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Numerical investigation on the nanofluids heat transfer inside a porous inclined cavity with wavy boundary

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In the present work, a numerical study on the free-convective heat transfer in a porous media cavity with a wavy boundary was carried out. The validation was done by comparing the results with the experimental data. The cavity inclination angle, material of nanofluid, nanoparticles volume fraction, the Rayleigh number, and porosity of the medium are the parameters which are investigated in this study. Results suggested that, due to the thermophysical properties of Cu particles in water, the heat transfer rate was increased for Cu-Water nanofluid in comparison to Al_2O_3-Water nanofluid, while the heat transfer rate decreased by increasing the volume fraction of nanoparticles. Numerical results showed that the Rayleigh number has significant effect on the heat transfer rate so that increase in the Rayleigh number from 100 to 10 000 increased the averaged Nusselt number between 2 to 3 times. The effect of porosity on heat transfer proved that the convective heat transfer rate increased with increasing the porosity of the porous medium. The effect of inclination angle of cavity on the heat transfer rate suggested that the optimum angle of cavity causing the highest heat transfer rate from wavy wall is 45°.

Key words: free-convective heat transfer, porous medium, nanofluid, inclined porous cavity.

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1. Introduction

Having advantages such as increase of heat transfer surface and improvement of heat transfer mechanism, heat transfer of nanofluids in porous medium has many applications in engineering including cooling of electronic equipment, solar energy collection, and crystal growth in liquids. Compared with nonporous medium, more effective heat transfer from high temperature surface to the target surface takes place in the porous medium. Because, in the saturated porous medium, heat is transferred via conduction and convection.

Several studies have been done on the heat transfer of nanofluids in porous enclosures. Effects of coherence and radiation on free-convective heat transfer of a nanofluid in a square cavity filled with porous material were investigated both numerically and experimentally. Results showed that the heat transfer rate increased with increasing the Lewis number [1]. Interaction of nanofluid and one layer of porous medium in free-convective heat transfer was investigated numerically in a square cavity. The thickness of porous layer, nanoparticles void fraction, the Darcy number, and the domain ratio were the studied parameters. Numerical data suggested that the heat transfer rate was significantly affected by the thickness of porous layer [2]. The results obtained from numerous experimental and numerical studies showed that free-convective heat transfer of nanofluids in porous medium depends on various factors such as buoyancy force, pore size, and thermo-physical properties of the porous medium and nanoparticles [3–7]. Bekerman is one of the first researchers working on the free-convective heat transfer of nanofluids in porous medium. He experimentally investigated the effect of various nanoparticles in a porous medium and proposed a semi-empirical model for the Nusselt number assessment [8]. Performance of square porous cavity was studied by Basak *et al.* They investigated the effect of conductivity and radiative characteristics of porous medium on the heat transfer rate [9]. Khanafer *et al.* have reported improving heat transfer with Nano-fluids inside a two-dimensional cavity for different pertinent parameters [10]. They presented a correlation for the mean Nusselt number versus volume fractions and also Grashof numbers. Triveni [11] analyzed numerically free-convective heat transfer inside a triangular enclosure with the zig-zag hot wall. They found that as the aspect ratio and the Rayleigh number increase, the mean Nusselt number augments. Mohebbi [12] numerically studied the Nano-fluid effect on free-convective heat transfer of a corrugated boundary enclosure. They reported as a height of grooves increases the heat transfer augments due to increasing of the hot surface and the slope of the temperature. Selimefendigil [13] studied magnetic field and corrugated boundary effects on free-convective heat transfer in a Nano-fluid filled three dimensional trapezoidal enclosure. They observed that heat exchange inside the cavity is affected by the boundary corrugation parameters. They also have shown the corrugated enclosure results in decreasing the average heat transfer.

Effects of porous media material and structure on the heat transfer rate in porous medium were studied numerically and experimentally [14–18]. Several studies showed that the volume fraction of the nanoparticles in a nanofluid mixture was an important property for the stable heat transfer mode and the net heat transfer rate [19–24].

Also several researchers have studied free-convective heat transfer in wavy boundary cavities. Sheremet *et al.* studied natural convection inside a porous wavy cavity filled with a nanofluid under the effect of thermal dispersion using the Forchheimer–Buongiorno approach. They found that heat transfer enhances with the Rayleigh number, the undulation number and the dispersion parameter [25]. HASHIM *et al.* studied thermophoresis and Brownian diffusion numerically relating to the natural convection in a wavy cavity that is filled with nanofluid possessing a central heat-conducting solid block that is influenced by the local heater located on the bottom wall. They found that the heat transfer inside the cavity is enhanced by introducing nanoparticles as well as a selection of optimal number of oscillations [26]. SHEREMET *et al.* also studied entropy generation in natural convection of nanofluid in a wavy cavity using a single-phase nanofluid model. They found that an insertion of nanoparticles leads to an attenuation of convective flow and enhancement of heat transfer [27].

To the best of our knowledge, there was no comprehensive study of diverse parameters affecting the heat transfer of nanofluids in a porous cavity. So a parametric study on the heat transfer of nanofluids in a porous medium cavity with a wavy boundary is carried out at the present work. The aim of this study is to investigate the effect of diverse conditions and parameters on the heat transfer rate in a porous medium cavity including nanofluid's properties, nanoparticles' volume fraction, porosity of the medium, a cavity inclination angle, and the Rayleigh number.

In order to investigate the process of free-convective heat transfer through porous material, a two-dimensional model is used and predicted results for the Nusselt number distribution are compared with experimental data. The equilibrium condition between the solid and fluid temperatures is considered and heat transfer in the porous medium is simulated. The Nusselt number, the heat transfer rate, fluid temperature, and a stream function were investigated and the effects of mentioned parameters on the heat transfer process were discussed.

2. Physical model

Two dimensional inclined cavity is filled up of Al_2O_3 porous matrix is shown schematically in Fig. 1 where θ is the inclination angle. The top, right and the left boundaries are straight stationary walls and the length of all of them equals L. The wavy bottom boundary is also stationary wall and is made by a sine function as

$$y = \frac{L}{4}\sin\left(\frac{2\pi x}{L} - \frac{\pi}{2}\right) + \frac{L}{4}.$$

The top wall of the cavity is kept at low temperature, T_c, the bottom wavy wall is kept at high temperature, T_h, and the left and right walls are considered as adiabatic walls.

Thermo-physical properties of Al_2O_3 lamella and materials of nanofluids are summarized in Table 1 [28]. The porous material considered as an inert medium.

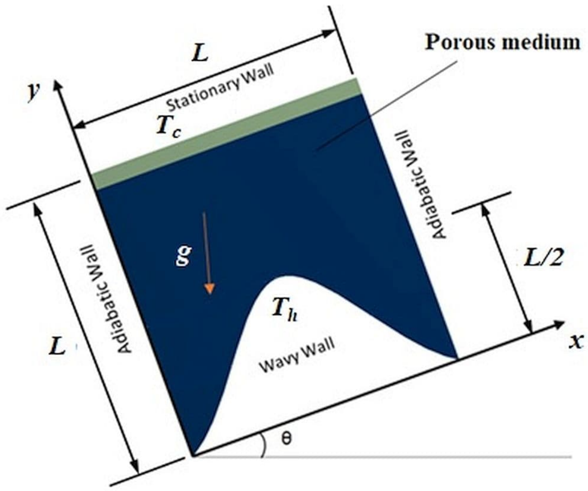

FIG. 1. Schematic of inclined cavity.

Table 1. Thermo-physical properties of the materials.

Properties	Symbol (unit)	Water	Cu	Al_2O_3
Specific heat capacity	c_p (J/kg · K)	4179	385	765
Conduction coeffitient	k (W/m · K)	0.613	401	40
Volumetric thermal expansion coefiicient	β (1/K)	0.00021	0.0000167	0.0000085
Density	ρ (kg/m^3)	997.1	8933	3970
Viscosity	μ (kg/(m · s))	0.00089	–	–

3. Governing equations

For a Newtonian, laminar, steady and two-dimensional flow through the porous medium, the free-convective heat transfer modeling was done by solving the governing equations including continuity, momentum, and energy. The governing equations are as follows:

The continuity equation:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \tag{3.1}$$

where u and v are superficial velocity components.

Momentum equations:

$$u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = -\frac{1}{\rho_{nf}}\left[\frac{\partial P}{\partial x} + \mu_{nf}\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2}\right) + g(\rho\beta)_{nf}\sin\theta(T_{nf} - T_c) - R_{P_x}\right], \tag{3.2}$$

$$u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y} = -\frac{1}{\rho_{nf}}\left[\frac{\partial P}{\partial y}+\mu_{nf}\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}\right)+g(\rho\beta)_{nf}cos\theta(T_{nf}-T_c)-R_{P_y}\right], \tag{3.3}$$

where μ is viscosity, ρ is density, β is the volumetric thermal expansion coefficient, nf subscript stands for nanofluid, T_{nf} is the nanofluid temperature, T_c is the cold wall temperature, and R_P is the pressure drop within the porous medium defined as [29]:

$$R_{P_x} = 180\frac{(1-\varepsilon)^2}{\varepsilon^3}\frac{\mu u}{d_p^2}+1.8\frac{1-\varepsilon}{\varepsilon^3}\frac{\rho_{|V|u}}{d_p}, \tag{3.4}$$

$$R_{P_y} = 180\frac{(1-\varepsilon)^2}{\varepsilon^3}\frac{\mu v}{d_p^2}+1.8\frac{1-\varepsilon}{\varepsilon^3}\frac{\rho_{|V|v}}{d_p}, \tag{3.5}$$

where ε is porosity of the porous medium which is the ratio of void space to the total volume of the medium and d_p is the diameter of solid particles making up the porous media structure.

The energy equation:

$$u\frac{\partial T_{nf}}{\partial x}+v\frac{\partial T_{nf}}{\partial y} = \frac{k_{nf}\varepsilon}{(\rho c_p)_{nf}}\left(\frac{\partial^2 T_{nf}}{\partial x^2}+\frac{\partial^2 T_{nf}}{\partial y^2}\right) \tag{3.6}$$

where k is the thermal conductivity and c_p is the specific heat capacity Density, the specific heat capacity, and the volumetric thermal expansion coefficient of the nanofluid are calculated by the following formulas [30]:

$$\rho_{nf} = (1-\phi)\rho_f+\phi\rho_s, \tag{3.7}$$

$$(\rho c_p)_{nf} = (1-\phi)(\rho c_p)_f+\phi(\rho c_p)_s, \tag{3.8}$$

$$(\rho\beta)_{nf} = (1-\phi)(\rho\beta)_f+\phi(\rho\beta)_s, \tag{3.9}$$

$$k_{nf} = k_f\frac{k_s+2k_f-2\phi(k_f-k_s)}{k_s+2k_f+\phi(k_f-k_s)}, \tag{3.10}$$

where ϕ is the nanoparticles' volume fraction. The Brinkman formula is implemented to calculate the effective dynamic viscosity of nanofluid [31]:

$$\mu_{nf} = \frac{\mu_f}{(1-\phi)^{2.5}}. \tag{3.11}$$

The dimensionless parameters of this problem are defined as:

$$
\begin{aligned}
T^* &= \frac{T - T_c}{T_h - T_c},\\
Ra &= \frac{g(\rho\beta)_{nf}(\rho c_p)_{nf} L^3 (T_h - T_c)}{k_{nf}\mu_{nf}},\\
Nu &= \frac{L}{(T_h - T_c)} \frac{\partial T}{\partial y}\bigg|_{y=L}.
\end{aligned}
\tag{3.12}
$$

4. Solution method

The nonlinear governing equations were solved by an iterative numerical approach using the finite volume method. The employed algorithm for pressure–velocity coupling was SIMPLE with the standard discretization for the pressure and second-order upwind discretization for momentum and energy equations [32]. A relative convergence of 10^{-6} was specified for all equations. Figure 2 shows the structured quadrilateral mesh used to discretize the geometry.

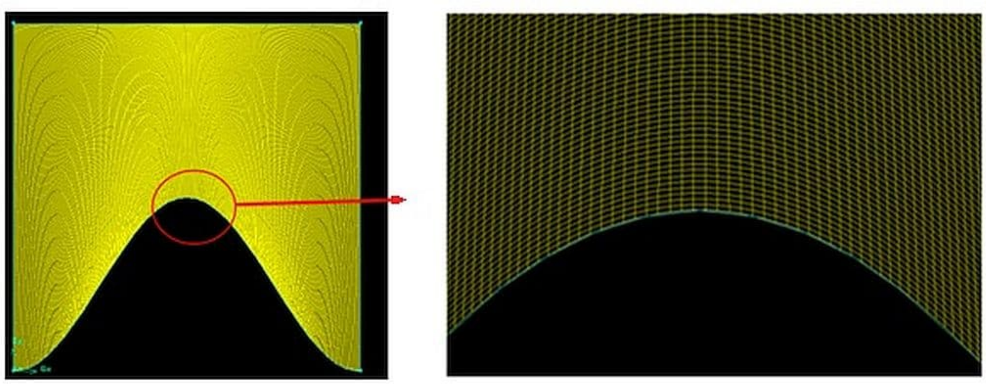

Fig. 2. Generated mesh for solution domain.

In order to study mesh independency, five structured mesh schemes were created and a fluid temperature profile was analyzed for each scheme (Fig. 3). In Table 2, the grids used for the mesh independency analysis are listed.

According to Fig. 3, it is obvious that the third mesh generation scheme indicates the best results while the results do not change with finer grids. Therefore, according to the third mesh pattern, grid dimensions were set to 200×200.

Table 2. Grids used to analyze mesh independency.

Mesh pattern	Dimensions	Number of cells
1	50×50	2500
2	100×100	10000
3	200×200	40000
4	400×400	160000
5	800×800	640000

5. Validation

In order to validate the obtained results, the computational results of a cavity investigated by SHEREMET *et al.* [33] is taken as the benchmark. The Nusselt number distribution results of the developed code is compared to those of [33] in Fig. 4.

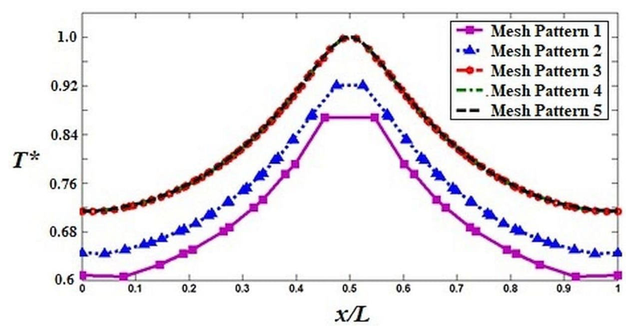

FIG. 3. The temperature profile for different mesh patterns at $y = L/2$.

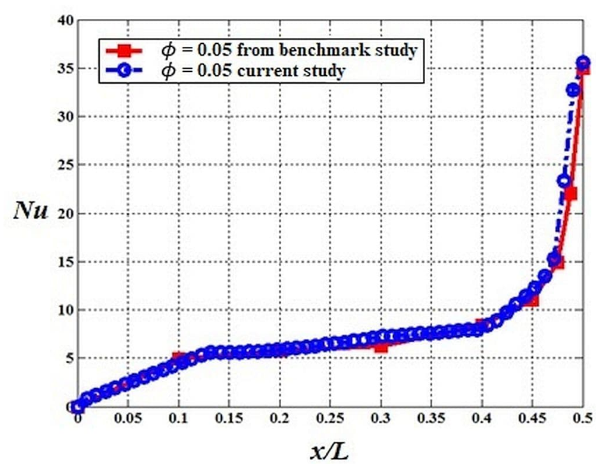

FIG. 4. Comparison of the numerical and empirical Nusselt number profiles for the Rayleigh number of 10^5 and volume fraction of 0.05% Cu-Water nanofluid with the benchmark study [33].

The distribution of the local Nusselt number through the centerline of the cavity well agrees with the benchmark results and the amount of an average error is about 7% (Fig. 4) which is acceptable.

6. Results and discussion

6.1. Effect of nanofluid on the heat transfer rate

Nanofluid has an important role in the free-convective heat transfer performance. An investigation on the effect of nanofluid on the averaged Nusselt number was carried out for Al_2O_3-Water and Cu-Water nanofluids. Variation of the averaged Nusselt number along the centerline of the cavity with a volume fraction of nanofluids for two different Rayleigh numbers is depicted in Fig. 5.

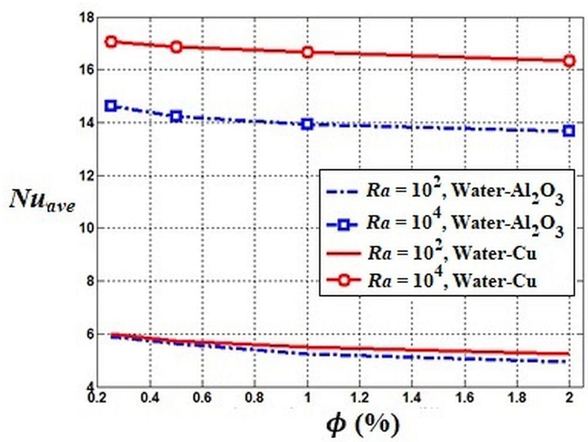

Fig. 5. Variation of the averaged Nusselt number along the centerline of the cavity with volume fraction of nanofluids for two nanofluids at different Rayleigh numbers.

As it can be seen, the averaged Nusselt number increases 2 to 3 times with the increase of the Rayleigh number from 100 to 10 000. This result was presented by Sheremet et al. [33]. Due to the thermo-physical properties of Cu nanoparticles within water, the Cu-Water nanofluid mixture increases heat transfer as compared to Al_2O_3-water nanofluid (Fig. 5). Figure 5 also shows that increasing the volume fraction of nanoparticles slightly decreases the Nusselt number. This phenomenon is due to the fact that the buoyancy force ($\rho\beta$) decreases by increasing the nanoparticles volume fraction. This effect of a nanoparticle volume fraction on the Nusselt number was reported in some of the previous studies such as [34].

Comparison of isothermal contours (T^*) for the Rayleigh numbers of 10^2 and 10^4 is depicted in Fig. 6. It is obvious that the heat transfer rate increases with the Rayleigh number augmentation. As the Rayleigh number increases, the

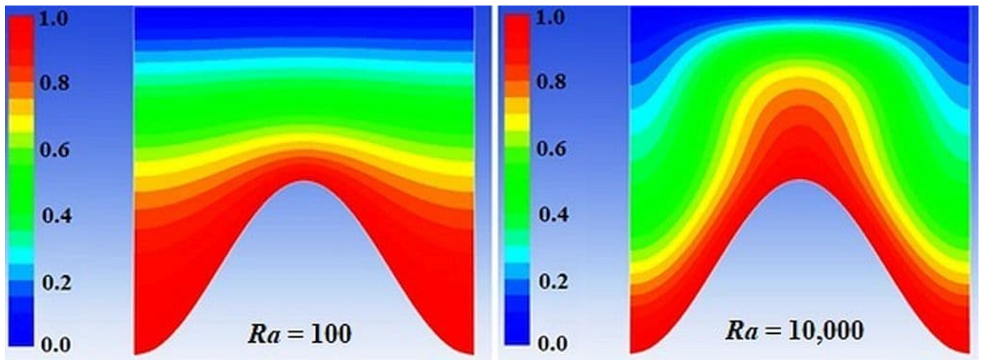

FIG. 6. Isothermal contours (T^*) for 0.25% mixture of Cu-Water nanofluid at different Rayleigh numbers.

temperature gradient between hot and cold wall increases and a high temperature zone moves to the upper part of the cavity increasing the heat transfer from a heated surface to a heat sink surface This happens due to the fact that at low Rayleigh numbers, the heat transfer occurs in a conduction mode which can be seen as straight horizontal isotherms near the cold wall for Ra = 100. But increasing the Rayleigh number above a certain critical value, changes the heat transfer from a conduction mode to a convection mode, increasing the heat transfer rate and making the hot fluid to penetrated into the top cold zone as it is seen for Ra = 10 000.

6.2. Effect of porosity on the heat transfer rate

Defined as the void volume to the total volume ratio, the porosity has an essential role in the structure of porous medium and fluid flow through the solid

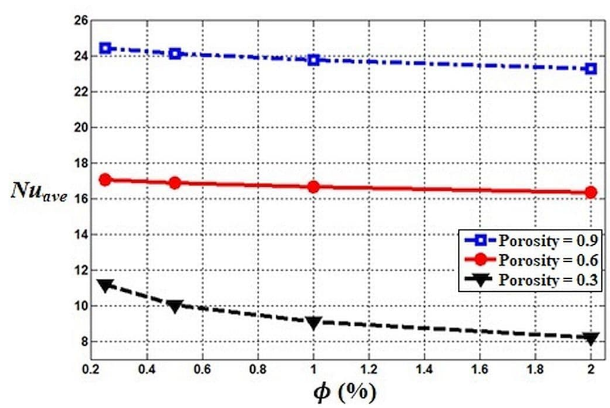

FIG. 7. Effect of porosity on the heat transfer rate for Cu-Water nanofluid at the Rayleigh number of 10^4.

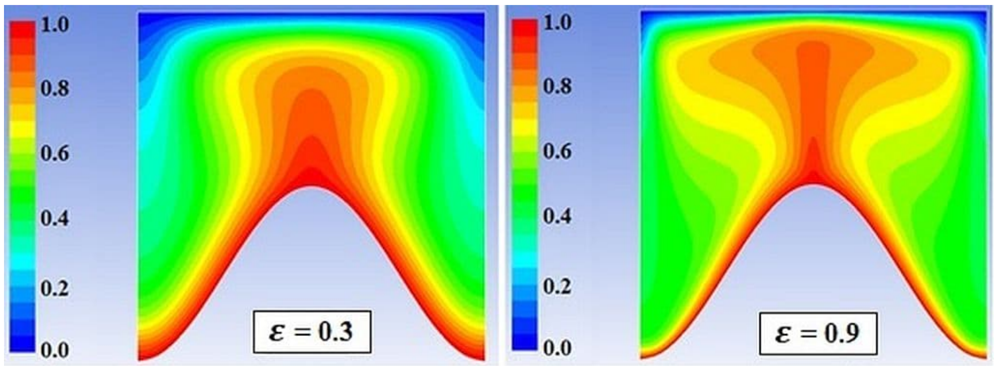

FIG. 8. Comparison of isothermal contours (T^*) for porosities of 0.3 and 0.9 at the Rayleigh number of 10^4.

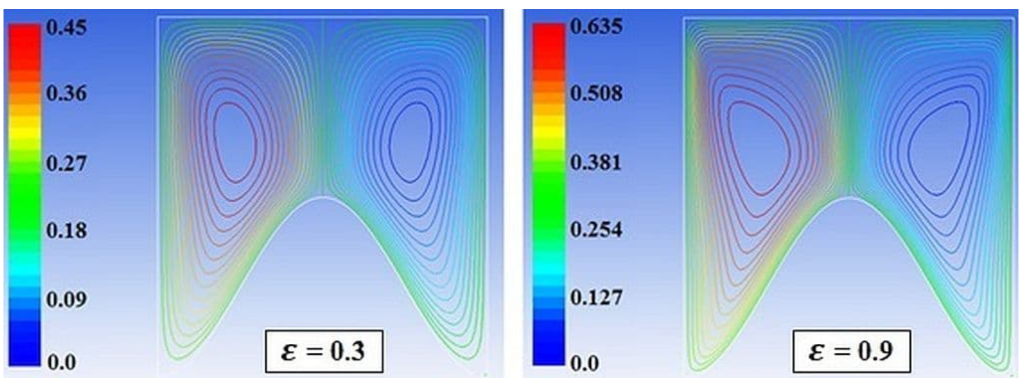

FIG. 9. Comparison of stream function contours for porosities of 0.3 and 0.9 at the Rayleigh number of 10^4.

matrix The influence of porosity on the freeconvective heat transfer of nanofluid was studied for Cu-Water nanofluid at the Rayleigh number of 10^4 for a range of volume fractions from 0.25% to 2% and the obtained results are depicted in Fig. 7. The results prove that for a constant Rayleigh number, the heat transfer rate from a wavy hot wall increases with increasing the porosity of the porous medium. The reason of this trend is that the porous medium is a resistance for fluid flow so with increasing the porosity, this resistance decreases [34]. Accordingly, the fluid flow and consequently the heat transfer rate increase. Comparison of isothermal contours and streamlines for porosity of 0.3 and 0.9 at the Rayleigh number of 10^4 are illustrated in Figs. 8 and 9, respectively.

Figure 8 shows that as the porosity of porous matrix increases, high temperature fluid moves to the upper part of the cavity and the temperature gradient increases near the hot surface which means a higher heat transfer rate. This trend is due to the fact that resistance to the flow of the fluid decreases as a void volume of the porous media increases. This lower flow resistance enhances the flow and increases the stream functions as seen in Fig. 9. Therefore, the net rate of free-convective heat transfer increases by augmentation of porosity.

6.3. Effect of inclination angle of the cavity on the fluid flow and heat transfer

In order to study the influence of the inclination angle of cavity alteration on the heat transfer rate and a fluid flow pattern, six cavities with different inclination angles were studied. The Rayleigh number is constant and is set to 10^4. The only geometrical distinction between these models is the amount of the inclination angle which was set to 15°, 30°, 45°, 60°, 75° and 90°.

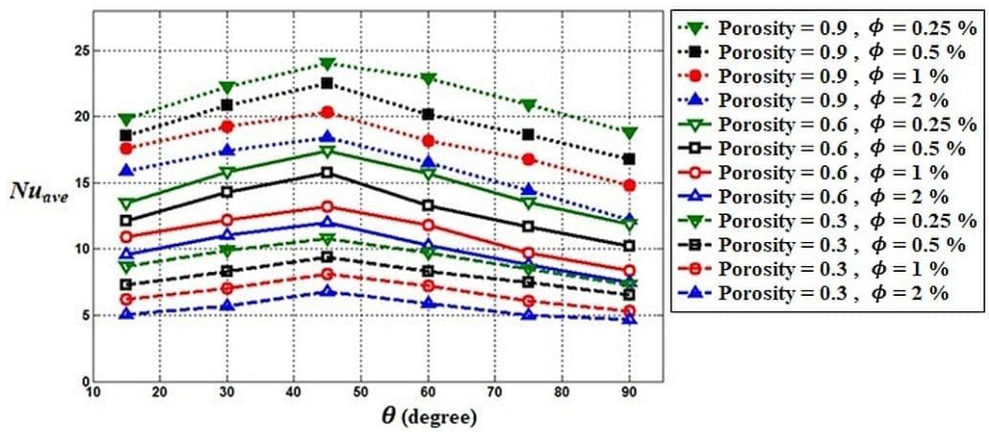

FIG. 10. Effect of inclination angle on the averaged Nusselt number for a range of volume fractions from 0.25% to 2% and for different porosities.

The effect of the inclination angle on the averaged Nusselt number for a range of volume fractions from 0.25% to 2% and for different porosities is illustrated in Fig. 10. The results suggest that by increasing the porosity, the heat transfer rate increases. Figure 10 demonstrates that for inclination angles from 15° to 45°, the averaged Nusselt number increases with increasing the inclination angle. The optimum inclination angle is 45°, while for angles higher than 45°, the amount of the averaged Nusselt number decreases slightly This result can be utilized in the process of a cavity design.

7. Conclusion

In this study, fluid flow and freeconvective heat transfer modeling of nanofluid through the porous medium having a wavy wall has been performed and effects of various parameters on the rate of heat transfer have been investigated with the computational fluid dynamics method. In order to validate the implemented numerical method, numerical results were compared with a benchmark data. Results suggested that due to the thermophysical properties of Cu particles in water, the heat transfer rate was increased for Cu-Water nanofluid in comparison to Al_2O_3-Water nanofluid while the heat transfer rate decreased by increasing the volume fraction of nanoparticles. Numerical results showed that the Rayleigh number had significant effect on the heat transfer rate so that increase in the Rayleigh number increased the averaged Nusselt number. Effect of porosity on heat transfer proved that the convective heat transfer rate increased with increasing the porosity of the porous medium. The effect of the inclination angle of a cavity on the heat transfer rate suggested that the optimum angle of the cavity inclination causing the highest heat transfer rate from wavy wall was 45°.

References

1. H.U. Kang, S.H. Kim, J.M. Oh, *Estimation of thermal conductivity of nanofluid using experimental effective particle volume*, Experimental Heat Transfer, **19**, 181–191, 2006.
2. V. Velagapudi, R.K. Konijeti, C.S.K. Aduru, *Empirical correlation to predict thermophysical and heat transfer characteristics of nanofluids*, Thermal Science, **12**, 27–37, 2008.
3. C. Murugesan, S. Sivan, *Limits for thermal conductivity of nanofluids*, Thermal Science, **14**, 65–71, 2010.
4. A.K. Nayak, R.K. Singh, P.P. Kulkarni, *Measurement of volumetric thermal expansion coefficient of various nanofluids*, Technical Physics Letters, **36**, 696–698, 2010.
5. M.M. Papari, F. Yousefi, J. Moghadasi, H. Karimi, A. Campo, *Modeling thermal conductivity augmentation of nanofluids using diffusion neural networks*, International Journal of Thermal Sciences, **50**, 44–52, 2011.
6. P.K. Namburu, D.K. Das, K.M. Tanguturi, R.S. Vajjha, *Numerical study of turbulent flow and heat transfer characteristics of nanofluids considering variable properties*, International Journal of Thermal Sciences, **48**, 290–302, 2009.
7. A.K. Santra, S. Sen, N. Chakraborty, *Study of heat transfer due to laminar flow of copper-water nanofluid through two isothermally heated parallel plates*, International Journal of Thermal Sciences, **48**, 391–400, 2009.
8. R. Strandberg, D.K. Das, *Finned tube performance evaluation with nanofluids and conventional heat transfer fluids*, International Journal of Thermal Sciences, **49**, 580–588, 2010.
9. S.K. Das, N. Putra, W. Roetzel, *Pool boiling characterization of nano-fluids*, International Journal of Heat and Mass Transfer, **46**, 851–862, 2003.
10. K. Khanafer, K. Vafai, M. Lightstone, *Buoyancy driven heat transfer enhancement in a two-dimensional enclosure utilizing nano-fluids*, International Journal of Heat and Mass Transfer, **46**, 3639–3653, 2003.
11. M.K. Triveni, R. Panua, *Numerical analysis of natural convection in a triangular cavity with different configurations of hot wall*, International Journal of Heat and Technology, **35**, 11–18, 2007.

12. R. MOHEBBI, S.H. KHALILABAD, Y. MA, *Effect of γ-Al2O3/Water nanofluid on natural convection heat transfer of corrugated shaped cavity: study the different aspect ratio of grooves*, Journal of Applied Fluid Mechanics, **12**, 1151–1160, 2019.

13. F. SELIMEFENDIGIL, H.F. ÖZTOP, *Role of magnetic foeld and surface corrugation on natural convection in a nano-fluid filled 3D trapezoidal cavity*, International Communications in Heat and Mass Transfer, **95**, 182–196, 2018.

14. A. AKBARINIA, A. BEHZADMEHR, *Numerical study of laminar mixed convection of a nanofluid in horizontal curved tubes*, Applied Thermal Engineering, **27**, 1327–1337, 2007.

15. M. AKBARI, A. BEHZADMEHR, F. SHAHRAKI, *Fully developed mixed convection in horizontal and inclined tubes with uniform heat flux using nanofluid*, International Journal of Heat and Fluid Flow, **29**, 545–556, 2008.

16. O. GHAFFARI, A. BEHZADMEHR, H. AJAM, *Turbulent mixed convection of a nanofluid in a horizontal curved tube using a two-phase approach*, International Communications in Heat and Mass Transfer, **37**, 1551–1558, 2010.

17. A.K. SANTRA, S. SEN, N. CHAKRABORTY, *Study of heat transfer augmentation in a differentially heated square cavity using copper-water nanofluid*, International Journal of Thermal Sciences, **47**, 1113–1122, 2008.

18. C.J. HO, M.W. CHEN, Z.W. LI, *Numerical simulation of natural convection of nanofluid in a square enclosure: effects due to uncertainties of viscosity and thermal conductivity*, International Journal of Heat and Mass Transfer, **51**, 4506–4516, 2008.

19. H.F. OZTOP, E. ABU-NADA, *Numerical study of natural convection in partially heated rectangular enclosures filled with nanofluids*, International Journal of Heat and Fluid Flow, **29**, 1326–1336, 2008.

20. E. ABU-NADA, H. OZTOP, *Effect of inclination angle on natural convection in enclosures filled with Cuewater nanofluid*, International Journal of Heat and Fluid Flow, **30**, 669–678, 2009.

21. S.M. AMINOSSADATI, B. GHASEMI, *Natural convection cooling of a localized heat source at the bottom of a nanofluid-filled enclosure*, European Journal of Mechanics-B/Fluids, **28**, 630–640, 2009.

22. E.B. ÖGÜT, *Natural convection of water-based nanofluids in an inclined enclosure with a heat sourc*e, International Journal of Thermal Sciences, **48**, 2063–2073, 2009.

23. E. ABU-NADA, Z. MASOUD, H. OZTOP, A. CAMPO, *Effect of nanofluid variable properties on natural convection in enclosures*, International Journal of Thermal Sciences, **49**, 479–491, 2010.

24. M. CORCIONE, *Heat transfer features of buoyancy-driven nanofluids inside rectangular enclosures differentially heated at the side walls*, International Journal of Thermal Sciences, **49**, 1536–1546, 2010.

25. M.A. SHEREMET, C. REVNIC, I. POP, *Free convection in a porous wavy cavity filled with a nanofluid using Buongiorno's mathematical model with thermal dispersion effect*, Applied Mathematics and Computation, **299**, 1–5, 2017.

26. I. HASHIM, A.I. ALSABERY, M.A. SHEREMET, A.J. CHAMKHA, *Numerical investigation of natural convection of Al2O3-water nanofluid in a wavy cavity with conductive inner block using Buongiorno's two-phase model*, Advanced Powder Technology, **30**, 399–414, 2019.

27. M. Sheremet, I. Pop, H.F. Öztop, N. Abu-Hamdeh, *Natural convection of nanofluid inside a wavy cavity with a non-uniform heating*, International Journal of Numerical Methods for Heat & Fluid Flow, **27**, 958–980, 2017.

28. C.C. Cho, C.L. Chen, C.K. Chen, *Natural convection heat transfer performance in complex-wavy-wall enclosed*, International Journal of Thermal Sciences, **60**, 255–263, 2012.

29. I.F. Macdonald, M.S. El-Sayed, K. Mow, F.A. Dullien, *Flow through porous media-the Ergun equation revisited*, Industrial & Engineering Chemistry Fundamentals, **18**, 199–208, 1979.

30. M. Mahmoodi, S.M. Hashemi, *Numerical study of natural convection of a nanofluid in C-shaped enclosures*, International Journal of Thermal Sciences, **55**, 76–89, 2013.

31. H.C. Brinkman, *The viscosity of concentrated suspensions and solutions*, The Journal of Chemical Physics, **20**, 571–581, 1952.

32. S.V. Patankar D.B. Spalding, *A calculation procedure for heat, mass and momentum transfer in three-dimensional parabolic flows*, Numerical Prediction of Flow, Heat Transfer, Turbulence and Combustion, 54–73, 1983.

33. M.A. Sheremet, I. Pop, H.F. Öztop, N. Abu-Hamdeh, *Natural convective heat transfer and nanofluid flow in a cavity with top wavy wall and corner heater*, Journal of Hydrodynamics, **28**, 873–885, 2016.

34. N.P. Karagiannakis, G.C. Bourantas, E.D. Skouras, V.C. Loukopoulos, K. Miller, V.N. Burganos, *Modeling the natural convection flow in a square porous enclosure filled with a micropolar nanofluid under magnetohydrodynamic conditions*, Applied Sciences, **10**, 1633, 2020.

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