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Effect of Brownian Motion in Heat Transfer of H_2O-Cu Nanofluid using LBM

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Abstract : The main objective of this study is to investigate the fluid flow and the heat transfer characteristics of nanofluids using multi-phase thermal LBM and to realize the enhancement of heat transfer characteristics considered in the Brownian motion. In multi-phase, fluid component(H_2O) is driven by Boussinesq approximation, and nanoparticles component by the external force gravity and buoyancy. The effect of Brownian motion as a random movement is modified to the internal velocity of nanoparticles(Cu). Simultaneously, the particles of both the phases assume the local equilibrium temperature after each collision. It has been observed that when simulating H_2O-Cu nanoparticles, the heat transfer is the highest, at the particle volume fraction 0.5% of the particle diameter 10 nm. The average Nusselt number is increased approximately by 33% at the particle volume fraction 0.5% of the particle diameter 10 nm when compared with pure water.

Key words : LBM, Nanofluids, Brownian motion, Multi-phase, Heat transfer, Natural convection

1. Introduction

Nanofluids should not only significantly improve heat transfer capabilities, but also should increase the stability of the suspensions. However, the mechanism of nanofluids is not known clearly until now. There are many parametric effects on nanofluids thermal conductivity enhancement, such as particle size and shape, concentration and Brownian motion, etc. In the middle of these, many researchers proposed that Brownian motion maybe one of the possible mechanisms of nanofluids. J. Buongiorno[1] indicated that Brownian diffusion and thermophoresis have been identified as the two most important nanoparticle/base-fluid slip mechanisms. Seok Pil Jang and Stephen U.S.Choi[2] found that the Brownian motion of nanoparticles at the molecular and nanoscale level is a key mechanism governing the thermal behavior of nanoparticle-fluid suspensions. Wang et al.[3] argued that the thermal conductivities of nanofluids should be dependent on the microscopic motion(Brownian motion and inter-particle forces) and particle structure. Koo and

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Kleinstreuer[4] discussed the effects of Brownian, thermo-phoretic, and osmo-phoretic motionson the effective thermal conductivities. In accordance with research conducted so far, one can conclude that Brownian motion plays an important role in nanofluids.

The Lattice Boltzmann Method (LBM) is one of the methods available to simulate flows containing multiple phases and components. But, in most of the study, researchers often use effective thermal conductivities to solve nanofluids at a single phase. M.A. Taher et.al [5] simulated H_2O-Cu nanofluids using LBM and concluded that the nanoparticle enhanced the heat transfer rate of maximum 41% in the range of Rayleigh number, $10^4 \leq Ra \leq 10^6$ for the particle volume fraction Φ = 2%. However, it was also simulated by effective thermal conductivities. So far only minimum research has been conducted in applying the Brownian motion using LBM.

Based on these facts, the main objective of this study is to investigate the fluid flow and the heat transfer characteristics of nanofluids using multi-phase thermal LBM and to investigate the enhancement of heat transfer characteristics when the effect of Brownian motion as a random movement is modified to the internal velocity of nanoparticles(Cu) in heat transfer of H_2O-Cu nanofluids.

2. Formulation of the problem

The evolution equation of multi-component Lattice-Boltzmann equation (LBE) can be written as

$$f_i^{\sigma}(x+e_i\Delta t, t+\Delta t) - f_i^{\sigma}(x,t) = -\frac{1}{\tau_m^{\sigma}}\left(f_i^{\sigma}(x,t) - f_i^{\sigma,eq}(x,t)\right) + \frac{2\tau_m^{\sigma}-1}{2\tau_m^{\sigma}}\frac{D}{A_i c^2}\vec{e}_i \cdot \vec{F}^{\sigma} \quad (1)$$

Here, $\omega^{\sigma} = 1/\tau_m^{\sigma}$ is the relaxation parameter of $\sigma = f, p$ components, where f is fluid, p is nanoparticle. e_i is the discrete velocity vector, A_i is the adjustable coefficient, which ensures the conservation of mass and momentum of fluids. A_i can expressed by Xuan[6] as $A_0 = 1, A_i = 6, i = 1,2,3,4$ and $A_i = 24, i = 5,6,7,8.$ D is the dimension and F^{σ} is applied force. For two dimensional D2Q9 (two dimensional lattice with nine velocities) model, the equilibrium distribution function $f_i^{\sigma,eq}(x,t)$ can be defined as

$$f_i^{\sigma,eq} = \rho^{\sigma}\omega_i[1 + \frac{3}{c^2}\vec{e}_i\vec{u}^{\sigma,eq} + \frac{9}{2c^4}(\vec{e}_i\vec{u}^{\sigma,eq})^2 - \frac{3}{2c^2}u^{\sigma,eq^2}] \quad (2)$$

where ω_i is the lattice weighting factors. Therefore the equilibrium velocity becomes

$$\vec{u}^{eq} = \frac{\sum_{\sigma}\rho^{\sigma}\vec{u}^{\sigma}/\tau_m^{\sigma}}{\sum_{\sigma}\rho^{\sigma}/\tau_m^{\sigma}} + \frac{\vec{F}^{\sigma}}{2\rho^{\sigma}} \quad (3)$$

Simultaneously, the lattice Boltzmann energy equation for two components defined as

$$g_i^{\sigma}(x+e_i\Delta t, t+\Delta t) - g_i^{\sigma}(x,t) = -\frac{1}{\tau_{\theta}^{\sigma}}\left(g_i^{\sigma}(x,t) - g_i^{\sigma,eq}(x,t)\right) \quad (4)$$

where τ_{θ}^{σ} is the relaxation time constant

for energy of the σ th component of the fluid. The energy distribution function at the equilibrium state $g_i^{\sigma,eq}$ canbewrittenas

$$g_i^{\sigma,eq} = \varepsilon^{\sigma} w_i [1 + \frac{3}{c^2}\vec{e}_i.\vec{u}^{\sigma,eq} + \frac{9}{2c^4}(\vec{e}_i.\vec{u}^{\sigma,eq})^2 - \frac{3}{2c^2}u^{\sigma,eq^2}] \quad (5)$$

Where ε^{σ} is the internal energy variable of the components and is defined as

$$\varepsilon^{\sigma}(x,t) = \sum_i g_i^{\sigma}(x,t) \quad (6)$$

It is noted that the internal energy e^s is related (proportional) to the temperature by the thermodynamic relation $\varepsilon^{\sigma} = \rho^{\sigma} c_p^{\sigma} T^{\sigma}$.

The viscosity coefficient n and thermal diffusivity a can be written as

$$\nu^{\sigma} = \left(\sum_{\sigma} c_m^{\sigma}\tau_m^{\sigma} - \frac{1}{2}\right)c^2\Delta t \quad (7)$$

$$\alpha^{\sigma} = \left(\sum_{\sigma} c_{\theta}^{\sigma}\tau_{\theta}^{\sigma} - \frac{1}{2}\right)c^2\Delta t \quad (8)$$

Where c_m^{σ} and c_{θ}^{σ} are the concentration of viscosity and diffusivity of each component respectively. The above equations are used to connect between microscopic and macroscopic. Finally the Lattice-Boltzmann equation can recover the N-S equations both for velocity and temperature as follows:

$$\vec{u} = \frac{\sum_{\sigma} m^{\sigma} \sum_i f_i^{\sigma}(x,t)\vec{e}_i}{\sum_{\sigma}\rho^{\sigma}} + \vec{F}_i^{\sigma} \quad (9)$$

$$T = \frac{\sum_{\sigma}\varepsilon^{\sigma}(x,t)}{\sum_{\sigma}\rho^{\sigma}C_p^{\sigma}} \quad (10)$$

In single-component of LBM, e_i is the discretevelocity of particles. And in D2Q9 model, $e^f = \sqrt{3RT} = c$. In order to apply the Brownian motion of random movement in multi-component of the LBE, fluids component are applied to the normal e^f, and the nanoparticle component is applied to the velocity, which is driven by the Brownian motion can be defined as:

$$e^p = \sqrt{\frac{2\alpha}{t}} \quad (11)$$

α is the diffusion coefficient of the nanoparticles, t is the time. It is deduced by the Brownian motion of Langevin's Approach as follows:

$$2\alpha t = \left(\frac{RT}{N}\frac{1}{3\pi\mu r}\right)t \quad (12)$$

$$\alpha = \frac{RT}{N}\frac{1}{6\pi\mu r} \quad (13)$$

μ is the viscosity of fluid medium, r is the radius of spherical particles, N is the Avogadro's number, R is gas constant, T is absolute temperature. So, the particle of velocities of each component e_i^{σ} canbewrittenas

$$e_i^{\sigma} = \begin{cases} (0,0) & i = 0 \\ e^{\sigma}[\cos(\frac{i-1}{2}\pi), \sin(\frac{i-1}{2}\pi)] & i = 1,2,3,4 \\ \sqrt{2}e^{\sigma}[\cos(\frac{i-5}{2}\pi + \frac{4}{\pi}), \sin(\frac{i-5}{2}\pi + \frac{4}{\pi})] & i = 5,6,7,8 \end{cases}$$

Another modification procedure similar to that of the velocity distribution (9) can be applied to the equilibrium temperature in order to account for heat exchange between the suspended nanoparticles and the carrier liquid. For such a purpose, the

particles of both the phases assume the local equilibrium temperature after each collision and the following expression for the energy exchange. It was proposed to renew the temperature value for each component[7]:

$$T_{new}^{\sigma} = T_{old}^{\sigma} + \Delta t \frac{dT}{dt} = T_{old}^{\sigma} + \Delta t \Phi^{\sigma\bar{\sigma}} \quad (14)$$

Where $\Phi^{\sigma\bar{\sigma}} = h^{\sigma\bar{\sigma}} S^{\sigma}[T^{\bar{\sigma}}(x,t-\Delta t) - T^{\sigma}(x,t-\Delta t)]/(\rho c_p^{\sigma})$. S^{σ} is the specific surface area of the σ phase inside a lattice, $h^{\sigma\bar{\sigma}}$ is the heat transfer coefficient between phase σ andphase $\bar{\sigma}$. This parameter accounts for the thermal non-equilibrium between these two phases and may be determined with the heat transfer correlations for spherical particles in a flow[8].

3. Result and discussion

Consider a two dimensional square cavity as shown in Figure 1. The four walls of the cavity are at rest, so that the wall speed is $(u, v) = (0,0)$. The horizontal walls are assumed to be insulated whereas the vertical walls aremaintained at constant but different temperatures T_h (hot) and T_c (cold).

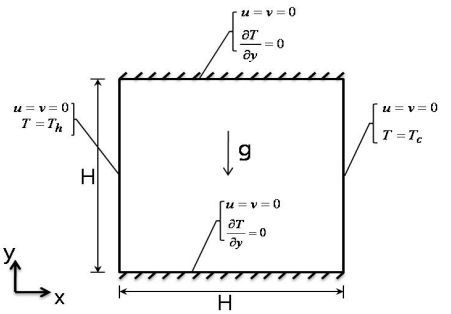


Figure 1: Schematic diagram of the computational configuration and coordinate system

It is considered that the cavity is filled uniformly with spherical copper nanoparticles. It is assumed that both the fluid phase and nanoparticles are in thermal equilibrium state and they flow at the same velocity. The properties of water and copper are shown in Table 1.

Table 1: Thermophysical properties of different phases

Property	**Water**(fluid phase) Pr=6.2	**Copper** (solid phase)
Cp (J/K-Kg)	4179	383
r (kg/m^3)	998	8954
K (W/m K)	0.6	400
b (1/k)	2.1×10^{-4}	1.67×10^{-5}
υ(m^2/s)	1.004×10^{-6}	

For natural convection, the momentum and energy equations are coupled and the flow is driven by temperature or mass gradient, i.e. buoyancy force. Hence there is an extra force term that needs to be considered in solving LB equations. Under Boussinesq approximation, the force term per unit mass can be written as

$$\vec{F}(\vec{x},t) = \rho(\vec{x},t)\, g\, \beta(T(\vec{x},t) - T_{ref}) \quad (15)$$

Where T_{ref} is the reference temperature of the fluid, g is the gravitation acceleration, β is the thermal expansion coefficient. The net buoyancy force acting on the fluid with a positive thermal expansion coefficient is in the opposite direction to the gravity. We need to calculate $g\beta$, from Rayliegh number definitions

$$\mathrm{Ra} = \frac{g\beta\Delta T H^3}{\nu\alpha} \quad (16)$$

where ν is the kinematic viscosity, $a = k/rCp$ is the thermal diffusivity and $DT = (T_h - T_c)$ is the temperature difference between left (hot) and right (cold) vertical walls. H is the physical dimension of the enclosure.

There are Several internal and external forces or potentials that are exerted on the nanofluid system. In this study, we considered the buoyancy and the gravitational force for the nanoparticle copper(Cu).

The buoyancy and gravity force of nanoparticles are given as:

$$F_H = -\frac{1}{6}\pi d_p g \Delta\rho' \tag{17}$$

Where d_p is the diameter of the nanoparticle and $\Delta\rho'$ is the mass density difference between the suspended nanoparticle and the base fluid.

In order to study the characteristics of nanofluids, two phase simulation was processed considering Brownian motion, simultaneously. And the result is as follows.

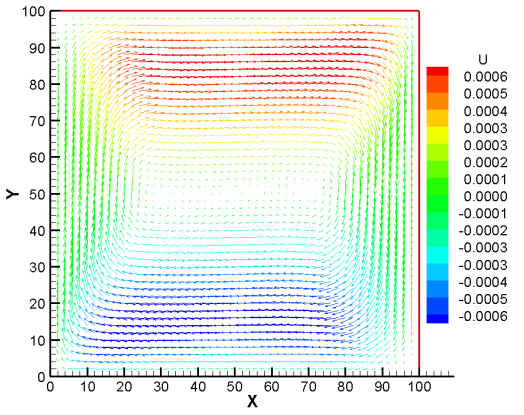


Figure 2: U-Velocity in Pure Water ($Ra=10^5$)

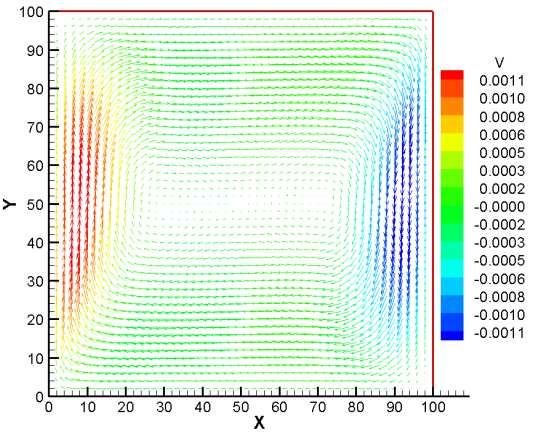


Figure 3: V-Velocity in Pure Water ($Ra=10^5$)

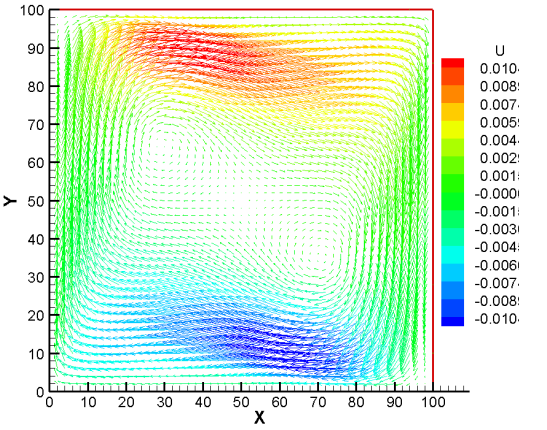


Figure 4: U-Velocity in Nanofluids(10nm, 1%Cu)

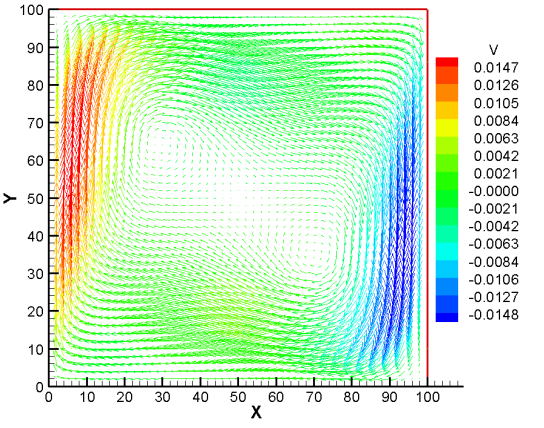


Figure 5: V-Velocity in Nanofluids(10nm, 1%Cu)

Figure 2. and Figure 3. is the U-Velocity and the V-Velocity in pure water at Ra=10^5, separately. Figure 4. and Figure 5. is the U-Velocity and V-Velocity in nanofluids at volume fraction 1% Cu of the particle diameter 10nm, separately. It can be seen that the velocity of the nanofluids is in order-of-magnitude typically higher than pure water due to Cu nanoparticles. Nanoparticles increases the temperature of nanofluids due to its high conductivities, and as a result in the molecular motion of nanofluids increases remarkably when compare with pure water.

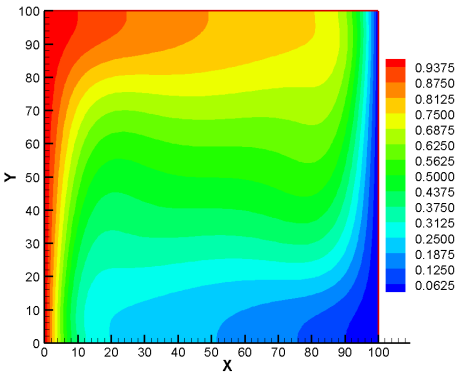
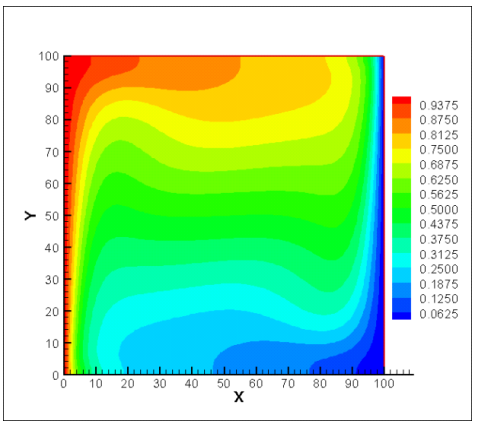
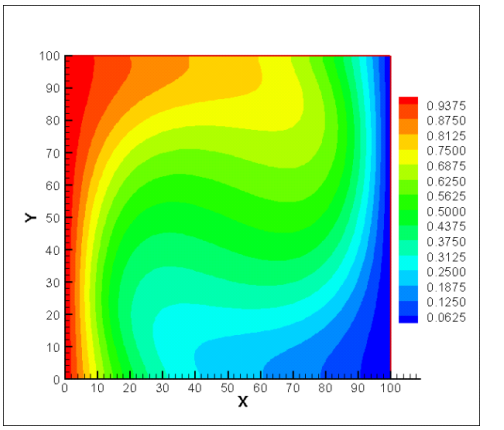


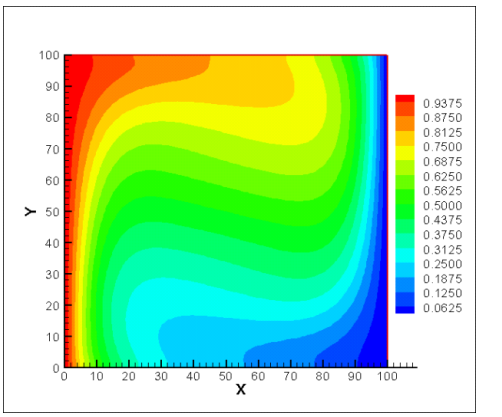
Figure 6: The temperature distribution in Pure Water (Ra=10^5)



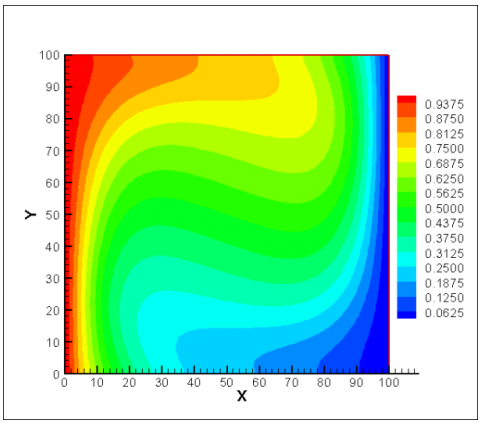
0.5%Cu (10nm)



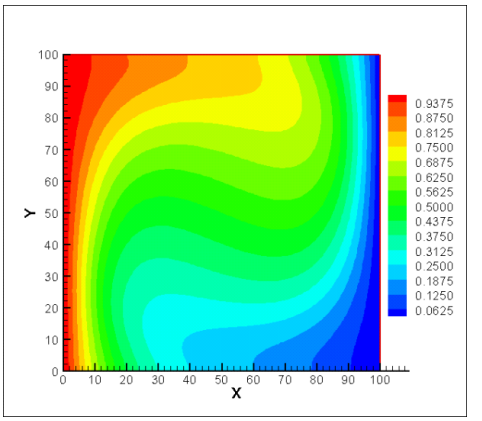
1%Cu (10nm)



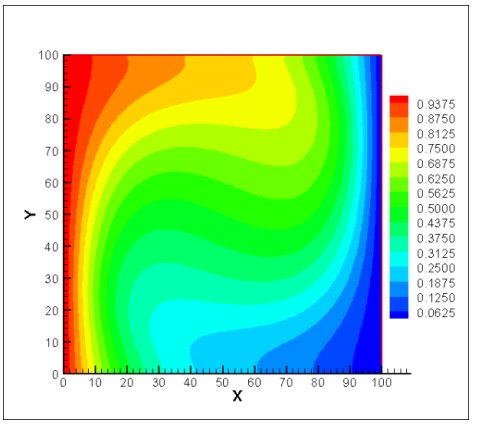
2%Cu (10nm)



3%Cu (10nm)



4%Cu (10nm)



5%Cu (10nm)

Figure 7: Comparison of the temperature distribution in Nanofluids at volume fraction 0.5%, 1%, 2%, 3%, 4%, 5%, separately

Figure 6. shows that the temperature distribution in pure water. Figure 7. shows that the temperature distribution in nanofluids at the copper volume fraction from 0.5% to 5% of the particle diameter 10 nm. Comparison between these two phase states, shows that the temperature distribution is different between pure water and nanofluids, especially in the copper volume fraction 0.5% and 1%. But from the copper volume fraction 2%, the temperature distribution change is not very clear while increasing the copper volume fraction. It means that the copper volume fraction is an important factor to affect the temperature of nanofluids.

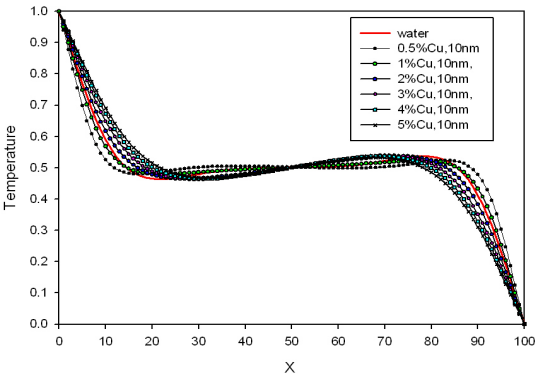


Figure 8: Comparison of the temperature profiles at mid-sections of the cavity

In order to understand the mechanism of nanofluids, it was analyzed more clearly. Figure 8. shows that the comparison of the temperature profiles at mid- sections of the cavity between pure water and different volume fraction at 0.5%, 1%, 2%, 3%, 4%, 5% of the particle diameter 10 nm. It can be seen that the temperature near the wall boundary increases when the copper volume fraction is increasing. And at the copper volume fraction 0.5% Cu and 1% Cu, the temperature near the hot wall boundary layer are lower than pure water and the temperature near the cold wall boundary layer are higher than pure water. From the copper volume fraction 2%, the temperature near the hot wall boundary layer are higher than pure water and the temperature near the cold wall boundary layer are lower than pure water.

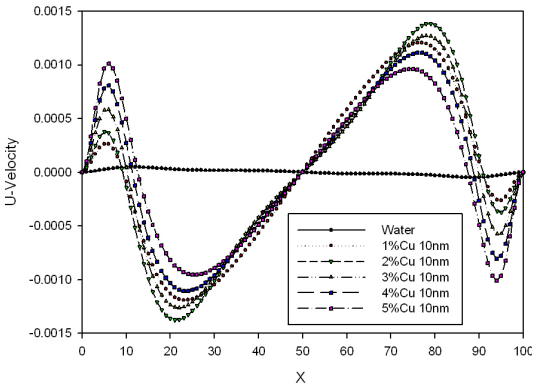


Figure 9: Comparison of the U-Velocity profiles of nanofluids at mid-sections of the cavity

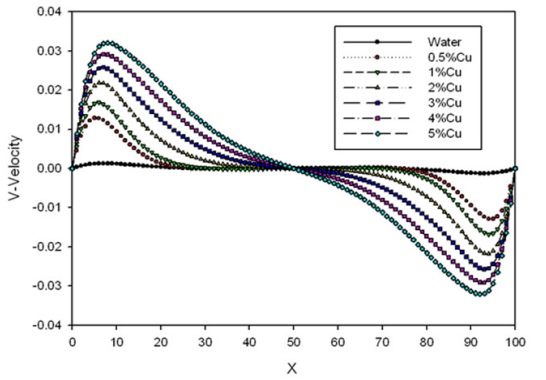


Figure 10: Comparison of the V-Velocity profiles of nanofluids at mid-sections of the cavity

Figure 9. and Figure 10. shows the U-Velocity and V-Velocity profiles separately at mid-sections of the cavity in different volume fraction of the particle diameter 10 nm. It can be seen that the velocity of nanofluids is much higher than pure water. when the copper volume fraction increases, the U-velocity and V-velocity of nanofluids increases.

To estimate the heat transfer performance of the nanofluids flowing over a solid surface in square cavity, the local Nusselt number Nu and the averaged Nusselt number $\overline{Nu}$ are respectively defined as follows [7]:

$$Nu(x) = \frac{h(x)D}{k_f} = \frac{D}{T_b(x) - T_c(x)} \left(\frac{\partial T}{\partial x}\right)_{x=0} \tag{18}$$

$$\overline{Nu} = \frac{\int_0^L Nu(x)dx}{L} \tag{19}$$

Where $h(x)$ is the local heat transfer coefficient, $k_f$is the thermal conductivity of the nanofluids, L is the square cavity length, T_b and $T_c$are the bulk temperature of the nanofluids and the wall temperature of the square cavity, respectively.

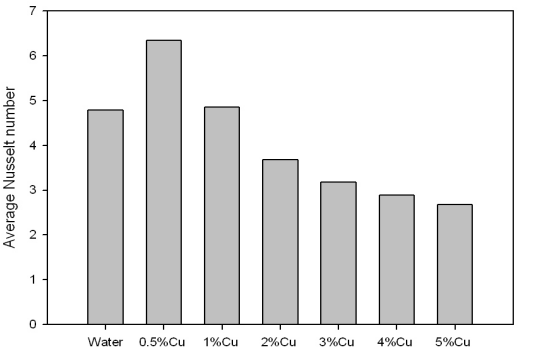


Figure 11: Comparison of the Average Nusselt number between pure water and nanofluids

Figure 11. shows the comparison of the average Nusselt number between pure water and nanofluids in different volume fraction of the particle diameter 10 nm. It can be seen that the average Nusselt number is highest near the hot wall at volume fraction 0.5%. The increasing rate of the average Nusselt number is approximately 33% when compared with pure water at volume fraction 0.5%. And the average Nusselt number decreased from the copper volume fraction 0.5% to

5%. The average Nusselt number is nearly between pure water and nanofluids at volume fraction 1%.

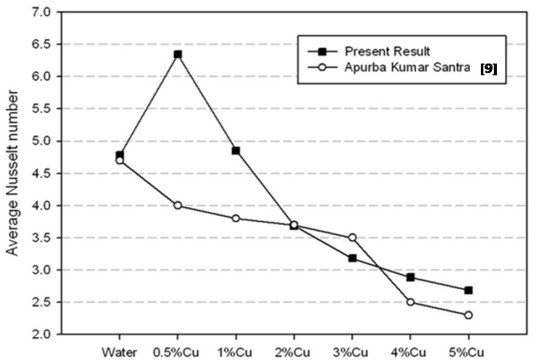


Figure 12: Comparison of the Average Nusselt number near the heat wall between present and Apurba Kumar Santra

Figure 12. shows the comparison of the average Nusselt number between Apurba Kumar Santra's[9] result and present. It can be seen that at the copper volume fraction 0.5% is highest and 1% are higher than Apurba Kumar Santra's. And from the volume fraction 2%, the average Nusselt number is decreased, the result are similar with Apurba Kumar Santra's. In low volume fraction, the effect of Brownian motion is larger than resultant force of gravity and buoyancy. But when the volume fraction increased, the nanoparticles are mainly governed by gravities. Consequently, the average Nusselt number is decreased from the volume fraction 2% to 5%.

The effect of Brownian motion as a random movement has been modified to the internal velocity of nanoparticles(Cu) in this paper. Since the modified methods of LBM are newly proposed, we would verify it more further.

4. Conclusions

In this paper both the single and multi-component thermal Lattice-Boltzmann Method are successfully applied to investigate the fluid flow and heat transfer characteristics of pure and nanofluids characteristics when the effect of Brownian motion as a random movement is modified to the internal velocity of nanoparticles(Cu) in heat transfer of H_2O-Cunanofluids.

(1) When considering the effect of the Brownian motion in the program of LBM, it is available to energy transport for nanofluids.

(2) In addition, nanoparticles remarkably increase the velocity of nanofluids because the copper nanoparticle has high conductivities, which means that the nanoparticles is a media to accelerate the heat transfer from hot wall to water in nanofluids.

(3) In low volume fraction, the effect of Brownian motion is larger than resultant force of gravity and buoyancy. But when the volume fraction increased, the nanoparticle are mainly governed by gravities. So, the heat transfer is the highest, at the particle volume fraction 0.5% of the particle diameter 10 nm. The average Nusselt number is increased approximately by 33% at the particle volume fraction 0.5% of the particle diameter 10 nm when compared with pure water. And the heat transfer is reduced from the particle volume fraction 1% to 5% of the particle diameter 10 nm.

Acknowledgements

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