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Effects of the nanoparticle shape on natural convection heat transfer in a square enclosure filled with Cu-H_2O nanofluid

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ABSTRACT

Heat is transferred by natural or forced convection in devices such as heat exchangers, which are frequently used in heating-cooling processes. One of the ways to passively increase heat transfer is to use nanofluid as the working fluid. In this study, natural convection heat transfer in a square enclosure having a hot vertical wall and a cold vertical wall was investigated numerically. The horizontal walls of the enclosure are perfectly insulated. The effects of the nanoparticle shape on natural convection heat transfer in a square enclosure filled with Newtonian Cu-H_2O nanofluid were investigated. In this study, different volume fractions of the spherical, cylindrical, and blade-shaped nanoparticles were examined. The numerical study was carried out in the range of Rayleigh number 10^4-10^6 and the nanoparticle volume fractions were taken as 0%, 2%, and 4%, respectively. The non-dimensional equations of the continuum, momentum, and energy are discretized by the SIMPLE (Semi Implicit Pressure Linked Equations) algorithm and solved by the finite volume method (FVM) in a Fortran code. As a result of the study, it was noted that nanoparticle volume fraction, Rayleigh number, as well as nanoparticle shape, increased heat transfer up to 19% compared to the base fluid.

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1. INTRODUCTION

Convection heat transfer is a type of heat transfer that is widely used in engineering and industrial applications. It is especially used in areas such as cooling of microprocessors in electronic devices, thermal insulation, heat exchangers, nuclear reactor design, solar energy systems, drying technologies, thermal comfort applications, and cooling of liquid metals in casting technology. Due to its simplicity, low cost, and structure, natural convection heat transfer can be used in all the above-mentioned applications.

To increase heat transfer from a heat source, active methods such as the use of fins, vibration of the heat transfer surface, and selection of materials with high thermal conductivity can be applied, as well as passive methods such as the selection of appropriate working fluid and flow type can be also applied. Instead of the traditional fluids used to increase the heat carried by a fluid, nanofluids are used in which certain amounts of nano-sized solid particles have been added. The heat transfer coefficients are increased with these fluids, which are composed of the base fluid and nanoscale particles, called nanofluid. However, if the solid nanoparticle ratio in the base fluid exceeds a certain volumetric mixture ratio, precipitation occurs in the base fluid, which brings undesirable results. While water, ethylene glycol, oil, glycerin, etc. liquids are generally used as the main fluid, copper (Cu), silver (Ag), aluminium (Al), aluminium oxide (Al_2O_3), titanium dioxide (TiO_2), carbon nanotubes (CNT), and boron nitride (BN) are used as nanoparticles in nanofluids.

Studies on nanofluids, which have become a common field of study in recent years, are increasing day by day. To examine the use of nanofluids in natural convection applications, it is first necessary to investigate the applications performed with conventional heat transfer fluids. Heat transfer by natural convection occurring in an air-filled square cavity heated from one vertical wall and cooled from another vertical wall was examined by de Vahl Davis [1]. Natural convection in a cubical enclosure heated differentially from its walls was explored by Fusegi et al. [2]. Barakos et al. [3] analyzed the laminar and turbulent natural convection in a square cavity using the finite control volume method. Markatos and Pericleous [4] investigated the laminar and turbulent natural convection within the square cavity at the Rayleigh number in the range of 10^3-10^6. Doostani et al. [5] examined the effects of the applied magnetic field on the melting characteristic and magnetohydrodynamic (MHD) natural convection for a square cavity filled with electrically conducted material. It was found that the increase in the Hartmann number slows down the melting process. It has also been found that the magnitude of the magnetic field plays an

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important role in controlling fluid flow. Raisi [6] investigated the effect of two obstacles of the same size mounted on the upper wall of the square cavity filled with power-law fluid on natural convection. In the study using the SIMPLE algorithm, he reported that heat transfer increased up to 283%. Various studies have been carried out to increase the thermal conduction properties of conventional fluids used in heat transfer applications. It was first observed by Choi and Eastman [7] that by adding metallic nanoparticles into the main fluid, significant increases in heat transfer occurred. After this research, studies on nanofluids created using different nanoparticles have increased rapidly. Khanafer et al. [8] numerically investigated the natural convection in a Cu-water-filled square cavity heated isothermally under four different models of the thermophysical properties of nanofluid. As a result of the study, a new correlation about heat transfer was developed based on the Grashof number and volumetric fraction of the nanoparticle. Buongiorno [9] analyzed seven different nanoparticle/fluid slip mechanisms and developed a new correlation for heat transfer in turbulent flow. Mahmoodi [10] examined the heat transfer and fluid flow in the L-shaped enclosure filled with Cu-H_20 nanofluid in different parameters such as nanoparticle volume fraction, Rayleigh number, and aspect ratio. As a result of the study, it was determined that heat transfer increased with decreasing aspect ratio. The natural convection problem for the water-based nanofluid containing SiO_2 nanoparticles was examined numerically by Kefayati et al. [11] by the Lattice Boltzmann method in different aspect ratios. It was found that heat transfer increased with both the increase in the volumetric fraction of nanoparticles and the increase in the aspect ratio. Ghasemi and Aminossadati [12] analyzed numerically the heat transfer behaviour of the square-enclosure filled with water-CuO nanofluid at different inclination angles according to the SIMPLE algorithm. It was found that at the angle of inclination of the enclosure up to 60°, the heat transfer increased with the Rayleigh number, and then began to decrease. Ghafouri and Salari [13] investigated the effect of eight different viscosity models on heat transfer by natural convection in a square cavity filled with water-CuO nanofluid. They found that the heat transfer as a result of experimental correlations was higher than the theoretical ones. Natural convection in a square cavity filled with Ag-water nanofluid that contains a horizontal or vertical heat source in the presence of a magnetic field applied from outside was studied numerically by Nithyadevi and Mahalakshmi [14]. As a result of the study, it was determined that heat transfer changes depending on the heater length and the size of the applied magnetic field. Besides, it was determined that the heat transfer increased by increasing the nanoparticle ratio in the fluid. Haddad et al. [15] discussed an extensive review paper on nanofluids. The empirical relations used to obtain different thermophysical properties of nanofluids such as viscosity and thermal conductivity coefficients were detailed. Also, a detailed summary of the previously studied geometry, nanofluid type, base fluid type, experimental or numerical methods, and obtained results were given in the study. Das et al. [16] examined in detail the studies involving heat transfer by natural convection occurring in cavities with different geometries that are not square. The studies carried out in the review article are divided into triangular, trapezoid, rhombus, and complex geometries, and the equations used are given in detail in case the cavity is filled with fluid or nanofluid or is a porous medium. Depending on the study, the effects of dimensionless numbers such as Rayleigh number, Prandtl number, and Darcy number, as well as parameters such as the nanoparticle type and the volumetric ratio in the base fluid were investigated. Wang and Mujumdar [17,18] prepared a review of theoretical and numerical studies with nano-particle-containing nanofluids and correlations that give heat transfer characteristics and experimental studies that give the characteristics of forced and natural convection of nanofluids, and their potential application areas. Heat transfer by natural convection occurring in the horizontal cylinder cavity heated from one end and cooled from the other end was studied experimentally by Putra et al. [19]. It was determined that there are deteriorations in heat transfer depending on the density of the particle, concentration, and aspect ratio of the cylinder. In the study conducted by Bairwa et al. [20], the general properties and application areas of nanofluids were examined and the problems encountered in nanofluids were mentioned. Heat transfer and entropy generation by natural convection in a square cavity, which is heated by the heat source of different dimensions from the left wall, and cooled from the opposite wall, was numerically solved by Bouchoucha and Bessaih [21] using the SIMPLER algorithm. It was found that as the rate of solid particles in the base fluid increases, heat transfer also increases, but the total entropy generation decreases. Mliki et al. [22] numerically analyzed the heat transfer by magneto-hydrodynamic (MHD) natural convection in a square cavity, filled with Cu-H_2O nanofluid, heated linearly from the left wall according to the Lattice-Boltzmann method (LBM). It was observed that the heat transfer increased with increasing Rayleigh number and decreased with increasing Hartmann number. Also, it has been determined that the increase in the volumetric ratio of nanoparticles increases heat transfer. Natural convection and fluid flow in a square cavity filled with Fe_3O_4-H_2O nanofluid were numerically investigated by Sheikholeslami and Vajravelu [23] when an external magnetic field was applied under a constant heat flux. It was determined that the thermal boundary layer thickness increased under the influence of increasing Lorentz forces. Belhaj and Ben-Beya [24] examined numerically the heat transfer and entropy generation in the presence and absence of an isothermal block in a square cavity filled with CNT-H_2O nanofluid. It was determined that heat transfer and entropy generation decreased with increasing Hartmann number. Another study in which theoretical and experimental studies on nanofluids were reviewed was conducted by Wang and Mujumdar [25]. In general, studies on heat transfer and fluid flow phenomena for natural and forced convection of nanofluids are examined. Natural convection in a square enclosure filled with Ag-H_2O nanofluid with a horizontal or vertical heat source placed in the centre was studied numerically by Mahalakshmi et al. [26]. As a result of the study, it was determined that the heat transfer increased due to the increase in the heater length and Rayleigh number. Natural convection heat transfer and entropy generation in a square cavity filled with non-Newtonian nanofluid were studied numerically by Kefayati for porous media [27] and the application of an external magnetic field [28]. It has been determined that the increase in nanoparticle volumetric ratio and Rayleigh number increases heat transfer. Ben-Cheikh et al. [29] numerically analyzed natural convection heat transfer in a cavity filled with water-based nanofluid containing Ag, Cu, Al_2O_3, or TiO_2 as nanoparticles for the sinusoidally changing bottom wall temperature. It was determined that heat transfer increases with increasing volumetric mixture ratio in all Rayleigh numbers. The change of natural convection heat transfer in the presence of a magnetic field effect in an inclined square cavity filled with nanofluid was explored by Al Kalbani et al. [30]. The critical geometry inclination angle, where the heat transfer is maximum, was found to depend on the nanoparticle volumetric mixture ratio and the direction of the magnetic field. Besides, it is concluded that the nanoparticle shape is an important parameter of heat transfer under the influence of the magnetic field. Turgut et al. [31] experimentally investigated the effect of particle size and volumetric mixing ratio on thermal conductivity and viscosity values for Al_2O_3-water nanofluid. It was determined that the thermal conductivity is not related to the particle size and is compatible with the Maxwell model. Also, it was concluded that the viscosity values increase in nanofluids with large particle sizes. Dogonchi et al. [32] scrutinized the effect of thermal radiation and magnetic field on flow and heat transfer in a porous wavy circular cylinder filled with CuO-water nanofluid. It was observed that the heat transfer increased with the use of platelet-shaped nanoparticles. In addition, it was also determined that Nusselt numbers reached higher values when the amplitude of the fluctuations was low. Thermal conductivity and viscosity values for nanofluid consisting of equal volumes of ethylene glycol and water with aluminium nanoparticles in different shapes were studied experimentally by Timofeeva et al [33]. As a result of the study, it was determined that the thermal conductivity and viscosity values of the nanofluid differ in non-spherical nanoparticles. Asmadi et all [34] numerically analyzed the effect of the shape of nanoparticles for hybrid nanofluid consisting of Cu and Al_2O_3 nanoparticles in a U-shaped enclosure. It is concluded that the blade shape of the nanoparticles has a maximum heat transfer rate. Effects of the SiO_2 nanoparticle shape on natural convection in a square cavity with two partitions mounted on its horizontal walls have been investigated numerically by Sheikhzadeh et all. [35].

As it can be noted from the studies in the literature, it has been observed that in nanofluids, parameters such as nanoparticle type and shape, volumetric mixing ratio, the inclination of the control volume, application of magnetic field at different angles have a significant effect on heat transfer. The number of studies investigating the effects of nanoparticle shape on flow and heat transfer is quite limited. In general, nanoparticles can be spherical, platelet, blade, cylindrical, and brick-shaped. In most theoretical studies, nanoparticles have been accepted as spherical shaped. In this study, the effects of nanoparticle shape (especially blade-shaped) on natural convection heat transfer and fluid flow were investigated for the square cavity filled with Cu-H_2O nanofluid. The solid nanoparticles in the nanofluid are assumed to be spherical, cylindrical, and blade-shaped, respectively.

2. THEORETICAL STUDY

The examined problem geometry and solid nanoparticle shapes are given in Figure 1 together with the boundary conditions. The length of the two-dimensional square-section cavity is indicated by L and the height of the cavity is indicated by H. Since the studied geometry is a square cross-section, the aspect ratio is taken as $L / H = 1$. The left vertical wall of the cavity is kept at a high temperature (T_h) and the right vertical wall is kept at a low temperature (T_c).

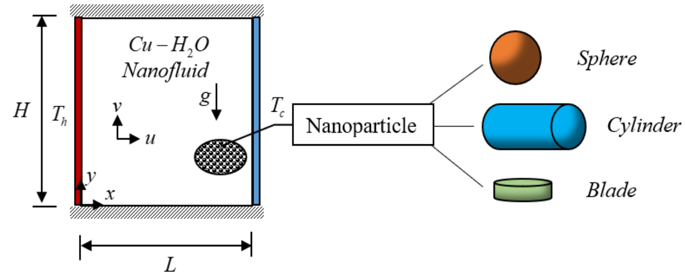


Fig. 1. The geometry of the present study and the shapes of nanoparticles.

The inside of the square cavity is filled with a water-based nanofluid (Cu-H_2O) containing copper (Cu) nanoparticles. The nanofluid is Newtonian has homogeneous properties all over the cavity and is considered incompressible. Thermophysical properties of the base fluid and solid nanoparticles, which are components of the nanofluid, are given in Table 1.

Table 1. Thermophysical properties of the base fluid and solid nanoparticle [29].

	Thermophysical properties			
Material	c_p (J/kgK)	ρ (kg/m3)	k (W/mK)	βx10-5 (1/K)
H_2O	4179	997.1	0.6	21
Cu	385	8933	401	1.67

The base fluid and nanoparticles are thermally equilibrium between each other, and all properties except the density of the nanofluid are independent of temperature and the Boussinesq approach is valid. The heat transfer by natural convection in the cavity is time-independent and laminar, and the radiation effects of the surfaces are neglected. Mass, momentum, and energy conservation Equations (1)-(4) according to the above approaches are given below in the nondimensional form:

$$\frac{\partial U}{\partial X}+\frac{\partial V}{\partial Y}=0 \tag{1}$$

$$U\frac{\partial U}{\partial X}+V\frac{\partial U}{\partial Y}=-\frac{\partial P}{\partial X}+Pr\frac{\nu_{nf}}{\nu_f}\left(\frac{\partial^2 U}{\partial X^2}+\frac{\partial^2 U}{\partial Y^2}\right) \tag{2}$$

$$U\frac{\partial V}{\partial X}+V\frac{\partial V}{\partial Y}=-\frac{\partial P}{\partial Y}+Pr\frac{\nu_{nf}}{\nu_f}\left(\frac{\partial^2 V}{\partial X^2}+\frac{\partial^2 V}{\partial Y^2}\right)+\frac{(\rho\beta)_{nf}}{\rho_{nf}\beta_f}Ra\,Pr\,\theta \tag{3}$$

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

Non-dimensional parameters are given according to the single-phase fluid approach as follows;

$$X = \frac{x}{L}, \quad Y = \frac{y}{L}, \quad U = \frac{uL}{\alpha_f}, \quad V = \frac{vL}{\alpha_f},$$
$$\theta = \frac{T - T_c}{T_h - T_c}, \quad P = \frac{pL^2}{\rho_{nf}\alpha_f{}^2} \tag{5}$$

The dimensionless numbers seen in Equation (2) and Equation (3) are Rayleigh numbers and Prandtl numbers, which are given below:

$$Ra = \frac{g\beta_f(T_h - T_c)L^3}{\nu_f \alpha_f}, \quad Pr = \frac{\nu_f}{\alpha_f} \tag{6}$$

The thermophysical properties of the nanofluid depending on the volumetric mixture ratio are as follows:

$$\rho_{nf} = (1-\phi)\rho_f + \phi\rho_p \tag{7}$$

$$(\rho c_p)_{nf} = (1-\phi)(\rho c_p)_f + \phi(\rho c_p)_p \tag{8}$$

$$(\rho\beta)_{nf} = (1-\phi)(\rho\beta)_f + \phi(\rho\beta)_p \tag{9}$$

The thermal conductivity (k_{nf}) of the nanofluid is obtained as follows according to the Hamilton model [36].

$$k_{nf} = k_f\left(\frac{k_p + (n-1)k_f - (n-1)\phi(k_f - k_p)}{k_p + (n-1)k_f + \phi(k_f - k_p)}\right) \tag{10}$$

The nanoparticle shape factor is represented by "n" in Equation 10 and takes the value 3 for spherical shape, 5.7 for platelet shape, 8.6 for blade shape, 4.9 for cylinder shape, and 3.7 for brick shape. When the nanoparticle shape factor is taken as 3 (spherical shape), Equation 10 turns into the Maxwell equation [37].

Dynamic viscosity (μ_{nf}) of the nanofluid is obtained according to the Brinkman model [38].

$$\mu_{nf} = \frac{\mu_f}{(1-\phi)^{2.5}} \tag{11}$$

Thermal diffusivity (α_{nf}) and kinematic viscosity (ν_{nf}) of the nanofluid as below;

$$\alpha_{nf} = \frac{k_{nf}}{(\rho c_p)_{nf}} \tag{12}$$
$$\nu_{nf} = \frac{\mu_{nf}}{\rho_{nf}} \tag{13}$$

The non-slip boundary condition is valid on all walls and the velocities (U, V) are zero on the wall surfaces. The boundary conditions for the problem geometry in Figure 1 are as follows:

θ=1 on the left wall at X=0
θ=0 on the right wall at X=L (14)
$\frac{\partial\theta}{\partial Y} = 0$ on the top wall and the bottom wall.

To determine the heat transfer from the heated left wall to the nanofluid, the local and average Nusselt numbers are calculated along the left wall, respectively, as follows:

$$Nu_h = -\left(\frac{k_{nf}}{k_f}\right)\frac{\partial\theta}{\partial X}\bigg|_{X=0} \quad \overline{Nu_h} = \frac{1}{H}\int_0^H Nu_h dY \tag{15}$$

Conservation equations obtained in Equations (1) to (4) in cartesian coordinates are written as follows, according to the SIMPLE (Semi Implicit Pressure Linked Equations) algorithm given by Patankar [39]:

$$\frac{\partial}{\partial X_j}(\rho U_j \varphi) = \frac{\partial}{\partial X_j}\left(\Gamma\frac{\partial\varphi}{\partial X_j}\right) + S \tag{16}$$

In the above expressions, φ, Γ, and S are the dependent variable, diffusion coefficient, and source term, respectively. These variables are given in Table 2.

Table 2. Coefficients of discretized equations.

φ	Γ	S
U	$Pr\frac{\nu_{nf}}{\nu_f}$	$-\frac{\partial P}{\partial X}$
V	$Pr\frac{\nu_{nf}}{\nu_f}$	$-\frac{\partial P}{\partial Y} + \frac{(\rho\beta)_{nf}}{\rho_{nf}\beta_f} Ra\, Pr\, \theta$
θ	$\frac{\alpha_{nf}}{\alpha_f}$	0

Algebraic equations used in calculations are obtained by the finite control volume method. Accordingly, the discrete algebraic form of Eq.16 is as follows:

$$a_P\varphi_P = a_E\varphi_E + a_W\varphi_W + a_N\varphi_N + a_S\varphi_S + b \tag{17}$$

The convergence criteria (ξ) in the study is 10^{-7} and given below:

$$\left|\frac{\xi_{i,j}^{m+1} - \xi_{i,j}^{m}}{\xi_{i,j}^{m}}\right| \le 10^{-7} \tag{18}$$

In the above equation, ξ represents a general dependent variable (U, V, θ), while m represents the number of iterations. A FORTRAN code has been developed to solve discrete equations. The boundary conditions for the solution are also the dimensionless boundary condition; θ=0 for the cold right wall and θ=1 for the hot left wall. Cu-H_2O nanofluid was used as the working fluid in the cavity and the Prandtl number was taken as 6.2 for nanofluid. Solutions for a square cavity at 10x10, 30x30, 60x60, 90x90, 120x120, and 150x150 staggered grids have been made and the average Nusselt numbers obtained at Rayleigh number Ra=10^5 are given in Table 3. Since it is seen that there are less than 0.5% changes in the results after a 90 x 90 uniform mesh structure, 90 x 90 uniform mesh structure is used in all solutions.

Table 3. Variation of average Nusselt number depending on grid sensitivity for Ra=10^5.

Grid size (n x n)	10x10	30x30	60x60	90x90	120x120	150x150
Nusselt number	5.643	4.900	4.687	4.642	4.624	4.615

To show the accuracy of the study, a comparison was made with the studies in the literature [29] for the square cavity filled with Cu-H_2O nanofluid, sinusoidally heated bottom wall, and uniformly cooled the other walls. It is seen in Figure 2 that the obtained results in different Rayleigh numbers are largely similar to those in the literature [29].

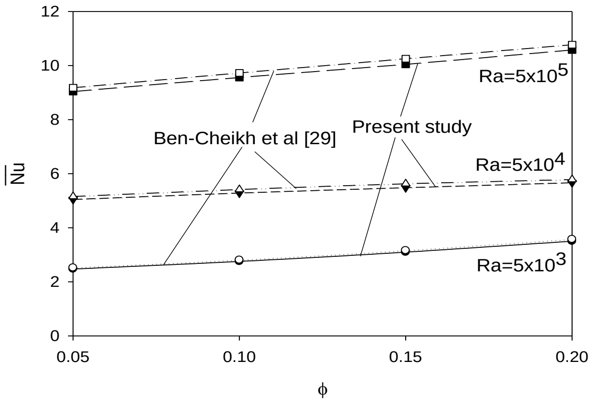


Fig. 2. Comparison of average Nusselt numbers in different Rayleigh numbers.

3. RESULTS AND DISCUSSION

In this study, natural convection heat transfer and fluid flow parameters in a square cavity filled with Cu-H_2O nanofluid when differentially heated vertical walls, while horizontal walls are insulated have been numerically examined. The effect of the fact that the solid nanoparticles' shapes in the form of a sphere (n = 3), cylinder (n = 4.9), and blade (n = 8.6), respectively, on heat transfer and flow parameters were examined at different Rayleigh numbers in the range of 10^4-10^6. The volumetric fraction of solid nanoparticles (ϕ) in the base fluid varies between $0 \leq \phi \leq 4$ %. The Prandtl number is taken as 6.2 for water-based nanofluid. Depending on the nanoparticle shape and volumetric fraction, isotherms and streamlines in the cavity, temperature and velocity profiles along the middle axis of the square cavity, and the local and average Nusselt numbers at the heated vertical wall are given in Figure 3-10. Streamline and isotherm curves for spherical nanoparticles in different Rayleigh numbers and solid nanoparticle volumetric fractions are given in Figure 3. As it can be seen from the figure, the streamlines formed around the centre of the cavity at low Rayleigh numbers then expand horizontally around the centre of the cavity with the increase in Rayleigh number and volumetric mixture ratio and its intensity increases by 7%. If the change in the isotherm curves is examined, it is seen that there is an inverse diagonal change and as the volumetric mixture ratio increases, the isotherm curves start to move away from the differentially heated vertical walls. Besides, with the increase in Rayleigh number, it was determined that the isotherm curves became more frequent in the regions close to the vertical walls and there were constant temperature curves at a certain value horizontally around the center of the cavity.

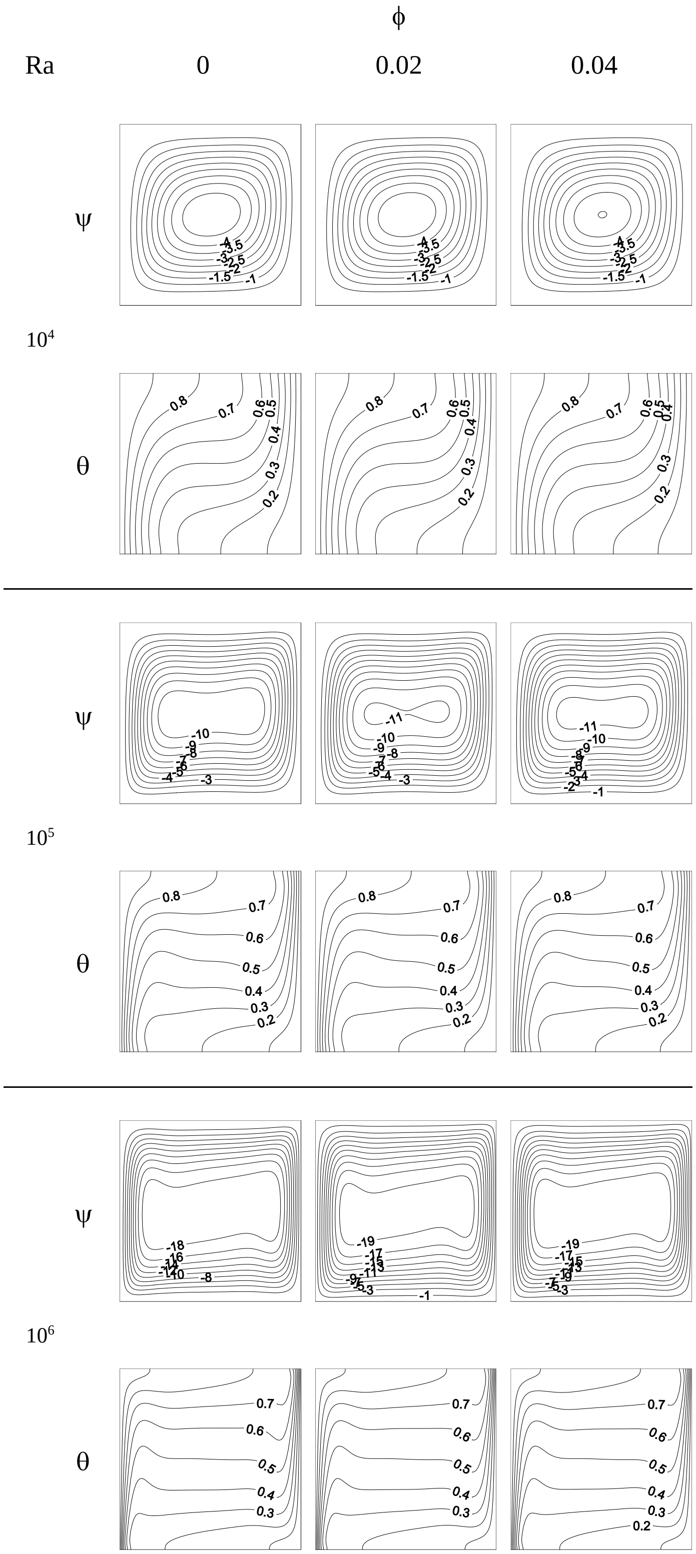


Fig. 3. Streamlines (ψ) and isotherms (θ) for spherical nanoparticle shape at different nanoparticle volumetric fractions.

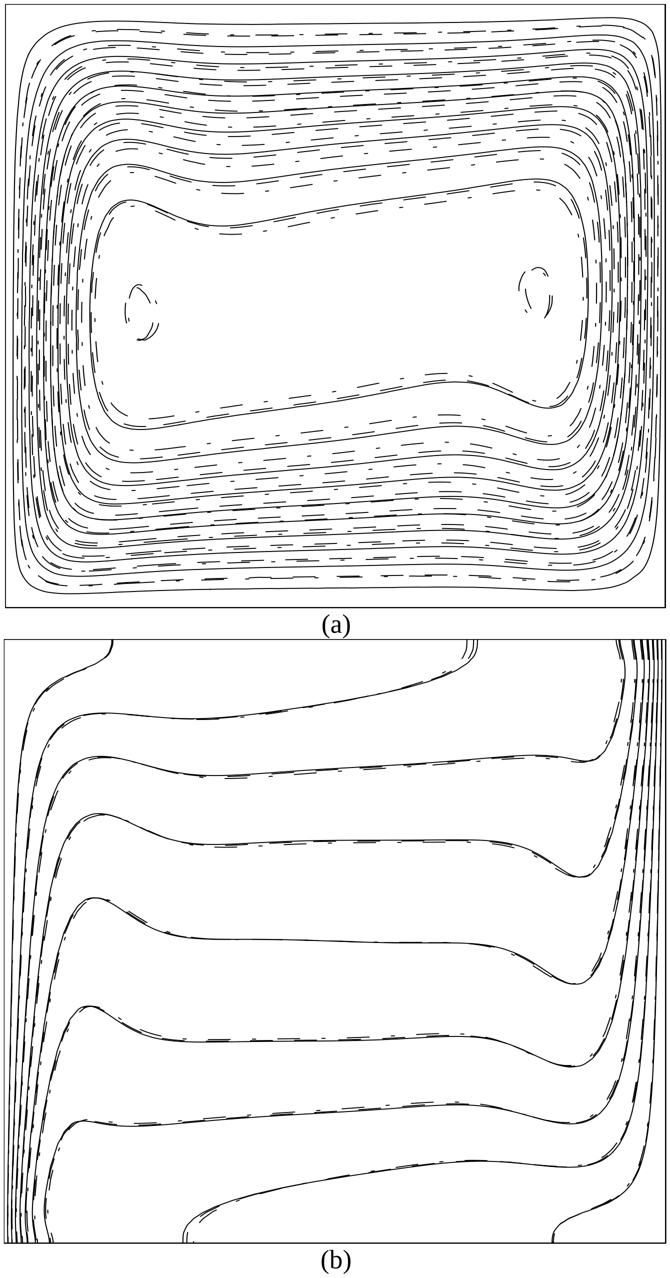
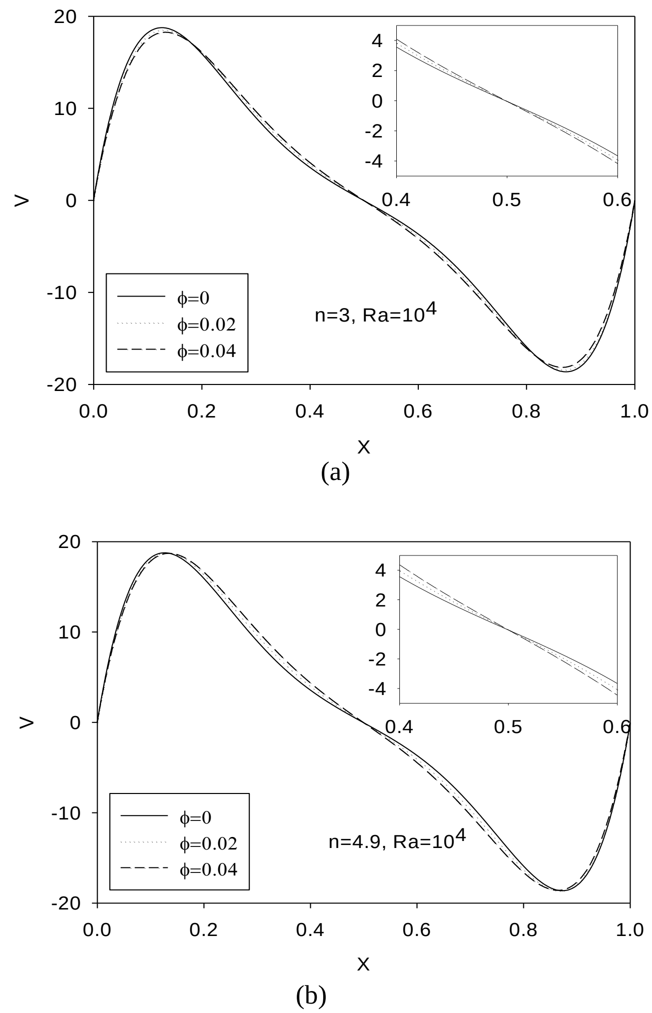
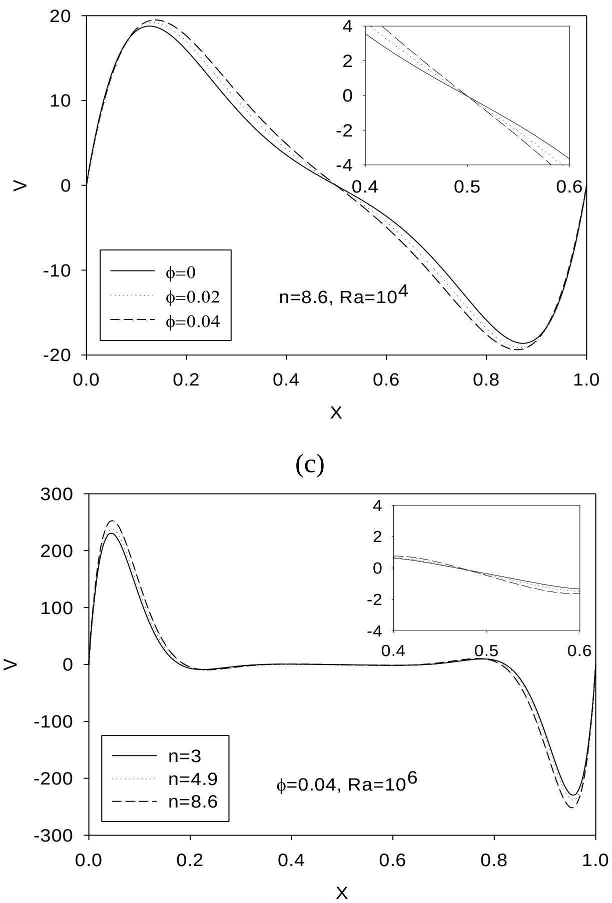


Fig. 4. Streamlines, (a) and isotherms, (b) for different shapes of nanoparticles at ϕ=0.04, Ra=10^6 (— n=3, - -n=4.9, –·– n=8.6).

The changes of isotherm and streamline curves at a fixed Rayleigh number (Ra = 10^6) and volumetric mixture ratio (ϕ = 0.04) depending on the nanoparticle shape are given in Figure 4. It was determined that streamlines shift towards the center of the closed environment for blade-shaped nanoparticles. In the isotherm curves, there is no significant change in the regions close to the vertical walls, but it is seen that the nanoparticle shape significantly changes the isotherm curves in the inner regions.

The change of the vertical velocity profile (*V*) along the central axis of the cavity at *Y=0.5* is given in Figure 5. It was observed that the vertical velocity increased with the increase of the nanoparticle shape factor (*n*) and the volumetric fraction of solid nanoparticles as shown in Figure 5(a, b, c). Maximum vertical velocity values occur at *X = 0.13* while the minimum velocity values occur at *X = 0.87* for Rayleigh number Ra=10^4. Compared to the base fluid, the biggest difference occurs locally in blade-shaped nanoparticles (*n = 8.6*) and at the volumetric mixture ratio of 0.04 as given in Figure 5(d). Also, with the increase of Rayleigh number, it is seen that the amplitudes of the velocity profiles increase and the flow accelerates. The maximum and minimum values of the vertical velocities approach the vertical walls with the increase of the Rayleigh number. In the high Rayleigh numbers, it was obtained that the speed profile remained nearly constant as in Figure 5(d) between *X = 0.2* and *0.8*. In all velocity profiles, under the effect of the buoyancy force due to natural convection, an upward velocity profile is formed in the neighbourhood of the hot left wall, while a downward velocity profile is formed in the region close to the cold right wall.



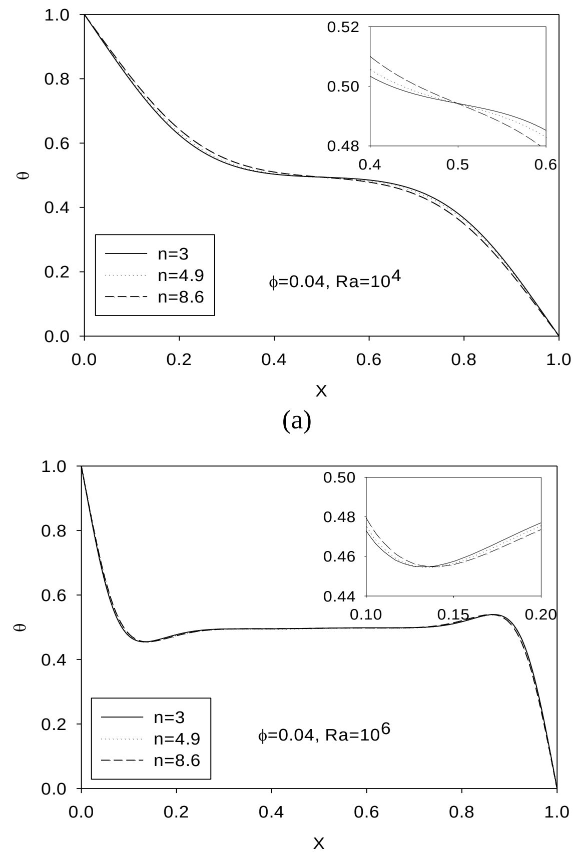


(d)

Fig. 5. Horizontal velocity profile at Y=0.5 depending on different values of volumetric fraction and nanoparticle shape, (a) n=3, Ra=10^4, (b) n=4.9, Ra=10^4 ,(c) n=8.6, Ra=10^4, (d) ϕ=0.04, Ra=10^6.

The change of the temperature profile (θ) along the central axis of the cavity at $Y=0.5$ is given in Figure 6. With the increase of the nanoparticle shape factor, there is a slight increase in the dimensionless temperature values locally. In low Rayleigh numbers, the temperature continuously changes depending on the dimensionless length as in Figure 6(a), while in high Rayleigh numbers, it remains approximately constant between $X = 0.25$ and 0.75 as in Figure 6(b). It is observed that there are sudden changes in the temperatures in the regions close to the hot and cold walls due to the effect of increasing buoyancy forces due to the increasing Rayleigh number.

Local Nusselt numbers in different volumetric fractions of blade-shaped nanoparticles are given in Figure 7. When the local Nusselt numbers were examined, it was observed that there were local increases in heat transfer with the increase of the nanoparticle volumetric mixture ratio in the areas near the wall, where the velocity and temperature values changed vertically. The heat transfer rises first in the lower parts of the wall due to the fluid flow through the hot left wall and then decreases depending on the boundary layer in the cavity.



(b)

Fig. 6. Variation of the temperature profile at Y=0.5. (a) ϕ=0.04, Ra=10^4, (b) ϕ=0.04, Ra=10^6.

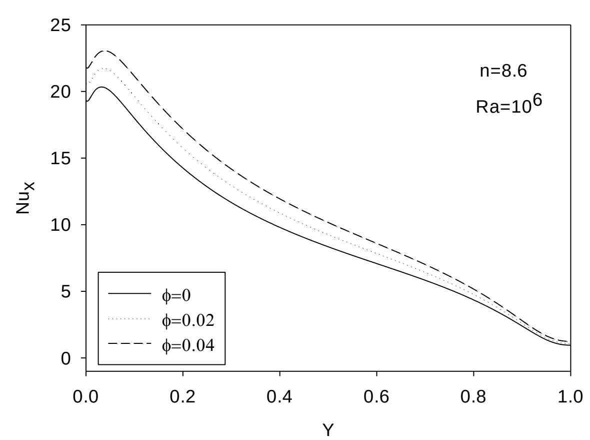
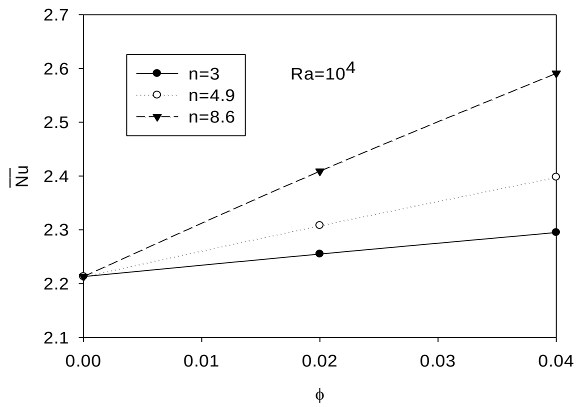
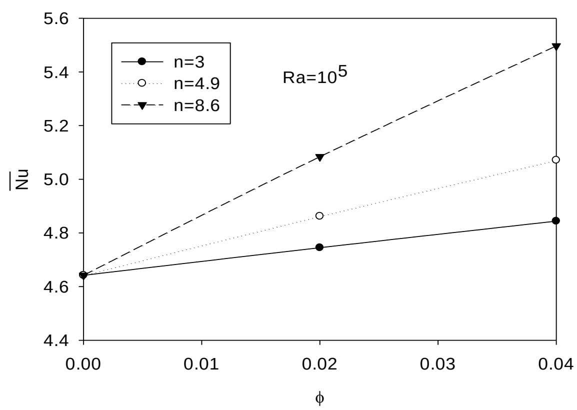


Fig. 7. Local Nusselt numbers in the use of blade-shaped nanoparticles (n=8.6, Ra=10^6).

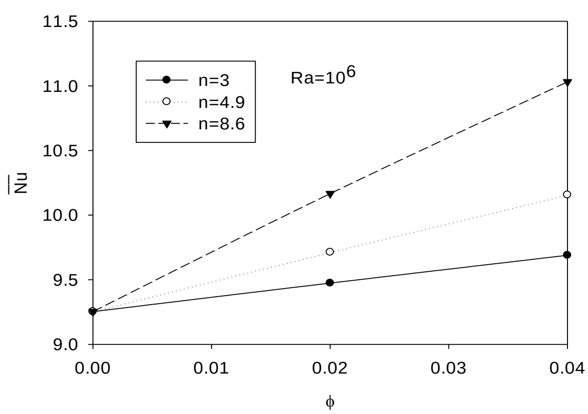
The average Nusselt numbers in different volumetric fractions (0, 0.02, 0.04) and different Rayleigh numbers (10^4, 10^5, and 10^6) are shown in Figure 8. The increase in the volumetric fraction increases the heat transfer less if the nanoparticle shape is spherical ($n = 3$), whereas the most increase is obtained when the nanoparticle shape is selected as the blade ($n = 8.6$). If the nanoparticle shape is selected as a cylinder ($n = 4.9$), the increase in heat transfer remains between those obtained for two nanoparticle shapes. In all Rayleigh numbers, the highest heat transfer was obtained when the nanoparticle shape was selected as the blade ($n = 8.6$). The lowest heat transfer was obtained when the nanoparticle shape was chosen spherical ($n = 3$). When the volumetric fractions were examined, the highest heat transfer was obtained at $\phi = 0.04$. The increase in the volumetric fraction also increases the heat transfer for all Rayleigh numbers and nanoparticle shapes.



(a)



(b)



(c)

Fig.8. Average Nusselt numbers in the use of different-shaped nanoparticles for different volume fractions and Rayleigh numbers. (a) Ra=10^4, (b) Ra=10^5, (c) Ra=10^6.

The variation of the average Nusselt number with the Rayleigh number depending on the nanoparticle shape at a fixed volumetric fraction is given in Figure 9. It was observed that the heat transfer increased with increasing Rayleigh number for a fixed volumetric fraction ($\phi=0.04$), but this increase was more pronounced in high Rayleigh numbers. It has been determined that the nanoparticle shape factor increases the heat transfer in low Rayleigh numbers albeit at a low rate.

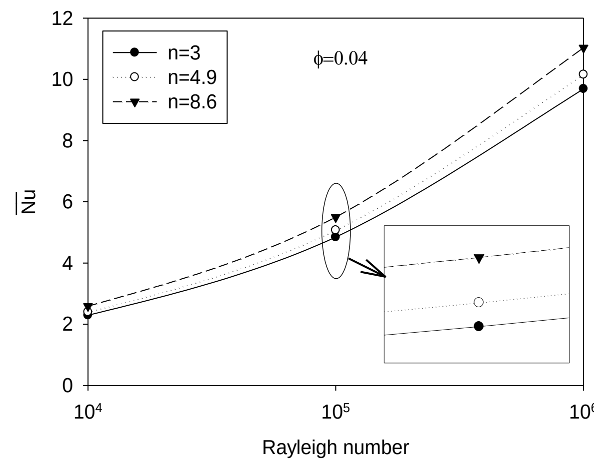


Fig. 9. Average Nusselt numbers in the use of different-shaped nanoparticles at a fixed volumetric fraction (ϕ=0.04).

The variations of the average Nusselt numbers depending on the Rayleigh number in different volumetric fractions for the spherical nanoparticle shape are given in Figure 10. It has been observed that the heat transfer increased slightly with the increase in the volumetric fraction of nanoparticles at a fixed Rayleigh number. It was also determined that as the Rayleigh number increases for a constant volumetric fraction, the heat transfer from the left wall to the nanofluid increases.

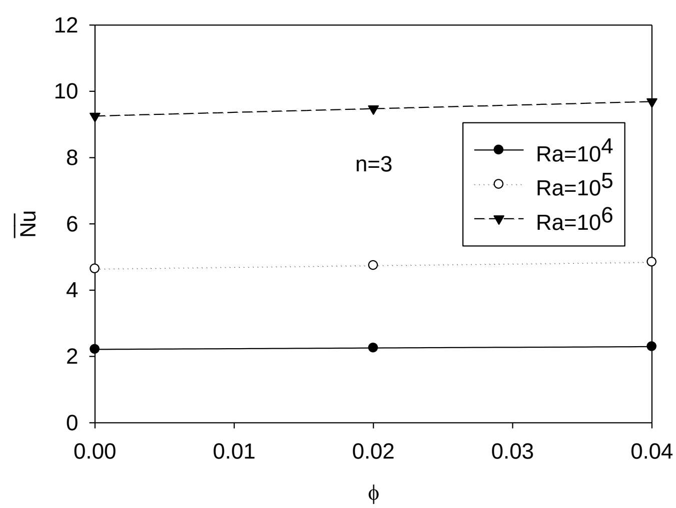


Fig. 10. Average Nusselt numbers in the use of spherical shapes (n=3) for different volume fractions and Rayleigh numbers.

Table 4. Average Nusselt numbers and relative changes depending on different parameters.

Ra	ϕ=0	n=3 (Spherical)				n=4.9 (Cylindrical)				n=8.6 (Blade)			
		ϕ=0.02	%	ϕ=0.04	%	ϕ=0.02	%	ϕ=0.04	%	ϕ=0.02	%	ϕ=0.04	%
10^4	2.213	2.255	1.898	2.295	3.705	2.308	4.293	2.398	8.360	2.409	8.857	2.591	17.081
10^5	4.642	4.745	2.219	4.844	4.352	4.862	4.739	5.071	9.242	5.084	9.522	5.497	18.419
10^6	9.253	9.474	2.388	9.689	4.712	9.713	4.971	10.156	9.759	10.166	9.867	11.031	19.215

The average Nusselt numbers and their relative changes as a result of using water (H_2O) as the base fluid and adding copper (Cu) nanoparticles into the water at different volumetric fractions are given in Table 4. As it can be noted from the table, the lowest heat transfer values are obtained when the volumetric fraction of nanoparticles is 0 (base fluid). It has been observed that there are improvements in heat transfer with nanofluid having different nanoparticle shapes. The greatest increase in heat transfer occurred when the blade-shaped nanoparticles were added to the base fluid (H_2O) at a volumetric fraction of 0.04%. The least increase in heat transfer was achieved when the spherical-shaped nanoparticles were added to the base fluid at a volumetric fraction of 0.02%.

While the heat transfer in spherical-shaped nanoparticles increases up to a maximum of 4.7%, this rate reaches up to 9.8% in cylindrical-shaped nanoparticles and 19.2% in blade-shaped nanoparticles. For this reason, it is recommended to use blade-shaped nanoparticles and to select a high volumetric fraction to increase heat transfer with natural convection in a water-based Cu-H_2O nanofluid. However, it is recommended to conduct experimental studies to observe the heat transfer losses that occur due to precipitation seen in high volumetric mixture ratios in nanofluids.

4. CONCLUSION

Heat transfer and fluid flow were numerically investigated when a square cavity whose left wall was kept at a high temperature and the right wall at a low temperature was filled with Cu-H_2O nanofluid. The effects of three different volumetric fractions of solid nanoparticles (ϕ=0, 0.02, and 0.04) three different Rayleigh numbers (Ra=10^4, 10^5, and 10^6) and three different nanoparticle shapes (spherical, cylindrical, and blade-shaped) on natural convection heat transfer and fluid flow were investigated.

In light of the findings obtained, the following conclusions were reached:

1. The nanoparticle shapes the volumetric fraction of nanoparticles in the base fluid, and the Rayleigh number significantly affects the heat transfer.
2. The heat transfer from the hot wall to the nanofluid increases with the increase of both Rayleigh number, volumetric fraction, and nanoparticle shape factor. The increase of the Rayleigh number significantly increases the heat transfer compared to the other examined parameters.
3. The change of the nanoparticle shape does not affect the isotherm curves and streamlines much.
4. The lowest increase in heat transfer was observed in low Rayleigh numbers (Ra=10^4) and a volumetric fraction (ϕ=0.02) of 1.9%. The greatest increase in heat transfer was determined by 19.2% in the use of blade-shaped nanoparticles (n = 8.6).

As a result, it was found that both the nanoparticle shape factor and the nanoparticle volumetric fraction and Rayleigh number should be selected high to increase the heat transfer by natural convection in a square cross-sectional cavity. Only by changing these parameters, the heat transferred from the hot surface to the nanofluid can be increased by 19.2%. The maximum value of the volumetric fraction at which precipitation and agglomeration will not occur in the nanofluid can be determined by experimental studies, and thus how much the heat transfer will increase can be predicted. Thus, in industrial areas where there is solid surface-fluid contact, especially in heat exchangers, larger amounts of heat can be transferred with nanofluids.

Nomenclature

a	coefficient of discretization equation
b	constant term in discrete equation
c_p	specific heat (J/kg.K)
g	gravitational acceleration (m/s²)
H	height of the cavity (m)
k	thermal conductivity (W/m.K)
L	length of the cavity (m)
n	nanoparticle shape factor
p, P	pressure, dimensionless pressure
Pr	Prandtl number, ν_f/α_f
Ra	Rayleigh number, $g\beta_f(T_h - T_c)L^3/\nu_f.\alpha_f$
S	source term
T	temperature
u, v	components of velocity (m/s)
U, V	dimensionless velocity components
x, y	Cartesian coordinates
X, Y	dimensionless coordinates

Greek Letters

α	thermal diffusivity
β	thermal expansion coefficient (1/K)
ϕ	nanoparticle volume fraction
φ	dependent variable
ψ	stream function
μ	dynamic viscosity (N.s/m^2)
ν	kinematic viscosity (m^2/s)
ρ	density (kg/m^3)
Γ	diffusion coefficient
θ	dimensionless temperature
ξ	convergence criteria

Subscripts

c cold
f base fluid
h hot
l local
nf nanofluid
p nanoparticle

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