EFFECTS OF BROWNIAN MOTIONS AND FRACTAL STRUCTURE OF NANOPARTICLES ON NATURAL CONVECTION

Zohreh Zobeidi[1], Roohollah Sadeghi[1, ✉], Mohamad−Taghi Rostami[2]

Abstract. The study simulated heat transfer in alumina-water nanofluid in a natural convection flow and Rayleigh-Benard configuration considering the Brownian motions and fractal structure of the nanofluids. The simulations were based on a two-dimensional, Eulerian-Eulerian method. Many simulations have been performed to examine the effect of aspect ratio, heat flux, and parameters related to the structure of the nanoclusters including size, fractal dimension, and volume fraction on the natural convective heat transfer coefficient. The comparison between the simulation results and the experimental data of heat transfer coefficient indicates a good agreement. The simulation results indicated that the enhancement of aspect ratio, heat flux, and fractal dimension increases the heat transfer coefficient. On the other hand, the reduction of nanoclusters and nanoparticle size decreased this coefficient. Moreover, the simulation results showed that in high heat transfer fluxes, the heat transfer coefficient first increases by increasing the nanoparticles solid volume fraction and then decreases. However, heat transfer coefficient decreased steadily with the increase in the nanoparticles solid volume fraction in low heat transfer fluxes. The results suggested that using the nanoparticles Brownian motion mechanism along with their fractal structure can be well-applied in natural-convection heat transfer modelling of nanofluids.

Keywords: nanofluid, alumina-water, nanoclusters, fractal dimension, natural convective heat transfer coefficient.

1. Introduction

Cooling and heating systems play a critical role in most of the most essential systems in different industries and heat transfer fluids. Technological developments have brought about to a new kind of heat transfer fluid, known as nanofluid, with superior performance over its conventional counterparts. Nanofluids are suspended mixture of solid nanoparticles in a base fluid. The usual nanoparticles used for this are carbon nanotubes, metals, and metal oxides with the usual base fluids as water, ethanol, ethylene glycol, and industrial oils.[1] The steady increase in the applications of nanofluids in heat transfer systems, engine oils, lubricants, *etc.*, has attracted the researchers to these fluids. Studies show that compared to the conventional fluids and suspensions with larger dimensions, nanofluids have higher heat transfer coefficients and suspension stability.[2]

As a heat transfer mechanism, natural convection has been used in different applications, although contradictory results have been obtained from numerical studies and experimental investigations in using nanofluids natural convective flow. Some of the seminal studies in this regard have been done by Kouloulias *et al*.,[1] Hadad *et al*.,[3] and Ma *et al*.[4] Their results show that adding nanoparticles to the fluids increases natural convective heat transfer, whereas Meng and Li,[5] Kouloulias *et al*.,[1] and Ilyas *et al*.[6] show that nanoparticles reduce natural heat transfer.

Many parameters are involved in natural convective heat transfer, some of which are Brownian motions, thermal conductivity, sedimentation and dispersion of nanoparticles, nanoparticle structure, and formation of nanoclusters because of the nanoparticle aggregation.[7] Sheikhzadeh *et al*.[8] examined the mixed convection of alumina water nanofluids in the cavity in a numerical study. Their model showed that using thermal conductivity and viscosity leads to different Nusselt numbers. Ehteram *et al*.,[9] Ghasemi and Aminsadat,[10] Aminfar and Haghgoo,[11] and Haddad *et al*.[12] examined the effect of Brownian motion of nanoparticles on natural heat transfer, showing that Brownian motion is a key mechanism in increasing the natural heat transfer of nanofluids.

Furthermore, different researchers have conducted some studies showing that besides the Brownian motions, nanoclustering of nanoparticles affects heat transfer in nanofluids.[13-16] Their studies show different results. Hong and Kim,[13] and Shalkevich *et al*.[14] suggested the positive effect of nanoclustering on heat conduction, whereas Hong *et al*.,[15] and Wu *et al*.[16] stated that the enlargement

[1] Department of Chemical Engineering, ACECR institute of Higher Education (Isfahan Branch), Isfahan, Iran
[2] Department of Engineering, Esfahan Oil Refining Company, P O Box 81465-415, Isfahan, Iran
✉ *sadeghi@jdeihe.ac.ir*

of nanoclusters decreases heat conduction. These differences may be due to the non-simultaneous consideration of the Brownian motion of nanoparticles and their cluster structure.

Various researchers have studied the motion of particles in a fluid. Eulerian-Eulerian and Eulerian-Lagrangian models are generally used. Sadeghi *et al.*[17] are used the Eulerian-Eulerian model to investigate the effect of nanoparticles on laminar force convection heat transfer. Artyukhor and Sklabinsky[18] also used the Eulerian-Lagrange model to study the hydrodynamics of particles the workspace of the vortex granulator. Nagursky *et al.*[19] and Kindzera *et al.*[20] also investigated the heat transfer between the particle and the continuous fluid.

The study is conducted to examine the role of Brownian motions, size and cluster structure of nanoparticles in enhancement of nanofluids heat transfer. Moreover, the purpose was to study the effect of configuration length, heat flux, solid volume fraction and size of nanoparticles on natural convective heat transfer of alumina-water nanofluid in a Rayligh-Benard configuration using a two-phase Eulerian-Eulerian model.

2. The Geometry and Governed Equations

We numerically examined heat transfer by alumina-water nanofluid in a Rayleigh-Benard configuration in steady state conditions. The geometry used in the study is identical to the geometry of an experimental study previously done by Kouloulias *et al.*[1] The geometry is a cube container with a heater on the base, a cooler on the top, and insulated side walls. Fig. 1 shows a schematic of the geometry used. The length of each side is considered 10 cm. The cube contains alumina-water nanofluid with 0.0003, 0.0006, and 0.0012 solid volume fractions and 19531.3, 23437.5, and 27343.8 (W/m^2) heat fluxes.

In this investigation, water is the continuous phase and alumina nanoparticles as nanoclusters are considered the dispersed phase. The governing equations are proposed based on the finite volume method and with the assumption of laminar and two-dimensional flow in heat transfer mechanism.

2.1. The Governed Equations and Numerical Methods

Continuity equation is as follows:

$$\frac{\partial \rho_\alpha}{\partial t} + \nabla \cdot \left(r_\alpha \rho_\alpha U_\alpha \right) = 0 \tag{1}$$

Here, t, U_α, ρ_α, r_α are time, local velocity, density and local volume fraction of α phase, respectively (α phase can be nanocluster phase c or water phase l).
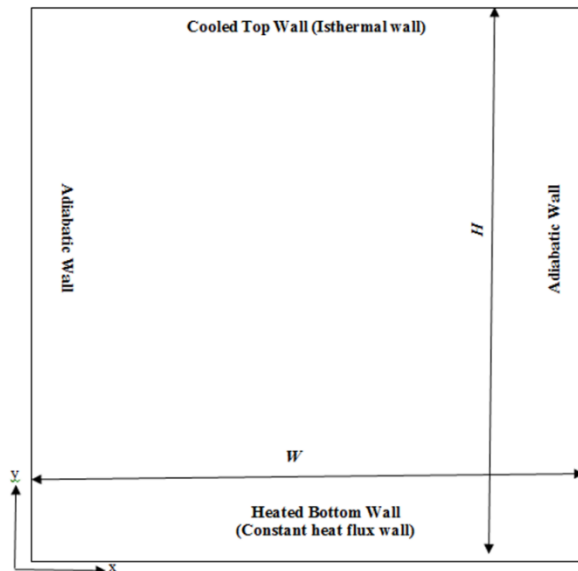

Fig. 1. Schematic diagram of the studied configuration

Momentum equation is:

$$\nabla \cdot \left(r_\alpha \rho_\alpha U_\alpha \nabla U_\alpha \right) = -r_\alpha \nabla p_\alpha + \nabla \cdot \left(r_\alpha \mu_\alpha \nabla U_\alpha \right) + \\ + F_{B_\alpha} + F_{Buo_\alpha} + F_{D_\alpha} \tag{2}$$

Here, r_α, ρ_α, U_α, and μ_α are volume fraction, density, local velocity and dynamic viscosity of the α phase, respectively.[21]

In Eq. (2), F_{D_α} is the drag force. This force can be defined using the following equation.

$$F_{D_\alpha} = \frac{3}{4} \frac{C_D}{D_{32}} r_\alpha \rho_\alpha \left| U_\alpha - U_\beta \right| \left(U_\alpha - U_\beta \right) \tag{3}$$

In this equation, C_D is the drag coefficient calculated using a Schiller-Naumann's model.[22] F_{Buo_α} is the Buoyancy force in Eq. (2). Boussinesq model is used for density variations. This force is defined by the following equation:[16]

$$F_{Buo_\alpha} = (\rho_\alpha \left(1 - \beta_\alpha \left(T_\alpha - T_{ref} \right) \right) - \rho_{ref}) g \tag{4}$$

Here, β_α, T_α, T_{ref}, ρ_{ref}, g are thermal expansivity and temperature of α phase, reference temperature, reference density and gravitational acceleration, respectively.

In Eq. (2), F_{B_α} originates from the Brownian motions of nanoclusters in a nanocluster phase. This force can be defined through following equations:[23]

$$F_{B_\alpha} = \varsigma_i \sqrt{\frac{\pi s_o}{\Delta t}} \quad , \quad S_o = \frac{216 v k_B T_c}{\pi^2 \rho_l d_{nc} \left(\frac{\rho_{nc}}{\rho_l} \right)^2} \tag{5}$$

Here, Δt, v, T_c, ς_i, k_B, d_{nc}, ρ_{nc}, ρ_l are the time step, kinematic viscosity of water, nanoclusters temperature, standard normal distribution Boltzmann constant, nanocluster diameters, nanoclusters and water density, respectively.

Heat transfer equation for obtaining temperature distribution of nanoclusters and water are as follows:

$$\nabla \cdot \left(r_\alpha \rho_\alpha U_\alpha e_\alpha \right) = \nabla \cdot \left(r_\alpha k_\alpha \nabla T_\alpha \right) + Q_\alpha \tag{6}$$

Here, e_α, k_α, T_α are internal energy, thermal conductivity and temperature of α phase, respectively. Q_α is the heat flux between two phases of nanoclusters and water. This flux is calculated from the equation presented by Ranz-Marshal[16] which is:

$$Nu = 2 + 0.6Re^{0.2}Pr^{0.3} \tag{7}$$

$$Re = \frac{\rho_l \bar{U} d_{nc}}{\mu}$$

$$Pr = \frac{C_{pl}\mu}{k_l}$$

Here, U, μ, C_{pl}, and k_l are average velocity of nanoclusters in the container, dynamic viscosity, heat capacity, and thermal conductivity of water, respectively.

Nanoclusters have fractal structure, which is the reason for the differences between their solid volume fraction and density with nanoparticles that constitute them. Solid volume fraction of nanocluster is calculated from the following equation:[24]

$$r_{nc} = \left(\frac{R_g}{R_p}\right)^{3-d_f} r_p \quad , \quad r_{nc} = r_{ncp}r_p \tag{8}$$

$$r_{ncp} = \left(\frac{R_g}{R_p}\right)^{3-d_f} = \left(\frac{D_{32}}{2R_p}\right)^{3-d_f} \tag{9}$$

Here, R_g, R_p, r_p, r_{npc}, D_{32}, and d_f are nanocluster radius, nanoparticle radius, solid volume fraction of nanoparticles, solid volume fraction of nanoparticles in each nanocluster, average diameter of nanoclusters and fractal dimension, respectively.

Nanoparticle density is calculated from the following equation:

$$\rho_{nc} = r_{npc}\rho_p + \left(1 - r_{npc}\right)\rho_l = \left(\frac{R_g}{R_p}\right)^{3-d_f}\rho_p +$$

$$+ \left(1 - \left(\frac{R_g}{R_p}\right)^{3-d_f}\right)\rho_l \tag{10}$$

Here, r_{npc} and ρ_p are solid volume fraction of nanoparticles in each nanocluster and nanoparticle density, respectively.

Heat capacity of nanocluster (C_{nc}) is calculated from the following equation.[17]

$$C_{nc} = r_{npc}C_p + \left(1 - r_{npc}\right)C_{pl} \tag{11}$$

C_p in this equation is the nanoparticle heat capacity.

Heat conduction (K_{nc}) of each nanocluster is calculated from the following equation:[25]

$$K_{nc} = K_l \frac{3+r_{npc}\left[2\beta_{11}\left(1-L_{11}\right)+\beta_{33}\left(1-L_{33}\right)\right]}{3-r_{npc}\left[2\beta_{11}L_{11}+\beta_{33}L_{33}\right]} \tag{12}$$

$$\beta_{11} = \frac{k_p - k_l}{k_p + L_{11}\left(k_p - k_l\right)}$$

$$L_{11} = \frac{0.5p^2}{p^2-1} - \frac{0.5pCosh\ p}{\left(p^2-1\right)^{1.5}}, L_{33} = 1 - L_{11}$$

Here, K_p, C_p, ρ_p are nanoparticles heat conductivity, heat capacity and density, respectively.

Following equations are used for comparison of the simulation results with the experimental data:

$$h = \frac{q}{T_h - T_c} \tag{13}$$

$$\rho_{nf} = r_p\rho_p + \left(1 - r_p\right)\rho_l \tag{14}$$

Here, q, T_h, and T_c are convective heat flux, temperature of the hot wall and temperature of the cold wall, respectively.

Percentage of error is calculated using the following equation. In this equation, h_{sim} and h_{exp} are simulated and experimental conductive heat transfer coefficients, respectively.

$$\%Error = \frac{h_{sim} - h_{exp}}{h_{exp}} \times 100 \tag{15}$$

Aspect ratio (ratio of the height to the length of the container) is calculated from the following equation:

$$AR = \frac{H}{L} \tag{16}$$

H and L are the height and the length of the container, respectively.

The governing equations of heat and momentum were solved based on finite element numerical method in ANSYS CFX 15 commercial software. The boundary conditions of no-slip, adiabatic, constant heat flux and isotherm for the walls were considered according to Fig. 1. The independence of the grid with different numbers of 8100, 9025, 10000, and 11025 elements was examined to calculate the heat transfer coefficient. These calculations show that increasing the number of elements to more than 10,000 does not lead to a large change in the heat transfer coefficient. Therefore, the number of elements was considered 10,000. Fig. 2 shows the computational grid with the quad elements used in this study. In this figure, the grid near the walls has become refine due to the increase in velocity and temperature gradients. The convergence criterion in the calculations was to reduce the momentum, continuity and energy residual diagrams to less than 10-4.
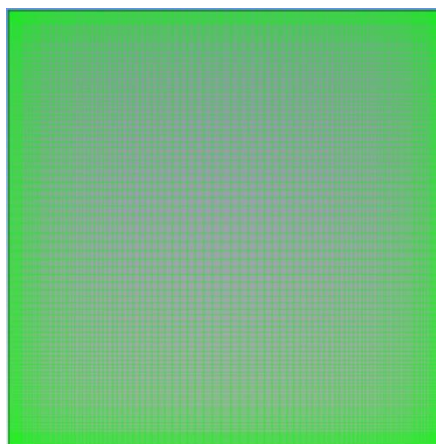

Fig 2. Computational grid

3. Results and Discussion

The study used the two-phase Eulerian-Eulerian model to examine the effect of Brownian motions on natural convective heat transfer in alumina-water nanofluid. Heat transfer coefficients were calculated in different conditions with the effects of various parameters like the aspect ratio (height to length ratio of the container), heat flux, nanoclusters sizes and fractal dimensions, solid volume fraction of nanoparticles and the size of nanoparticles examined.

Nusselt number was compared with experimental data in Kouloulias *et al.*[1] in Fig. 3 for solid volume fractions of 0.0003, 0.0006, and 0.0012 to evaluate the results of numerical solution. The figure shows a good agreement between the results of the present study and the experimental data with maximum relative errors 5.8 %. Moreover, the figure shows the difference between the simulation results where the experimental data increase with the increase in Riley number. The Riley range is $2.6 \times 10^{-9} < Ra < 5.2 \times 10^{-9}$, showing a natural heat transfer in the study.
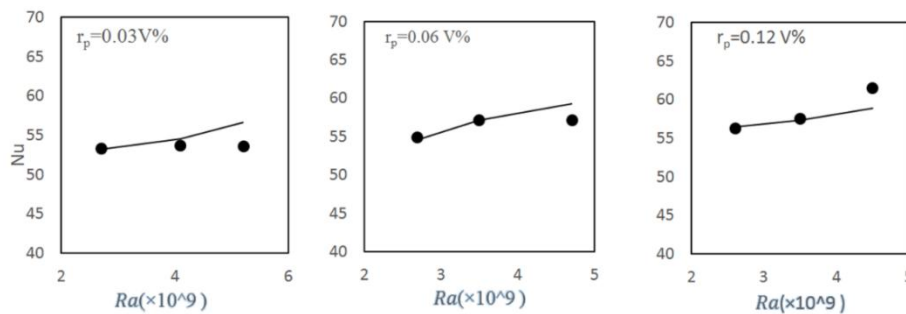

Fig 3. Comparison of Nusselt number of the study with experimental data of Ref. 1
(experimental data (circles), simulation results(black line))

Fig. 4 shows the effect of aspect ratio on natural convective heat transfer. Convective heat transfer coefficient is plotted for different aspect ratio in this figure. Solid volume fraction and heat flux are 0.12 (Vol %) and q"=19531.3 (W/m²), respectively. According to this figure, convective heat transfer coefficient increases with the increase in the aspect ratio. Indeed, the difference between the cold and warm fluid density causes this convection and increases the heat transfer.

Fig. 5 shows the effect of heat flux on the convective heat transfer of water-alumina nanofluid. Convective heat transfer coefficient is plotted for different heat fluxes in a solid volume fraction of 0.12 vol. % in this figure. It shows that convective heat transfer coefficient increases with the increase in the heat flux. When heat flux increases, more heat energy transfers to the surface resulting in an increase in a surface temperature. This temperature enhancement causes an increase in the temperature gradient which, in turn, increases the heat transfer coefficient. On the other hand, the enhancement of the surface temperature can decrease the density of the adjacent fluid further that leads to a higher natural convective flow in the fluid.

Fig. 6 shows the fluid temperature contour at different heat fluxes. As is seen, the values of the fluid temperature increase when the thermal flux increases from 1953.3 to 35161.7 (W/m²). This increase in temperature shows that the Brown motion varies the temperature gra-

dient near the wall and leads to an increase in the heat transfer coefficient.

Generally, nanoparticles collision occurs because of the Brownian motions and results in formation of nanoclusters. Size and structure of nanoclusters can affect the heat transfer. Fig. 7 shows the effect of nanocluster size on convective heat transfer coefficient. The figure clearly indicates that convective heat transfer coefficient decreases with the increase in nanoclusters size. Based on the simulation results for 0.03, 0.06, and 0.12 vol. % nanoparticle concentrations, convective heat transfer coefficient decreases by 31 %, 33 %, and 35 % when nanocluster size varies from 50 nm to 200 nm. The reason is the reduction in Brownian motions due to the enhancement in nanoclusters size and sedimentation.

Fig. 8 shows the fluid velocity profile during the clustering process. Considering this figure, one can conclude that when nanocluster size increases from 50 nm to 200 nm, fluid velocity decreases. In fact, when nanocluster size increases, microconvections of nanoparticles resulting from the Brownian motion decrease that results in the reduction of heat transfer.

Fig. 9 shows the effect of nanocluster structure (fractal dimension d_f) on the convective heat transfer coefficient of water-alumina nanofluid. Convective heat transfer coefficient is plotted for different fractal dimensions in this figure. Furthermore, nanoparticle solid volume fractions of 0.03 %, 0.06 %, and 0.12 % are plotted

for nanoparticles with 150 nm size. According to the figure, convective heat transfer coefficient increases with the increase in the fractal dimension. Eqs. (9) and (10) imply that nanocluster density decreases with increase in the fractal dimension. On the other hand, based on the Eq. (5), nanoclusters Brownian motions increase with the decrease in the nanoclusters density. Therefore, the enhancement of the fractal dimension increases microconvections caused by the Brownian motions and increases the convective heat transfer coefficient.

Fig. 10 shows the effect of nanoparticles solid volume fraction on the convective heat transfer coefficient in various heat fluxes. Heat fluxes $q'' = 19531.3$, 23437.5, and 27343.8 (W/m^2) are considered in this figure. Enhancement of nanoparticle solid volume frac-

tion has two effects on nanofluids. It increases the overall density of the fluid which results in the reduction of natural convection in the fluid, which in turn can decrease the heat transfer coefficient. On the other hand, the enhancement of nanoparticle solid volume fraction increases the number of nanoparticles, which results in an increase in Brownian motion that in turn increases the heat transfer coefficient. Therefore, variations in solid volume fraction have two opposite effects on the natural convective heat transfer coefficient. This figure shows that in higher heat fluxes, the heat transfer coefficient initially increases with the increase in the solid volume fraction and then decreases, but in lower heat fluxes, this coefficient decreases with the increase in the solid volume fraction of nanoparticles.
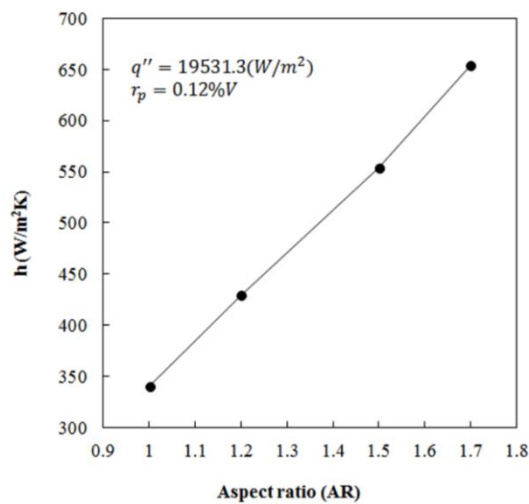

Fig 4. The effect of aspect ratio on the convective heat transfer coefficient in the nanoparticle solid volume fraction of 0.12 %
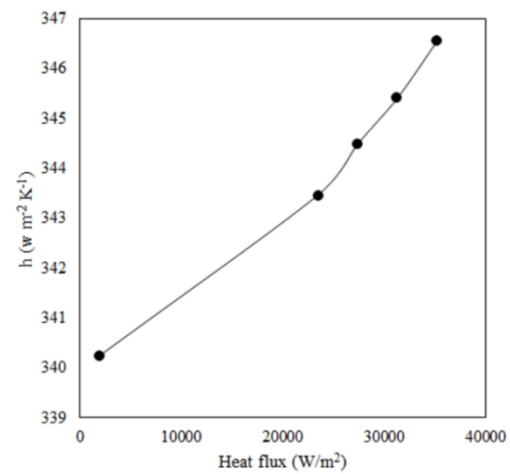

Fig 5. The effect of heat flux on convective heat transfer coefficient in 0.12 % solid volume fraction of nanoparticles
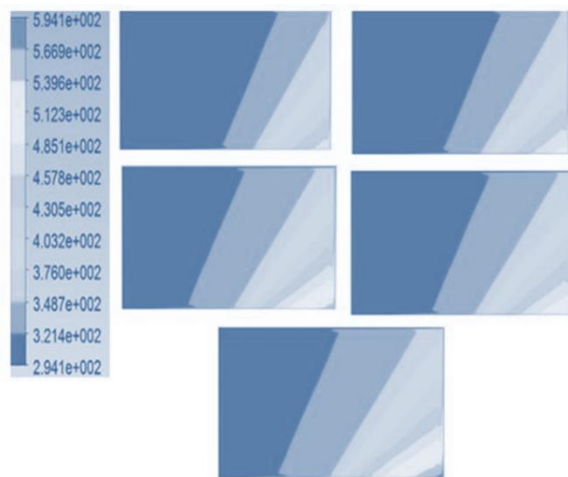

Fig 6. The effect of heat flux on the temperature profile 0.12 % solid volume fraction of nanoparticles
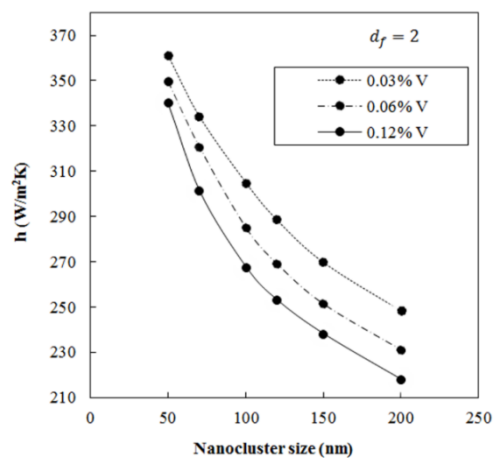

Fig 7. Effect of nanocluster size on the convective heat transfer coefficient in various nanoparticle solid volume fractions
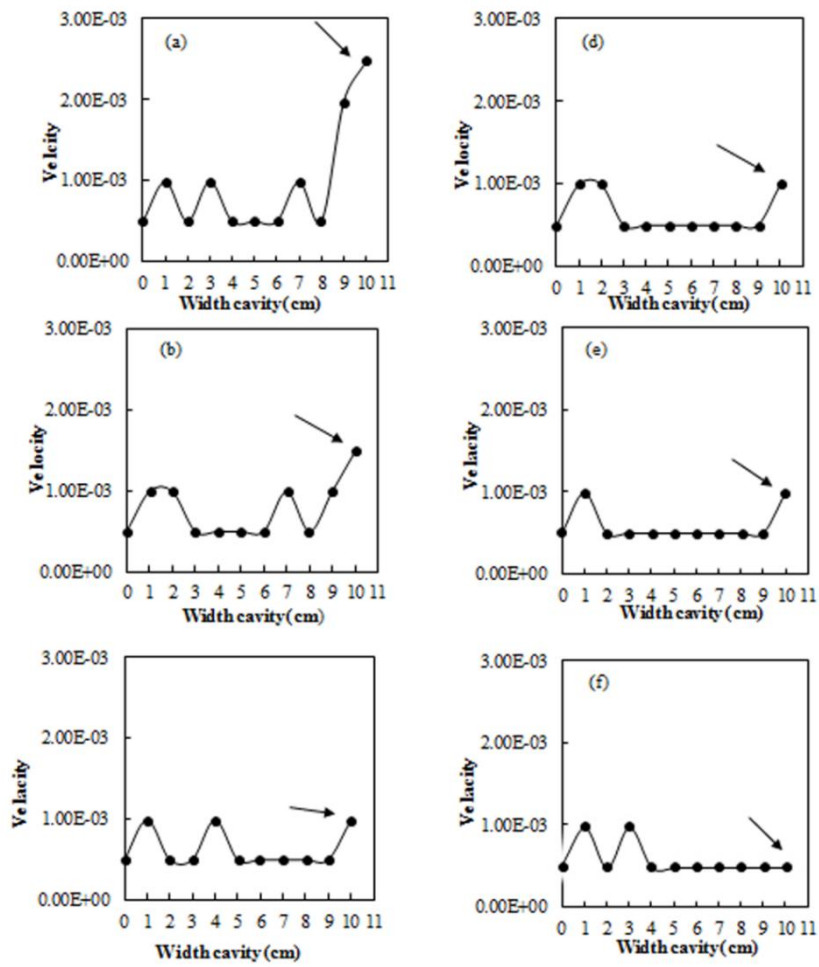
Fig 8. Fluid velocity profile during the clustering process in the solid volume fraction of 0.12 %
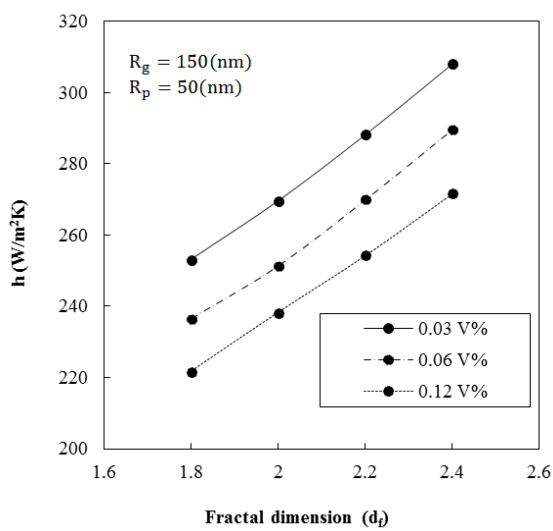nanocluster sizes (a) 50 nm, (b): 70 nm, (c): 100 nm, (d): 120 nm, (e): 150 nm, (f): 200 nm

Fig 9. The effect of convective heat transfer coefficient
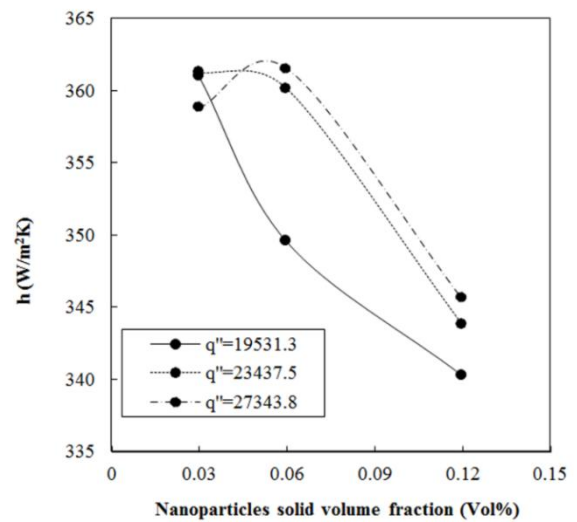on various nanoparticle solid volume fractions

Fig 10. The effect of nanoparticles solid volume fraction on the
convective heat transfer coefficient in various heat fluxes

Fig. 10 shows that in high heat fluxes, the negative effect of increase in fluid density decreases because of the enhancement of solid volume fraction and the role of the Brownian motion is more significant when natural convection is high in the fluid.

Fig. 11 shows the effect of nanoparticle size on natural convective heat transfer. Convective heat transfer coefficient is plotted versus different alumina nanoparticle sizes. Nanoparticles solid volume fraction and heat flux are 0.12 vol. % and q'' =19531.3 W/m², respectively. According to this figure, the convective heat transfer coefficient and Brownian motion increase as nanoparticle size decreases. Furthermore, smaller nanoparticles are more resistant to sedimentation and this increases the heat transfer. The results show that the considered Brownian mechanism for increasing the heat transfer in this study is advisable.
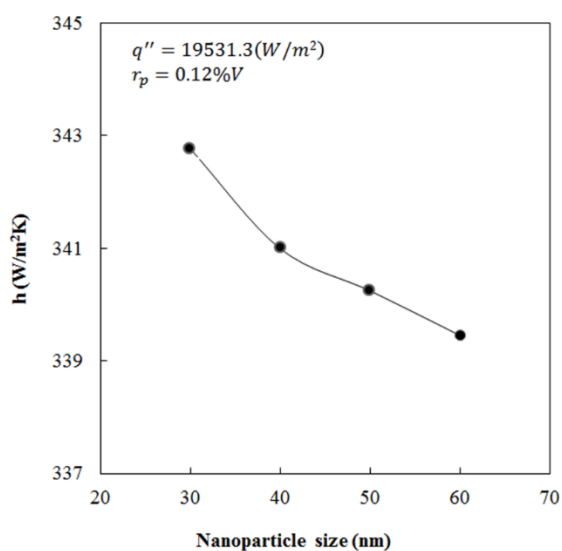
of the height to the length of the container) increases, so does the convection heat transfer ratio. The natural convective heat transfer coefficient in the configuration increases with the increase in the heat flux. Additionally, the convective heat transfer coefficient in water-alumina nanofluid is a function of the nanoparticle and nanocluster sizes, fractal structure, and solid volume fraction, which increases with the decrease in nanoparticle and nanocluster sizes and increase in the fractal dimension. In low heat fluxes, natural convective heat transfer decreases with the increase in the solid volume fraction of nanoparticles in nanofluid, decreasing the convective heat transfer coefficient. The increase in the solid volume fraction of nanoparticles in the higher heat fluxes initially increases and then decreases the heat transfer coefficient. These show that the Brownian mechanism and fractal structure considered for nanoparticles in the modeling of heat transfer in nanofluids are advisable.

Fig 11. The effect of nanoparticle size on the convective heat transfer coefficient in 0.12 % nanoparticle solid volume fraction

References

[1] Kouloulias, K.; Sergis, A.; Hardalupas, Y. Sedimentation in Nanofluids During a Natural Convection Experiment. *Int. J. Heat Mass Transf.* **2016**, *101*, 1193-1203. https://doi.org/10.1016/j.ijheatmasstransfer.2016.05.113
[2] Ghadimi, A.; Saidur, R.; Metselaar, H. A Review of Nanofluid Stability Properties and Characterization in Stationary Conditions. *Int. J. Heat Mass Transf.* **2011**, *54*, 4051-4068. https://doi.org/10.1016/j.ijheatmasstransfer.2011.04.014
[3] Hadad, Z.; Oztop, H.F.; Abu-Nada, E.; Mataoui, A. A Review on Natural Convective Heat Transfer of Nanofluids. *Renew. Sust. Energ. Rev*. **2012**, *16*, 5363-5378. https://doi.org/10.1016/j.rser.2012.04.003
[4] Yuan, M.; Mohebbi, R.; Rashidi, M.M.; Zhigang, Y. Simulation of Nanofluid Natural Convection in a U-Shaped Cavity Equipped by a Heating Obstacle: Effect of Cavity's Aspect Ratio. *J Taiwan Inst Chem Eng* **2018**, *93*, 263-276. https://doi.org/10.1016/j.jtice.2018.07.026
[5] Meng, X.; Li, Y. Numerical Study of Natural Convection in a Horizontal Cylinder Filled with Water-Based Alumina Nanofluid. *Nanoscale. Res. Let*. **2015**, *10*, 142. https://doi.org/10.1186/s11671-015-0847-x
[6] Ilyas, S.U.; Pendyala, R.; Narahari, M. Experimental Investigation of Natural Convection Heat Transfer Characteristics in MWCNT-thermal Oil Nanofluid. *J Therm Anal Calorim* **2019**, *135*, 1197-1209. https://doi.org/10.1007/s10973-018-7546-7
[7] Sarkar, J. A Critical Review on Convective Heat Transfer Correlations of Nanofluids. *Renew. Sust. Energ. Rev*. **2011**, *15*, 3271-3277. https://doi.org/10.1016/j.rser.2011.04.025
[8] Sheikhzadeh, G.A.; Ebrahim Qomi, M.; Hajialigol, N.; Fattahi, A. Numerical Study of Mixed Convection Flows in a Lid-Driven Enclosure Filled with Nanofluid Using Variable Properties. *Results Phys*. **2012**, *2*, 5-13. https://doi.org/10.1016/j.rinp.2012.01.001
[9] Ehteram, H.R.; Abbasianarani, A.A.; Sheikhzadeh, G.A.; Aghaei, A.; Malihi, A.R. The Effect of Various Conductivity and Viscosity Models Considering Brownian Motion on Nanofluids Mixed Convection Flow and Heat Transfer. *Chall. Nano Micro Scale Sci. Tech*. **2016**, *4*, 19-28. https://doi.org/10.7508/tpnms.2016.01.003

4. Conclusions

The study investigated the natural convection heat transfer by the water-alumina nanofluid in a Rayleigh-Benard configuration considering the Brownian motions and fractal structure of nanoparticles using computational fluid dynamics. It was a two-dimensional, two-phase Eulerian-Eulerian simulation in a steady-state and laminar condition. In this simulation, the convection heat transfer coefficient was calculated and compared to the experimental data. The results showed that the simulated convective heat transfer coefficients are in line with the experimental data. Furthermore, as the aspect ratio (the ratio

[10] Ghasemi, B.; Aminossadati S.M. Brownian Motion of Nano-particles in a Triangular Enclosure with Natural Convection. *Int. J. Therm. Sci.* **2010**, *49*, 931-940.
https://doi.org/10.1016/j.ijthermalsci.2009.12.017
[11] Aminfar, H.; Haghgoo, M.R. Brownian Motion and Thermophoresis Effects on Natural Convection of Alumina–Water Nanoflu-id. *J. Mech. Eng. Sci.* **2012**, *227*, 100.
https://doi.org/10.1177/0954406212445683
[12] Haddad, Z.; Abu-Nada, E.; Oztop, H F.; Mataoui, A. Natural Convection in Nanofluids: Are the Thermophoresis and Brownian Motion Effects Significant in Nanofluid Heat Transfer Enhancement? *Int. J. Therm. Sci.* **2012**, *57*, 152-162.
https://doi.org/10.1016/j.ijthermalsci.2012.01.016
[13] Hong, J.; Kim, D. Effects of Aggregation on the Thermal Conductivity of Alumina/Water Nanofluids. *Thermochim. Acta* **2011**, *542*, 28-32. https://doi.org/10.1016/j.tca.2011.12.019
[14] Shalkevich, N.; Shalkevich, A.; Bu□rgi, T. Thermal Conductivity of Concentrated Colloids in Different States. *J. Phys. Chem.* **2010**, *114*, 9568-9572. https://doi.org/10.1021/jp910722j
[15] Hong, K.S.; Hong, T.K.; Yang, H.S. Thermal Conductivity of Fe nanofluids Depending on the Cluster Size of Nanoparticles. *App. Phys. Lett.* **2006**, *88*, 031901. https://doi.org/10.1063/1.2166199
[16] Wu, C.; Cho, T.J.; Xu, J.; Lee, D.; Yang, B.; Zachariah, M.R. Effect of Nanoparticle Clustering on the Effective Thermal Conductivity of Concentrated Silica Colloids. *Phys. Rev.* **2010**, *81*, 011406. https://doi.org/10.1103/PhysRevE.81.011406
[17] Sadeghi, R.; Haghshenasfard, M.; Etemad, S.Gh.; Keshavarzi, E. Theoretical Investigation of Nanoparticles Aggregation Effect on Water-Alumina Laminar Convective Heat Transfer. *Int. Commun. Heat Mass Transf.* **2016**, *72*, 57-63.
https://doi.org/10.1016/j.icheatmasstransfer.2016.01.006
[18] Artyukhov, A.; Sklabinskyi, V. Theoretical Analysis of Granules Movement Hydrodynamics in the Vortex Granulators of Ammonium Nitrate and Carbamide Production. *Chem. Chem. Technol.* **2015**, *9*, 175-180. https://doi.org/10.23939/chcht09.02.175
[19] Nagursky, O.; Gumnitsky, Ya.; Vaschuk, V. Unsteady Heat Transfer during Encapsulation of Dispersed Materials in Quasi-liquefied State. *Chem. Chem. Technol.* **2015**, *9*, 497-501.
https://doi.org/10.23939/chcht09.04.497
[20] Kindzera, D.; Hosovskyi, R.; Atamanyuk, V.; Symak, D. Heat Transfer Process During Filtration Drying of Grinded Sunflower Biomass. *Chem. Chem. Technol.* **2021**, *15*, 118-124.
https://doi.org/10.23939/chcht15.01.118
[21] *ANSYS CFX Solver Theory Guide r15*; ANSYS Inc., 2015.
[22] Schiller, L.; Naumann, A. A Drag Coefficient Corre-lation. *VDI Zeitung* **1935**, *77*, 318-320.
[23] Li, A.; Ahmadi, G. Dispersion and Deposition of Spherical Particles from Point Sources in a Turbulent Channel Flow. *Aerosol. Sci. Technol.* **1992**, *16*, 209-226. https://doi.org/10.1080/02786829208959550
[24] Evans, W.; Prasher, R.; Fish, J.; Meakin, P.; Phelan, P.; Keblinski, P. Effect of Aggregation and Interfacial Thermal Resistance on Thermal Conductivity of Nanocomposites and Colloidal Nanofluids. *Int. J. Heat Mass Transf.* **2008**, *51*, 1431-1438.
https://doi.org/10.1016/j.ijheatmasstransfer.2007.10.017
[25] Nan, C.-W.; Birringer, R.; Clarke, D.R.; Gleiter, H. Effective Thermal Conductivity of Particulate Composites with Interfacial Thermal Resistance. *J. App. Phys.* **1997**, *81*, 6692-6699.
https://doi.org/10.1063/1.365209

ВПЛИВ БРОУНІВСЬКОГО РУХУ ТА ФРАКТАЛЬНОЇ СТРУКТУРИ НАНОЧАСТИНОК НА ПРИРОДНУ КОНВЕКЦІЮ

Анотація. *У дослідженні модельовано теплопередачу в нанорідині оксид алюмінію-вода в природному конвекційному потоці та конфігурації Релея-Бенара з урахуванням броунівських рухів і фрактальної структури нанорідин. Моделювання базувалися на двовимірному методі Ейлера-Ейлера. Проведено численні моделювання для дослідження впливу аспектного відношення, теплового потоку та параметрів, пов'язаних зі структурою нанокластерів, включаючи розмір, фрактальну розмірність та об'ємну частку, на коефіцієнт природної конвекційної теплопередачі. Порівняння результатів моделювання з експериментальними даними коефіцієнта теплопередачі свідчить про те, що вони добре узгоджуються. Результати моделювання показали, що збільшення аспектного відношення, теплового потоку та фрактальної розмірності підвищує коефіцієнт теплопередачі. З іншого боку, зменшення нанокластерів і розміру наночастинок знижує цей коефіцієнт. Крім того, результати моделювання показали, що у потоках високої теплопередачі коефіцієнт теплопередачі спочатку збільшується через збільшення об'ємної частки твердих наночастинок, а потім зменшується. Проте коефіцієнт тепловіддачі неухильно зменшувався зі збільшенням об'ємної частки твердих наночастинок у потоках низької теплопередачі. Результати свідчать про те, що використання механізму броунівського руху наночастинок разом із їхньою фрактальною структурою може бути успішно застосоване в моделюванні природної конвекційної теплопередачі нанорідин.*

Ключові слова: *нанорідина, оксид алюмінію-вода, нанокластери, фрактальна розмірність, коефіцієнт природної конвекційної теплопередачі.*