Journal of Advanced Research in Fluid Mechanics and Thermal Sciences 93, Issue 1 (2022) 110-122

SEMARAK ILMU PUBLISHING

Journal of Advanced Research in Fluid Mechanics and Thermal Sciences

Journal homepage:
https://semarakilmu.com.my/journals/index.php/fluid_mechanics_thermal_sciences/index
ISSN: 2811-3950

Mixed Convection in a Lid-Driven Horizontal Rectangular Cavity Filled with Hybrid Nanofluid by Finite Volume Method

I. R. Ali[1], Ammar I. Alsabery[2], Norhaliza Abu Bakar[3], Rozaini Roslan[4,5,*]

[1] Business Administration Department, Al-Mustaqbal University College, 51001 Babylon, Iraq
[2] Refrigeration & Air-Conditioning Technical Engineering Department, College of Technical Engineering, The Islamic University, Najaf 54001, Iraq
[3] Centre for Diploma Studies, Universiti Tun Hussein Onn Malaysia, Pagoh, Muar 84600, Malaysia
[4] Faculty of Applied Sciences and Technology, Universiti Tun Hussein Onn Malaysia, Pagoh, Muar 84600, Malaysia
[5] ANNA Systems LLC, Moscow Region, Dubna, 9 Maya Street, Building 7B, Building 2 Office 10.141707, Moscow, Dolgoprudnenskoe Highway, 3, Fiztekhpark, Moscow 141980, Russia

ARTICLE INFO

Article history:
Received 29 October 2021
Received in revised form 29 December 2021
Accepted 9 January 2022
Available online 7 March 2022

Keywords:
FVM; mixed convection; hybrid nanofluid; rectangular cavity

ABSTRACT

In the present work, a new type of nanofluid called the hybrid nanofluid (Al_2O_3-Cu-water) is used to enhance the heat transfer. The Finite-Volume-Method (FVM) along with the SIMPLE-algorithm has been utilized to study the heat-transfer and, mixed convection fluid-flow of the hybrid nanofluid (Al_2O_3-Cu-water), placed within the lid-driven rectangular cavity. The bottom and top walls are subjected to constant high temperature (T_h) and low temperature (T_c) respectively. The side walls are treated as adiabatic. The top wall moves in the positive x-direction. The effects of Reynolds number and hybrid nanoparticle volume fraction on the flow field have been investigated. It is found that the mean Nusselt number increases with respect to Reynolds numbers and hybrid nanoparticle volume fraction.

1. Introduction

Tremendous amount of heat is generated from various engineering applications such as those encountered in manufacturing, thermal power plants, microelectronics, transportation, etc. Efficient coolers have been designed to adequately dissipate heat. In general, cooling method can be categorized into passive and active methods [1–4]. Traditional coolers such as propylene glycol, water, oils and, ethylene glycol have low thermal conductivities. In order to enhance the heat transfer, the thermal conductivity of the fluid should be enhanced. One of the methods is mixing the base fluid with nano-sized particles (hence the term nanofluid [5]). The frequently used nanoparticles are metals (Ni, Ag, Au and, Cu), metal-oxides (CuO, Al_2O_3, ZnO, MgO, Fe_2O_3, TiO_2 and, SiO_2), metal-nitride (AlN), metal-carbide (SiC) and carbon materials (MWCNTs, CNT, Diamond and, Graphite). In general, the thermal conductivity of nanofluid is dependent on parameters such as shape, size, stability of scattered nano-particles, type of base-fluid, mass concentration of nanoparticles and fluid

[*] *Corresponding author.*
E-mail address: rozaini@uthm.edu.my

https://doi.org/10.37934/arfmts.93.1.110122

temperature [6,7]. As compared to traditional fluids, nanofluids have been shown to exhibit better thermal performance in a wide range of engineering applications [8-11].

Rasul *et al.,* [12] studied the effect of the presence of a heat source and its location on natural convection in a C-shaped enclosure saturated by a nanofluid is investigated numerically using the lattice Boltzmann method. They concluded that maximum increase is obtained when the heat source is located in the upper part of the vertical. Dogonchi *et al.,* [13] studied numerically investigate the effects of shape factors of nanoparticles on natural convection in a fluid-saturated porous annulus developed between the elliptical cylinder and square enclosure. They concluded that enhancement of Rayleigh number increases the velocity of nanofluid. Seyed *et al.,* [14] studied Hybrid thermal performance enhancement of a circular latent heat storage system by utilizing partially filled copper foam and Cu/GO nano-additives. They found that the charging power can be enhanced to about four times at the cost of only a 3% reduction of the thermal storage's capacity. Mohammad *et al.,* [15] studied free convection heat transfer analysis of a suspension of nano-encapsulated phase change materials (NEPCMs) in an inclined porous cavity. They found that the presence of the NEPCM particles generally leads to heat transfer improvement.Sadeghi *et al.,* [16] studied the effect of charging and discharging of multi-layers of Phase Change Materials (PCMs) in coaxial cylinders with a time-periodic boundary condition. Mehryan *et al.,* [17] studied conjugate phase change heat transfer in an inclined compound cavity partially filled with a porous medium. They found that the rates of melting and heat transfer are enhanced as the thickness of the porous layer increases. Tilehnoee *et al.,* [18] studied natural convection analysis conjugated with entropy generation analysis in an incinerator shaped permeable enclosure loaded with Al_2O_3-water nanofluid subjected to the magnetic field with a rectangular wavy heater block positioned on the bottom of the cavity wall. They found that the Nusselt number and entropy generation number increase as the Rayleigh number and the Darcy number grow. Menni *et al.,* [19] studied the hydrodynamic and thermal analysis of turbulent forced-convection flows of pure water, pure ethylene glycol and water-ethylene glycol mixture, as base fluids dispersed by Al_2O_3 nano-sized solid particles, through a constant temperature-surfaced rectangular cross-section channel. They found that the pure ethylene glycol with Al2O3 nanoparticles showed a significant heat transfer enhancement.

Also, the thermal conductivity of nanoparticle can be further enhanced by mixing (hybridization) two (or more) types of nanoparticles (or hybrid-nanoparticles). Their hybrid nanoparticles are simply the extension of mono-nanoparticles. Undoubtedly, hybrid nanofluids exhibit higher thermal-conductivity than conventional nanofluids consisting of only one type of nano-particles[20–23].

Internal flow in enclosures could be driven by natural or mixed convections. Mixed convection is commonly found in manufacturing of float glass, solar collectors, solar ponds, food-processing and lubrication. Cimpean *et al.,* [24] studied mixed convection in a trapezoidal porous cavity filled with the hybrid nanofluid (Al_2O_3, Cu -water). They found that higher Reynolds number would increase the heat transfer. Ismael *et al.,* [25] investigated the mixed convection in a lid-driven cavity filled with Al_2O_3-Cu-water hybrid nanofluid. The nanofluid was heated by a triangular heater and cooled isothermally from the right vertical wall. They found that the hybrid nanofluid is a cost-effective solution as the amount of nanoparticles can be reduced. Mohammad *et al.,* [26] studied conjugate natural convection flow of Ag–MgO/water hybrid nanofluid in a square cavity. They found that the local Nusselt number at the surface of the conjugate wall decreases substantially by moving from the bottom of the cavity toward the top. Wakif *et al.,* [27] studied the effects of thermal radiation and surface roughness on the complex dynamics of water conveying alumina and copper oxide nanoparticles. They found that the partial substitution of the alumina nanoparticles by the copper oxide nanomaterials in the mixture stabilizes importantly the hybrid nanofluidic medium. Some advanced experimental studies using hybrid nanofluids have been reported [28–34]. The aim of this study is to investigate the effects of hybrid nanofluid volume fraction and Reynolds number on the flow field in the rectangular cavity.

2. The Mathematical Modelling (Formulation)

The two dimensional (2D) Mixed convection problem in the rectangular cavity of length (L=2) is shown in Figure 1. The upper and lower walls are isothermal, where the lower wall temperature Th is higher than the upper wall temperature Tc. Both side walls are adiabatic. The fluid inside the rectangular cavity is water-based hybrid nanofluid (Al_2O_3, Cu). The dimensional governing equations are (Ali *et al.,* 2020) and (Azizul *et al.,* 2020)

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

$$u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=-\frac{1}{\rho_{hnf}}\frac{\partial p}{\partial x}+\nu_{hnf}\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}\right) \quad (2)$$

$$u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}=-\frac{1}{\rho_{hnf}}\frac{\partial p}{\partial y}+\nu_{hnf}\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}\right)+g\beta_{hnf}(T-T_c) \quad (3)$$

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

The definition of the boundary-conditions as follows

The top wall-side: $u = u_0$; $v = 0$; $T = T_c$ (5)

The bottom wall-side: $u = 0$; $v = 0$; $T = T_h$ (6)

The left and, right wall-sides: $u = v = 0$; $\frac{\partial T}{\partial x} = 0$ (7)

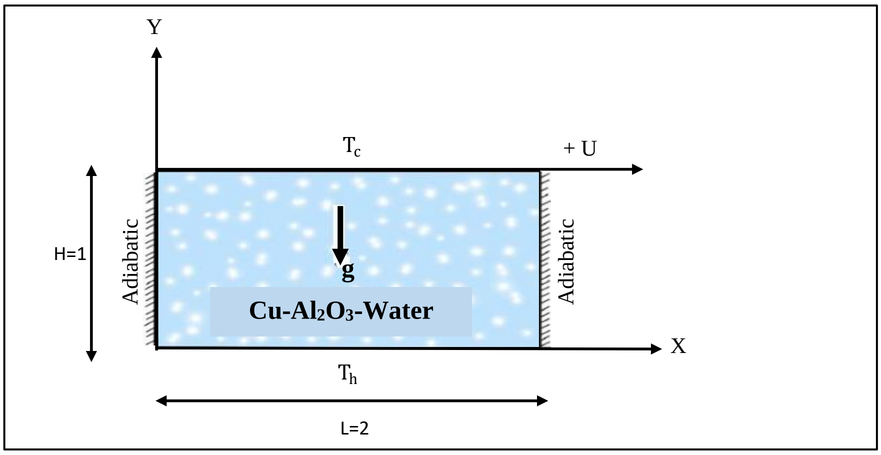


Fig. 1. Physical model

where the x and y indicate the Cartesian coordinates in the horizontal and vertical directions, respectively, g is the gravity acceleration, ρ_{hnf} is the density of the hybrid nanofluid, β_{hnf} is the thermal expansion coefficient of the hybrid nanofluid, ϕ is the solid volume fraction, α is the thermal diffusivity of the hybrid nanofluid and, ν_{hnf} is the kinematic viscosity of the hybrid nanofluid. The physical properties of the hybrid nanofluid [35] are given below.

The hybrid nanofluid density ρ_{hnf} is given as

$$\rho_{hnf} = \phi_{Cu}\rho_{Cu} + \phi_{Al_2O_3}\rho_{Al_2O_3} + \left(1 - \phi_{Cu} - \phi_{Al_2O_3}\right)\rho_f \quad (8)$$

The hybrid nanofluid heat capacitance $(\rho c_p)_{hnf}$ is given as

$$(\rho c_p)_{hnf} = \phi_{Cu}\rho(\rho c_p)_{Cu} + \phi_{Al_2O_3}(\rho c_p)_{Al_2O_3} + \left(1 - \phi_{Cu} - \phi_{Al_2O_3}\right)(\rho c_p)_f \quad (9)$$

The hybrid nanofluid buoyancy coefficient $(\rho\beta)_{hnf}$ can be calculated via

$$(\rho\beta)_{hnf} = \phi_{Cu}(\rho\beta)_{Cu} + \phi_{Al_2O_3}(\rho\beta)_{Al_2O_3} + \left(1 - \phi_{Cu} - \phi_{Al_2O_3}\right)(\rho\beta)_f \quad (10)$$

The dynamic viscosity ratio of a nanofluid can be determined using the method developed by Corcione *et al.,* [36]

$$\frac{\mu_{nf}}{\mu_f} = 1/(1 - 34.87\,(\frac{d_p}{d_f})^{-0.3}\phi^{1.03}) \quad (11)$$

Finally, the thermal conductivity ratio of the nanofluid is determined as [36]

$$\frac{k_{nf}}{k_f} = 1 + 4.4\,Re_B^{0.4}Pr^{0.66}\left(\frac{T}{T_{fr}}\right)^{10}\left(\frac{k_p}{k_f}\right)^{0.03}\phi^{0.66} \quad (12)$$

where T_{fr} is the freezing point of the base fluid $(273.15K)$.

Based on these mathematical models, the dynamic viscosity ratio and the thermal-conductivity ratio of the hybrid nanofluids (Al_2O_3-Cu)-water of particle sizes 33 nm and 29 nm in the ambient condition can be calculated as

$$\frac{\mu_{hnf}}{\mu_f} = 1/\{1 - 34.87\,(d_f)^{0.3}[(d_{Cu})^{-0.3}(\phi_{Cu})^{1.03} + \left(d_{Al_2O_3}\right)^{-0.3}\left(\phi_{Al_2O_3}\right)^{1.03}]\} \quad (13)$$

$$\frac{k_{hnf}}{k_f} = 1 + 4.4\,Re_B^{0.4}Pr^{0.66}\left(\frac{T}{T_{fr}}\right)^{10}(k_f)^{-0.03}[(k_{Cu})^{0.03}(\phi_{Cu})^{0.66} + \left(k_{Al_2O_3}\right)^{0.03}\left(\phi_{Al_2O_3}\right)^{0.66}] \quad (14)$$

where Re_B defined for hybrid nanofluid is

$$Re_B = \frac{\rho_f u_B\left(d_{Cu} + d_{Al_2O_3}\right)}{\mu_f} \quad (15)$$

$$u_B = \frac{2\,k_b\,T}{\pi\,\mu_f\left(d_{Cu} + d_{Al_2O_3}\right)^2} \quad (16)$$

Here; $k_b = 1.380648 \times 10^{-23}$(J/K) is the Boltzmann-constant, $l_f = 0.17\text{nm}$ is the mean-path of fluid particles and, d_f is the molecular-diameter of water [36]

$$d_f = \frac{6\,M}{N^*\pi\rho_f} \quad (17)$$

where; M denotes the molecular-mass of the working-fluid, N^* define is the Avogadro-number and, ρ_f is the working fluid-density at normal temperature (310K). In the present work, thenon-dimensional variables are presented as

$$X = \frac{x}{L}, Y = \frac{y}{L}, U = \frac{u}{U_0}, V = \frac{v}{U_0}, \theta = \frac{T - T_c}{T_h - T_c} = \frac{T - T_c}{\Delta T}, Pr = \frac{\upsilon_f}{\alpha_f}, P = \frac{pL^2}{\rho_f \alpha_f^2}, Ri = \frac{Gr}{Re^2} \tag{18}$$

Then, the non-dimensional governing equations

$$\frac{\partial U}{\partial X} + \frac{\partial V}{\partial Y} = 0 \tag{19}$$

$$U\frac{\partial U}{\partial X} + V\frac{\partial U}{\partial Y} = -\frac{\partial P}{\partial X} + \frac{1}{Re}\frac{\mu_{hnf}}{\mu_f}\frac{\rho_f}{\rho_{hnf}}\left(\frac{\partial^2 U}{\partial X^2} + \frac{\partial^2 U}{\partial Y^2}\right) \tag{20}$$

$$U\frac{\partial V}{\partial X} + V\frac{\partial V}{\partial Y} = -\frac{\partial P}{\partial Y} + \frac{1}{Re}\frac{\mu_{hnf}}{\mu_f}\frac{\rho_f}{\rho_{hnf}}\left(\frac{\partial^2 V}{\partial X^2} + \frac{\partial^2 V}{\partial Y^2}\right) + \left(\frac{(\rho\beta)_{hnf}}{\rho_{hnf}\beta_f}\right) Ri\,\theta \tag{21}$$

$$U\frac{\partial \theta}{\partial X} + V\frac{\partial \theta}{\partial Y} = \frac{\alpha_{hnf}}{\alpha_f}\frac{1}{Pr\,Re}\left(\frac{\partial^2 \theta}{\partial X^2} + \frac{\partial^2 \theta}{\partial Y^2}\right) \tag{22}$$

As well as, the dimensionless of boundary conditions are

The top wall-side: $U = 1;\ V = 0;\ \theta = 0$ (23)

The bottom wall-side: $U = 0;\ V = 0;\ \theta = 1$ (24)

The left and, right wall-sides: $U = V = 0;\ \frac{\partial \theta}{\partial X} = 0$ (25)

The local Nusselt numbers for the hot wall, cold wall and the average Nusselt number are given in Eq. (26) – Eq. (28), respectively

$$Nu_x = -\frac{k_{hnf}}{k_f}\left(\frac{\partial \theta}{\partial Y}\right)_{Y=0} \tag{26}$$

$$Nu_x = -\frac{k_{hnf}}{k_f}\left(\frac{\partial \theta}{\partial Y}\right)_{Y=1} \tag{27}$$

$$\overline{Nu} = \int_0^D Nu_x\, dx \tag{28}$$

3.Numerical Technique

The governing equations are solved numerically using FVM [37]. The convection term is approximated using the power-law scheme. The SIMPLE algorithm is used for pressure-velocity coupling. Then, the algebraic system of equations is solved using the TDMA algorithm written in FORTRAN 90 programming language. The relaxation factor is set below 0.5 for momentum and energy equations in order to obtain convergence. The convergence criterion is calculated as

$$error = \frac{\sum_{j=1}^{m}\sum_{i=1}^{n}\left|\eta_{i,j}^{k+1} - \eta_{i,j}^{k}\right|}{\sum_{j=1}^{m}\sum_{i=1}^{n}\left|\eta_{i,j}^{k+1}\right|} \leq 10^{-7} \tag{29}$$

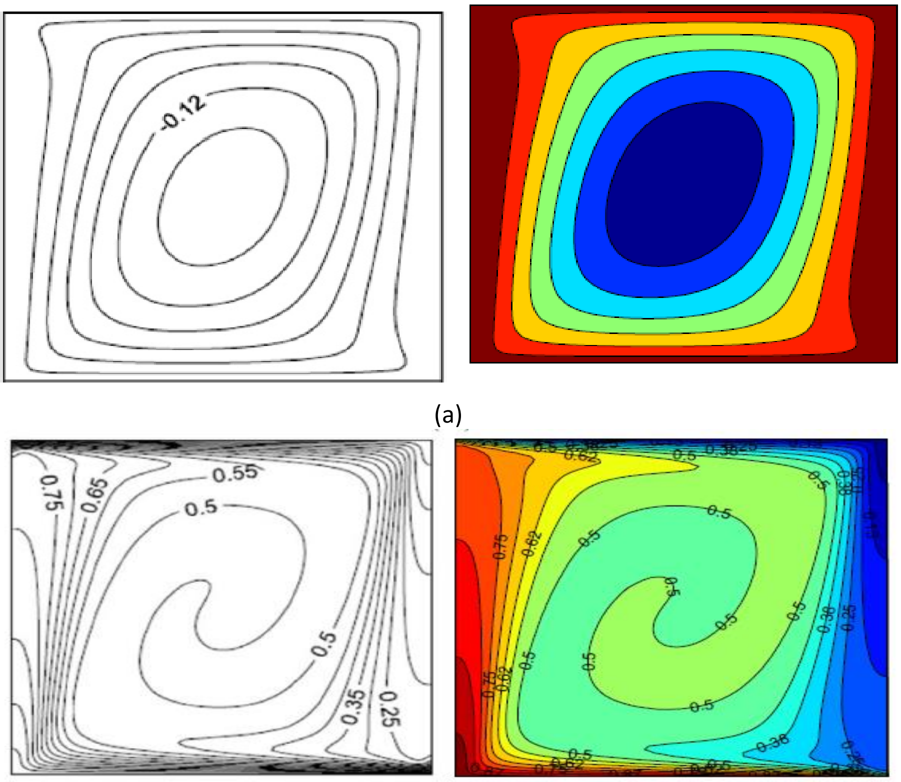
where m and n are denoted as the grid-point numbers in the x and, y directions, respectively, η is any transport quantity and k is the iteration number.

4. Mesh Independent and Validation

To check for grid-independence, simulations using four different grid sizes, i.e.$80 \times 40, 100 \times 50, 120 \times 60, 140 \times 70$ are executed. The numerical setting can be found in Table. 1. Based on the table, the result obtained on the 120×60 grid is already grid - independent. The result has been compared to that of Ismael *et al.,* [38] who studied the mixed convection in a double lid-driven square cavity with the partial slip. The results showed good agreement has been found as shown in Figure 2.

Table 1
Mesh convergence

Size	Average Nusselt number $\overline{\text{Nu}}$
80×40	4.869276
100×50	4.889277
120×60	4.897964
140×70	4.900624



(a)

(b)

Fig. 2. Streamlinespatterns (a), in left Ismael *et al.,* [38]; in right present study and, validation of isotherms (lines) (b), in left Ismael *et al.,* [38], in right present study

5. Results and Discussion

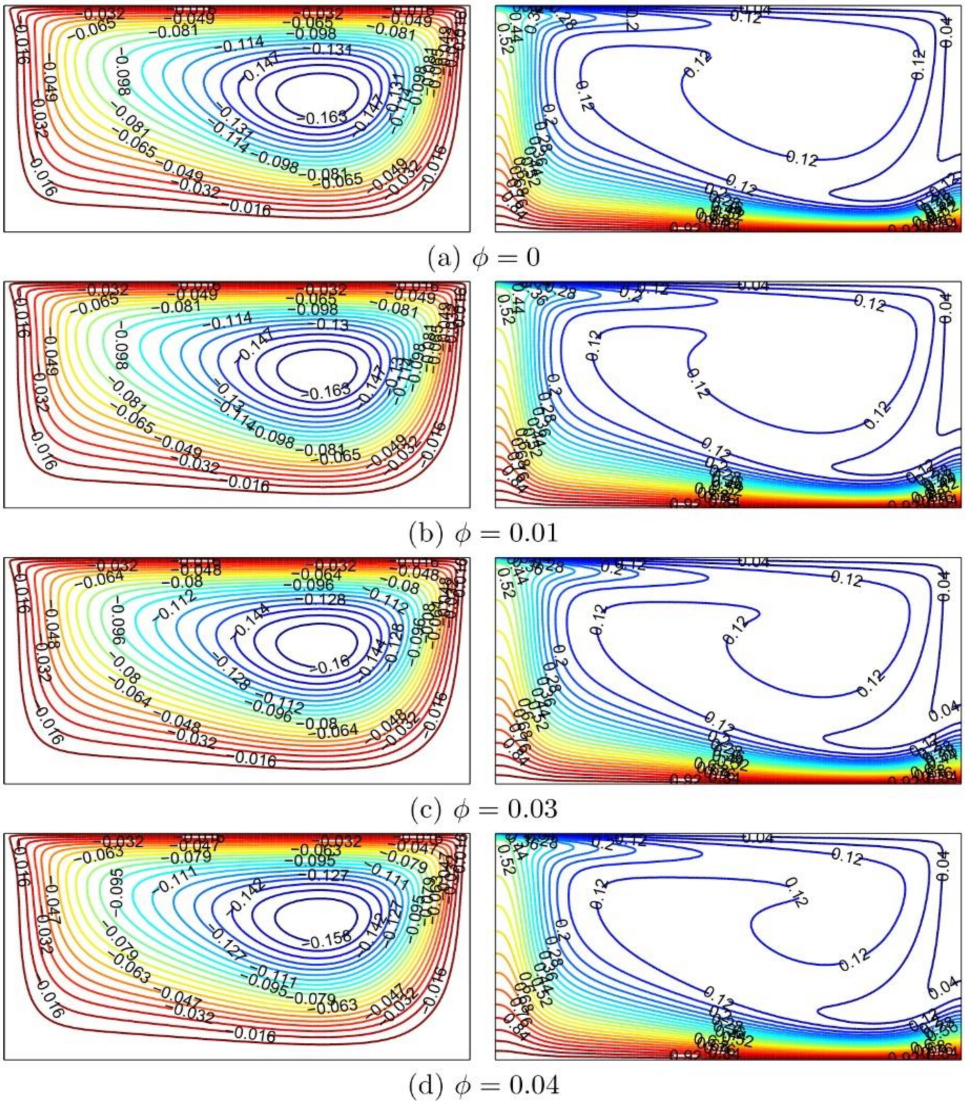
The heat transfer properties within the rectangular cavity filled with hybrid nanofluid (Al_2O_3-Cu-water) have been studied. The effects of parameters such as volume fraction and Reynolds number on the heat transfer with $\mathrm{Pr} = 6.2$ have been investigated. Streamlines, isotherms and averaged Nusselt number have been investigated. The thermo-physical characteristics of the basic fluid (water) and the Al_2O_3 + Cu nanoparticles are reported in Table 2. Figure 3 shows the streamlines and isotherms at $\mathrm{Re} = 10$, $\mathrm{L} = 2.5$, $\mathrm{Ri} = 1$. A primary recirculation cell rotating in the clockwise direction can be observed. As the volume fraction of the hybrid nanoparticle increases, the intensity of the vortex increases, and the streamlines move closer to each other. The isothermal lines are clustered near the isothermal walls, indicating that the temperature gradients are relatively high in these regions. As the volume fraction of nanoparticle increases, the isothermal lines become less congested.

Figure 4 shows the effect of Re on the streamlines and isotherms at $\mathrm{Ri} = 10, \mathrm{L} = 2.5, \phi = 0.02$. There is a central vortex rotating in the clockwise direction. The isotherms at Re = 1 follow closely to those observed in the pure conduction case. Pure conduction occurs due to weak convection as shown in Figure 4 (a, b). Stratification tends to be more apparent as Re is increased up to 10. By further increasing the Re as shown in Figure 4 (c, d), the cavity center tends to become isothermal. Figure 5 shows the distribution of local (area) Nusselt number along the hot wall for different Re values ($\mathrm{Ri} = 10, \varphi = 0.02$ and, $\mathrm{L} = 2$).

As shown in Figure 6, the local Nusselt number increases with respect to Re due to more intense mixing. Figure 7 shows the effect of volume fraction on the local Nusselt number ($\mathrm{Re} = 10, \mathrm{Ri} = 10, \mathrm{L} = 2$). As expected, the increase in volume fraction can enhance the local Nusselt number in the warm regions.

Table 2
Thermo-physical characteristics of water, Cu, Al_2O_3 nanoparticles($\mathrm{T} = 310$ K) [39]

Physical properties	Base fluid water	Cu	Al_2O_3
$\mathrm{k}\ (\mathrm{Wm^{-1}K^{-1}})$	0.628	400	40
$\mu \times 10^6 (\mathrm{kg/ms})$	695	-	-
$\rho (\mathrm{kg/m^3})$	993	8933	3970
$\mathrm{C_p} (\mathrm{J/kgK})$	4178	385	765
$\beta \times 10^{-5} (1/\mathrm{K})$	36.2	1.67	0.85
$\mathrm{d_p} (\mathrm{nm})$	0.385	29	33



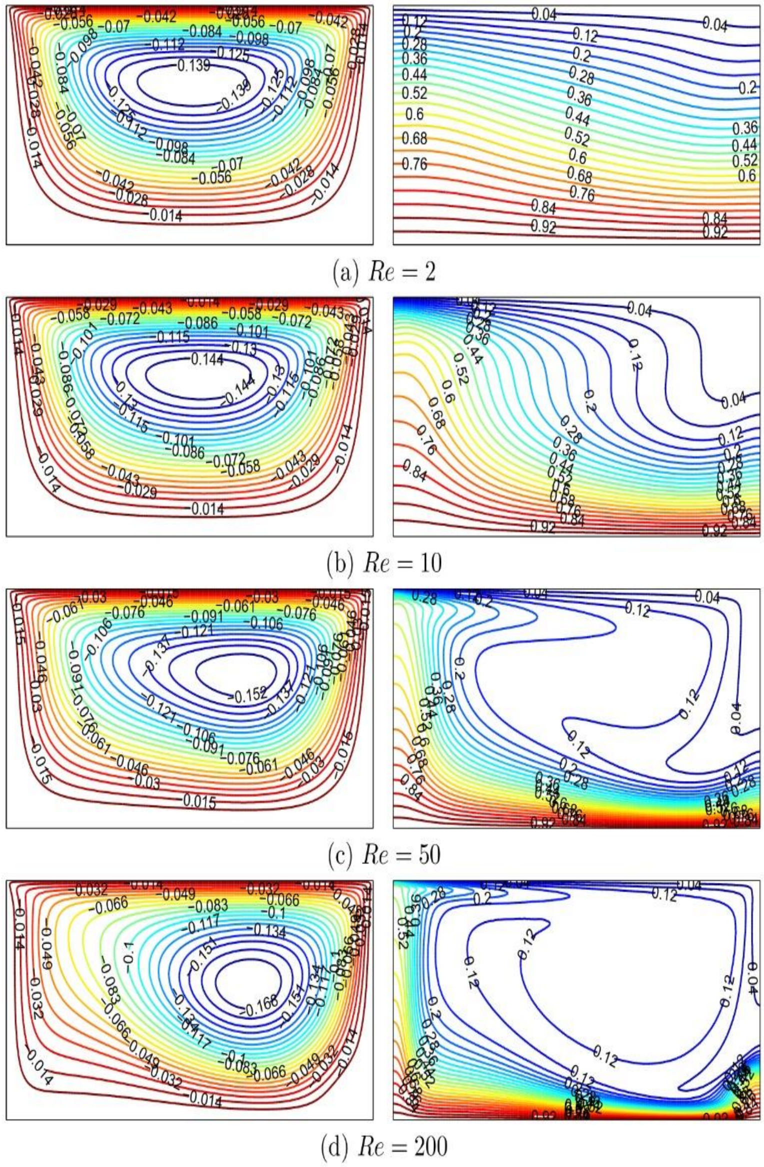
(a) $\phi = 0$

(b) $\phi = 0.01$

(c) $\phi = 0.03$

(d) $\phi = 0.04$

Fig. 3. Variations of streamlines in left and, isotherms in right, when (a) ϕ = 0.0, (b) ϕ = 0.01, (c) ϕ = 0.03, (d) ϕ = 0.04



(a) $Re = 2$

(b) $Re = 10$

(c) $Re = 50$

(d) $Re = 200$

Fig. 4. Variations for streamlines in left and, isotherms in right, when (a) $\mathrm{Re} = 2$, (b) $\mathrm{Re} = 10$, (c) $\mathrm{Re} = 50$, (d) $\mathrm{Re} = 200$

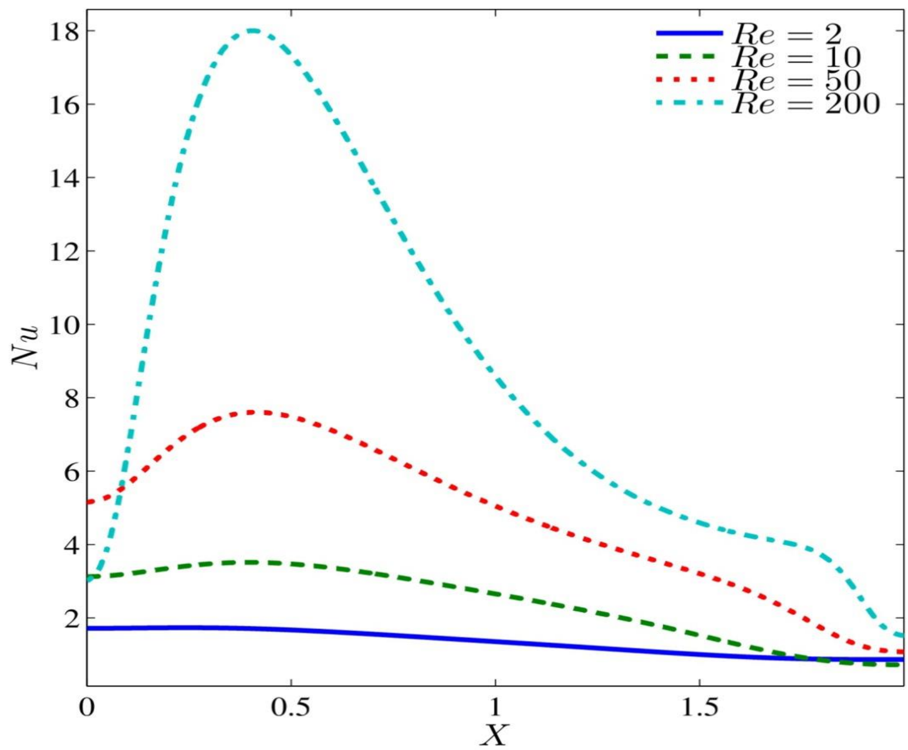


Fig. 5. Variations of the local Nusselt-number against X for different Re

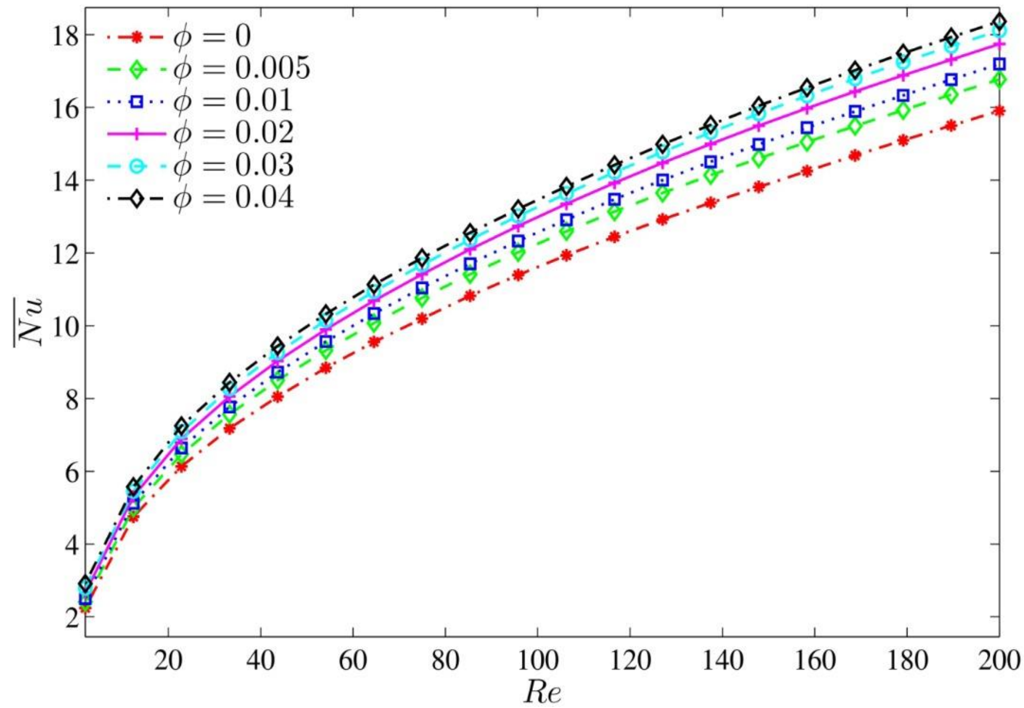


Fig. 6. Variations of the average Nusselt-number against Re for different ϕ

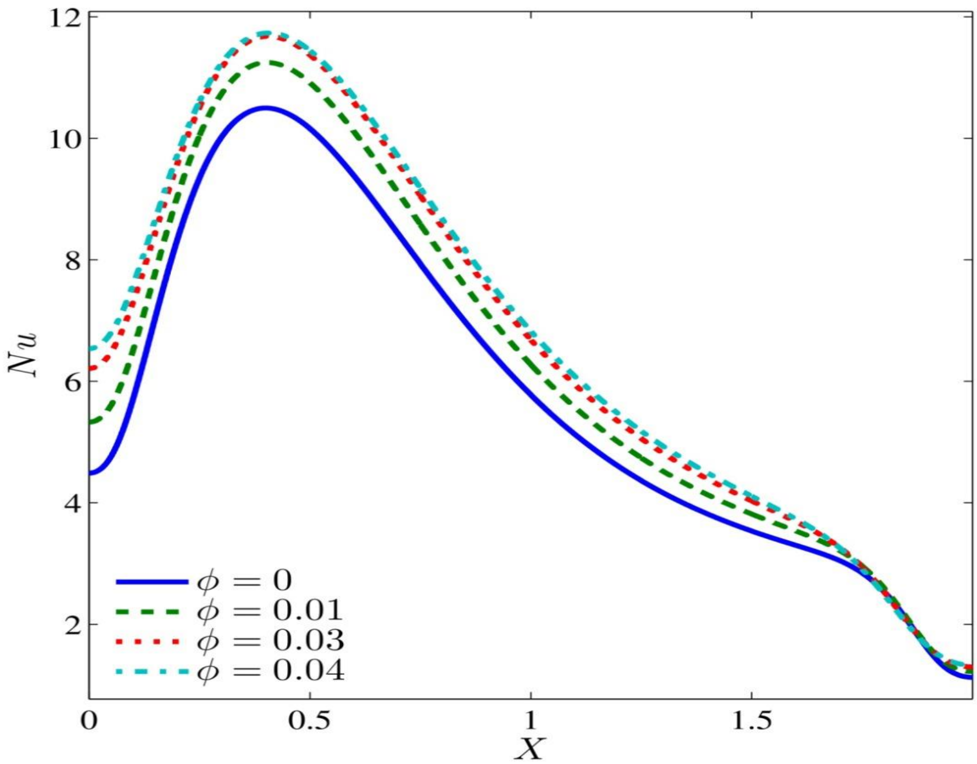


Fig. 7. Variations of the local Nusselt-number against X for different ϕ

6. Conclusions

The purpose of this study is to numerically study the mixed convection in a rectangle lid-driven cavity filled with hybrid nanofluid by employing the finite volume method. The walls on the left and right are fully isolated. The bottom horizontal wall is kept at a constant high temperature, while the top horizontal wall is kept at a stable low temperature and moves to the positive direction. The effects of Reynolds number Re and, solid volume fraction ϕ on the hybrid nanofluid flow and heat transfer behavior were discussed. The increase in the Reynolds number increases heat transfer. Heat transfer occurs higher in nanofluids in unlike pure water and is maximum in the case of Al_2O_3-Cu-Water hybrid nanofluids. The increase in the volume fraction increases the heat transfer.

Acknowledgement

This research was supported by Ministry of Higher Education Malaysia (MOHE) through Fundamental Research Grant Scheme (FRGS/1/2019/STG06/UTHM/01/1) Vot No. K197.

References

[1] Ali, Hafiz Muhammad, Hassan Ali, Hassan Liaquat, Hafiz Talha Bin Maqsood, and Malik Ahmed Nadir. "Experimental investigation of convective heat transfer augmentation for car radiator using ZnO–water nanofluids." *Energy* 84 (2015): 317-324. https://doi.org/10.1016/j.energy.2015.02.103

[2] Ali, Hafiz Muhammad, Adeel Arshad, Mark Jabbal, and Patrick G. Verdin. "Thermal management of electronics devices with PCMs filled pin-fin heat sinks: a comparison." *International Journal of Heat and Mass Transfer* 117 (2018): 1199-1204. https://doi.org/10.1016/j.ijheatmasstransfer.2017.10.065

[3] Ali, Hafiz Muhammad, Muhammad Mustafa Generous, Faseeh Ahmad, and Muhammad Irfan. "Experimental investigation of nucleate pool boiling heat transfer enhancement of TiO2-water based nanofluids." *Applied Thermal Engineering* 113 (2017): 1146-1151. https://doi.org/10.1016/j.applthermaleng.2016.11.127

[4] Alsabery, Ammar I., Ishak Hashim, Ahmad Hajjar, Mohammad Ghalambaz, Sohail Nadeem, and Mohsen Saffari Pour. "Entropy generation and natural convection flow of hybrid nanofluids in a partially divided wavy cavity including solid blocks." *Energies* 13, no. 11 (2020): 2942. https://doi.org/10.3390/en13112942

[5] Arshad, Adeel, Hafiz Muhammad Ali, Muzaffar Ali, and Shehryar Manzoor. "Thermal performance of phase change material (PCM) based pin-finned heat sinks for electronics devices: Effect of pin thickness and PCM volume fraction." *Applied Thermal Engineering* 112 (2017): 143-155. https://doi.org/10.1016/j.applthermaleng.2016.10.090

[6] Arshad, Adeel, Hafiz Muhammad Ali, Shahab Khushnood, and Mark Jabbal. "Experimental investigation of PCM based round pin-fin heat sinks for thermal management of electronics: effect of pin-fin diameter." *International Journal of Heat and Mass Transfer* 117 (2018): 861-872. https://doi.org/10.1016/j.ijheatmasstransfer.2017.10.008

[7] Arshad, Waqas, and Hafiz Muhammad Ali. "Graphene nanoplatelets nanofluids thermal and hydrodynamic performance on integral fin heat sink." *International Journal of Heat and Mass Transfer* 107 (2017): 995-1001. https://doi.org/10.1016/j.ijheatmasstransfer.2016.10.127

[8] Ashraf, Muhammad Junaid, Hafiz Muhammad Ali, Hazrat Usman, and Adeel Arshad. "Experimental passive electronics cooling: parametric investigation of pin-fin geometries and efficient phase change materials." *International Journal of Heat and Mass Transfer* 115 (2017): 251-263. https://doi.org/10.1016/j.ijheatmasstransfer.2017.07.114

[9] Azizul, Fatin M., Ammar I. Alsabery, and Ishak Hashim. "Heatlines visualisation of mixed convection flow in a wavy heated cavity filled with nanofluids and having an inner solid block." *International Journal of Mechanical Sciences* 175 (2020): 105529. https://doi.org/10.1016/j.ijmecsci.2020.105529

[10] Baby, Tessy Theres, and Ramaprabhu Sundara. "Synthesis and transport properties of metal oxide decorated graphene dispersed nanofluids." *The Journal of Physical Chemistry C* 115, no. 17 (2011): 8527-8533. https://doi.org/10.1021/jp200273g

[11] Stephen, J. A. E., and U. S. Choi. "Enhancing thermal conductivity of fluids with nanoparticles." *Developments and Applications of Non-Newtonian Flows* 231 (1995): 99-105.

[12] Cimpean, D. S., M. A. Sheremet, and I. Pop. "Mixed convection of hybrid nanofluid in a porous trapezoidal chamber." *International Communications in Heat and Mass Transfer* 116 (2020): 104627. https://doi.org/10.1016/j.icheatmasstransfer.2020.104627

[13] Corcione, Massimo. "Empirical correlating equations for predicting the effective thermal conductivity and dynamic viscosity of nanofluids." *Energy conversion and management* 52, no. 1 (2011): 789-793. https://doi.org/10.1016/j.enconman.2010.06.072

[14] Das, Pritam Kumar, Arnab Kumar Mallik, Ranjan Ganguly, and Apurba Kumar Santra. "Synthesis and characterization of TiO2–water nanofluids with different surfactants." *International Communications in Heat and Mass Transfer* 75 (2016): 341-348. https://doi.org/10.1016/j.icheatmasstransfer.2016.05.011

[15] Farbod, Mansoor, and Ameneh Ahangarpour. "Improved thermal conductivity of Ag decorated carbon nanotubes water based nanofluids." *Physics Letters A* 380, no. 48 (2016): 4044-4048. https://doi.org/10.1016/j.physleta.2016.10.014

[16] Ghalambaz, Mohammad, Ali Doostani, Ehsan Izadpanahi, and Ali J. Chamkha. "Conjugate natural convection flow of Ag–MgO/water hybrid nanofluid in a square cavity." *Journal of Thermal Analysis and Calorimetry* 139, no. 3 (2020): 2321-2336. https://doi.org/10.1007/s10973-019-08617-7

[17] Ghalambaz, Mohammad, S. A. M. Mehryan, Iman Zahmatkesh, and Ali Chamkha. "Free convection heat transfer analysis of a suspension of nano–encapsulated phase change materials (NEPCMs) in an inclined porous cavity." *International Journal of Thermal Sciences* 157 (2020): 106503. https://doi.org/10.1016/j.ijthermalsci.2020.106503

[18] Zadeh, Seyed Mohsen Hashem, S. A. M. Mehryan, Mohammad Ghalambaz, Maryam Ghodrat, John Young, and Ali Chamkha. "Hybrid thermal performance enhancement of a circular latent heat storage system by utilizing partially filled copper foam and Cu/GO nano-additives." *Energy* 213 (2020): 118761. https://doi.org/10.1016/j.energy.2020.118761

[19] Hashemi-Tilehnoee, M., A. S. Dogonchi, Seyyed Masoud Seyyedi, Ali J. Chamkha, and D. D. Ganji. "Magnetohydrodynamic natural convection and entropy generation analyses inside a nanofluid-filled incinerator-shaped porous cavity with wavy heater block." *Journal of Thermal Analysis and Calorimetry* (2020): 1-13. https://doi.org/10.1007/s10973-019-09220-6

[20] Esfe, Mohammad Hemmat, Ali Akbar Abbasian Arani, Mohammad Rezaie, Wei-Mon Yan, and Arash Karimipour. "Experimental determination of thermal conductivity and dynamic viscosity of Ag–MgO/water hybrid nanofluid." *International Communications in Heat and Mass Transfer* 66 (2015): 189-195. https://doi.org/10.1016/j.icheatmasstransfer.2015.06.003

[21] Ali, I. R., Ammar I. Alsabery, N. A. Bakar, and Rozaini Roslan. "Mixed Convection in a Double Lid-Driven Cavity Filled with Hybrid Nanofluid by Using Finite Volume Method." *Symmetry* 12, no. 12 (2020): 1977. https://doi.org/10.3390/sym12121977

[22] Alsabery, Ammar I., Muneer A. Ismael, Engin Gedik, Ali J. Chamkha, and Ishak Hashim. "Transient nanofluid flow

and energy dissipation from wavy surface using magnetic field and two rotating cylinders." *Computers & Mathematics with Applications* 97 (2021): 329-343. https://doi.org/10.1016/j.camwa.2021.05.030

[23] Ismael, Muneer A., Ioan Pop, and Ali J. Chamkha. "Mixed convection in a lid-driven square cavity with partial slip." *International Journal of Thermal Sciences* 82 (2014): 47-61. https://doi.org/10.1016/j.ijthermalsci.2014.03.007

[24] Jajja, Saad Ayub, Wajahat Ali, and Hafiz Muhammad Ali. "Multiwalled carbon nanotube nanofluid for thermal management of high heat generating computer processor." *Heat Transfer—Asian Research* 43, no. 7 (2014): 653-666. https://doi.org/10.1002/htj.21107

[25] Jena, P. K., E. A. Brocchi, and M. S. Motta. "In-situ formation of Cu–Al2O3 nano-scale composites by chemical routes and studies on their microstructures." *Materials Science and Engineering: A* 313, no. 1-2 (2001): 180-186. https://doi.org/10.1016/S0921-5093(00)01998-5

[26] Megatif, L., A. Ghozatloo, A. Arimi, and M. Shariati-Niasar. "Investigation of laminar convective heat transfer of a novel TiO2–carbon nanotube hybrid water-based nanofluid." *Experimental Heat Transfer* 29, no. 1 (2016): 124-138. https://doi.org/10.1080/08916152.2014.973974

[27] Mehryan, S. A. M., Kasra Ayoubi-Ayoubloo, Mohammad Shahabadi, Mohammad Ghalambaz, Pouyan Talebizadehsardari, and Ali Chamkha. "Conjugate phase change heat transfer in an inclined compound cavity partially filled with a porous medium: a deformed mesh approach." *Transport in Porous Media* 132, no. 3 (2020): 657-681. https://doi.org/10.1007/s11242-020-01407-y

[28] Menni, Younes, Ali J. Chamkha, Nicola Massarotti, Houari Ameur, Noureddine Kaid, and Mohammed Bensafi. "Hydrodynamic and thermal analysis of water, ethylene glycol and water-ethylene glycol as base fluids dispersed by aluminum oxide nano-sized solid particles." *International Journal of Numerical Methods for Heat & Fluid Flow* (2020). https://doi.org/10.1108/HFF-10-2019-0739

[29] Mintsa, Honorine Angue, Gilles Roy, Cong Tam Nguyen, and Dominique Doucet. "New temperature dependent thermal conductivity data for water-based nanofluids." *International journal of thermal sciences* 48, no. 2 (2009): 363-371. https://doi.org/10.1016/j.ijthermalsci.2008.03.009

[30] Mohebbi, Rasul, Mohsen Izadi, and Ali J. Chamkha. "Heat source location and natural convection in a C-shaped enclosure saturated by a nanofluid." *Physics of Fluids* 29, no. 12 (2017): 122009. https://doi.org/10.1063/1.4993866

[31] Dogonchi, A. S., M. K. Nayak, Nader Karimi, Ali J. Chamkha, and D. Domiri Ganji. "Numerical simulation of hydrothermal features of Cu-H2O nanofluid natural convection within a porous annulus considering diverse configurations of heater." *Journal of Thermal Analysis and Calorimetry* 141 (2020): 2109-2125. https://doi.org/10.1007/s10973-020-09419-y

[32] Nine, Md J., B. Munkhbayar, M. Sq Rahman, Hanshik Chung, and Hyomin Jeong. "Highly productive synthesis process of well dispersed Cu2O and Cu/Cu2O nanoparticles and its thermal characterization." *Materials Chemistry and Physics* 141, no. 2-3 (2013): 636-642. https://doi.org/10.1016/j.matchemphys.2013.05.032

[33] Rashad, A. M., Ali J. Chamkha, Muneer A. Ismael, and Taha Salah. "Magnetohydrodynamics natural convection in a triangular cavity filled with a Cu-Al2O3/water hybrid nanofluid with localized heating from below and internal heat generation." *Journal of Heat Transfer* 140, no. 7 (2018). https://doi.org/10.1115/1.4039213

[34] Patankar, Suhas V. "Numerical heat transfer and fluid flow(Book)." *Washington, DC, Hemisphere Publishing Corp., 1980. 210 p* (1980).

[35] Sadeghi, Hadi Mohammadjafari, Morsal Babayan, and Ali Chamkha. "Investigation of using multi-layer PCMs in the tubular heat exchanger with periodic heat transfer boundary condition." *International Journal of Heat and Mass Transfer* 147 (2020): 118970. https://doi.org/10.1016/j.ijheatmasstransfer.2019.118970

[36] Sajid, Muhammad Usman, and Hafiz Muhammad Ali. "Thermal conductivity of hybrid nanofluids: a critical review." *International Journal of Heat and Mass Transfer* 126 (2018): 211-234. https://doi.org/10.1016/j.ijheatmasstransfer.2018.05.021

[37] Wakif, Abderrahim, Ali Chamkha, Thirupathi Thumma, I. L. Animasaun, and Rachid Sehaqui. "Thermal radiation and surface roughness effects on the thermo-magneto-hydrodynamic stability of alumina–copper oxide hybrid nanofluids utilizing the generalized Buongiorno's nanofluid model." *Journal of Thermal Analysis & Calorimetry* 143, no. 2 (2021). https://doi.org/10.1007/s10973-020-09488-z

[38] Wei, Baojie, Changjun Zou, Xihang Yuan, and Xiaoke Li. "Thermo-physical property evaluation of diathermic oil based hybrid nanofluids for heat transfer applications." *International Journal of Heat and Mass Transfer* 107 (2017): 281-287. https://doi.org/10.1016/j.ijheatmasstransfer.2016.11.044

[39] Alsabery, A. I., H. T. Kadhim, M. A. Ismael, I. Hashim, and A. J. Chamkha. "Impacts of amplitude and heat source on natural convection of hybrid nanofluids into a wavy enclosure via heatline approach." *Waves in Random and Complex Media* (2021): 1-25. https://doi.org/10.1080/17455030.2021.1896819