STUDY OF CONVECTION HEAT TRANSFER ENHANCEMENT INSIDE LID DRIVEN CAVITY UTILIZING FINS AND NANOFLUID

by

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In the present study, the effect of suspension of nanoparticle on mixed convection flow is investigated numerically in lid driven cavity with fins on its hot surface. Study is carried out for Richardson numbers ranging from 0.1 to 10, fins height ratio change from 0.05 to 0.15 and volume fraction of nanoparticles from 0 to 0.03, respectively. The thermal conductivity ratio (k_{fin}/k_f) is equal to 330 and Grashof number is assumed to be constant (10^4) so that the Richardson numbers changes with Reynolds number. Results show that the heat transfer enhances by using nanofluid for all studied Richardson numbers. Adding fins on hot wall has different effects on heat transfer depend to Richardson number and height of fins. Use of low height fin in flow with high Richardson number enhances the heat transfer rate while by increasing the height of fin the heat transfer reduces even lower than it for pure fluid. The overall enhancement in Nusselt number by adding 3% nanoparticles and 3 fins is 54% at Ri=10. They cause reduction of Nusselt number by 25% at Ri = 0.1. Higher fins decrease the heat transfer due to blocking fluid at corners of fins.

Key words: *mixed convection, fin, nanoparticle, thermal conductivity*

Introduction

Mixed convection heat transfer within enclosure can be found in many industrial and engineering applications such as chemical processing equipment, electronic component cooling, food drying process, nuclear reactors, and so on. It is a complex phenomenon rather than natural or forced convection heat transfer because of considering the interaction between natural and forced convection. For this reason, there are a large number of published papers that deal with mixed convection especially inside lid driven cavity. The lid driven cavity problem has been extensively used as a benchmark case for evaluation of numerical solution algorithms [1-4]. Moallemi and Jang [5] studied the effect of Prandtl and Reynolds numbers on the flow and thermal characteristics of a laminar mixed convection in a rectangular cavity. Prasad and Koseff [6] have reported experimental results on mixed convection heat transfer process in a lid driven cavity for a different Richardson numbers ranging from 0.1 to 1000. Heat transfer results for mixed convection from a bottom heated open cavity subjected to an external flow were

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studied for $1 \le Re \le 2000$, $0 \le Gr \le 10^6$ and various aspect ratios ($A = 0.5$, 1, 2, and 4) by Leong *et al.* [7]. Darzi *et al.* [8] investigated the effect of the fins on mixed convection in lid driven cavity for various Richardson number and different height and number of fins. They found that heat transfer enhancement occurs in low fin height and high Richardson number.

There are a large number of published papers that deal with augmenting the heat transfer in various geometries by adding fins, coil and twisted tape insert, corrugation, dimple in regular and non-regular configurations [9-13]. In recent years, nanofluids have attracted more attention for cooling and heating in various geometries because of remarkable increase in effective thermal conductivity of base fluid [14-19]. Masuda *et al.* [20] reported on enhanced thermal conductivity of dispersed ultra-fine (nanosize) particles in liquids. Soon thereafter, Choi [21] was the first to coin the term *nanofluids* for this new class of fluids with superior thermal properties. There are some large numbers of researches and published papers about the role of nanoparticles in natural and mixed convection heat transfer [22-26]. Khanafer *et al.* [27] investigated the heat transfer enhancement in a 2-D enclosure utilizing nanofluids for a range of Grashof numbers and volume fractions. It was found that the heat transfer across the enclosure increases with the volumetric fraction of the Cu nanoparticles in water for different Grashof numbers. Talebi *et al.* [28] presented a numerical study of laminar mixed convection through Cu-water nanofluid in a square cavity for different Reynolds and Rayliegh numbers. They concluded that the effect of solid concentration decreases by the increase of Reynolds number. Hajmohammadi *et al.* [29] carried out a numerical study on laminar boundary-layer flow of nanofluid (Cu-water and Ag-water) over a permeable flat plate with convective boundary condition. They investigated for first time the effect of type of nanofluid, concentration of nanoparticles, and permeability of flow on skin friction and heat transfer coefficients. They found that the skin friction and heat transfer coefficients are more sensitive by concentration of nanoparticles than the type of nanofluid. Also their results indicated that the convective heat transfer rate is augmented by increasing nanoparticles concentration for case of injection and impermeable surface while in the case of suction, adding Cu and Ag particles reduces the convection heat transfer coefficient at the surface. Nemati *et al.* [30] investigated the effect of various nanofluids on mixed convection flows using lattice Boltzmann method. They achieved the effects of solid volume fraction grow stronger sequentially for Al_2O_3, CuO, and Cu. Hosseini *et al.* [31] applied Lattice Boltzmann method to study the heat transfer of different nanofluids in cavity with partially heated walls. They investigated the effects of Rayleigh number, nanoparticles type, inclination angle of cavity and nanoparticle concentration on heat transfer and flow field. They found that the type of nanoparticles is the key factor for enhancing the heat transfer. The Cu nanoparticles had highest enhancement in heat transfer among investigated nanoparticles (Ag, Al_2O_3, TiO_2, Cu). Rashidi *et al.* [32] performed a numerical study on natural convection heat transfer of nanofluid in cavity with heterogeneous heating from bottom. They considered the right wall as cold wall while left and top walls are adiabatic. They used nine different cases for non-uniform heat flux to investigate the effects of Rayleigh number, volume fraction of nanoparticles and aspect ratio of cavity on Nusselt number. They found that the trend of Nusselt number is different at low Rayleigh number where heat conduction is the dominant heat transfer mechanism. Abu-Nada and Chamkha [33] investigated a numerical study on heat transfer of CuO-water nanofluid in lid driven cavity. They studied the effects of nanoparticles concentration at different Richardson number for various aspect ratios of cavity. They reported the significant enhancement in heat transfer by adding nanoparticles.

In present study, the combined effect of the fins and various volume fraction of Cu nanoparticle on mixed convection flows are investigated numerically for different Richardson numbers ranging from 0.1 to 10. Study is carried out for constant Grashof number of 10^4 so that Richardson number changes with Reynolds number. Results are provided as streamlines, isotherms, local and average Nusselt number plots.

Governing equation

The treated problem is a 2-D square lid driven cavity with sides length, H. The computational domain considered in present study is shown in fig. 1.

The fins thickness is considered to be $0.01H$. The vertical walls are assumed adiabatic, while the horizontal walls are maintained at uniform temperature. The top and bottom walls are considered as cold and hot walls, respectively. In addition, the top wall is slide at a constant speed. The properties of Cu nanoparticles and water as base fluid are given in tab. 1.

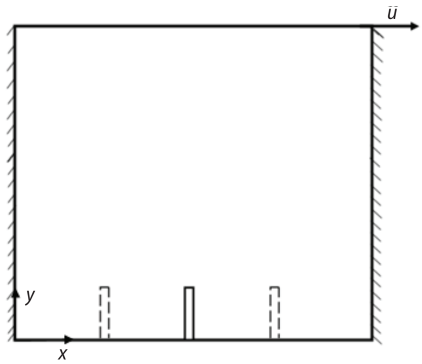

Figure 1. Geometry of problem for cavity with fins

Table 1. Thermophysical properties of base fluid and nanoparticles

Property	Water	Cu
ρ [kgm^{-3}]	997.1	8954
c_p [kJkg^{-1}]	4179	383
k [Wm^{-1}K^{-1}]	0.6	400
β [K^{-1}]	$2.1\cdot10^{-4}$	$1.67\cdot10^{-5}$

Considering the nanofluid as a continuous media with thermal equilibrium between the base fluid and the solid nanoparticle, the governing equations are:

– Continuity

- X-momentum equation

$$u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=\frac{1}{\rho_{\text{nf}}}\left(-\frac{\partial p}{\partial x}+\mu_{\text{nf}}\nabla^2 u\right) \tag{1}$$

- Y-momentum equation

$$u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}=\frac{1}{\rho_{\text{nf}}}\left[-\frac{\partial p}{\partial y}+\mu_{\text{nf}}\nabla^2 v+(\rho\beta)_{\text{nf}}g_y(T-T_{\text{ref}})\right] \tag{2}$$

– Energy equation

$$u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}=\frac{\partial}{\partial x}\left[\frac{k_{\text{eff}}}{(\rho c_p)_{\text{nf}}}\frac{\partial T}{\partial x}\right]+\frac{\partial}{\partial y}\left[\frac{k_{\text{eff}}}{(\rho c_p)_{\text{nf}}}\frac{\partial T}{\partial y}\right] \tag{3}$$

The effective density of nanofluid is defined:

$$\rho_{\text{nf}}=(1-\phi)\rho_{\text{f}}+\phi\rho_{\text{s}} \tag{4}$$

Whereas the heat capacitance of the nanofluid and part of the Boussinesq term are:

$$(\rho c_p)_{\text{nf}}=(1-\phi)(\rho c_p)_{\text{f}}+\phi(\rho c_p)_{\text{s}} \tag{5}$$

$$(\rho\beta)_{\text{nf}}=(1-\phi)(\rho\beta)_{\text{f}}+\phi(\rho\beta)_{\text{s}} \tag{6}$$

with ϕ being the volume fraction of the solid particles and subscripts f, nf, and s stand for base fluid, nanofluid and solid particle, respectively. The effective viscosity of nanofluid was introduced by Brinkman [34]:

$$\mu_{\mathrm{eff}} = \frac{\mu_{\mathrm{f}}}{(1-\phi)^{2.5}} \tag{7}$$

The effective thermal conductivity of nanofluid was given by Patel *et al.* [35]:

$$k_{\mathrm{eff}} = k_{\mathrm{f}} + k_{\mathrm{p}} \frac{A_{\mathrm{p}}}{A_{\mathrm{f}}} + c k_{\mathrm{p}} \,\mathrm{Pe} \frac{A_{\mathrm{p}}}{A_{\mathrm{f}}} \tag{8}$$

where c is constant and must be determined experimentally, $A_{\mathrm{p}}/A_{\mathrm{f}}$ and Pe here are defined:

$$\frac{A_{\mathrm{p}}}{A_{\mathrm{f}}} = \frac{d_{\mathrm{p}}}{d_{\mathrm{f}}} \frac{\phi}{1-\phi} \tag{9}$$

$$\mathrm{Pe} = \frac{u_{\mathrm{p}} d_{\mathrm{p}}}{\alpha} \tag{10}$$

where d_{p} is the diameter of solid particles that in this study is assumed to be equal to 100 nm, d_{f} – the molecular size of liquid that is taken as 2Å for water, and u_p – the Brownian motion velocity of nanoparticle which is defined:

$$u_{\mathrm{p}} = \frac{2 k_{\mathrm{B}} T}{\pi \mu_{\mathrm{f}} d_{\mathrm{p}}^2} \tag{11}$$

where k_{B} is the Boltzmann constant. The local and average Nusselt numbers are defined:

$$\mathrm{Nu}_{\mathrm{l}} = \frac{k_{\mathrm{eff}}}{k_{\mathrm{f}}} \left. \frac{\partial \theta}{\partial n} \right|_{n=0} \tag{12}$$

$$\mathrm{Nu}_{\mathrm{m}} = \frac{1}{L} \int_0^L \mathrm{Nu}_{\mathrm{l}} \,\mathrm{d}l \tag{13}$$

where L (path of bottom wall and fins) and θ (dimensionless temperature) are calculated:

$$L = H + 2 \times (\text{number of fins}) \times A \tag{14}$$

$$\theta = \frac{T - T_{\mathrm{c}}}{T_{\mathrm{h}} - T_{\mathrm{c}}} \tag{15}$$

Numerical procedure and validation

The mentioned equations in the previous section are solved by unsteady turbulent flow at non-orthogonal co-ordinates code which is a house computer code for computation of 2-D steady/unsteady and turbulent/laminar flows in FORTRAN [36]. The finite volume method is applied to transfer the PDE to algebraic relations. Then the strongly implicit procedure algorithm is used to solve the obtained algebraic equations. The present code utilizes the collocated variable arrangement and use Cartesian velocity components in which all variables are stored at the same control volume. In order to solve the Navier-Stoks and continuity equations the SIMPLE method supplying the pressure-velocity coupling, is used. This method has its origin in staggered grid methodology and is adapted to collocated grid methodology through the use of Rhio and Chow interpolation in [37]. This interpolation can increase the stability of solution too. The unsteady term is discretized by a three-time levels method (not used here). In addition, three different discretization schemes are available to approximate the convective terms, upwind/central difference and hybrid schemes. Diffusion term is discretized by central difference scheme (CDS). In this study, the convection and diffusion term of the equations are discretized by CDS. Convergence of the solution was checked at each case, with the convergence criterions of 10^{-5} for momentum and continuity and 10^{-8} for energy. Further details about the numerical method have been discussed by Farhadi *et al.* [38]. A validation is performed and its results are showed in tab. 2. The comparison is fulfilled at three Rayleigh numbers, 10^4, 10^5, and 10^6. As it can be observed from tab. 2, the accuracy of present work in comparison with benchmark [2] is good.

Table 2. The validation of the current results in a square cavity

	$\dfrac{u_{max}H}{\alpha}$	$\dfrac{v_{max}H}{\alpha}$	Nu_m
$Ra = 10^4$			
Benchmark	16.187	19.617	2.243
Present work	15.71	20.15	2.2394
$Ra = 10^5$			
Benchmark	34.730	68.590	4.519
Present work	35.54	70.341	4.56
Ra = 106			
Benchmark	64.630	219.36	8.800
Present work	58.43	223.1	8.95

In order to validate our finding by Talebi *et al.* [28] results, a comparison of average Nusselt number is done for Re = 100 and Ra = $1.47 \cdot 10^5$ at various volume fraction of nanoparticles, fig. 2. To check the grid independency, the average Nusselt number over the bottom wall (hot wall) was calculated at different grid points. The study of grid dependence has been performed at Ri = 0.4 for three non-uniform grids that is listed in tab. 3. Results show that, when the numbers of grid points pass from a 250 × 50 to 302 × 80 and after to 352 × 100, the average Nusselt number increases 4.2% and 0.5%, respectively. Therefore, the grid 302 × 80 is sufficient for this simulation.

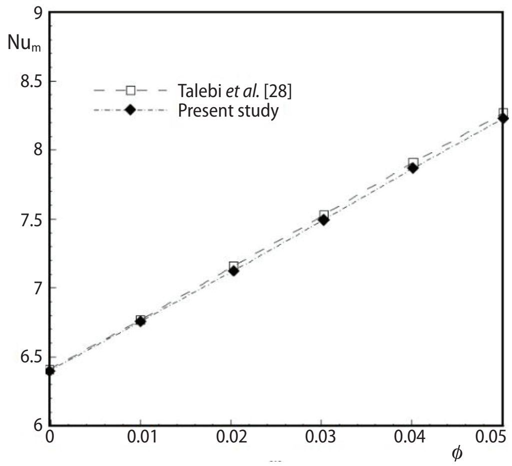

Figure 2. Comparison of the average Nusselt number along hot surface between present study and Talebi *et al.* [28] at Re = 100, Ra = $1.47 \cdot 10^5$, and Pr = 6.2

Results and discussion

Mixed convection flows is investigated for a Cu-water nanofluid in a square cavity with the fins on hot wall for different Richardson numbers and solid volume fraction ranging from 0.1 to 10 and 0 to 0.03, respectively. Streamlines and temperature contours for cavity without fin, with 1 fin (A = 0.05 and 0.1) and 3 fins (A = 0.05) are presented at different Richardson numbers in figs. 3-5. In these figures, lines and dashed lines refer to pure fluid and nanofluid with solid volume fraction of 0.03, respectively. Result indicates there is a vortex in right corner of cavity. It gets greater by increasing Richardson number. Richardson number represents the power of natural convection to forced convection. At high Richardson number, where natural convection is dominant, the momentum of fluid driven by lid is not enough to overcome the natural

Table 3. Study of solution sensitivity to number of grids

Number of grids	Averaged Nusselt number on hot wall
250 × 50	5.0402
302 × 80	5.2617
352 × 100	5.2880

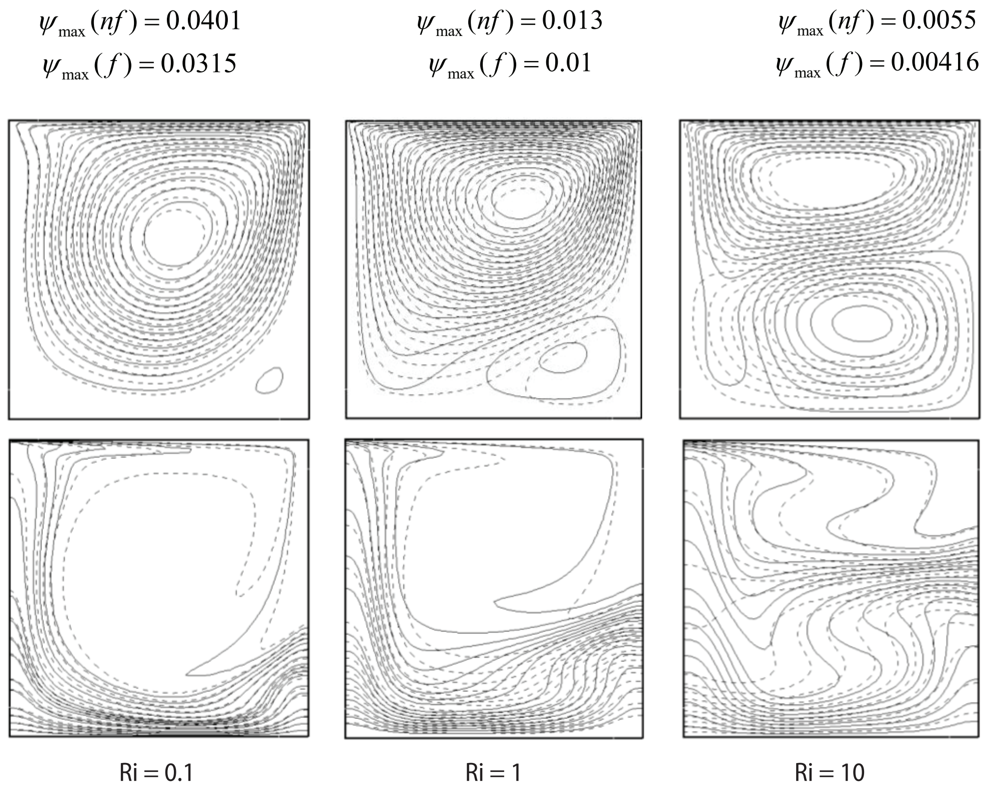

Figure 3. Streamlines and temperature contours for cavity without fin; solid line ($\phi = 0$), dashed line ($\phi = 0.03$)

convection and therefore, a large vortex covers right corner of bottom region. While for low and moderate Richardson number, the cold fluid close to lid moves down and passes over hot wall. The temperature contour shows that temperature gradient near hot wall decreases by increasing the Richardson number.

Adding nanoparticle to base fluid increases the viscosity and thermal conductivity of mixture. Results show that the stream function for nanofluid is greater than one for pure fluid at Richardson number of 0.1. However, at low Richardson number, where forced convection is dominant, the nanoparticles have not significant effect on streamline where the momentum of flow is great enough to be not affected. By increasing the Richardson number, momentum of fluid is weakened as natural convection is empowered. The vortex expands all over hot wall by adding nanoparticles (dash line). In this way, it does not allow the cold fluid driven by lid to pass over hot wall. For cases with mixed convection dominant (Ri = 1), although the value of stream function has no significant changes, the size of small vortex in the right corner of cavity reduces and therefore, the stream become closer to the hot wall. The effect of flow pattern variation with nanofluid can be seen in the temperature contours. It is due to the variation of the thermal conductivity and subsequently the heat transfer rate to the fluid in the cavity. Adding fin on hot wall increase the heat conduction while it causes some little changes on streamline especially for higher height of fin, figs. 4 and 5. At low and moderate Richardson number, the fin has a negative effect on flow field and reduces the momentum of the fluid next to hot wall, so the convection heat transfer decreases in this situation. By adding the fins, the effect of the nanofluid in the heat transfer is more sensitive at low Richardson number in comparison with pure fluid which are shown in the temperature contours and streamlines at figs. 4 and 5. Using the fin with low height has a positive effect on heat transfer rate only for high Richardson number regime where natural convection is dominant. This effect is weaker at moderate Richardson number of 1.

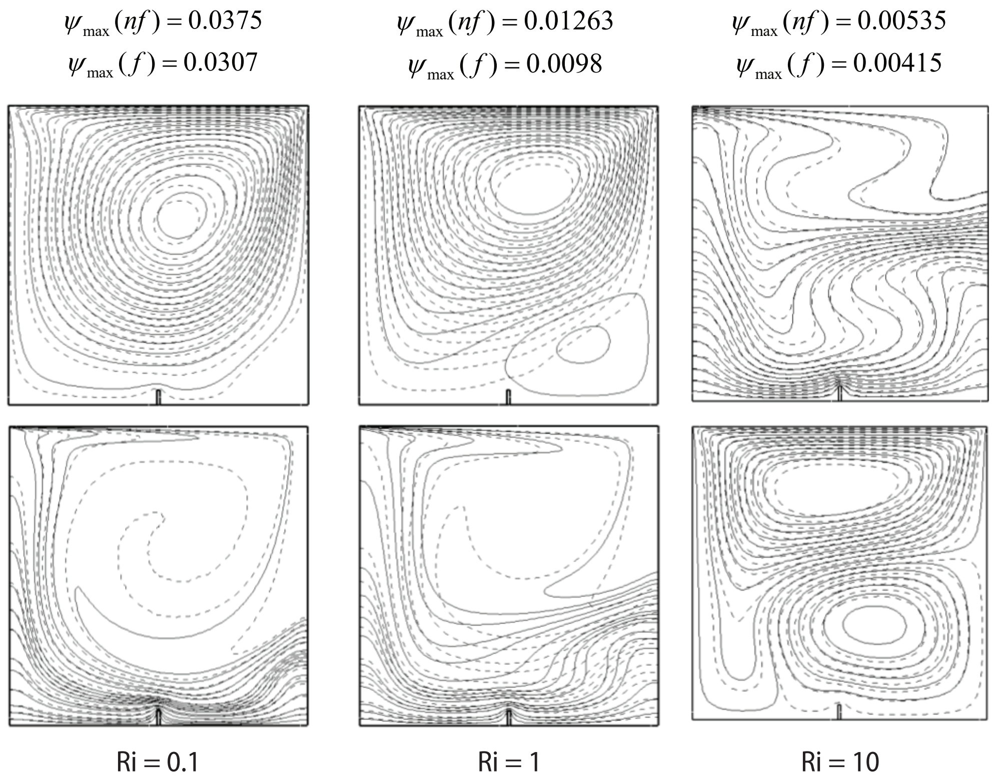

Figure 4. Streamlines and temperature contours for cavity with 1 fin (A = 0.05); solid line (ϕ = 0), dashed line (ϕ = 0.03)

Figure 6 illustrates the evaluations of y-velocity in the middle of the cavity for different Richardson numbers and different volume of Cu nanoparticles for case without fin. It indicates that the velocity decreases significantly by rise of Richardson numbers where momentum of flow induced by lid is reduced. At Ri = 0.1, the velocity of fluid in central region (from 0.25 to 0.75) of middle line of the cavity decreases for higher volume fraction of nanoparticles. The maximum difference between y-velocity for different volume fractions occurs in vicinity of vertical wall (x = 0.15 and x = 0.85) where the velocities have its maximum values. By increasing Richardson number, the relative difference between flow velocities for different volume fractions of nanoparticles grows. It indicates that the adding nanoparticles have more influence on flow dominated by natural convection where the momentum of flow is low. This effect becomes more significant at Richardson number of 10 where the behavior of velocity changes at right part of the cavity.

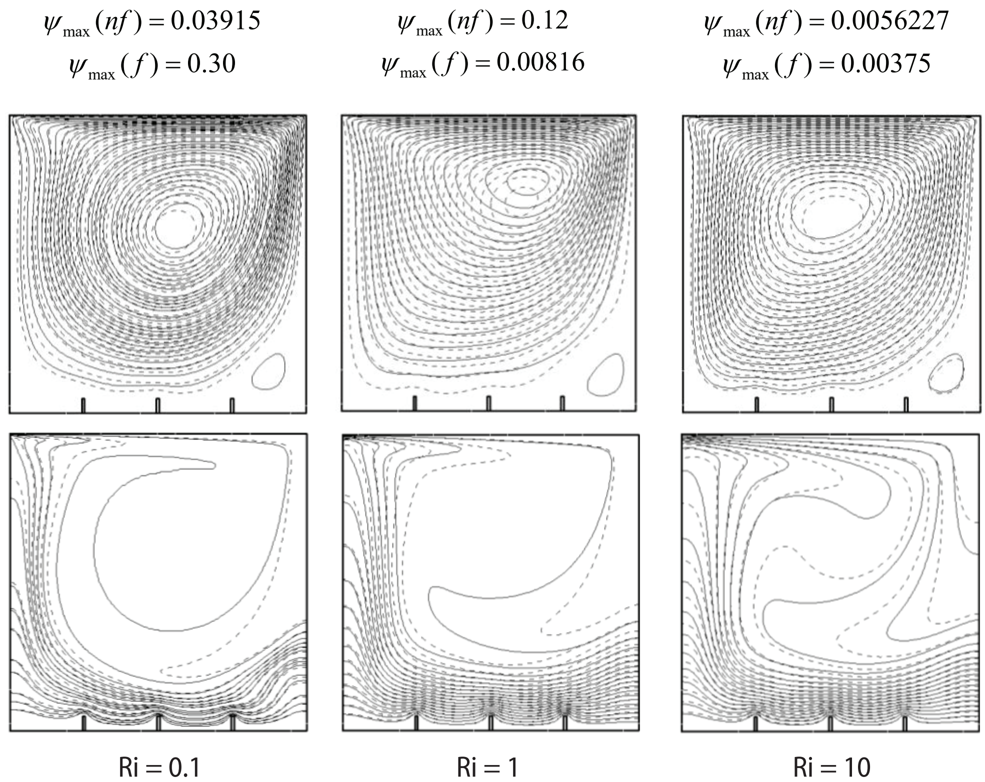

Figure 5. Streamlines and temperature contour for cavity with 3 fins (A = 0.05); solid line (ϕ = 0), dashed line (ϕ = 0.03)

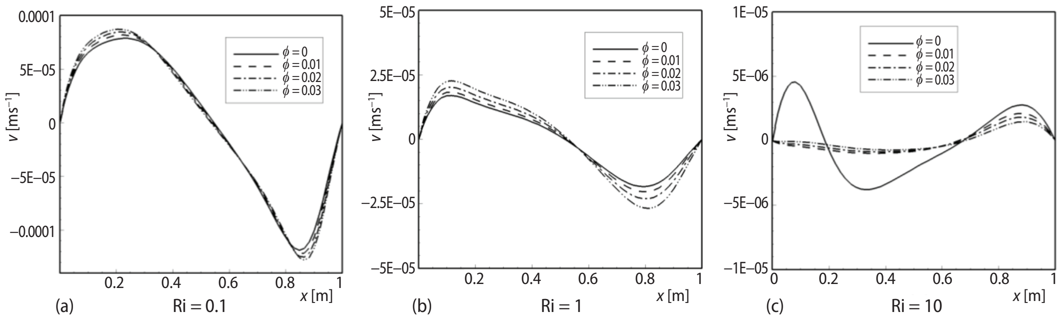

Figure 6. Velocity in the middle of the cavity for different Richardson numbers and volume of nanoparticles

The local variation of Nusselt number on hot wall of cavity are illustrated for different Richardson number in fig. 7, it can be seen that for low and moderate Richardson numbers, the local Nusselt number increase throughout hot wall by increasing volume fraction of nanoparticles. While it indicates that for high Richardson number, the heat transfer enhances only at left part of hot wall. At right part of wall where covered by big vortex, the base fluid has better heat transfer.

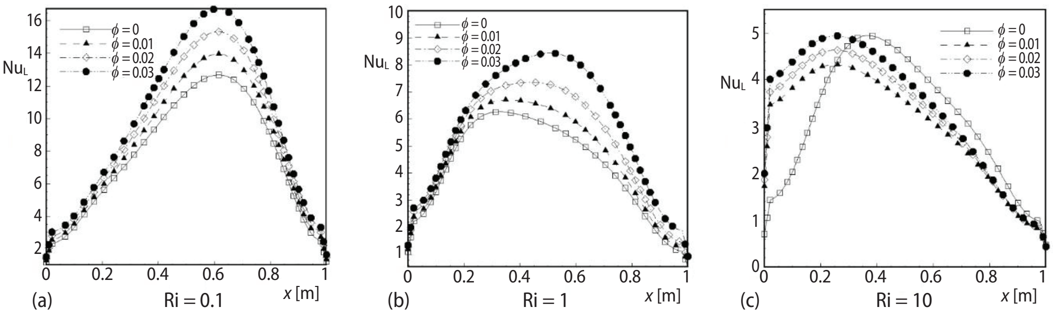

Figure 7. Variation of local Nusselt number along hot surface for cavity without fin

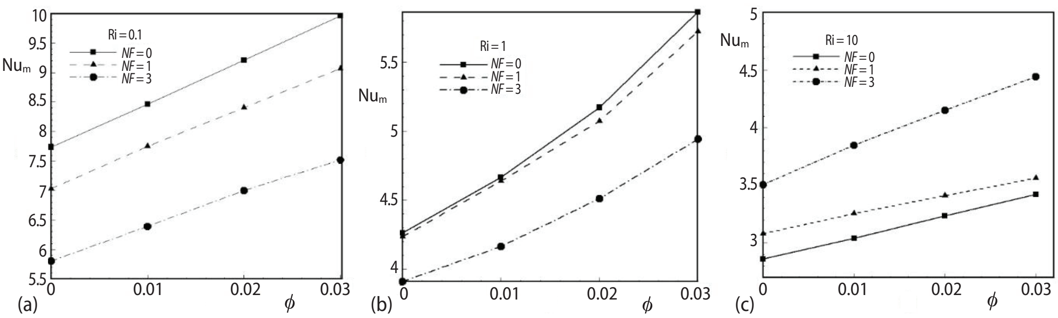

Figure 8. Variation of average Nusselt number over the hot surface of cavity for A = 0.05

Figure 8 indicates that increasing the fin numbers reduces heat transfer rate where the momentum of cold fluid driven by lid which moves over hot wall and then the heat convection decreases. Results reveals that the adding 1 and 3 fins to cavity at Ri = 0.1 decrease Nusselt number by 10% and 25%, respectively. These reductions are identical for nanofluid with different volume fractions in this Richardson number while this behavior changes for Ri = 1 where the maximum reduction in Nusselt number occurs at high volume fraction (4% for case with 1 fin and 21% for case with 3 fins). In contrary with low and moderate Richardson numbers, adding fins cause significant enhancement in the heat transfer at Ri = 10 where natural convection is dominant. Also, the result depicts that at Ri = 10, adding more fins to nanofluid with higher volume fraction is more efficient. The overall increment in Nusselt number by 3 fins and nanoparticles (ϕ = 0.03) is 54%.

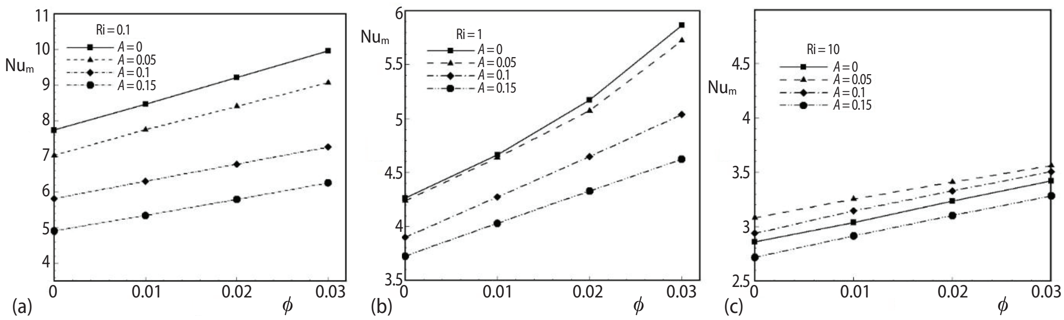

Figure 9. Variation of average Nusselt number over the hot surface with 1 fin for different fin height

Our investigation shows that the fin height is also important in this enhancement, fig. 9. When the fin height is bigger than 0.05, the rate of the heat transfer enhancement decreases and even fall down to lower than the heat transfer in the cavity without fin at A = 0.15 for all Richardson numbers. It is due to creation of small recirculation areas between fins which decreases the temperature gradient near the hot wall of the cavity, fig. 10.

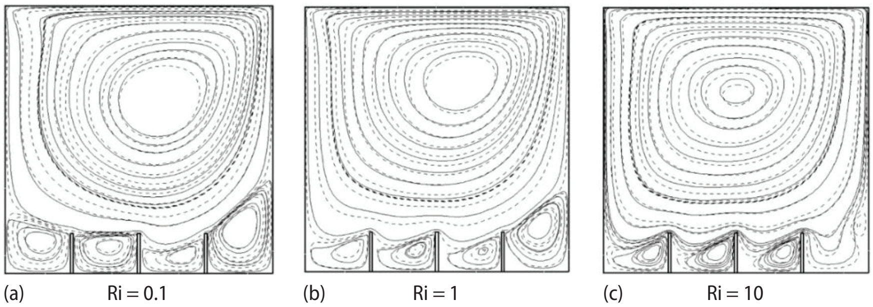

Figure 10. Streamlines for cavity with 3 fins (A = 0.15)

Conclusion

In the present study, the effect of nanofluid on mixed convection flow was investigated numerically in lid driven cavity with fins mount on its hot surface. The results were presented at different Richardson numbers, fin height and numbers and different volume fraction of the nanoparticles. Results show that the fin enhances the heat transfer rate only at high Richardson number. It is observed that the fin height has a main role in heat transfer. At low fin height, the heat transfer rate increases and by increasing the fin height, the heat transfer decreases. Adding nanoparticle has a positive effect and increases the Nusselt number in all cases.

Acknowledgment

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Nomenclature

A – dimensionless fin height, [–]
Gr – Grashof number, $(= g\beta H^3 \Delta T / \nu^2)$, [–]
g – gravitational acceleraion, [ms^{-2}]
H – cavity length, [m]
k – thermal conductivity of fluid, [Wm^{-1}K^{-1}]
L – path of hot surface, [m]
NF – number of fins, [–]
Nu – Nusselt number, [–]
n – normal to any direction, [–]
Pr – Prandtl number, $(= \nu_f / \alpha_f)$, [–]
p – pressure, [Pa]
Re – Reynolds number, $(= U_0 H / \nu)$, [–]
Ri – Richardson number, $(= \mathrm{Gr} / \mathrm{Re}^2)$, [–]
T – temperature, [K]
U_0 – sliding top wall velocity, [ms^{-1}]
u, v – velocity components in x, and y co-ordinate, [ms^{-1}]

Greek symbols

α – thermal difussivity, [m^{2}s^{-1}]
β – thermal expansion coefficient, [K^{-1}]
θ – dimensionless temperature, [–]
μ – dynamic viscosity, [kgm^{-1}s^{-1}]
ν – kinematic viscosity, [m^{2}s^{-1}]
ρ – density of the fluid, [kgm^{-3}]
ψ – stream function
ϕ – volume fraction of nanoarticles

Subscripts

c – cold
f – fluid
h – hot
l – local
max – maximum
m – mean
nf – nanofluid
s – solid

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