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Free Convection Heat Transfer of Alumina-Water Nanofluid in an Enclosure: Assessment of Viscosity and Conductivity Models

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ABSTRACT

In this paper, the free convection heat transfer of Al_2O_3-Water nanofluid in a square cavity is simulated, employing the finite volume technique. The homogeneous model is utilized to determine the influence of nanoparticles. The obtained results are compared with the experiment. At higher Rayleigh numbers, higher agreement between the results is observed. The nanofluid average Nusselt number increases with the Rayleigh number. For a concentration of 0.1%, the average Nusselt number increases, and for higher concentrations, it decreases, as compared with the pure fluid. Different viscosity and conductivity models were evaluated. It was found that the viscosity correlation, which takes into account the Brownian motion effect, produces more accurate results. The results obtained using different conductivity correlations were almost the same.

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1. INTRODUCTION

Nowadays, fluids play an important role in heating and cooling systems. Having working fluids with higher heat transfer capacities is of great importance. Adding appropriate nanoparticles to heat transfer fluids usually enhances their heat conductivity coefficient and, consequently the heat transfer rate. The heat conductivity enhancement is a great advantage; However, for the purpose of evaluating the cooling capacity of nanofluids, their performance under convective heat transfer conditions must be considered.

Numerous studies have been carried out into the influence of nanofluids on free convective heat transfer. To model the influence of nanoparticles, researchers often adopt the single-phase approach in which the nanofluid is supposed to be homogenous. The physical properties are determined, using the nanoparticles and base fluid properties. This model is straightforward. However, it fails to consider some physical aspects of the nanofluid flow. Hence, sometimes there are considerable discrepancies between numerical and experimental results.

Wen et al. [1] investigated the free convection of nanofluids under different conditions numerically and concluded that convection heat transfer coefficient reduces with nanoparticle concentration, especially at lower Rayleigh numbers. Phelan et al. [2] reported that only if nanoparticles are dispersed well throughout the bulk fluid, the thermal conduction coefficient of nanofluids enhances. They also found that the aggregation of nanoparticles in a region has an adverse effect on thermal conduction coefficient. Nanna et al. [3] focused on the influence of the concentration of nanoparticles on the free convection process in a cavity. They noticed an increase in Nusselt number for concentrations less than 0.2%. However, at higher concentrations, the average Nusselt number did not necessarily increase [3, 4]. Peterson et al. [5] reported that the enhancement of nanoparticles reinforces the Brownian and thermophoresis effects. This postpones the initiation of free convection flow, smoothes the temperature field, and consequently reduces the heat transfer coefficient. Abu-Nada et al. [6] experimentally studied the natural convection of Al_2O_3-Water and concluded that at lower and higher Rayleigh numbers, the Nusselt number increases and decreases with volume fraction, respectively. Ho et al. [7] carried out an experiment to study the same problem and reported that the heat transfer coefficient is affected by both concentration and size of nanoparticles. Yang et al. [8] simulated the Alumina-Water flow in an enclosure by utilizing the lattice-Boltzmann technique. They considered the influence of Rayleigh number and volume fraction on this phenomenon.

Wang et al. [9] carried out a study into magnetic nanofluids and observed that for smaller nanoparticles, higher thermal conduction coefficient is achieved for nanofluids. Hu et al. [10] both numerically and experimentally investigated the nanofluid free convection in a cavity. In comparison with water, for concentrations of 1%, 2%, and 3%, the nanofluid heat transfer rate was higher, remained almost unchanged, and was lower, respectively. Hassani et al. [11] presented a correlation for the calculation of nanofluid conduction coefficient based on dimensional analysis. They showed that increasing the volume fraction, decreasing the size of nanoparticles, and raising the temperature increase the thermal conductivity of nanofluids. Qi et al. [12] reported that decreases in the particle diameter increase the Nusselt number. In addition, they found higher thermal efficiency in enclosures with smaller sizes. Saber et al. [13] studied the free convection of nanofluids in an inclined cavity by utilizing a two-phase model. They showed that at low Rayleigh numbers, the inclination angle has no remarkable influence on the Nusselt number. However, at high Rayleigh numbers, the Nusselt number first increases and then decreases with the inclination angle. Solomon et al. [14] investigated the influence of the ratio of cavity dimensions on heat transfer and observed that the heat transfer rate increases as the ratio of cavity dimensions decreases. Wang et al. [15] investigated the nanofluid heat transfer in a shear flow by adopting the Boltzmann approach and reported that the higher temperature gradient in the vicinity of the nanoparticles enhances the convective heat transfer rate. Karimpour [16] studied the natural convection along with the radiation through nanofluids. He observed that increasing the concentration increases the natural convection heat transfer but decreases the radiation heat transfer.

Sheikholelsami et al. [17] considered the free convection flow of magnetic nanofluids and found that the Nusselt number enhances with nanoparticle's volume fraction and Rayleigh number. Pordanjani et al. [18] investigated the influence of two isothermal obstacles on nanofluid free convection under a magnetic field. In this case, the Nusselt number enhances by an increase in volume fraction and Rayleigh number. However, the Nusselt number decreases with the dimension ratio. Pordanjani et al. [19] studied the free convection heat transfer under magnetic field and thermal radiation and observed that adding nanoparticles to the bulk fluid reduces the heat transfer rate. Manjunatha et al. [20] focused on hybrid nanofluids and, in all cases, found an enhanced heat transfer rate in comparison with regular nanofluids. Etesami et al. [21] studied free convection of SiO_2-Water nanofluids in an inclined cavity. They reported that at low concentrations, heat transfer rate remains almost unchanged. However, at concentrations greater than 0.5%, the heat transfer rate reduces with concentration. Baïri and Laraqi [22] experimentally studied Cu-Water nanofluid free convection in a hemispherical enclosure and found that the cooling effectiveness decreases with the nanofluid age. Giwa et al. [23] investigated free convection heat transfer of Al_2O_3-MWCNT/Water hybrid nanofluids in an enclosure and found that the Nusselt number enhances with concentration of nanoparticles.

The literature review suggests that numerous studies have been carried out into the nanofluid natural convection in cavities, using the homogeneous approach. Besides, many correlations have been proposed for the calculation of nanofluid viscosity and thermal conduction coefficients. However, to the best of the current authors' knowledge, there has been no comprehensive study evaluating the performance of these correlations in the natural convection heat transfer process. In this study, the natural convection heat transfer of Al_2O_3-Water in a square enclosure is simulated, and different viscosity and conductivity correlations are evaluated.

2. GOVERNING EQUATIONS

2.1. Flow and Temperature Equations

In this paper, the single-phase approach is employed for nanofluid modeling. It is assumed that nanoparticles are dispersed uniformly throughout the base fluid. There is no slip and temperature difference between nanoparticles and bulk fluid. The nanofluid is considered a homogenous single-phase fluid. Assuming the Newtonian behavior, the steady-state and incompressible flow and temperature equations are expressed as follows [24]:

$$\nabla.\overrightarrow{V} = 0 \tag{1}$$

$$\rho_{nf}\left(\vec{V}\cdot\nabla\right)\vec{V} = -\nabla P + \mu_{nf}\nabla^2\vec{V} + \rho_{nf}\beta_{nf}\,\vec{g}\left(T - T_c\right) \tag{2}$$

$$\rho_{nf}C_{p,nf}\left(\vec{V}\cdot\nabla\right)T = k_{nf}\nabla^2 T \tag{3}$$

In these equations, $\vec{V}$, *P*, *T*, $\vec{g}$ are velocity vector, pressure, temperature, and gravity vector, respectively. ρ_{nf} , μ_{nf} , k_{nf} , $C_{p,nf}$ and β_{nf} are density, viscosity, conductivity, specific heat, and thermal expansion coefficient of nanofluid, respectively.

2.2. Thermo-physical Properties of Nanofluid

As pointed out above, in this study, nanofluid is considered as a single-phase fluid, and its properties are modified based on the thermo-physical properties of bulk fluid and nanoparticles. Density, specific heat, and volumetric expansion coefficient are computed by the following equations [25, 26]:

$$\rho_{nf} = (1-\phi)\rho_f + \phi\rho_{np} \tag{4}$$

$$(\rho C_p)_{nf} = (1-\phi)(\rho C_p)_f + \phi(\rho C_p)_{np} \tag{5}$$

where ϕ represents the volume fraction of nanoparticles, and subscripts *f* and *np* refer to bulk fluid and nanoparticles. The thermal expansion coefficient of nanofluid is also computed as [20]:

$$(\rho\beta)_{nf} = (1-\phi)(\rho\beta)_f + \phi(\rho\beta)_{np} \tag{6}$$

Conductivity coefficient and viscosity are computed based on the experimental correlations presented by Ho et al. [7] for Al_2O_3-Water nanofluid:

$$\frac{k_{nf}}{k_f} = 1 + 2.944\phi + 19.672\phi^2 \tag{7}$$

$$\frac{\mu_{nf}}{\mu_f} = 1 + 4.93\phi + 222.4\phi^2 \tag{8}$$

There are other relations for the computation of nanofluid viscosity. In the present study, some of these equations are expressed and evaluated. Einstein [27] presented a theoretical model for the estimation of the viscosity of nanofluids with spherical particles and low concentration:

$$\frac{\mu_{nf}}{\mu_f} = 1 + 2.5\phi \tag{9}$$

For concentrations greater than 2%, the Einstein correlation lacks sufficient accuracy. To take into account higher concentrations, Brinkman [28] generalized the Einstein model and presented the following correlation:

$$\frac{\mu_{nf}}{\mu_f} = \frac{1}{\left(1-\phi\right)^{2.5}} \tag{10}$$

The following correlation was presented by Frankel and Acrivos [29] for the estimation of nanofluid viscosity:

$$\frac{\mu_{nf}}{\mu_f} = \frac{9}{8}\left(\frac{\left(\frac{\phi}{\phi_m}\right)^{\frac{1}{3}}}{1-\left(\frac{\phi}{\phi_m}\right)^{\frac{1}{3}}}\right) \tag{11}$$

Considering the influence of the Brownian motion, Batchelor [30] derived the following correlation:

$$\frac{\mu_{nf}}{\mu_f} = 1 + 2.5\phi + 6.5\phi^2 \tag{12}$$

Graham [31] used the cell theory and developed the following expression for nanofluid viscosity:

$$\frac{\mu_{nf}}{\mu_f}=\left(\frac{9}{4}\right)\left[1+\left(\frac{h}{2a}\right)\right]^{-1}\times\left[\frac{1}{\left(\frac{h}{a}\right)}-\frac{1}{\left[1+\left(\frac{h}{a}\right)\right]}-\frac{1}{\left[1+\left(\frac{h}{a}\right)\right]^2}\right]+\left(1+\left(\frac{5}{2}\right)\phi\right) \tag{13}$$

where, h/a is computed as:

$$\left(\frac{h}{a}\right)=(2)\left[\frac{\left(1-\left(\frac{\phi}{\phi_m}\right)^{\frac{1}{3}}\right)}{\left(\frac{\phi}{\phi_m}\right)^{\frac{1}{3}}}\right] \tag{14}$$

In the above equation, $\phi_m = 0.625$.

Taking into account the Brownian motion effect, Masoumi et al. [32] developed a correlation for effective viscosity of nanofluids:

$$\mu_{nf}=\mu_f+\frac{\rho_{np}V_B d_{np}^2}{72C\delta} \tag{15}$$

In this equation, d_{np} is the diameter of nanoparticles. V_B is the Brownian velocity of particles and is computed as:

$$V_B=\frac{1}{d_{np}}\sqrt{\frac{18K_BT_f}{\pi\rho_{np}d_{np}}} \tag{16}$$

where K_B is the Boltzmann constant. In Equation (15), δ is the distance between nanoparticles and is obtained as:

$$\delta=\sqrt[3]{\frac{\pi}{6\phi}}d_{np} \tag{17}$$

The correction factor *C* is computed as:

$$C=\mu_f^{-1}\left[\left(c_1d_{np}+c_2\right)\phi+\left(c_3d_{np}+c_4\right)\right] \tag{18}$$

where,

$$\begin{aligned}c_1&=0.000001133\\c_2&=0.000002771\\c_3&=-0.00000009\\c_4&=0.000000393\end{aligned} \tag{19}$$

In addition to Equation (7), some other equations are used and evaluated for the calculation of nanofluid conductivity. The Maxwell [33] and kinetic [34] models for the calculation of nanofluid conductivity are expressed as Equations (20) and (21), respectively:

$$k_{nf}=\frac{k_{np}+2k_f-2\phi(k_f-k_{np})}{k_{np}+2k_f+\phi(k_f-k_{np})} \tag{20}$$

$$k_{nf}=k_f\left[1+\frac{k_{np}\phi r_f}{k_f(1-\phi)r_{np}}\right] \tag{21}$$

r_f and r_{np} represent the radius of bulk fluid particles and nanoparticles, respectively.

Maïga and Nguyen [35] presented a correlation for the computation of the conductivity of Alumina-Water nanofluids:

$$\frac{k_{nf}}{k_f} = 1 + 2.72\phi + 4.97\phi^2 \tag{22}$$

Prasher et al. [36] proposed a convective-conductive model based on the Brownian motion of nanoparticles for calculation of conductivity coefficient of nanofluids:

$$\frac{k_{nf}}{k_f} = (1 + A\,\mathrm{Re}^m\,\mathrm{Pr}^{0.333}\,\phi) \times \left(\frac{\left[k_{np}(1+2\alpha) + 2k_m\right] + 2\phi\left[k_{np}(1-\alpha) - k_m\right]}{\left[k_{np}(1+2\alpha) + 2k_m\right] - \phi\left[k_{np}(1-\alpha) - k_m\right]} \right) \tag{23}$$

where,

$$k_m = k_f\left[1 + (1/4)\,\mathrm{Re}\,\mathrm{Pr}\right] \tag{24}$$

In Equations (23), $\alpha = 2R_b k_m / d_{np}$. R_b is the interfacial thermal resistance between nanoparticles and base fluid. In the current study, $R_b = 0.77 \times 10^{-8}$ $\mathrm{Km^2W^{-1}}$, $A = 4 \times 10^4$, and $m = 2.5$. The Brownian-Reynolds number is calculated based on the Brownian velocity of a nanoparticle (Equation (16)) and is given as:

$$\mathrm{Re} = \frac{1}{\nu_f}\sqrt{\frac{18K_B T_f}{\pi \rho_{np} d_{np}}} \tag{25}$$

3. NUMERICAL METHODS

The flow and temperature equations are discretized by adopting the finite volume approach. The flow equations are solved by using the SIMPLE algorithm. The diffusion terms are discretized by employing the second-order central approximation. Moreover, the convective terms are discretized by adopting the second-order upwind method.

4. RESULTS

In this study, the free convection heat transfer of Alumina-Water nanofluid in a cavity is considered. Figure 1 depicts the geometry of the problem. The cavity dimension is considered to be L=25mm. The temperatures of hot (i.e., left) and cold (i.e., right) walls are constant and equal to T_h and T_c, respectively. The top and bottom surfaces are insulated. Thermo-physical properties of Al_2O_3 and Water are based on the data presented in [25]. The diameters of nanoparticles and bulk fluid particles are considered to be 33 nm and 0.64 nm, respectively. In the following simulations, the correlations presented by Ho et al. [7] (Equations (7), (8)) are used for nanofluid conductivity and viscosity computation.

4.1. Verification of the Results

In this section, first, the results of the grid convergence study are presented. Subsequently, the simulation results are compared with the experiment [7]. The important non-dimensional parameters for free convection heat transfer problem are Rayleigh and Nusselt numbers, which are expressed as:

$$Ra = \frac{g\,\beta_{nf}\,(T_h - T_c)\,L^3}{\alpha_{nf}\,\nu_{nf}} \tag{26}$$

$$Nu = \frac{hL}{k_{nf}} \tag{27}$$

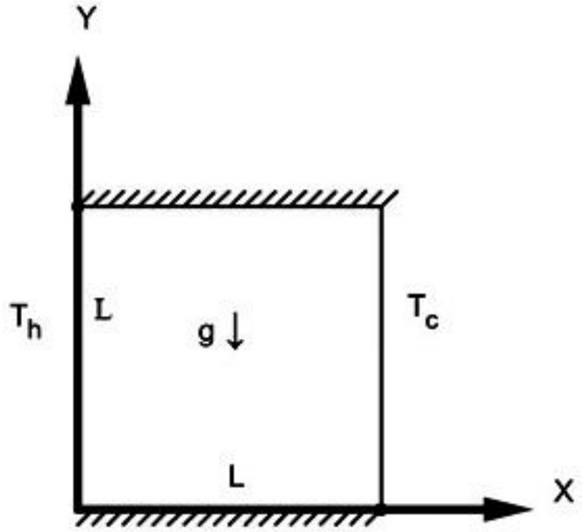

Figure 1. Schematic description of the problem.

where α , ν and h are thermal diffusivity, kinematic viscosity, and convective heat transfer coefficient, respectively.

First, the free convection of water in the enclosure for different mesh sizes at a Rayleigh number of 7.55E5 is simulated. Figure 2 depicts the variations of the Nusselt number along the hot wall. According to this figure, the differences between the results for grid sizes of 200*200 and 400*400 are very small. Therefore, the grid with a size of 200*200 is appropriate for simulations.

Figure 3 represents the variations of the average Nusselt number versus the Rayleigh number. As the Rayleigh number increases, in comparison with the viscous forces, the buoyancy forces increase. Therefore, the free convection phenomenon is reinforced,

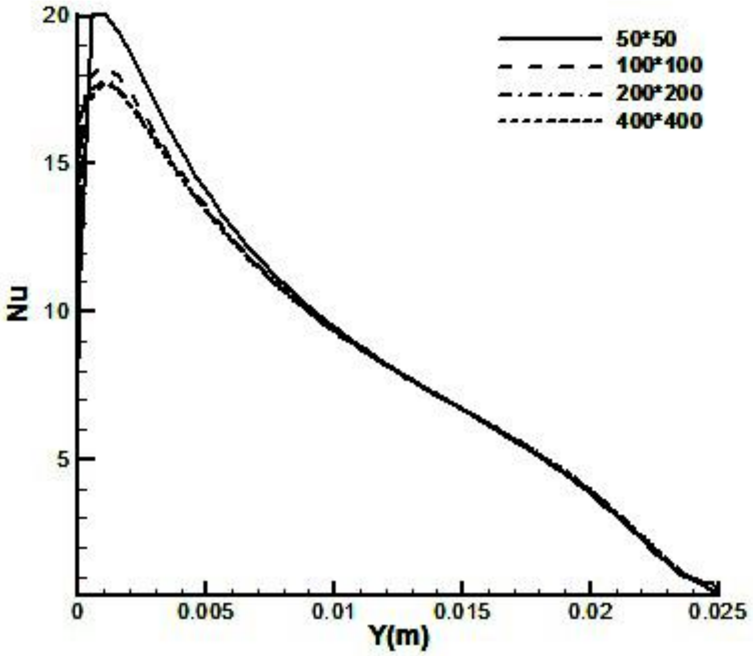

Figure 2. Grid convergence study (Ra=7.55E5)

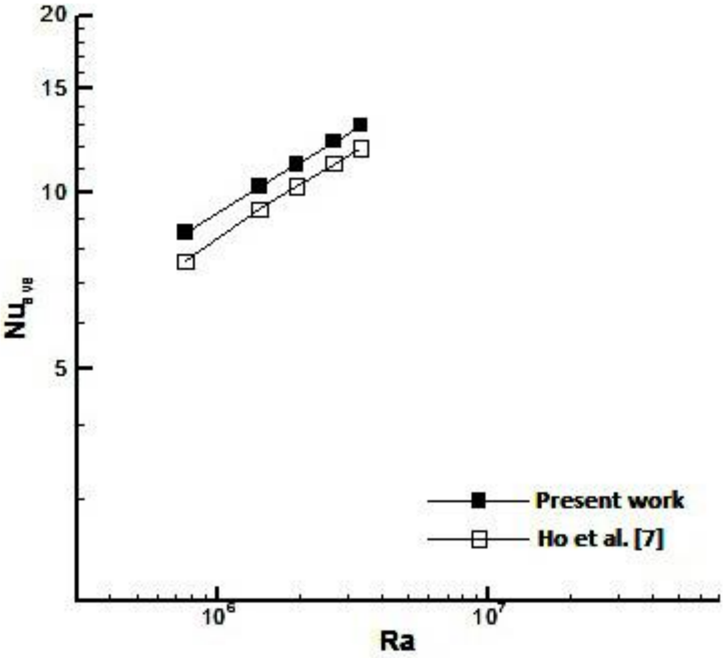

Figure 3. Comparison of simulation and experimental results [7] for natural convection of water.

and as a result, the average Nusselt number increases. In this figure, the simulation results have been compared with the experiment [7]. The numerical procedure predicts a higher value for the average Nusselt number. This can be attributed to the numerical errors. By increasing the Rayleigh number, the difference between the results decreases. The upwind scheme used in our simulations introduces an artificial viscosity during the solution procedure. This stabilizes the numerical method. However, due to higher viscosity, the numerical Rayleigh number becomes less than the real Rayleigh number, and as a result, the numerical accuracy reduces. By enhancing the Rayleigh number, as compared with the viscous resisting forces, the magnitude of motivating buoyancy forces increases. Therefore, the effect of the artificial viscosity on the solution process is decreased, which, in turn, leads to higher agreement between the results.

Figure 4 compares simulation and experimental results [7] for nanofluid natural convection flow at concentrations of 0.1% and 3%. Similar to the pure water case, the numerical procedure overestimates the average Nusselt number for nanofluid, too. As in the pure water case, the difference between the results decreases with the Rayleigh number, which can be justified as before. In addition, at higher concentrations, the difference between the simulation and experimental results is higher, which can be attributed to the approach adopted for nanofluid modeling. The homogenous approach used in our study does not consider a number of phenomena in nanofluid flow, such as Brownian motion, thermophoresis effect, slip between nanoparticles and fluid. Moreover, the accuracy of the correlations used in the homogenous model for the estimation of the nanofluid properties affects the obtained results.

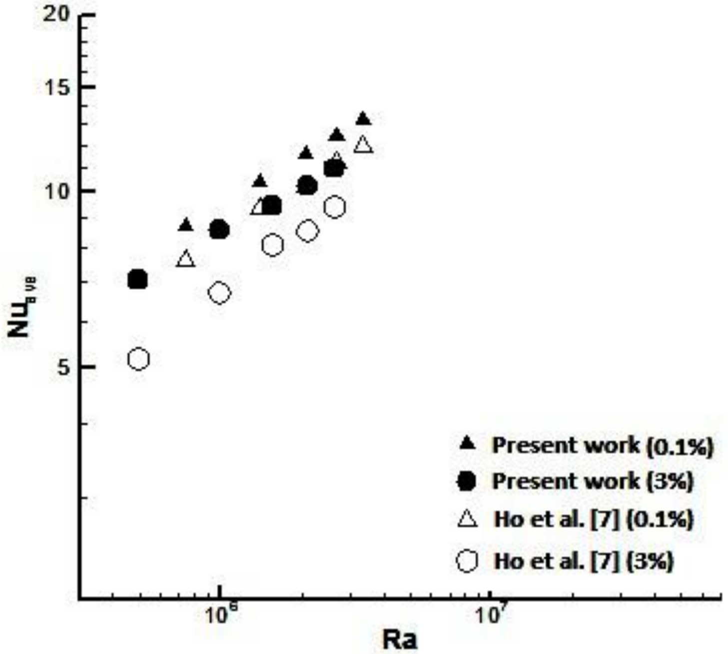

Figure 4. Comparison of simulation and experimental results [7] for natural convection of nanofluid.

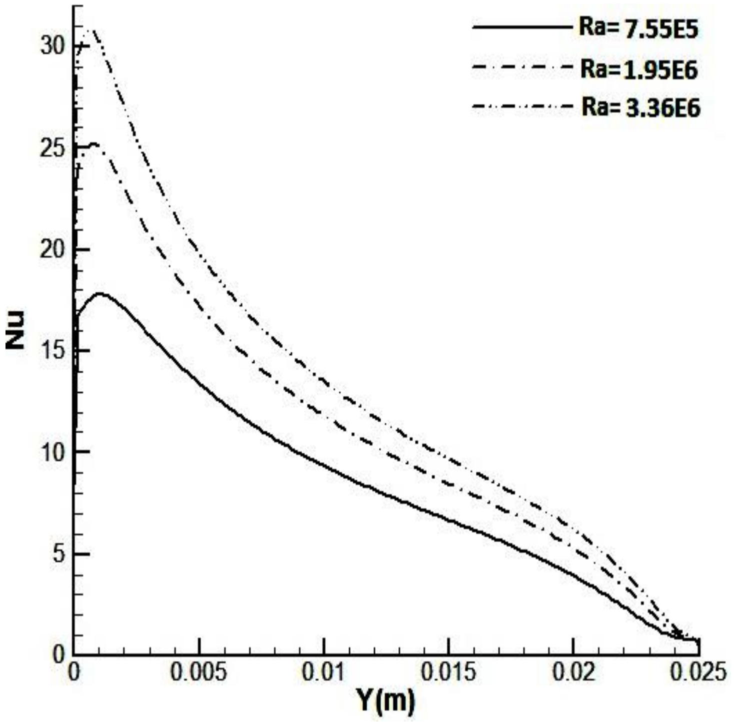

Figure 5. Variations of Nusselt number at various Rayleigh numbers (ϕ =0%).

4.2. Rayleigh Number and Nanoparticles Concentration Effects

In this section, the influences of the Rayleigh number and the concentration of nanoparticles on the heat transfer are evaluated. Figures 5 and 6 depict the variations of the Nusselt number along the hot wall at various Rayleigh numbers for pure water and nanofluid with a volume fraction of 3%, respectively. For both pure water and nanofluid, the Nusselt number increases with the Rayleigh number. In the free convection phenomenon, buoyancy and viscous forces play the role of motivating and resisting forces, respectively. By increasing the Rayleigh number, the buoyancy force relative to the viscous force increases. Therefore, the natural convection phenomenon is reinforced, and as a result, the convective heat transfer increases. Figure 7 compares the temperature distribution for two different Rayleigh numbers at a volume concentration of 3%. A stronger temperature gradient is observed near the hot wall for the higher Rayleigh number.

Figure 8 presents the variations of Nusselt number at Rayleigh number of 1.9E6 for various volume fractions. In a small distance, the Nusselt number increases with the wall height and subsequently decreases. Figure 9 demonstrates the average Nusselt number versus Rayleigh number for various concentrations. According to Figures 8 and 9, a slight enhancement in Nusselt number is observed at a volume fraction of 0.1%. For a concentration of 1%, the Nusselt number remains almost unchanged. By further enhancement of the concentration of nanoparticles, the Nusselt number decreases. Adding nanoparticles improves the thermal properties, especially thermal conduction coefficient. On the other hand, nanoparticles enhance the nanofluid viscosity. Enhancement of the resisting viscous force reduces the Rayleigh number and subsequently weakens the natural convection effect. Therefore, the heat transfer rate may reduce. At a concentration of 0.1%, the influence of thermal conductivity enhancement is dominant. Thus, the Nusselt number increases slightly. At a concentration of 1%, the effects of thermal conductivity and viscosity enhancement are almost the same. Therefore, no sensible change in the Nusselt number occurs. However, at higher concentrations, the viscosity enhancement effect becomes dominant, and the Nusselt number reduces with volume fraction.

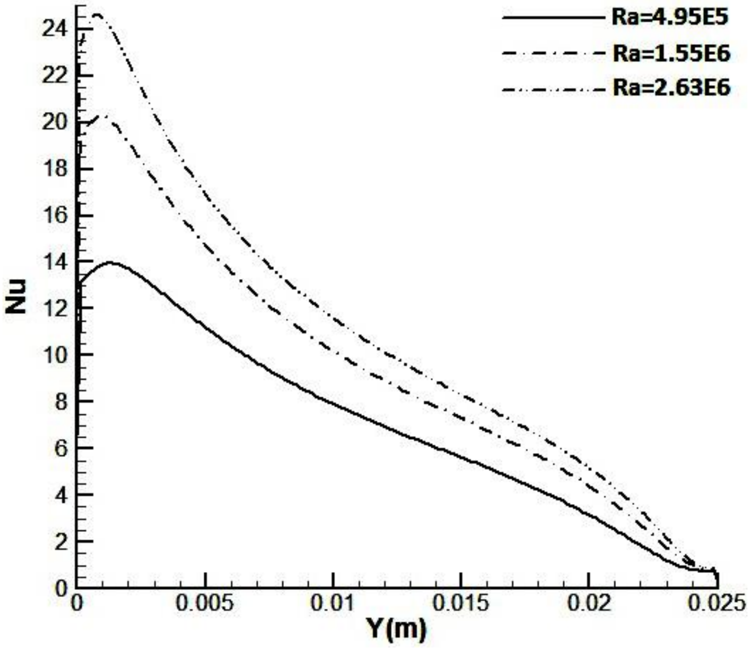

Figure 6. Variations of Nusselt number at different Rayleigh numbers (ϕ =3%).

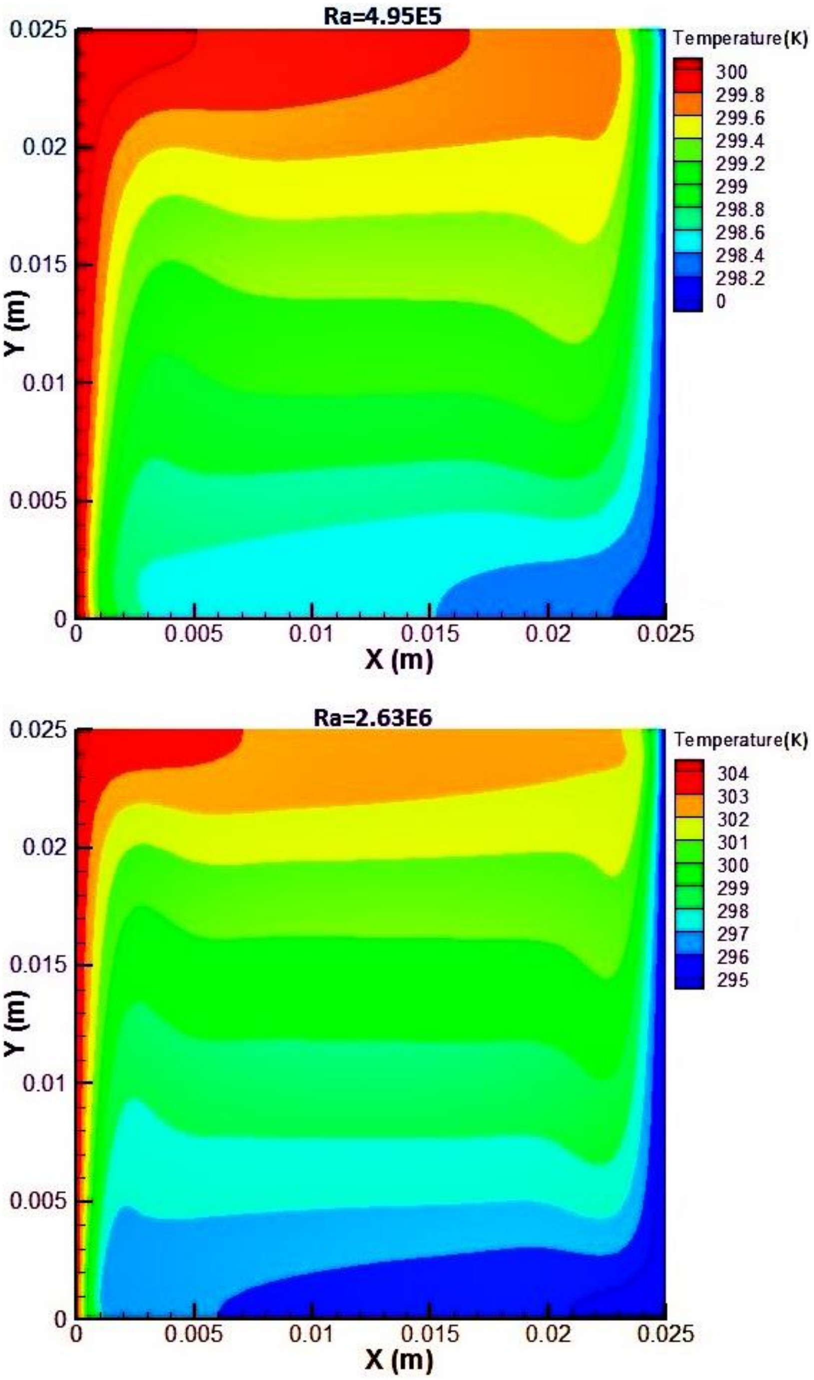

Figure 7. Temperature distribution for two different Rayleigh numbers (ϕ =3%).

Figure 10 represents the thermal enhancement factor $\left(\eta = ((Nu_{nf} - Nu_f)/Nu_f)\times 100\%\right)$ versus Rayleigh number for various values of concentration. According to this figure, the effect of the Rayleigh number on this parameter is slight. For a concentration of 0.1%, the thermal enhancement factor is positive. For concentrations of 0.3% and 1%, the same parameter is near zero and for higher concentrations, it decreases remarkably. These results reveal that only for a very low concentration of 0.1%, the nanofluid indicates a better heat transfer performance, compared with water.

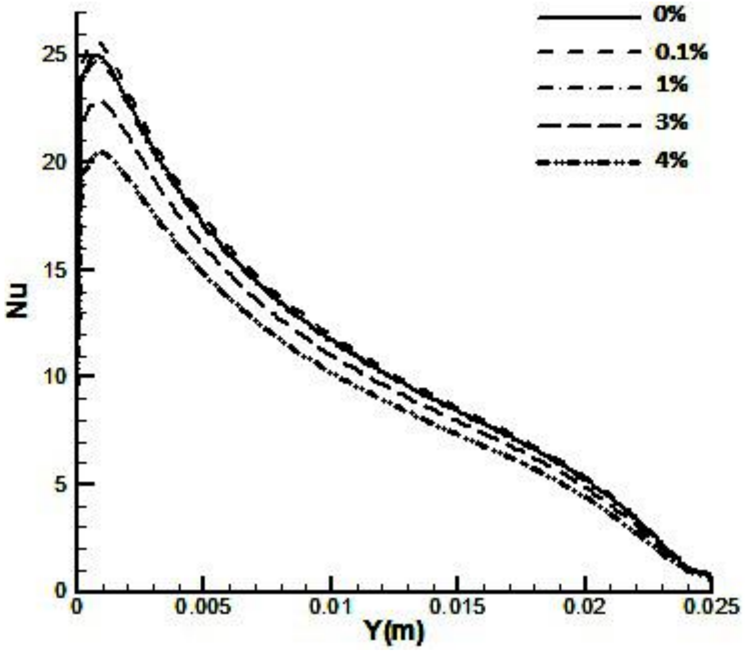

Figure 8. Variations of Nusselt number at different concentrations (Ra=1.9E6).

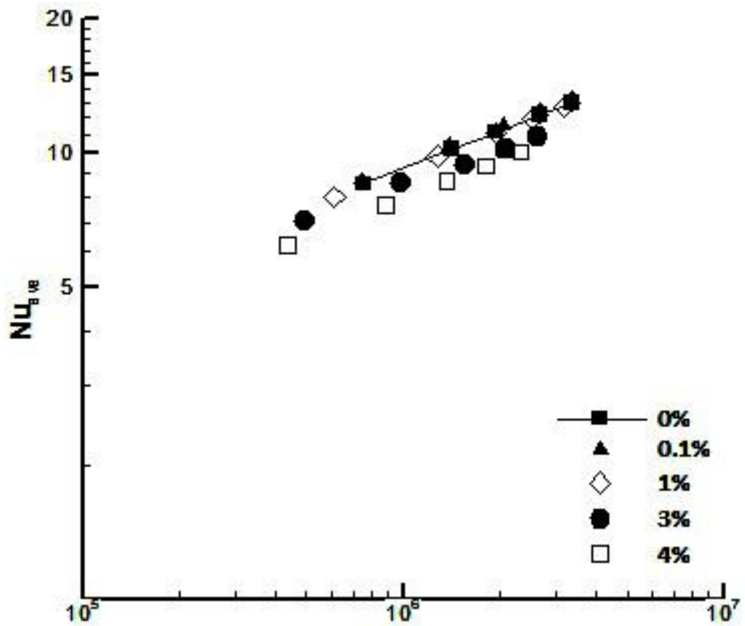

Figure 9. The influence of concentration on Nusselt number.

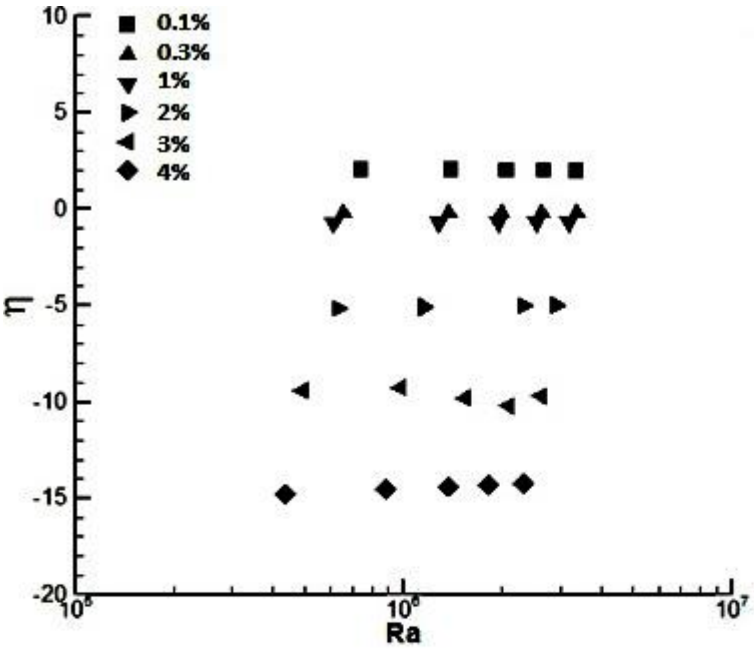

Figure 10. Thermal enhancement factor versus Rayleigh number for various values of concentration.

4.3. Assessment of Different Viscosity Models

The Rayleigh number is the important non-dimensional parameter in the natural convection phenomenon. Therefore, it can be concluded that the viscous forces play a key role in this phenomenon. Hence, the accurate computation of nanofluid viscosity is of great importance. Different viscosity models have been proposed for the estimation of nanofluid viscosity. As observed in Section 4.1., there are discrepancies between simulation and experimental results. These discrepancies may bepartly due to the errors associated with the viscosity estimation. Thus, it is necessary to assess the accuracy of different viscosity correlations. In this section, the accuracy of viscosity correlations presented by Einstein [27], Brinkman [28], Frankel and Acrivos [29], Batchelor [30], Graham [31], Masoumi et al. [32], and Ho et al. [7] is evaluated. Figures 11, 12, 13, and 14 show the variations of the average Nusselt number versus Rayleigh number at concentrations of 0.1%, 1%, 2%, and 4%, respectively. In these figures, the results obtained using the above-mentioned viscosity correlations are compared with the experimental results obtained by Ho et al. [7]. As suggested by these figures, the results obtained based on the Frankel and Acrivos [29] correlation show the maximum deviation from the experimental results [7]. However, this deviation decreases by increasing the volume fraction. In addition, no significant difference was observed between the results of Einstein [27], Brinkman [28], Batchelore [30], and Graham [31] models. In comparison with the models considered, the correlation presented by Ho et al. [7] represents better results, especially at higher concentrations. The minimum deviation from experiment [7] is associated with the Masoumi et al. [32] correlation. They have taken into account the Brownian motion of nanoparticles in their theoretical model. The effective parameters in their model are temperature, physical properties of bulk fluid, concentration, diameter and the density of nanoparticles. This result shows that the Brownian motion is an effective

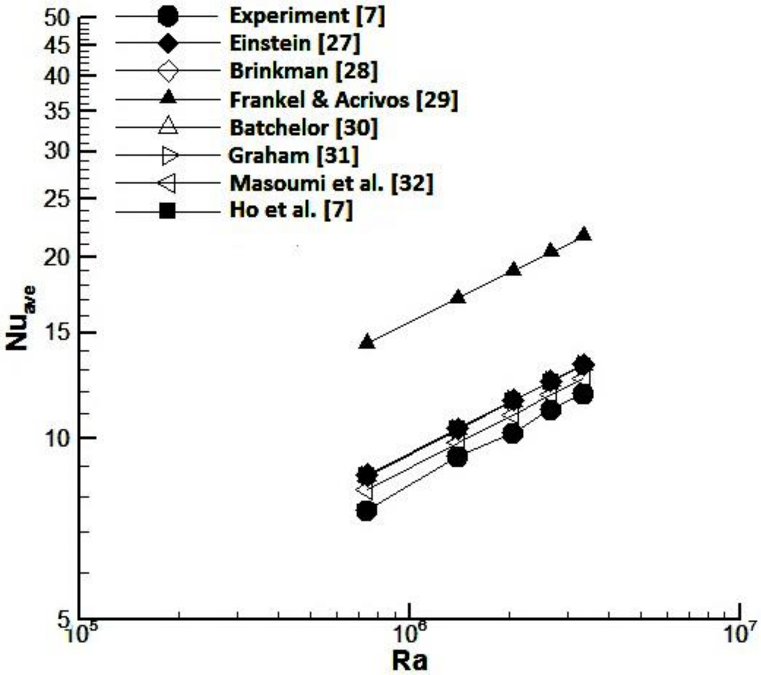

Figure 11. Evaluation of different viscosity correlations (ϕ =0.1%).

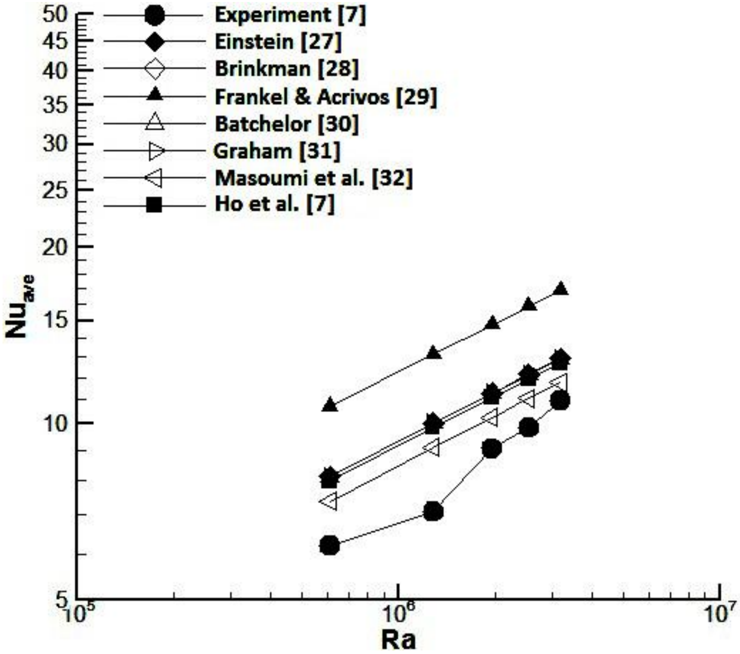

Figure 12. Evaluation of different viscosity correlations (ϕ =1%).

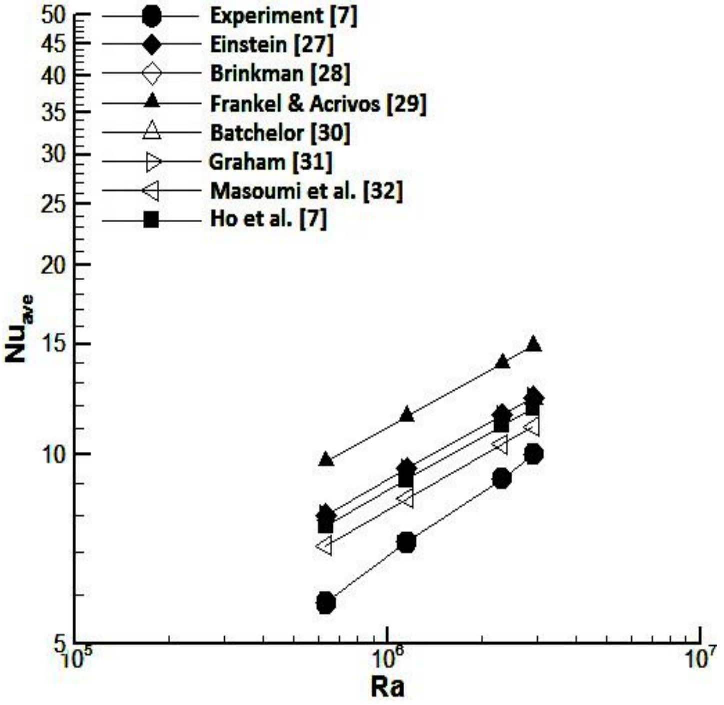

Figure 13. Evaluation of different viscosity correlations (ϕ =2%).

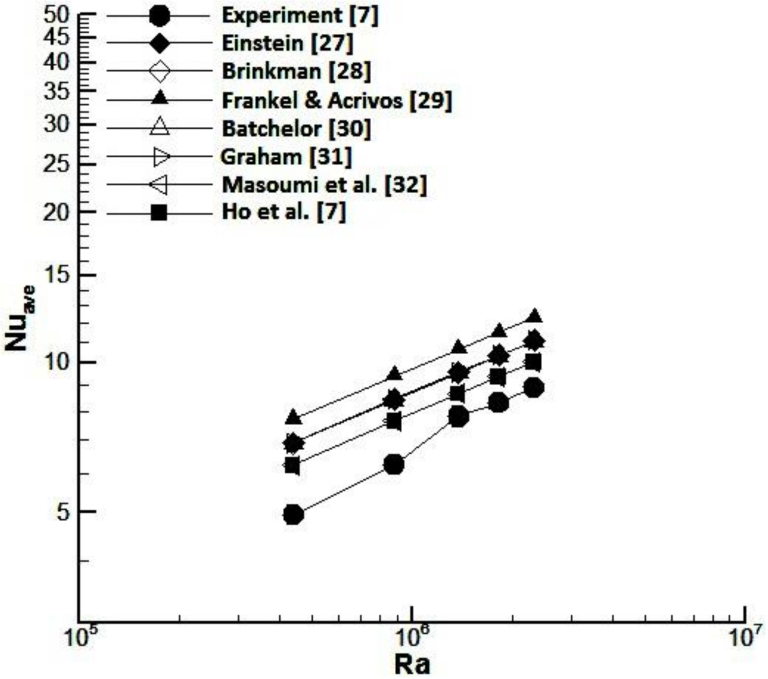

Figure 14. Evaluation of different viscosity correlations (ϕ =4%).

mechanism in the heat transfer process of nanofluids. At a concentration of 0.1%, the accuracy of the average Nusselt number presented by the correlation presented by Masumi et al. [32] is about 8% higher than the correlations presented by Einstein [27], Brinkman [28], Batchelore [30], and Graham [31]. At a concentration of 4%, this value increases to 12-14%. At this concentration, the Nusselt number values obtained by Ho et al.'s [7] and Masoumi et al.'s correlations agree well. In Figure 15, the two more accurate correlations (i.e., Ho et al.'s [7] and Masoumi et al.'s [32]) are compared. As stated above, Masoumi et al.'s correlation yields better results. However, the difference between the results reduces with volume fraction.

4.4. Assessment of Different Conductivity Models

The accurate computation of the nanofluid conductivity coefficient is of great importance in the successful modeling of nanofluid flow. Different correlations have been proposed for the calculation of nanofluid conductivity. In this section, several conductivity models, including the Maxwell [33], kinetic [34], Brownian [35], Maïga and Nguyen [36], and Ho et al. [7] correlations for free convection of Al_2O_3-Water nanofluid are employed and compared in a square enclosure.

Figures 16 and 17 depict the average Nusselt number versus Rayleigh number for various conductivity correlations for concentrations of 1% and 4%. According to these figures, at low and high concentrations, the results obtained, using different conductivity correlations are almost the same, and no considerable difference is observed between the results.

4.4. CONCLUSION

In this study, the finite volume approach was adopted to simulate the natural convection heat transfer of Al_2O_3-Water in a cavity. The effect of nanoparticles was considered by employing the homogeneous model. The simulation results were compared with the experiment, and satisfactory agreement was observed, especially at higher Rayleigh numbers. The main results can be expressed as follows:

1- The average Nusselt number enhances with the Rayleigh number.
2- For a concentration of 0.1%, nanofluid exhibits better heat transfer characteristics than the pure fluid. However, at higher concentrations, the heat transfer rate of the nanofluid reduces relative to the pure fluid. At concentrations greater than 1%, this reduction is considerable.
3- Viscosity correlations presented by Einstein [27], Brinkman [28], Frankel and Acrivos [29], Batchelor [30], Graham [31], Masoumi et al. [32], and Ho et al. [7] were evaluated. The results obtained based on the Frankel and Acrivos [29] correlation showed a considerable deviation from the experiment. In addition, the viscosity correlation proposed by Masoumi et al. [32], in which the Brownian motion effect is taken into account, produced the most accurate results.
4- Conductivity models including the Maxwell [33], kinetic [34], Brownian [35], Maïga and Nguyen [36], and Ho et al. [7] correlations were evaluated, and no significant difference was observed between the results.

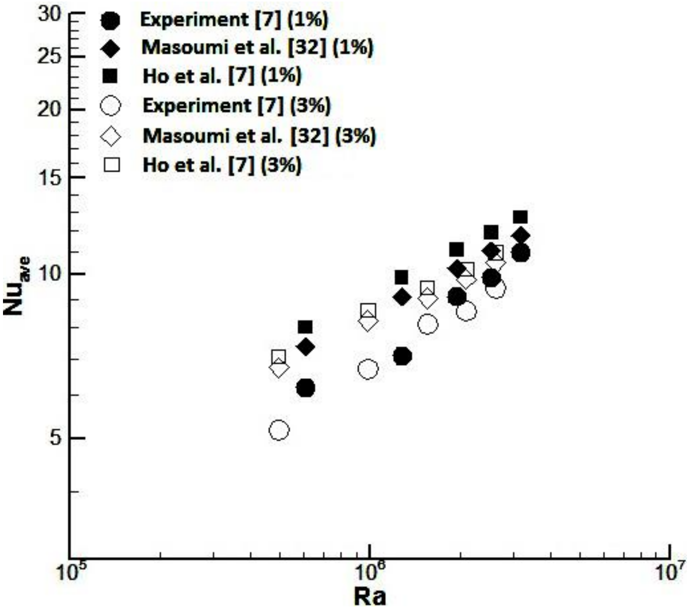

Figure 15. Average Nusselt number based on Ho et al.'s [7] and Masoumi et al.'s [32] correlations, in comparison with the experiment [7].

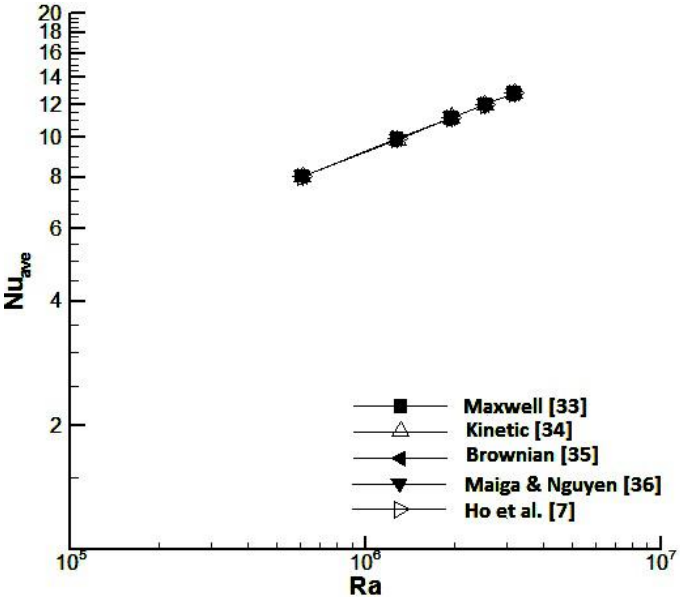

Figure 16. Evaluation of different conductivity correlations (ϕ =1%).

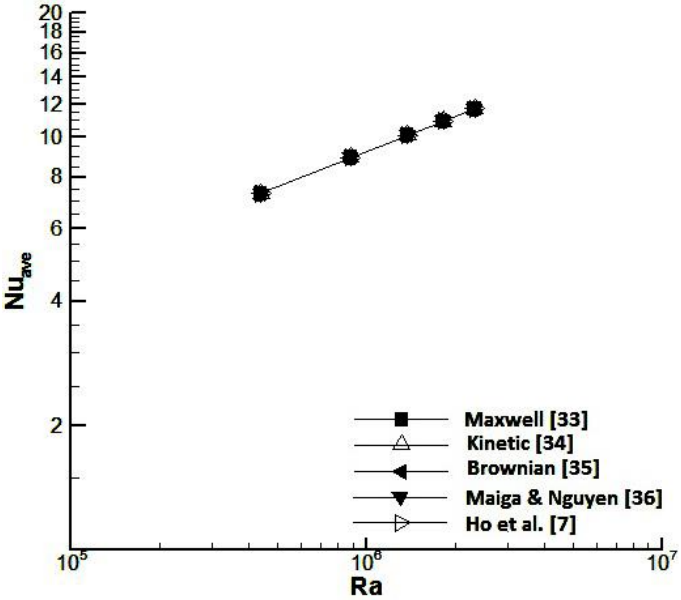

Figure 17. Evaluation of different conductivity correlations (ϕ =4%).

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