NUMERICAL ANALYSIS OF Al_2O_3-WATER NANOFLUIDS THROUGH SQUARE CROSS-SECTION DUCT WITH SINGLE PHASE MODELS

by

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In this study, the effect of various concentrations of Al_2O_3-water nanofluid on heat transfer in duct with a square cross-section, under conditions of continuous heat flux and laminar forced flow, investigated numerically. Reference experimental application parameters are accepted as reference, calculated with single phase homogeneous model (SPHM) and single phase Brownian model (SPBM) models, and the average heat transfer coefficient results of numerical models are compared with each other and reference experimental data. Numerical results obtained with SPHM and SPBM are in comparison to the relevant experimental data. For SPHM and SPBM results, 0.5%, %1.5, %2.5 Al_2O_3-water nanofluids, the average deviation rate for the average heat transfer coefficient is 3.35% and 2.36%, 5.24%, 3.43%, 7.74%, and 5.3% according to the reference experimental data respectively. 0.5%, %1.5, %2.5, 2.24%, and 3.81%, 5.86% and 7.47%, 9.58% and 11.6%, respectively, the average heat transfer coefficient is increased by using Al_2O_3-water nanofluid compared to water. It has been observed that, SPBM has closer results than SPHM model according the relevant experimental data.

Keywords: *nanofluid, numerical analysis, heat transfer coefficient, SPBM, SPHM*

Introduction

Numerous numerical models are used in numerical studies, and the researchers numerical findings are compared with reference experimental data to determine which models are more accurate than the others [1-4]. Heris *et al*. [5], experimentally calculated the Al_2O_3-water nanofluid heat transfer under laminar flow and constant heat flux. A square section channel with a length of 1 m and a hydraulic diameter of 1 cm was used as the test area. Different percentage concentrations of Al_2O_3 nanoparticles and the impact of various Peclet numbers on heat transfer were examined. Azari *et al*. [6], the heat transfer and pressure drop of water-based nanofluids including Al_2O_3, TiO_2, and SiO_2 in a circular tube under laminar flow conditions and constant heat flux were experimentally examined. According to the results obtained, it was observed that the addition of nanofluid particles to water positively affects heat transfer. Saffar-Avval *et al*. [7], experimentally investigated the heat transfer coefficient (HTC) of graphene-water nanofluid under conditions of laminar flow and continuous

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heat flux. Koo and Kleinstreuer [8], created a new set of equations by including Brownian motions in Maxwell's equation, which is used to determine the thermal conductivity of nanofluids. Bhattacharya *et al*. [9], included Brownian motions in calculating the thermal conductivity of nanofluids in their numerical studies. The numerical results were more in line with the compared experimental data and indicated that the Hamilton and Crosser equations could not explain the thermal conductivity coefficient and therefore the heat transfer well. The result that Brownian motions have a positive effect on the HTC and heat transfer, Prasher *et al*. [10], Li and Peterson [11], and Evans *et al*. [12] has also been observed in the studies.

The effect of Brownian motions on heat transfer is a researched topic. While some researchers report that Brownian motions affect heat transfer positively, despite that has been reports of studies concluding that the effect of Brownian motions is negligible. In this study, using equations derived from single-phase methods to determine thermophysical properties of nanofluid, which include Brownian motions in the calculation of thermophysical properties and the equations neglect Brownian motions are used and compared with each other and reference experimental data. In this study, this is specified as a single-phase homogeneous model and a single-phase Brownian model. Additional, the effect of the change of other effective parameters such as nanoparticle concentration, Peclet number on heat transfer was investigated.

Theoretical study

Thermophysical properties of nanofluids

One of the key parameters is the concentration, shape, purity, and size of the added nanoparticles that significantly alter thermophysical properties.

Thermal conductivity of nanofluids

Maxwell equation [13]:

$$K_{\mathrm{nf}} = \frac{2K_{\mathrm{bf}} + K_p + 2\varphi\left(K_p - K_{\mathrm{bf}}\right)}{2K_{\mathrm{bf}} + K_p - \varphi\left(K_p - K_{\mathrm{bf}}\right)} K_{\mathrm{bf}} \tag{1}$$

Hamilton and Crosser [14]:

$$K_{\mathrm{nf}} = K_{\mathrm{bf}}\left[\frac{K_p + (n-1)K_{\mathrm{bf}} - (n-1)\varphi\left(K_{\mathrm{bf}} - K_p\right)}{K_p + (n-1)K_{\mathrm{bf}} + \varphi\left(K_{\mathrm{bf}} - K_p\right)}\right] \tag{2}$$

$$n = \frac{3}{\psi} \tag{3}$$

Koo and Kleunstreuer [8] developed another formula for calculating the thermal conductivity of nanofluids. In this equation, the nanoparticle size, nanoparticle concentration, the effects of temperature, and Brownian motion are the parameters that affect the thermal conductivity of the nanofluid.

$$k_{\mathrm{nf}} = k_{\mathrm{statik}} + k_{\mathrm{brown}} \tag{4}$$

$$K_{\mathrm{nf}} = \frac{2K_{\mathrm{bf}} + K_p + 2\varphi\left(K_p - K_{\mathrm{bf}}\right)}{2K_{\mathrm{bf}} + K_p - \varphi\left(K_p - K_{\mathrm{bf}}\right)} K_{\mathrm{bf}} + 5\times10^4\,\beta(\varphi)\varphi\rho_p c_p\sqrt{\frac{k_B T}{\rho_p D}}\,f\left(T,\varphi\right) \tag{5}$$

The structures of these functions are expressed by Koo and Klaunstreuer with the following equations:

$$k_{\mathrm{br}} = 5\times10^4 \beta(\varphi_p)\varphi_p \rho_{\mathrm{pf}} c_{p,\mathrm{bf}} \sqrt{\frac{k_B T}{\rho_p D}} f(T,\varphi_p) \tag{6}$$

$$f(T,\varphi_p) = (-0.8467\varphi_p + 0.0753)T + (237.67\varphi_p - 21.998) \tag{7}$$

$$\beta(\varphi_p) = 0.0017(100\varphi_p)^{-0.0841} \tag{8}$$

Viscosity of nanofluids

The following equation represents the viscosity model created by Einstein [15] using these equations:

$$\mu_{\mathrm{nf}} = \mu_{\mathrm{nf}}(1+2.5\varphi) \tag{9}$$

Viscosity model developed by Batchelor [16]:

$$\mu_{\mathrm{nf}} = \mu_{\mathrm{bf}}(1+2.5\varphi+6.5\varphi^2) \tag{10}$$

In this model, the effect of Brownian motion is also included in the calculation.

Specific heat capacity of nanofluids

Specific heat is another thermophysical characteristic. It is an equation established by Pak and Cho [17]. This equation can be expressed as:

$$C_{p.\mathrm{nf}} = \varphi(C_p)_p + (1-\varphi)(C_p)_{\mathrm{bf}} \tag{11}$$

Density of nanofluids

Density equation of nanofluids [17]:

$$\rho_{\mathrm{nf}} = \varphi\rho_p + (1-\varphi)\rho_{\mathrm{bf}} \tag{12}$$

Single phase models

In single-phase models, nanofluids are treated as homogenous fluids. It is acknowledged that nanoparticles flow with the primary fluid at the same speed and in the same thermal equilibrium. For single-phase models, the same momentum, energy, and continuity equations used for the base fluid are employed [18, 19]. The following governing equations are provided:

Continuity equation:

$$\nabla(\rho_{\mathrm{nf}}\upsilon) = 0 \tag{13}$$

Momentum equation:

$$\rho_{\mathrm{nf}}(\upsilon\nabla\upsilon) = -\nabla P + \mu_{\mathrm{eff}}\nabla^2\upsilon \tag{14}$$

Energy equation:

$$\nabla(\rho_{\mathrm{nf}}\upsilon C_{p.\mathrm{nf}}T) = \nabla(k_{\mathrm{eff}}\nabla T) \tag{15}$$

Using equations that include Brownian motions in the calculation of thermophysical characteristics from SPM, SPBM. and SPHM were used. The equations used to determine the thermophysical characteristics of nanofluids in the relevant models are displayed in tab. 1.

Table 1. Thermophysical properties equations of single phase models

Model	k_{nf} [$Wm^{-1}K^{-1}$]	μ_{nf} [$kgm^{-1}s^{-1}$]	$C_{p,nf}$ [$Jkg^{-1}K^{-1}$]	ρ_{nf} [kgm^{-3}]
SPHM	1	9	11	12
SPBM	5	10	11	12

Boundary conditions and mesh independence

The geometric structure of the square channel used in this study is shown in fig. 1. Experimental study by Heris *et al*. [5] used as reference experimental data. The length of one side of the square section channel was determined as 10 mm, and the channel length was determined as 1000 mm.

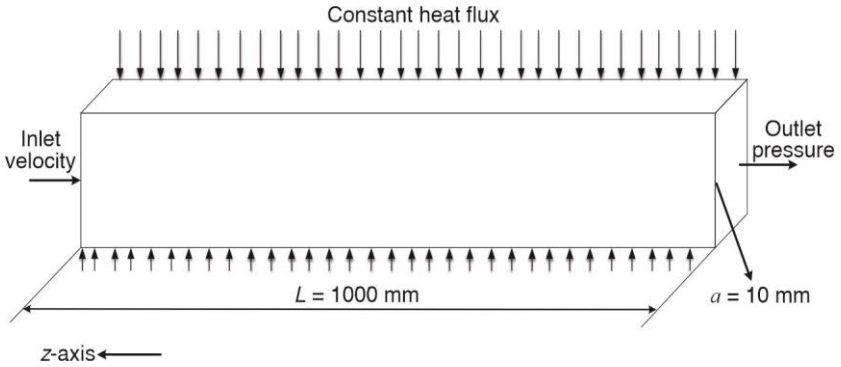

Figure 1. Dimensions and geometric design of the square channel

The initial and boundary conditions, as well as the reference experimental investigation, were all precisely modeled using the commercial program ANSYS-FLUENT. The numerical analysis boundary conditions were chosen the same as the boundary conditions of the reference experimental data. Laminar flow, forced convection and constant heat flux were applied through the test channel walls. Uniform velocity and temperature are defined in the entrance region. Constant pressure was applied at the outlet of the test unit. Thermophysical properties of the base fluid and the nanoparticle used are given in tab. 2. A study on grid independence was conducted based on the node count and mesh structure with a Peclet number of 3500 as illustrated in tab. 3 for water. Following the node structure where there is minimal modification, as shown in tab. 3. It was decided to use the tested 50×50×100 node structure. The Shah London equations are the equation used to theoretically calculate the Nusselt number.

Shah London Equations [20, 21]:

$$\mathrm{Nu}_{\mathrm{avg}} = 1.953\left(\mathrm{Re}_{D_h}\mathrm{Pr}\frac{D_h}{L}\right)^{(1/3)}, \quad \left(\mathrm{RePr}D_h / \mathrm{L}\right) > 33.33 \tag{16}$$

$$\mathrm{Nu}_{\mathrm{avg}} = 4.364 + 0.0722\left(\mathrm{Re}_{D_h}\mathrm{Pr}\frac{D_h}{L}\right)^{(1/3)}, \quad \left(\mathrm{RePr}D_{\mathrm{h}} / \mathrm{L}\right) < 33.33 \tag{17}$$

where Re is the Reynolds number, D_h – the hydraulic diameter of the channel, Pr – the Prandtl number, and L – the length of the channel.

Table 2. Thermophysical characteristics of nanoparticles and water [5]

	ρ [kgm^{-3}]	μ [kgm^{-1}s^{-1}]	k [Wm^{-1}K^{-1}]	C_p [Jkg^{-1}K^{-1}]
Water	998.2	0.001003	0.6	4182
Al_2O_3	3700	–	46	880

Table 3. Change of average HTC according to node number Pe = 3500

Grid numbers (x,y,z)	h_{avg} [Wm^{-2}K^{-1}]
10×10×50	287.21
10×10×100	288.43
10×10*200	289.41
20×20×50	289.23
20×20×200	352.09
20×20×400	353.21
30×30×100	367.72
30×30×400	367.22
40×40×100	376.42
40×40×400	376.58
50×50×100	388.95
50×50×400	388.21
100×100×100	389.13

Peclet number, Reynolds number, Prandtl number, average HTC, average fluid temperature and Nusselt number are defined as follows, respectively:

$$\mathrm{Pe}_{\mathrm{nf}} = \frac{\rho_{\mathrm{nf}} \times C_{p,\mathrm{nf}} \times \bar{U} \times D_h}{k_{\mathrm{nf}}} \tag{18}$$

$$\mathrm{Re}_{\mathrm{nf}} = \frac{\rho_{\mathrm{nf}} \times \bar{U} \times D_h}{\mu_{\mathrm{nf}}} \tag{19}$$

$$\mathrm{Pr}_{\mathrm{nf}} = \frac{C_{p,\mathrm{nf}} \times \mu_{\mathrm{nf}}}{k_{\mathrm{nf}}} \tag{20}$$

$$h_{\mathrm{avg}} = \frac{q}{\left(T_{\mathrm{w}} - T_{\mathrm{b}}\right)} \tag{21}$$

$$T_b = \frac{T_{\mathrm{i}} + T_{\mathrm{o}}}{2} \tag{22}$$

$$\mathrm{Nu} = \frac{h \times D_h}{k} \tag{23}$$

Results and discussions

In this section, Heris *et al*. [5] boundary conditions and application parameters were modeled in ANSYS FLUENT to closely resemble real systems analyzed numerically investigated using single-phase methods.

The experimental data and the computational findings for water at various Peclet numbers were compared using the Shah-London eqs. (16) and (17), and the results are dis-

played in fig. 2. Comparing the numerical results with the experimental results and the theoretical results, it was seen that the average deviation rate about %1 average. It has been observed that increasing the Peclet number increases the Nusselt number in both experimental, numerical and theoretical results. It is observed that numerical study revealed that in good agreement with the data from the experiments and the theories.

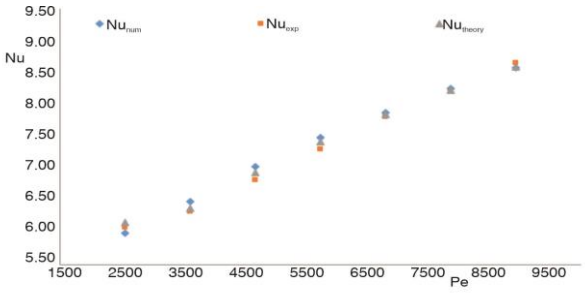

Figure 2. Comparison of numerical results for water by experimental and theoretical results by Nusselt number

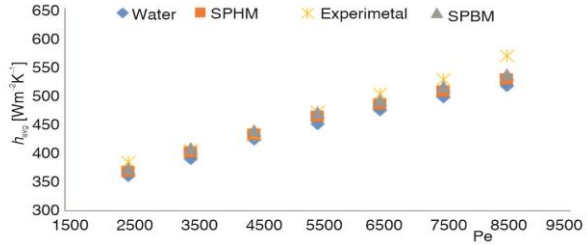

Figure 3. Comparison of the average HTC of 0.5% Al_2O_3-water nanofluid in different Peclet numbers by SPHM and SPBM

The SPHM and SPBM were utilized to perform numerical analyses and compared referred experimental findings and water results. In order to compare reference experimental findings with numerical findings, variations in the average HTC were taken into account. For 0.5% Al_2O_3-water nanofluid with reference experimental data is shown in fig. 3. According to the results obtained, the SPHM was found to be 3.35% and SPBM 2.36% deviation rate. It has been noted that results from SPBM are more in line with the experimental data. In both single-phase numerical models, the highest deviation rate was obtained as 7.83% and 6.03% for SPHM and SPBM at 8500 Peclet number, respectively. The SPHM and SPBM models, 0.5% Al_2O_3-water nanofluid, the increase the average HTC was 2.24%, 3.81% compared to water.

According to variations in the HTC, experimental and numerical results were compared. Figure 4 compares the SPHM and SPBM analyses of the 1.5% Al_2O_3-water nanofluid with referred experimental findings. The observed average deviation rates were 5.24% in SPHM and 3.43% in SPBM, according to the referred experimental findings. It has been observed that SPBM results closer to the reference compared experimental data. The highest deviation rate was observed as 11.79% and 9.38% for SPHM and SPBM at 8500 Peclet number, respectively. SPHM and SPBM models, 1.5% Al_2O_3-water nanofluid, compared to water the increase rate of the average HTC was 5.86%, 7.47%.

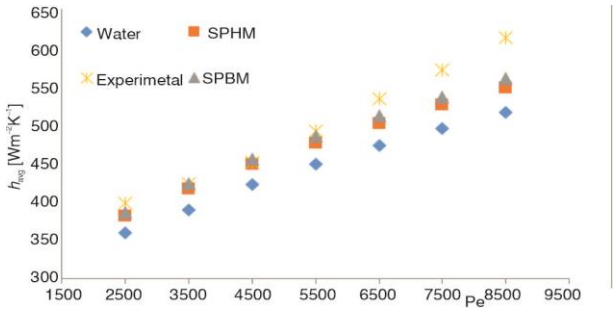

Figure 4. Comparison of the average HTC of 1.5% Al_2O_3-water nanofluid in different Peclet numbers by SPHM and SPBM

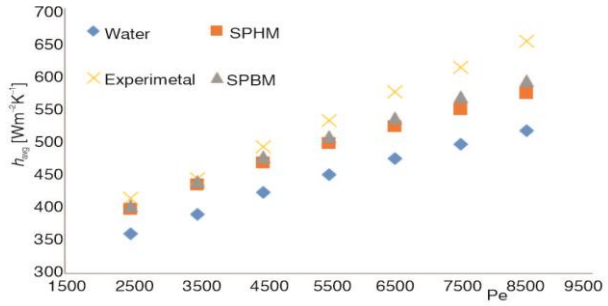

Figure 5. Comparison of the average HTC of 2.5% Al_2O_3-water nanofluid in different Peclet numbers by SPHM and SPBM

The deviation rate of 2.5% Al_2O_3-water according to the compared experimental findings is shown in fig. 5. According to the results obtained, the standard deviation rate of SPHM compared to the reference experimental data was 7.74%, and 5.30% in SPBM. It has been observed that SPBM outcomes that are more closer with experimental data. In both single-phase numerical models, according to the experimental data, the highest error rate was obtained as 13.76% and 10.13% for SPHM and SPBM at 8500 Peclet numbers, respectively. The SPHM and SPBM models, 1.5% Al_2O_3-water nanofluid, the increase the average HTC was 9.58%, 11.6% compared to water.

Conclusion

In this study, the effect of various concentrations of Al_2O_3-water nanofluid on heat transfer under laminar forced flow and steady heat flux conditions in a square section channel was investigated numerically. The water results of the reference experimental data at different Peclet numbers were compared with the Shah-London equations used in the Nusselt number calculation theoretically and the numerically obtained water results were compared according to the Nusselt number for SPHM and SPBM results, 0.5%, %1.5, %2.5 Al_2O_3-water nanofluids, the deviation rate for the average HTC is 3.35% and 2.36%, 5.24%, 3.43%, 7.74%, and 5.3% according to the compared experimental data respectively. 0.5%, %1.5, %2.5 Al_2O_3-water nanofluid, the increase the average HTC was 2.24% and 3.81%, 5.86%, and 7.47%, 9.58%, and 11.6% respectively compared to water. It has been seen that the growth in the Peclet number, the average HTC is favourably impacted. SPBM, the average HTC are higher for each

Peclet number compared to SPHM. According to the reference experimental data, it has been observed that SPBM delivers outcomes that are closer to the compared experimental data.

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