Review

Buoyancy-driven heat transfer of water–Al₂O₃ nanofluid in a closed chamber: Effects of solid volume fraction, Prandtl number and aspect ratio

Rehena Nasrin a,⇑, M.A. Alima, Ali J. Chamkha b
aDepartment of Mathematics, Bangladesh University of Engineering and Technology, Dhaka, Bangladesh
bManufacturing Engineering Department, The Public Authority for Applied Education and Training, Shuweikh 70654, Kuwait

Abstract

This paper analyzes heat transfer and fluid flow of natural convection in a vertical closed chamber filled with Al₂O₃/water nanofluid that operates under differentially heated walls. The Navier–Stokes and energy equations are solved numerically using the finite element technique with Galerkin’s weighted residual simulation. The heat transfer rates are examined for parameters of nanoparticle volume fraction (ϕ), Prandtl number (Pr) and cavity aspect ratio (AR). Enhanced and mitigated heat transfer effects due to the presence of nanoparticles are identified and highlighted. Based on these insights, the impact of fluid temperature on the heat transfer of nanofluid are determined. Decreasing the Prandtl number results in amplifying the effects of nanoparticles due to increased effective thermal diffusivity. The results highlight the range where the heat transfer uncertainties can be affected by the volume fraction of the nanoparticles. In addition, a correlation is developed graphically for the average Nusselt number as a function of the cavity aspect ratio.

© 2012 Elsevier Ltd. All rights reserved.
1. Introduction

Heat transfer materials like water, ethylene glycol, engine oil, alumina, copper and silver have been widely used in numerous important fields, such as heating, ventilating, air-conditioning systems, micro-electronics, transportation, manufacturing and nuclear engineering. Cooling or heating performances for thermal systems play vital roles in the development of energy-efficient heat transfer equipment, such as MEMS and NEMS (Micro and Nano Electro Mechanical Systems, respectively). Natural convection heat transfer is an important phenomenon in engineering systems due to its wide applications in electronic cooling, heat exchangers, double pane windows etc. Enhancement of heat transfer performance in these systems is an essential topic from an energy saving perspective. The low thermal conductivity of conventional fluids such as water and oils is a primary limitation in enhancing the heat transfer performance and the compactness of such systems.

Over the last years, it has been demonstrated that thermal conductivity of fluids suspended with metallic nanoparticles (nanofluids) is significantly higher than that of pure fluids by Choi et al. [1]. Additional benefits of nanofluids include high stability with low sedimentation, no clogging in micro-channels, reduction in pumping power and design of small heat exchanger systems by Murshed et al. [2] where research conducted by different groups on heat transfer characteristics of nanofluids showed little agreement. A great amount of experimental research in this field has recently been reported in literature. Eastman et al. [3] observed that Al2O3/water and CuO/water with 5% nanoparticle volume fractions increased the thermal conductivity by 29% and 60%, respectively. In addition, Xie et al. [4] showed that Al2O3/ethylene glycol with 5% nanoparticle volume fraction enhanced thermal conductivity by 30% and Patel et al. [5] reported that Au/toluene and Au/water with 0.0013–0.011% nanoparticle volume fractions increased the thermal conductivity by 4–7% and 3.2–5%, respectively. Recently, in the natural convection of nanofluids inside a horizontal cylinder, Putra et al. [6] observed the paradoxical behavior of heat transfer due to different particle concentrations, types of particles and different shapes of the containing cavity. Kim et al. [7] analyzed the convective instability driven by buoyancy and heat transfer characteristics of nanofluids and indicated that as the thermal conductivity and shape factor of nanoparticles decrease, the convective motion in a nanofluid sets in easily. At the same year, in a series of experiments in laminar tube flows, Wen and Ding [8] showed that the local heat transfer coefficients increased 41% and 46% at \( Re = 1050 \) and 1600, respectively in the presence of nanoparticle volume fraction of 0.016. Jung et al. [9] reported that the heat transfer coefficient increased 32% by dispersing 1.8% nanoparticles in a micro-rectangular channel with Al2O3/water nanofluid.

The computational studies reported in this area include two main approaches: (1) a two-phase model, in which both liquid and solid heat transfer behaviors are solved in the flow fields [10,11] and (2) a single-phase model, in which solid particles are considered to behave as fluids, because the nanoparticles are easy fluidized [12–17]. The model of nanofluids in a cavity was first proposed by Kankanai et al. [12] and the authors investigated the natural convection effect on the enhancement of heat transfer. Tiwari and Das [13] further studied the forced convection effect with two-sided lid-driven differentially heated square cavity. A theoretical study on a heated cavity reported by Hwang et al. [18] showed that the heat transfer coefficient of Al2O3/water nanofluids reduced when there was an increase in size of nanoparticles and a decrease in average temperatures. Particle concentration and tube size dependence of viscosities of Al2O3–water nanofluids flowing

---

**Nomenclature**

- \( C_p \) specific heat at constant pressure (J kg\(^{-1}\)K\(^{-1}\))
- \( d_p \) mean nanoparticle diameter (m)
- \( g \) gravitational acceleration (ms\(^{-2}\))
- \( H \) height of the chamber (m)
- \( K \) thermal conductivity (W m\(^{-1}\)K\(^{-1}\))
- \( L \) length of the chamber (m)
- \( Nu \) Nusselt number
- \( Nu^* \) normalized Nusselt number
- \( P \) dimensional pressure (N m\(^{-2}\))
- \( P \) non-dimensional pressure
- \( Pr \) Prandtl number
- \( Ra \) Rayleigh number
- \( T \) dimensional temperature (K)
- \( \overline{T} \) time
- \( u, v \) velocity components (m s\(^{-1}\)) along \( x, y \) direction respectively
- \( U, V \) dimensionless velocity components along \( X, Y \) direction respectively
- \( x, y \) Cartesian coordinates (m)
- \( X, Y \) non-dimensional Cartesian coordinates

**Greek symbols**

- \( \alpha \) thermal diffusivity (m\(^2\) s\(^{-1}\))
- \( \beta \) thermal expansion coefficient (K\(^{-1}\))
- \( \phi \) solid volume fraction
- \( \theta \) non-dimensional temperature
- \( \mu \) dynamic viscosity of the fluid (kg m\(^{-1}\)s\(^{-1}\))
- \( \nu \) kinematic viscosity of the fluid (m\(^2\) s\(^{-1}\))
- \( \rho \) density of the fluid (kg m\(^{-3}\))
- \( \omega \) dimensionless velocity field

**Subscripts**

- \( \text{av} \) average
- \( c \) less heated wall
- \( f \) base fluid
- \( h \) heated wall
- \( nf \) water–Al2O3 nanofluid
- \( s \) solid particle

---

Fig. 1. Schematic diagram of the square chamber.
through micro- and mini-tubes was conducted by Jang et al. [19], Li and Peterson [20] experimentally investigated temperature and volume fraction variations on the effective thermal conductivity of nanoparticle suspensions. They indicated that the effect of volume fraction may play an important role in changing the velocity and temperature profiles.

Very recently, Muthamilselvan et al. [21] rigorously performed the problem of heat transfer enhancement of copper–water nanofluids in a lid-driven enclosure, where both the aspect ratio and solid volume fraction affected the fluid flow and heat transfer in the enclosure. Lin and Violi [22] analyzed natural convection heat transfer of nanofluids in a vertical cavity. They showed the effects of non-uniform particle diameter and temperature on thermal conductivity, where decreasing the Prandtl number resulted in amplifying the effects of nanoparticles due to increased effective thermal diffusivity. Parvin et al. [23] analyzed thermal conductivity variations on convection flow of water–alumina nanofluid in an annulus. They found significant heat transfer enhancement due to the presence of nanoparticles and it was accentuated by increasing the nanoparticles volume fraction and Prandtl number as well as large Grashof number. Control volume finite element simulation of MHD forced and natural convection in a vertical channel with a heat-generating pipe was analyzed by Nasrin and Alim [24]. Their results indicated that the flow and thermal fields in the vertical channel depend markedly on the mentioned parameters and rate of heat transfer was obtained optimum in the absence of both MHD and Joule heating effects.

This study addresses the effects of nanoparticle volume fraction, Prandtl number and cavity aspect ratio on Al2O3/water nanofluid to simulate natural convection in a square cavity. The Navier–Stokes and energy equations are coupled with the nanoparticle volume fraction, Prandtl number and cavity aspect ratio to produce a systematic description of the phenomenon. Enhanced and mitigated heat transfer effects based on these insights, the impact of fluid temperature on the heat transfer of nanofluids is determined. The flow fields, temperature distributions and the rate of heat transfer are presented for different φ, Pr and AR graphically. Cavity aspect ratio is defined as the ratio of length and height of the chamber. The theoretical prediction in this paper is hoped to be a useful guide for the experimentalists to study the effectiveness of the natural convection in a vertical closed enclosure filled with Al2O3/water nanofluids to increasing the rate of heat transfer.

2. Physical configuration

Fig. 1 shows a schematic diagram of the differentially heated vertical chamber. The left and right vertical walls have constant but different temperatures T_L and T_R, respectively where T_L > T_R. The top and bottom horizontal surfaces are kept adiabatic. The fluid in the enclosure is Al2O3/water nanofluid. L and H are the length and height of the cavity. The gravitational force acts in the vertically downward direction.

2.1. Assumptions

The mathematical equations describing the physical model are based on the following assumptions:

(i) The thermophysical properties are constant except for the density in the buoyancy force (Boussinesq’s hypothesis).

(ii) The fluid phase and nanoparticles are in a thermal equilibrium state.

(iii) Nanoparticles are spherical.

(iv) The nanofluid in the cavity is Newtonian, incompressible, and laminar and

(v) Radiation heat transfer between the sides of the cavity is negligible when compared with the other mode of heat transfer.

2.2. Governing equations

The governing equations in dimensional form used in the present study are as follows:

Continuity equation:

\[ \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \]  

(1)

x-momentum equation:

\[ \rho f \left( \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} \right) = -\frac{\partial p}{\partial x} + \mu f \left( \frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} \right) \]  

(2)

y-momentum equation:

\[ \rho f \left( \frac{\partial v}{\partial x} + u \frac{\partial v}{\partial y} \right) = -\frac{\partial p}{\partial y} + \mu f \left( \frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} \right) + g \rho f \beta f (T - T_c) \]  

(3)

Energy equation:

\[ u \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y} = \alpha f \left( \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} \right) \]  

(4)

where \( \rho_f = (1 - \phi) \rho_1 + \phi \rho_2 \) is the density, \( (\rho C_p)_f = (1 - \phi) (\rho C_p)_1 + \phi (\rho C_p)_2 \) is the heat capacitance, \( \beta_f = (1 - \phi) \beta_1 + \phi \beta_2 \) is the thermal expansion coefficient, \( \alpha_f = k_f / (\rho C_p)_f \) is the thermal diffusivity, \( \mu_f = \mu_f (1 - \phi)^{-2.5} + 5 \times 10^4 \gamma \phi (\rho C_p)_f \sqrt{3} / \rho_f \) is the dynamic viscosity and \( k_f = k_f (2 - 1 \phi_1 \phi_2 / \phi_2 + 2 - 1 \phi_1 / \phi_2) + 5 \times 10^4 \gamma \phi (\rho C_p)_f \sqrt{\rho_f} \) is the thermal conductivity of the nanofluid.

The first term of the thermal conductivity and viscosity is the Maxwell model and second term is based on heat convection due to Brownian motion. Here \( \kappa \) is the Boltzmann constant \( (\kappa \approx 1.38 \times 10^{-23} \text{J/K}) \). \( d_p \) is the diameter of nanoparticles by assuming that these nanoparticles have a uniform size and are perfectly spherical \( (d_p = 5 \text{nm}) \). \( T_0 \) is a reference temperature that is chosen as \( (T_h < T < T_c). \) \( \gamma \) is a function of the volume fraction \( \phi \), which is taken as \( 0.0011(100 \phi)^{-0.7272} \) for \( \phi \geq 0.01 \). The function \( F(T_0, \phi) \) is given by \( (-6.046 + 0.4705(T_0) + (172.23 \phi - 134.63), \) which is valid for \( \phi \geq 0.01 \) and \( 300 \text{K} < T_0 < 325 \text{K} \).

The boundary conditions are

- at the left vertical wall \( T = T_h \)
- at the right vertical wall \( T = T_R \)
- at horizontal surfaces \( \frac{\partial T}{\partial x} = 0 \)
- at all solid boundaries \( u = v = 0 \)

The above equations are non-dimensionalized by using the following dimensionless dependent and independent variables.

\[ X = \frac{x}{L}, \quad Y = \frac{y}{L}, \quad U = \frac{u L}{v}, \quad V = \frac{v L}{u}, \quad P = \frac{\rho f p L^2}{\rho_f u^2}, \quad \theta = \frac{T - T_c}{T_h - T_c} \]

After substitution of the above variables into Eqs. (1)–(4), we get the following non-dimensional equations as

\[ \frac{\partial U}{\partial X} + \frac{\partial V}{\partial Y} = 0 \]  

(5)

\[ U \frac{\partial U}{\partial X} + V \frac{\partial U}{\partial Y} = -\frac{P}{\rho_f} \frac{\partial P}{\partial X} + \frac{\rho_f C_p}{\nu_f} \left( \frac{\partial^2 U}{\partial X^2} + \frac{\partial^2 U}{\partial Y^2} \right) \]  

(6)
3. Numerical technique

In analysis such as computational fluid dynamics (CFD), nanofluids can be assumed to be single phase fluids. The classical theory of single phase fluids can be applied, where physical properties of nanofluid are taken as a function of properties of both constituents and their concentrations.

The momentum and energy balance equations are the combinations of mixed elliptic–parabolic system of partial differential equations that have been solved by using the Galerkin weighted residual finite element technique. The six node triangular element is used in this work for the development of the finite element equations. All six nodes are associated with velocities as well as temperature. Only three corner nodes are associated with pressure. This means that a lower order polynomial is chosen for pressure and which is satisfied through continuity equation. Firstly, the solution domain is discretized into finite element meshes, which are composed of non-uniform triangular elements. Then the nonlinear governing partial differential equations are transferred into a system of integral equations by applying Galerkin’s method. The integration involved in each term of these equations is performed by using Gauss’s quadrature method. The nonlinear algebraic equations so obtained are modified by imposition of boundary conditions. These modified nonlinear equations are transferred into linear algebraic equations by using reduced integration technique [25,26] and Newton–Raphson method [27]. Finally, these linear equations are solved by applying Triangular Factorization method.

3.1. Mesh generation

In the finite element method, the mesh generation is the technique to subdivide a domain into a set of sub-domains, called finite elements, control volume, etc. The discrete locations are defined by the numerical grid, at which the variables are to be calculated. It is basically a discrete representation of the geometric domain on which the problem is to be solved. The computational domains with irregular geometries by a collection of finite elements make the method a valuable practical tool for the solution of boundary value problems arising in various fields of engineering. Fig. 2 displays the finite element mesh of the present physical domain.

3.2. Grid refinement test

In order to determine the proper grid size for this study, a grid independence test is conducted with five types of mesh for $Pr = 6.2$, $Ra = 10^7$ and $AR = 1$. The extreme value of $Nu$ is used as a sensitivity measure of the accuracy of the solution. Also it is selected as the monitoring variable. Considering both the accuracy of numerical value and computational time, the present calculations are performed with 39,295 nodes and 10,536 elements grid system (see Table 1).

3.3. Thermo-physical properties

The thermo-physical properties of fluid (water) and solid $Al_2O_3$ are tabulated in Table 2 and the value of $Pr = 6.2$ (water at 300 K). The properties are taken from Lin and Violi [22].

3.4. Code validation

The model validation is an important part of a numerical investigation. Hence, the outcome of the present numerical code is benchmarked against the numerical result of Lin and Violi [22] which was reported for natural convection heat transfer of
nanofluids in a square cavity. The comparison is conducted while employing the dimensionless parameters \( Gr = 10^5 \), \( dp = 5 \), \( K_{nf}/K_f = 1.424 \), \( \varphi = 0.05 \) and \( Pr = 6 \) for both the streamlines and isothersms. This validation boosts the confidence in our numerical code to carry on with the above stated objective of the current investigation. As shown in Fig. 3, the new model is able to reproduce the published result of Lin and Violi [22].

In addition, to ensure the accuracy and validity of this model, a system composed of pure fluid in an enclosure with \( Pr = 0.7 \) and \( Ra = 10^5 \) is analyzed. This system has been studied by other research groups, including Lin and Violi [22] and Tiwari and Das [13]. Table 3 shows the comparison between the results obtained with the new model and the values presented in the literature. The quantitative comparisons for the average Nusselt numbers along the hot wall and the maximum velocity values and their corresponding locations indicate an excellent agreement.

### 4. Results and discussion

In this section, numerical results of streamlines and isotherms for various values of solid volume fraction \( \varphi \), Prandtl number \( Pr \) and cavity aspect ratio \( AR \) (ratio of length and height of vertical chamber i.e. \( L/H \)) are displayed while Rayleigh number \( Ra \) is fixed at \( 10^5 \). The considered values of solid volume fraction, Prandtl number and cavity aspect ratio are \( \varphi = 0.01, 0.03, 0.05 \) and 0.07, \( Pr = 1.47 \) at 390 K, 3.77 at 320 K, 6.2 at 300 K and 8.81 at 285 K) and \( AR = 0.5, 1, 1.5 \) and 2). In addition, the values of the average Nusselt number \( Nu \) have been calculated for different \( \varphi \), \( Pr \) and \( AR \) for both water and water–Al\(_2\)O\(_3\) nanofluid. Therefore, the findings of this study provide more information on the heat transfer characteristics of nanofluids.

#### 4.1. Effect of solid volume fraction

Snapshots of the velocity and the temperature profiles are executed in Fig. 4(a) and (b) for water–Al\(_2\)O\(_3\) nanofluid with different volume fractions of the solid nanoparticles, i.e. \( \varphi = 0.01, 0.03, 0.05 \) and 0.07 while \( Pr = 6.2 \). Numerical analysis shows that nanofluids type and the concentration level do not have a significance influence on the shape of entire cell. Due to the variation of \( \varphi \), the small eddy created in the middle right corner of the chamber rises in size and takes the profile similar to other lines as shown in Fig. 4(b). Increasing \( \varphi \) has the effect of increasing the strength of the flow and the average rate of heat transfer. This is due to high concentration of solid nanoparticles as shown in Fig. 4 that eventually leads to higher energy, which accelerates the flow. Actually, this phenomenon is also accompanied by an undesirable effect promoted by the viscosity that will suppress the flow but small compared to a favorable affect driven by the presence of the high thermal conductivity. Rising solid volume fraction of nanofluid enhances thermal conductivity and existing temperature. But this property reduces velocity of the nanofluid because of increasing solid concentration. Then nanofluid cannot move freely like base fluid water.

#### 4.2. Effect of Prandtl number

Fig. 5(a) and (b) indicate the influence of different Prandtl number on velocity and temperature profiles while \( AR \) and \( \varphi \) are fixed at 1 and 0.03. It is important to note that in the figure of the lowest \( Pr \),

---

**Table 1**

<table>
<thead>
<tr>
<th>Nodes (elements)</th>
<th>7224 (4816)</th>
<th>12,982 (5784)</th>
<th>26,538 (8992)</th>
<th>39,295 (10,536)</th>
<th>78,524 (17,880)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nu</td>
<td>7.536724</td>
<td>7.738752</td>
<td>7.829735</td>
<td>7.838754</td>
<td>7.838761</td>
</tr>
<tr>
<td>Time (s)</td>
<td>226.265</td>
<td>292.594</td>
<td>388.157</td>
<td>421.328</td>
<td>627.375</td>
</tr>
</tbody>
</table>

**Table 2**

<table>
<thead>
<tr>
<th>Physical properties</th>
<th>Water</th>
<th>Al(_2)O(_3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( C_p )</td>
<td>4179</td>
<td>850</td>
</tr>
<tr>
<td>( \rho )</td>
<td>997.1</td>
<td>3900</td>
</tr>
<tr>
<td>( k )</td>
<td>0.61</td>
<td>46</td>
</tr>
<tr>
<td>( \beta )</td>
<td>( 21 \times 10^3 )</td>
<td>( 1.67 \times 10^3 )</td>
</tr>
</tbody>
</table>

**Table 3**

<table>
<thead>
<tr>
<th>Physical properties</th>
<th>Water–Al(_2)O(_3) nanofluid at ( Pr = 6.2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( u_{max} )</td>
<td>36.732</td>
</tr>
<tr>
<td>( y )</td>
<td>0.858</td>
</tr>
<tr>
<td>( v_{max} )</td>
<td>68.288</td>
</tr>
<tr>
<td>( x )</td>
<td>0.063</td>
</tr>
<tr>
<td>( Nu )</td>
<td>4.511</td>
</tr>
</tbody>
</table>

**Fig. 3.** Streamlines and isotherms for present work compared with Lin and Violi [22] using \( Gr = 10^5 \), \( dp = 5 \), \( \varphi = 0.05 \) and \( Pr = 6 \).
the streamlines and isotherms for base fluid (pure water) and nano-fluid (water–Al₂O₃) are superimposed. But variation in velocity fields between two types of considered fluids becomes more efficient for higher values of \( Pr \). For base fluid, the pattern of the main cell becomes trapezoidal where a couple of inner tiny vortices appear at \( Pr = 8.81 \). But the nanofluid pattern remains similar.

**Fig. 4.** Effect of \( \phi \) on (a) isotherms and (b) Streamlines, while \( Pr = 6.2, AR = 1 \) (solid lines for nanofluid and dashed lines for base fluid).
strength of the flow circulation is much higher in the presence of nanoparticles in particular for a high Pr values. This fact due to solid concentration of nanoparticles does not have considerable effect when Pr is low. On the other hand, the isotherms are clustered near the left inclined surface of the enclosure, which indicates a temperature gradient in the horizontal direction in this region. The thin

Fig. 5. Effect of Pr on (a) isotherms and (b) Streamlines, with $\phi = 0.03$, $AR = 1$ (solid line for nanofluid and dashed line for base fluid).
boundary layer enhances when the Prandtl number devalues. It is well known that, temperature of fluid devalues with escalating Pr. Then rate of heat transfer is enhanced.

4.3. Influence of cavity aspect ratio

The streamlines and isotherms for various AR at Pr = 6.2 and φ = 0.03 are displayed in Fig. 6(a) and (b). For all AR, the flow rotates in the clockwise direction, indicating that the fluid filling the enclosure is moving up along both the left heated wall and the top insulated wall, down along the cool right wall and horizontally to the left along the insulated base enclosure. The shape of eddy changes from vertical to horizontal due to increasing AR. For the lower aspect ratio which is considered to be tall cavity, there exist a greater dissimilarity between base fluid and nanofluid. The distance between hot and cold surfaces in this tall enclosure is very small. Cold surface can takes heat from hot wall very rapidly. Thus, the rate of heat transfer becomes more effective than the other values of AR. The boundary layer thickness near the hot inclined surface decreases with growing AR. In addition, isotherm patterns are almost similar for both fluid and water–Al₂O₃ nanofluid.

4.4. Heat transfer rate, mean temperature of fluids and average velocity field

The effect of solid volume fraction (φ) on the normalized Nusselt number (Nu*), average Nusselt number (Nu), mean bulk temperature (θₐᵥ) and average velocity field (ωₓav) respectively are depicted in Fig. 7(a)–(d). It is clearly seen that the values of Nu* and Nu enhance as the values of the nanoparticles volume fraction φ rise from 1% to 7%. But the value of base fluid (φ = 0%) becomes constant. Rate of heat transfer enhances by 27% with the increasing values of φ from 1% to 7%. The rate of heat transfer for water–alumina nanofluid is found to be more effective than the clear water due to higher thermal conductivity of solid nanoparticles. Consequently, θₐᵥ grows with the variation of solid volume fraction. This is due to the fact that temperature of fluid rises for the higher thermal conductivity of nanofluid than base fluid (φ = 0%). ωₓav has notable changes with different values of solid volume fraction. Here base fluid has higher mean velocity than the water–Al₂O₃ nanofluid. Fig. 8(a)–(c) expresses the average Nusselt number along the hot wall, mean bulk temperature (θₐᵥ) of both type of fluids in the enclosure and average velocity field (ωₓav) respectively for the variation of Prandtl number Pr. Nu*, θₐᵥ and ωₓav are considered as a function of Pr. It is seen that the average Nusselt number, a measure of heat transfer is optimized at the highest Pr for both type of fluids. Fig. 8(a) shows that heat transfer rate increases by 46% and 37% due to rising Pr from 1.47 to 8.81 for nanofluid and base fluid respectively. Thus, the heat transfer rate is more effective for nanofluid than the base fluid. This mitigation of heat transfer is mainly attributed to the effective dynamic viscosity which is predominant in the natural convection of nanofluid for low effective thermal conductivity. On the other hand, it is observed from
Fig. 8(b) that $h$ devalues due to the variation of $Pr$ as temperature of fluid grows down with growing $Pr$. $x$ falls with different values of rising Prandtl number. This is due to the fact that the highly viscous fluid can’t move freely like low viscous fluid having lower Prandtl number.

The average Nusselt number, average temperature ($h_{av}$) and mean sub domain velocity ($x_{av}$) profile along with the cavity aspect ratio (AR) for both type of fluids are depicted in Fig. 9(a)–(c). It is seen from Fig. 9(a) that $Nu$ diminishes gradually due to variation of AR. Rate of heat transfer devalues by 18% and 13% with escalating values of AR from 0.5 to 2 for water alumina nanofluid and clear water respectively. It is well known that heat transfer rate is always higher for convection than radiation and is justified by the current investigation. Consequently Fig. 9(b) shows that ($h_{av}$) grows sequentially for all AR. Enhancing phenomena is seen from the Fig. 9(c) in the $x_{av}$–AR profile. Base fluid deserves higher average velocity than the nanofluid.

Future work is recommended to extend the current investigation to a model with concentration distributions of solid volume
5. Conclusion

The problem of natural convection heat transfer in a closed enclosure filled with water–Al₂O₃ nanofluid has been studied numerically. Various solid volume fraction, Prandtl number and aspect ratio have been considered for the flow and temperature fields as well as the heat transfer rate while $Re = 10^5$. The results of the numerical analysis lead to the following conclusions:

- The structure of the fluid flow and temperature field within the closed chamber is found to significantly depend upon the nanoparticle volume fraction, Prandtl number and cavity aspect ratio. The nanoparticle with the highest $\varphi$, $Pr$ as well as the lowest $AR$ are established to be most effective in enhancing performance of heat transfer rate.
- Escalating $\varphi$, $AR$ as well as the lowest $Pr$ causes the mean bulk temperature of the fluids maximum.
- Average velocity field is obtained higher for the base fluid than water alumina nanofluid.

Overall, the analysis also defines the operating range where water–Al₂O₃ nanofluid can be considered effectively in determining the level of heat transfer augmentation.

References


