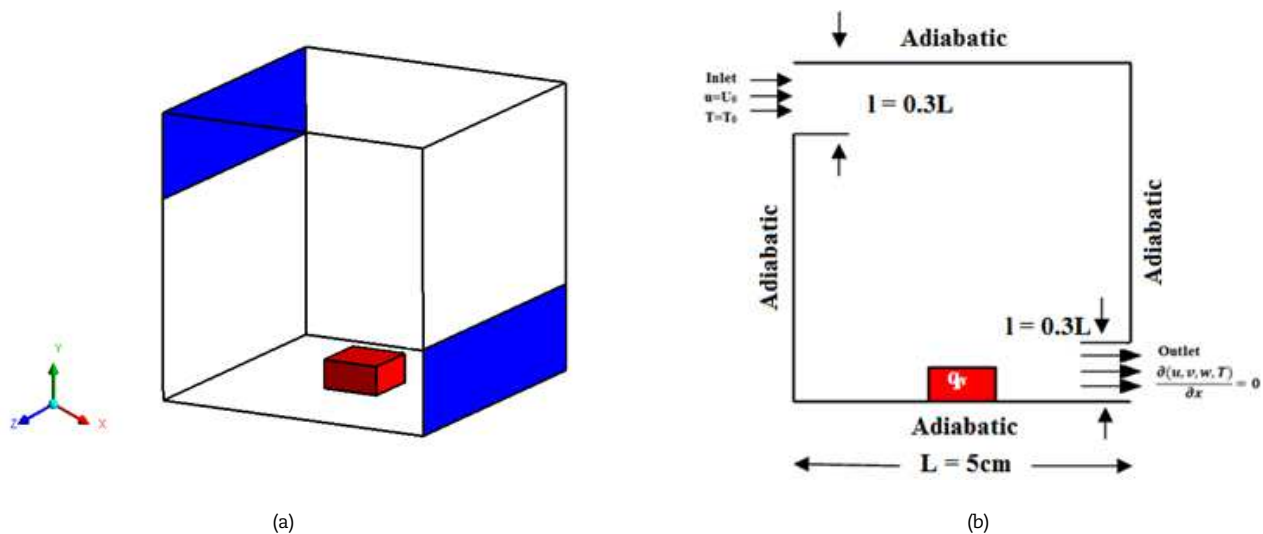


Fig. 1. Studied configuration: (a): 3D geometry and (b): in the x-y plane.



z-momentum:

$$u \frac{\partial w}{\partial x} + v \frac{\partial w}{\partial y} + w \frac{\partial w}{\partial z} = \frac{1}{\rho_{hbn}} \left[-\frac{\partial p}{\partial z} + \mu_{hnf} \left(\frac{\partial^2 w}{\partial x^2} + \frac{\partial^2 w}{\partial y^2} + \frac{\partial^2 w}{\partial z^2} \right) \right] \quad (4)$$

Energy [38]:

$$(\rho C_p)_{hnf} \left(u \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y} + w \frac{\partial T}{\partial z} \right) = k_{hnf} \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right) + q_v \quad (5)$$

The entropy generation equation is defined [39]:

$$S_{gen} = \frac{k_{nf}}{(T_0)^2} \left[\left(\frac{\partial T}{\partial x} \right)^2 + \left(\frac{\partial T}{\partial y} \right)^2 + \left(\frac{\partial T}{\partial z} \right)^2 \right] + \frac{\mu_{nf}}{T_0} \left\{ 2 \left[\left(\frac{\partial u}{\partial x} \right)^2 + \left(\frac{\partial v}{\partial y} \right)^2 + \left(\frac{\partial w}{\partial z} \right)^2 \right] + \left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} \right)^2 + \left(\frac{\partial v}{\partial z} + \frac{\partial w}{\partial y} \right)^2 + \left(\frac{\partial w}{\partial x} + \frac{\partial u}{\partial z} \right)^2 \right\} \quad (6)$$

The total entropy generation S_t is given by [39]:

$$S_t = \int S_{gen} dv \quad (7)$$

and the Bejan number as [39]:

$$Be = \frac{S_h}{S_t} \quad (8)$$

The thermophysical properties of the nanofluid $Al_2O_3/Water$ ($\phi = \phi_{Al_2O_3}$) are defined as follows [40-42]:

$$\rho_{nf} = (1 - \phi)\rho_f + \phi\rho_p \quad (9)$$

$$(\rho C_p)_{nf} = (1 - \phi)(\rho C_p)_f + \phi(\rho C_p)_p \quad (10)$$

$$(\rho\beta)_{nf} = (1 - \phi)(\rho\beta)_f + \phi(\rho\beta)_p \quad (11)$$

$$\alpha_{nf} = \frac{k_{nf}}{(\rho C_p)_{nf}} \quad (12)$$

$$\mu_{nf} = \frac{\mu_f}{(1 - \phi)^{2.5}} \quad (13)$$

$$k_{nf} = \frac{\left[(k_p + 2k_f) - 2\phi(k_f - k_p) \right]}{\left[(k_p + 2k_f) + \phi(k_f - k_p) \right]} \quad (14)$$

Table 1. Boundary conditions (h is the heat transfer coefficient).

Conditions	Dynamics	Thermal
x=0 cm $0 < y < 0.7L$ $0 < z < L$	$u=v=w=0$ [m/s]	$\frac{\partial T}{\partial x} = \frac{\partial T}{\partial y} = \frac{\partial T}{\partial z} = 0$
x=0 cm $0.7L < y < L$ $0 < z < L$	$u=U_0$ $v=w=0$ [m/s]	$T = T_0$
x=5 cm $0 < y < 0.3L$ $0 < z < L$	$\frac{\partial u}{\partial x} = \frac{\partial v}{\partial x} = \frac{\partial w}{\partial x} = 0$	$\frac{\partial T}{\partial x} = 0$
x=5 cm $0.3L < y < 0.7L$ $0 < z < L$	$u=v=w=0$ [m/s]	$\frac{\partial T}{\partial x} = \frac{\partial T}{\partial y} = \frac{\partial T}{\partial z} = 0$
y=0 cm $0 < x < L$ $0 < z < L$	$u=v=w=0$ [m/s]	$\frac{\partial T}{\partial x} = \frac{\partial T}{\partial y} = \frac{\partial T}{\partial z} = 0$
y=5 cm $0 < x < L$ $0 < z < L$	$u=v=w=0$ [m/s]	$\frac{\partial T}{\partial x} = \frac{\partial T}{\partial y} = \frac{\partial T}{\partial z} = 0$
z=0 cm $0 < x < L$ $0 < z < L$	$u=v=w=0$ [m/s]	$\frac{\partial T}{\partial x} = \frac{\partial T}{\partial y} = \frac{\partial T}{\partial z} = 0$
z=5 cm $0 < x < L$ $0 < z < L$	$u=v=w=0$ [m/s]	$\frac{\partial T}{\partial x} = \frac{\partial T}{\partial y} = \frac{\partial T}{\partial z} = 0$
Heat source d=2 cm	$u=v=w=0$ [m/s]	$-k \frac{\partial T}{\partial x} = h(T - T_0)$ $q_v = 2 \times 10^6 (W / m^3)$



Table 2. Mesh test results, for $\phi=0\%$, $Re = 300$ and $q_v = 2 \times 10^6$ W/m.

Mesh	$12 \times 50 \times 12$	$14 \times 61 \times 14$	$16 \times 61 \times 16$	$18 \times 61 \times 18$	$20 \times 94 \times 20$
Nu_{av}	6.9681	7.8724	7.9386	8.1634	8.1502
T_{max}	305.1499	304.885	304.6933	304.5672	304.5679

For the case of hybrid nanofluid (Al_2O_3 -Cu/water), the thermophysical properties are given by Takabi et al. [16], where $\phi = \phi_{Al_2O_3} + \phi_{Cu}$. The thermophysical properties of liquid water and nanoparticles are given in [23]. The boundary conditions are shown in Table 1.

3. Numerical Method

To simulate the flow with heat transfer we used Ansys-Fluent 14.5 [43]. The SIMPLE algorithm and second upwind scheme are used. Convergence was obtained when the maximum variation of velocities and temperature between two iterations is less than 10^{-5} .

The influence of the mesh on the numerical solution was examined before proceeding to the calculations. Five meshes were tested ($12 \times 50 \times 12$, $14 \times 61 \times 14$, $16 \times 72 \times 16$, $18 \times 83 \times 18$ and $20 \times 94 \times 20$) nodes for $Re = \rho_f U_0 L / \mu_f = 300$, where $U_0 = 2.5$ cm/s, $q_v = 2 \times 10^6$ W/m³ and $\phi = 0\%$.

According to table 2, we note the maximal temperature T_{max} and average Nusselt number Nu_m become insensitive to the number of nodes starting from the grid $18 \times 83 \times 18$ to $20 \times 94 \times 20$. Therefore, and to make the compromise between cost, precision and the computation time, the grid of $18 \times 83 \times 18$ nodes was chosen for all our numerical simulations.

To confirm the accuracy of the obtained results, it is essential to assess the Ansys-Fluent 14.5 [43] calculation code's reliability. The first validation was made with the numerical results of Sourtiji et al. [7] in an open cavity for the nanofluid (Al_2O_3 -water) at $Re = 500$, $Ri = 1$ (Richardson number, $Ri = Gr/Re^2$) and $\phi = 5\%$ (Figure 2 (a)). The second validation was made with the results of Takabi et al. [16] for the hybrid nanofluid (Al_2O_3 -Cu/water) at $Re = 1275$ and $\phi = 0.1\%$ (Figure 2 (b)). The third validation was carried out in a square cavity for the nanofluid (Cu/water) at $\phi = 0.1$ with the numerical results of Aminossadati and Ghesemi [25]. A good agreement was obtained according to these figures.

4. Results and Discussion

4.1 Reynolds Number Effect

Figure 3 (a) shows the streamlines throughout the cavity, for the nanofluid (Al_2O_3 /water) and the hybrid nanofluid (Al_2O_3 -Cu/water) at different Re . Note that the fluid enters at a velocity U_0 and leaves at a maximum velocity, where the inertia forces are large compared to the friction forces. We also see the formation of vortices around the heat source. The hybrid nanofluid speed is more significant and more remarkable compared to the nanofluid and that the latter increases with the increase in Re .

Figure 3 (b) gives the isotherms for different Re of nanofluid and hybrid nanofluid. We observe the creation of thermal boundary layers at the heat source; the temperature distribution propagates where the mechanism of convection becomes more and more dominant, the heat diffuses from the source, where the volumetric heat generation (q_v) towards the center of the cavity. It is also seen that the isotherms increase for low flow regimes, where the temperature gradients are important.

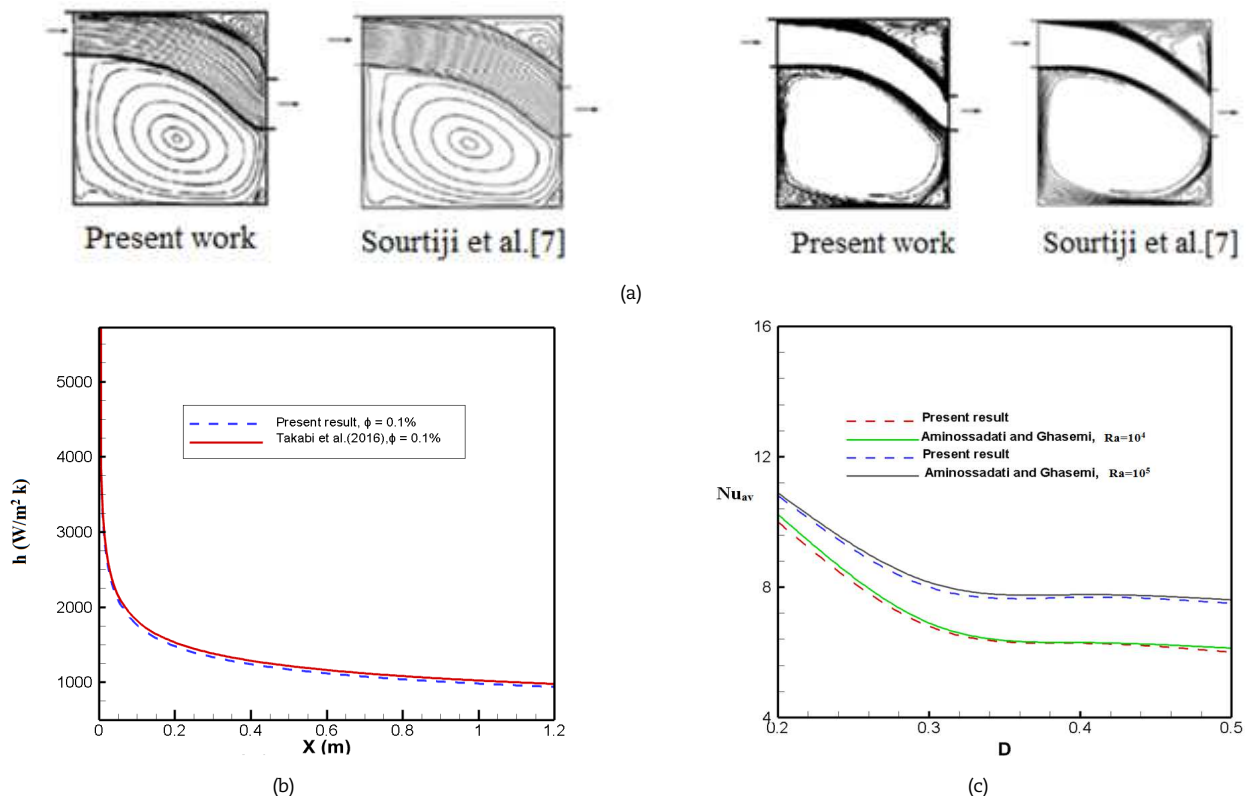


Fig. 2. Validation between our simulations and those of Sourtiji et al. [7] (a), Takabi et al. [16] (b) and Aminossadati and Ghasemi [25] (c).



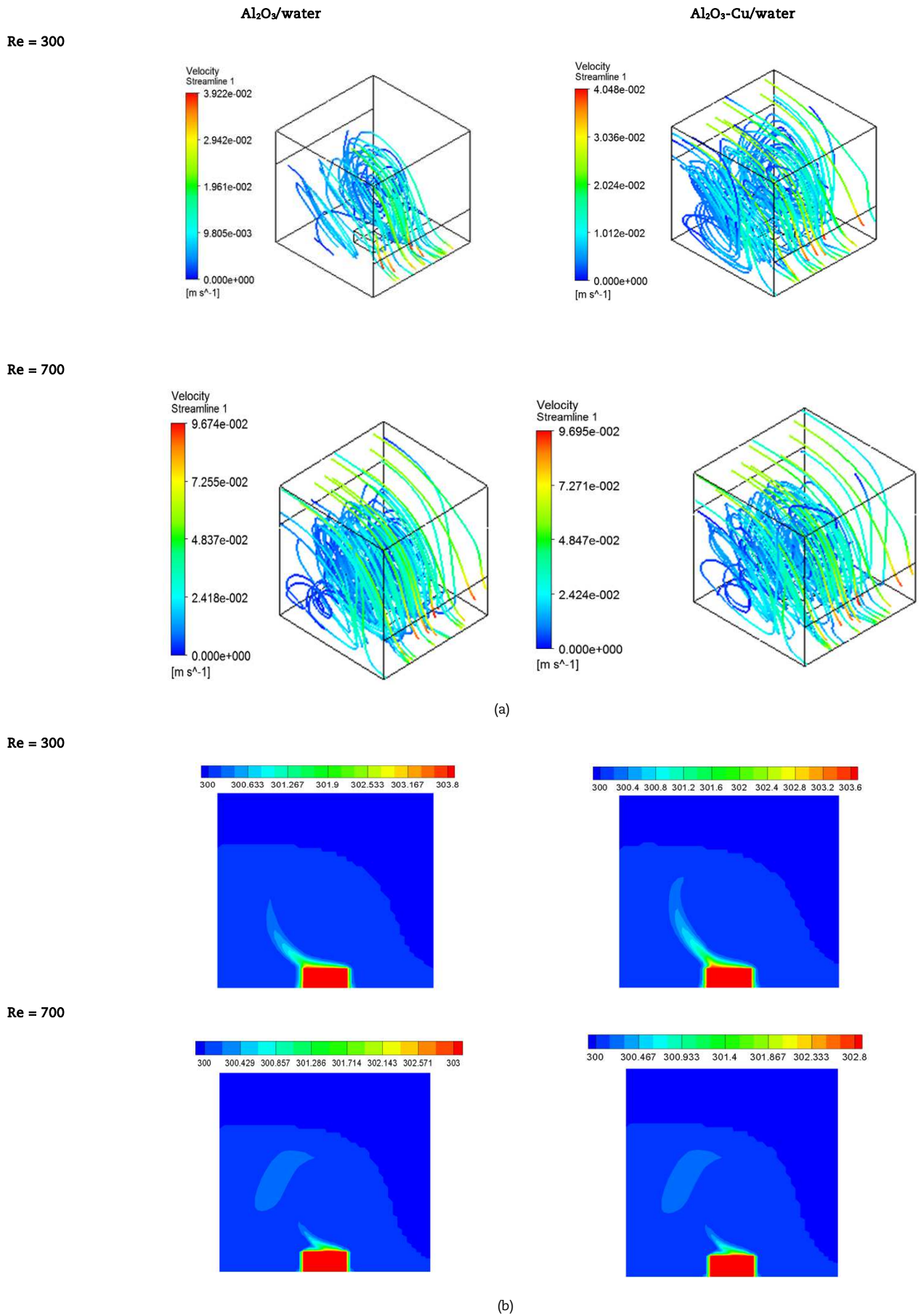


Fig. 3. Streamlines (a) isotherms (b) for nanofluid and hybrid nanofluid, at $\phi=6\%$ and different Re.



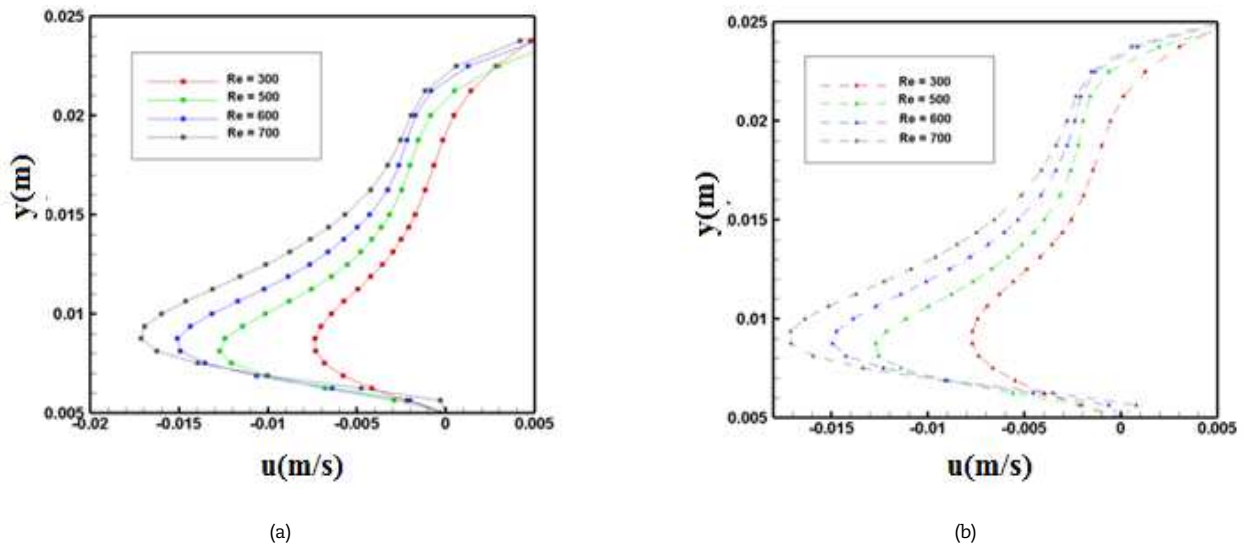


Fig. 4. Velocity profile as a function of y at $x=0.025m$ for $(Al_2O_3/water)$ (a) and $(Al_2O_3-Cu /water)$ (b), at $\phi=6\%$ and different values of Re .

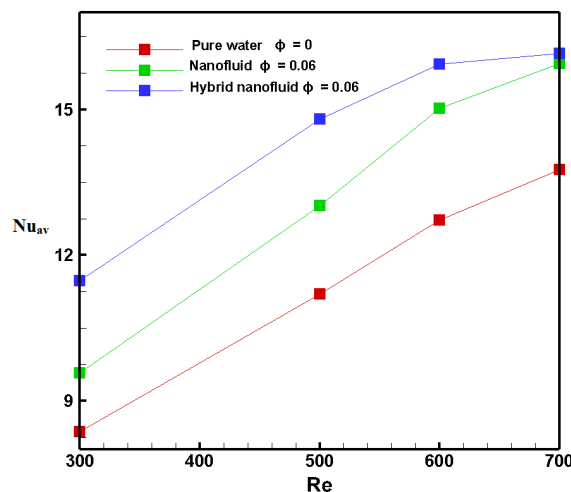


Fig. 5. Variation of Nu_{av} with Re for pure water, nanofluid and hybrid nanofluid.

Figure 4 illustrates the evolution of the velocity profile as a function of y for the nanofluid and hybrid nanofluid. Note that the flow velocity takes a parabolic form with negative speeds due to the creation of a reversal of the fluid and causes recirculation zones, which increase when Re increases.

Figure 5 shows the variation of Nu_{av} with Re for pure water ($\phi = 0\%$), nanofluid, and hybrid nanofluid ($\phi = 6\%$). It is found that there is a proportional relationship between the heat transfer rate and the increasing values of Re and ϕ . It is due to the fluid particles enhancing thermal conductivity. Saeed et al. [5] and Suresh et al. [14] obtained the same results.

4.2 Solid Volume Fraction Effect

Figure 6 shows the isotherms in the x - y plane for different solid volume fraction values, at $Re = 600$. We can see the heating of a fluid particle at the heat source level and that the temperature gradients near the source increase with the increase in ϕ . We note that the temperature distribution has an inverse relationship with ϕ when the density of hybrid nanofluid is lower, the temperature is hot.

Figure 7 shows the evolution of Nu along the heat source as a function of ϕ for the nanofluid and the hybrid nanofluid at $Re = 600$. We show that with the increase of ϕ , Nu increases. So we can say that the addition of solid particles of nanometric size leads to significant heat transfer changes inside the cavity. We also observe that the use of the hybrid nanofluid presents Nu 's significant values compared to the nanofluid and pure fluid $\phi = 0\%$; this is due to the thermal conductivity has increased. With the results of Ahmed et al. [44], the same results were obtained.

The analysis of Figure 8, which represents the temperature profile at $y = 0.005m$, shows that the hybrid nanofluid is the best for cooling compared to the nanofluid and pure water. The quality of cooling increases with ϕ . In the literature published by Takabi et al. [16] and Muhammad et al. [45], the same results were obtained.

4.3 Heat Source Position Effect

Figure 9 shows the influence of the vertical and horizontal positions of heat source on Nu and Nu_{av} for the nanofluid and hybrid nanofluid, at $Re=700$ and $\phi=8\%$. There is a rise in the Nusselt number with a decrease in horizontal displacement d_h .



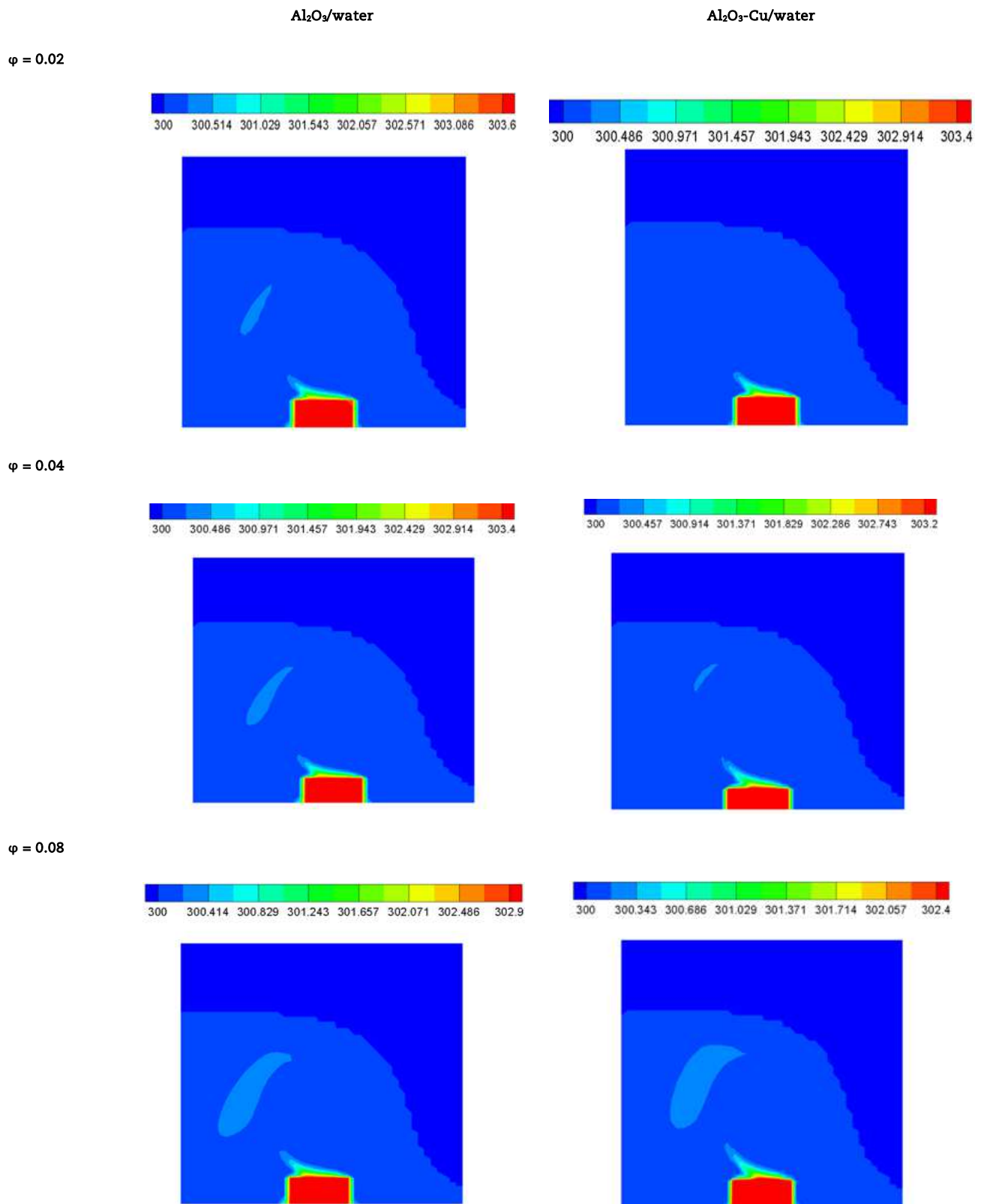


Fig. 6. Isotherms for nanofluid and hybrid nanofluid, for different ϕ , at $Re = 600$.

4.4 Entropy Generation

The total entropy generation St with Re for various ϕ is represented in Figure 10. It is observed that by increasing ϕ , St decreases linearly due to the decrease in the velocity gradients. With the work reported by Gabriela and Angel [37], these results are well-validated.



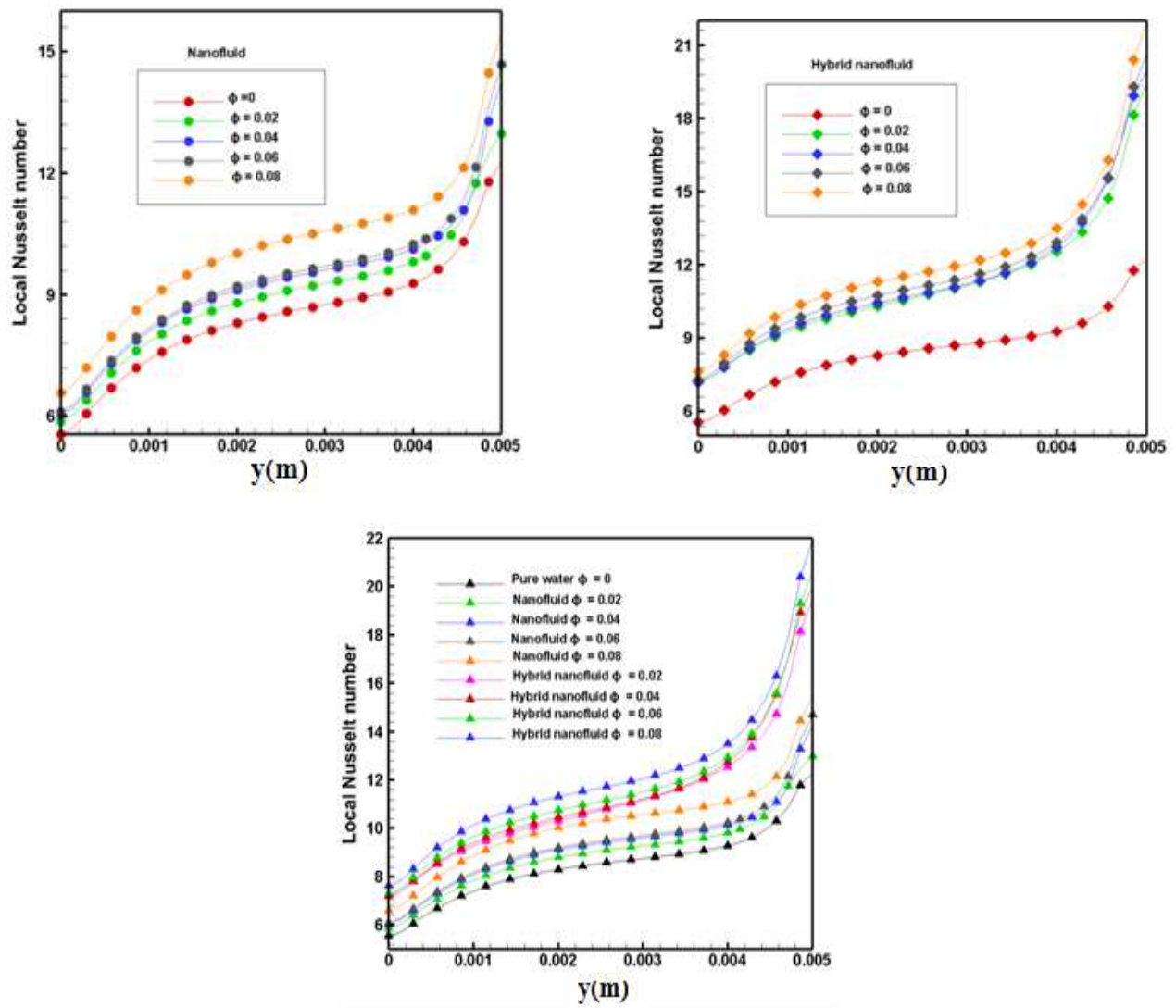


Fig. 7. The evolution of Nu along the heat source as a function of ϕ for nanofluid and hybrid nanofluid, at $Re = 300$.

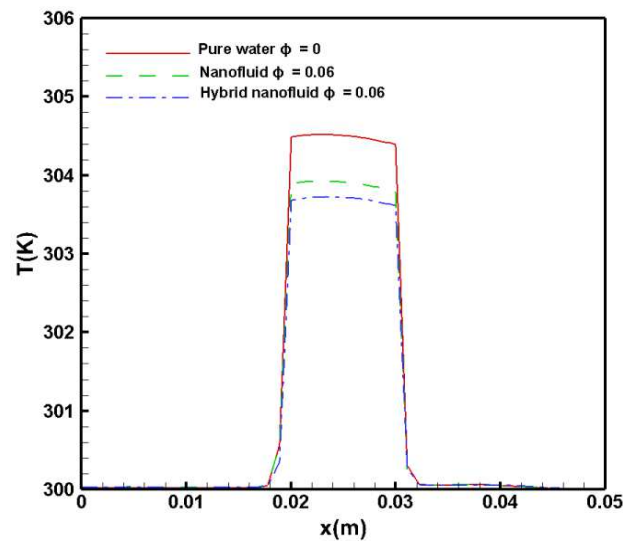


Fig. 8. Temperature profile at $y = 0.005m$ and $Re = 300$.



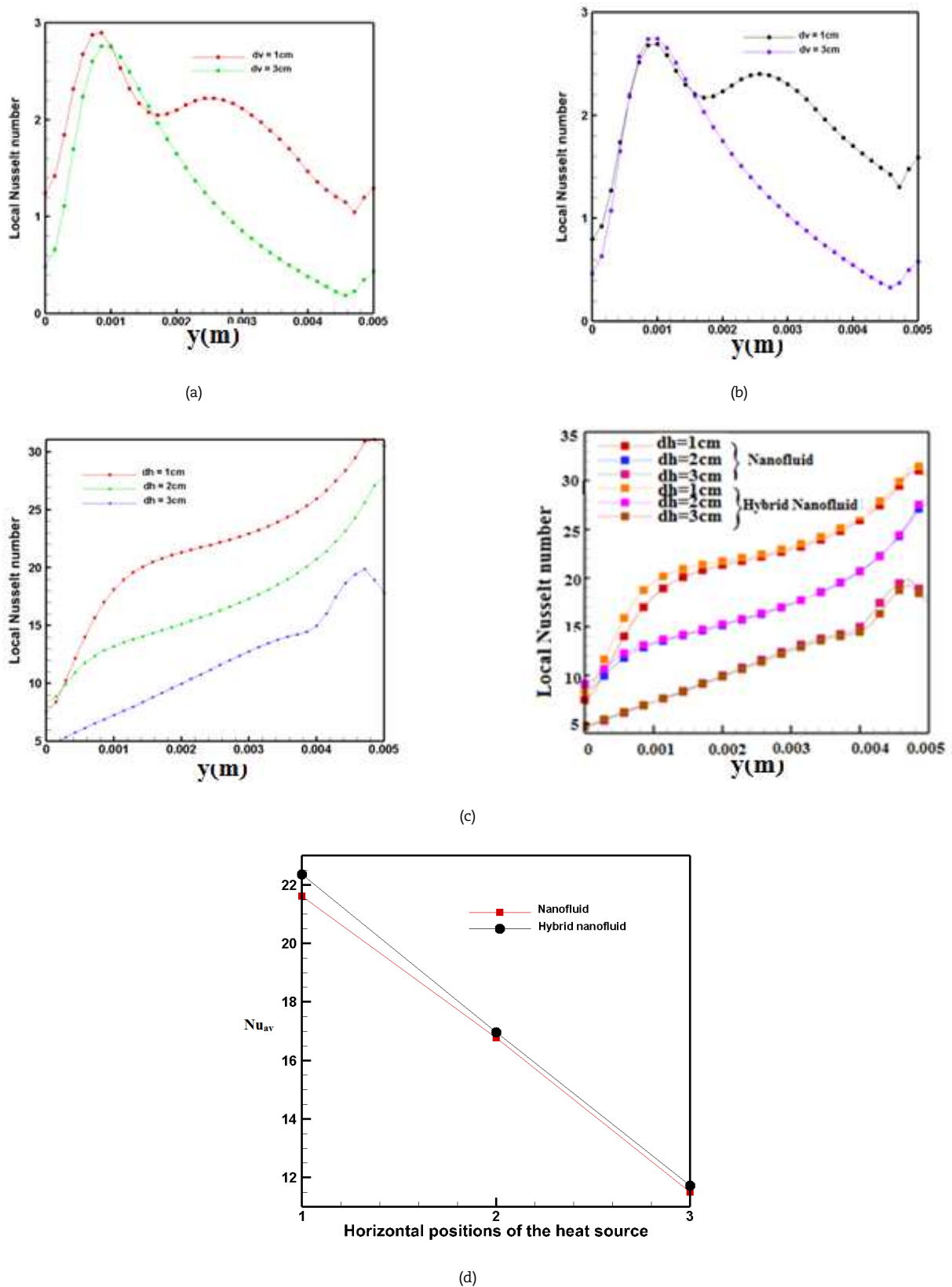


Fig. 9. Variation in the local Nusselt number (a, b, c) and average (d) with the position vertical (a, b) and horizontal (c, d) positions of the heat source for (Al₂O₃/water) and (Al₂O₃- Cu/water), at $\phi = 8\%$.

For different horizontal displacements of the heat source, the Bejan number Be variation is shown in Figure 11. It is noted that with the decrease in the horizontal displacement of the heat source, Be decreases.



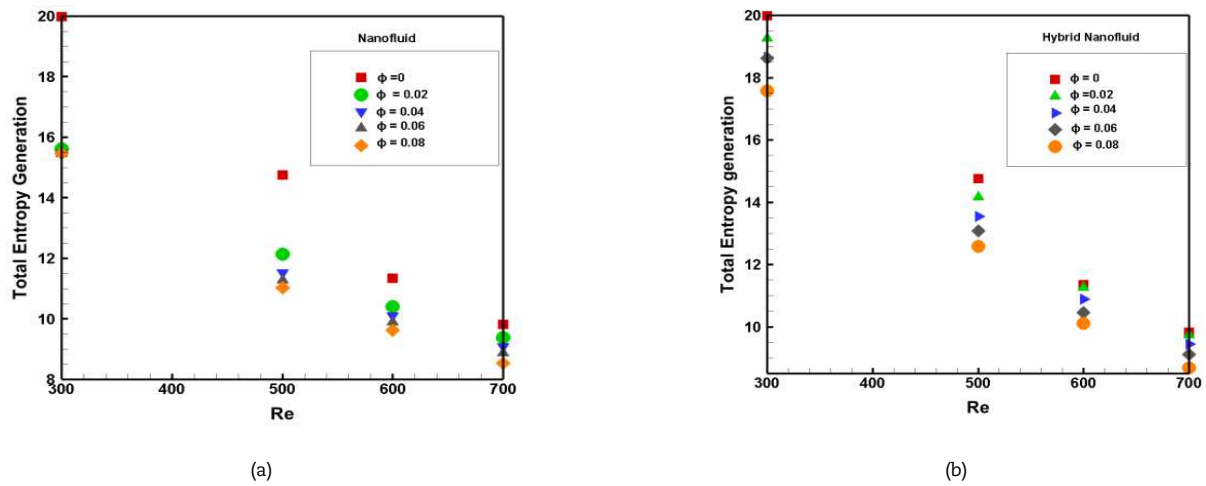


Fig. 10. Variation of St with Re, for different ϕ of (a) $\text{Al}_2\text{O}_3/\text{water}$ and (b) $\text{Al}_2\text{O}_3\text{-Cu/water}$.

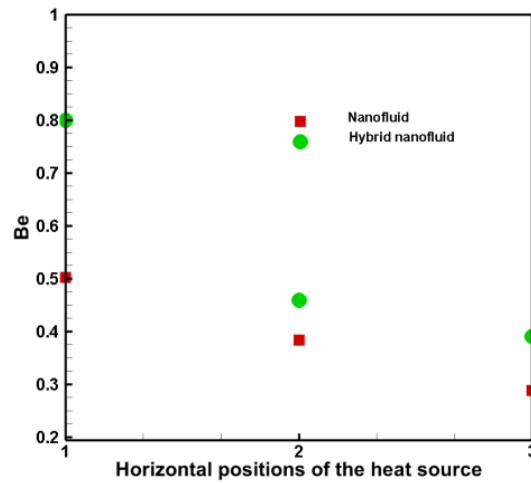


Fig. 11. Effects of different horizontal displacement of the position of the heat source on the Bejan number (Be) for nanofluid and hybrid nanofluid, at $\text{Re}=700$ and $\phi = 8\%$.

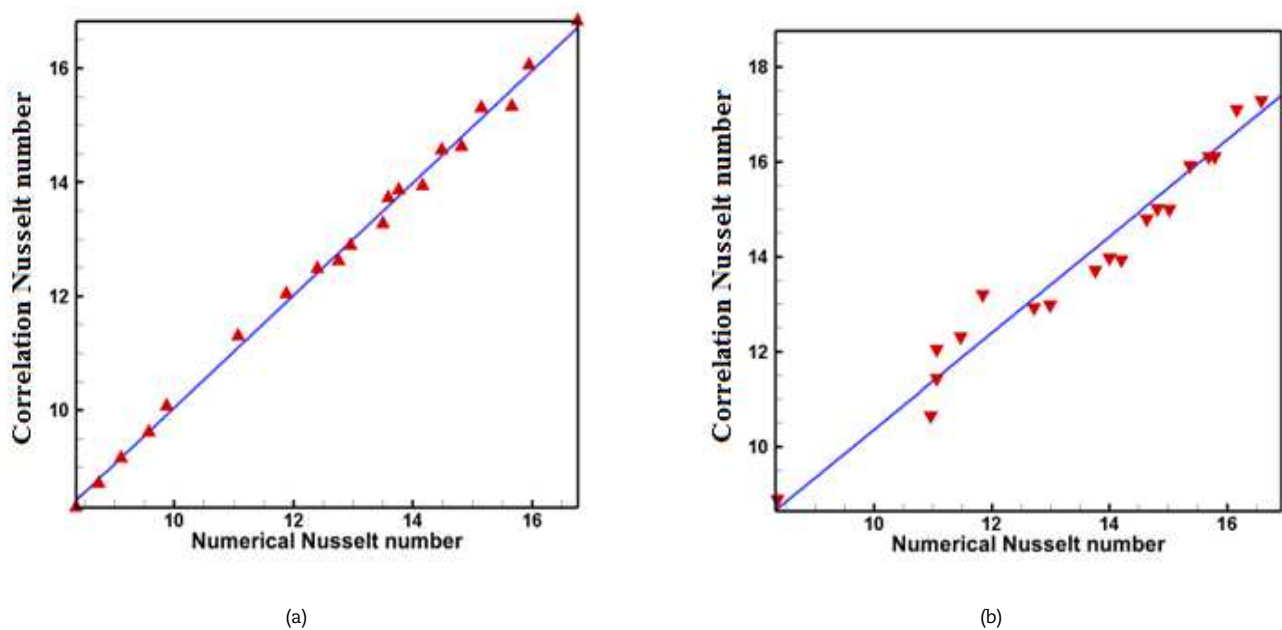


Fig. 12. Comparison between numerical results and correlations: $\text{Al}_2\text{O}_3/\text{water}$ nanofluid (a) and $\text{Al}_2\text{O}_3\text{-Cu/water}$ hybridnanofluid (b).



4.5 Nusselt Number Correlations

The correlations of Nu_{av} can be written as:

$$Nu_{av,nf} = 0.261 Re^{0.606} (1 + \phi)^{2.524} \quad (\text{For nanofluid}) \quad (15)$$

$$Nu_{av,hnf} = 1.081 Re^{0.388} (1 + \phi)^{3.771} \quad (\text{For hybrid nanofluid}) \quad (16)$$

5. Conclusion

A laminar mixed convection computational analysis in an open cavity using a hybrid nanofluid has been carried out. The effects of Re , ϕ , dh and dv on heat transfer and entropy production are analyzed. The main results are:

- The flow and thermal fields are affected by the Reynolds number and volume fraction.
- The nanoparticles affect Nusselt number and total entropy production.
- Due to the location of the heat source in the cavity, the structure of flow and thermal fields is complex.
- The use of hybrid nanofluid (Al_2O_3 - Cu/water) has a better heat transfer rate than nanofluid (Al_2O_3 -water).
- Heat transfer increases with increasing Re and ϕ .
- In comparison to the nanofluid and pure water, the hybrid nanofluid is the best for cooling heat source.
- The horizontal position of the heat source provides an improvement in heat transfer compared to the vertical position.
- A decrease in entropy generation in the nanofluid (Al_2O_3 -water) compared to the hybrid nanofluid (Al_2O_3 - Cu/water).
- Determination of two correlations to predict both nanofluid and hybrid nanofluid heat transfer.

Our perspective would be to study mixed convection in an open cavity under a magnetic field.

Authors Contributions

Bellout's contribution concerns the writing of the article and the curves. Bessaih Rachid enriched the discussion of the results and the correction of the revised version of our paper.

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Conflict of Interest

The authors declared no potential conflicts of interest with respect to the research, authorship, and publication of this article.

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Nomenclature

Be	Bejan number	Nu_{av}	Average Nusselt number
C_p	Specific Heat [J/kg.K]	q_v	Volumetric heat generation [W/m ³]
d_h	Horizontal displacement of the heat source [cm]	Re	Reynolds number
d_v	Vertical displacement of the heat source [cm]	S_{gen}	Entropy generation [W/m ³ .K]
k	Thermal conductivity [W/m.K]	S_t	Total entropy generation [W/K]
L	Cavity length [cm]	S_h	Entropy generation due to heat transfer [W/K]
l	Distance of entry and exit [cm]	T	Temperature [K]
Nu	Local Nusselt number	T_0	Inlet temperature [K]
		u,v,w	Velocity components [cm/s]
		U_0	Inlet velocity [cm/s]

Greek Symbols

α	Thermal diffusivity [m ² /s]
β	Coefficient of thermal expansion [K ⁻¹]
μ	Dynamic viscosity [kg.m/s]
ρ	Density [kg/m ³]
ϕ	Solid volume fraction

Symbols

f	Pure fluid
nf	Nanofluid
hnf	Hybrid nanofluid
p	Particle

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ORCID iD

Saliha Bellout  <https://orcid.org/0000-0002-2181-9141>

Rachid Bessaih  <https://orcid.org/0000-0002-0764-7731>





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