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The comparative study of single and two-phase models for magnetite nanofluid forced convection in a tube ☆

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ABSTRACT

The main aim of this study is to compare two-phase and single-phase approaches in simulating forced convective heat transfer of Fe_3O_4–water nanofluid in both developing and fully developed regions of a tube under constant heat flux. Three different two-phase models, namely, mixture, Volume of Fluid and Eulerian models have been utilized in the numerical analysis for the simulation of the nanofluids flow. In the single-phase models, four different correlations have been chosen for estimation of conductivity of nanofluid (constant, Maxwell, Brownian, proposed model). In order to validate single and two-phase simulations, an experimental setup is designed and fabricated. The experiments have been performed for nanofluids in volume fraction range of 0.5 to 2% and Reynolds number range of 300 to 1200 in the tube with the diameter and length of D = 0.0098 m, L = 2.375 m, respectively. Results of the two-phase models have been compared with that of the best single-phase model and the collected experimental data. It is concluded that considering the Brownian motion effect in the static Maxwell model significantly improves the accuracy. However, the presented correlations for thermal conductivity and viscosity lead to the closest results to the experimental data.

1. Introduction

Convection heat transfer plays an important role in the design and performance of very diverse thermal systems such as power plants, domestic refrigerators and electronic devices. Great efforts are expended to increase the heat flux and reduce the size of heat exchangers. The low conductivity of liquids such as water, ethylene glycol and engine oil which are used as working fluids in many industrial and residential applications constitutes an important drawback which limits the performance of engineering equipment such as heat exchangers. Although various techniques are applied to enhance the heat transfer, the low heat transfer performance of these conventional fluids obstructs the performance enhancement and the compactness of heat exchangers. The use of solid particles as an additive suspended in the base fluid is a technique for the heat transfer enhancement. The recent advance in materials technology has made it possible to produce nanometer-sized particles that can overcome conventional problems of millimeter- or micrometer-sized particles, such as sedimentation, erosion, fouling and increased pressure drop of the flow channel. Moreover, magnetite flows have recently become popular in biomechanics applications such as drug delivery, chemotherapy and magnetic hyperthermia.

There are large numbers of experimental and numerical investigations on the analysis of nanofluids convective heat transfer. The first numerical study of nanofluid heat transfer has been performed by Choi and Z. Z [4]. Single-phase method is the first numerical technique that has been used for the study of nanofluid convective heat transfer. In this method, transport properties of nanofluid play the main role in studying pseudo-fluid behavior. It is assumed that the fluid phase and particles are in thermal equilibrium and moving with the same velocity in certain conditions. The advantage of single-phase flow is about its simplicity and required less computational time. Maiga and C.T [13] considered forced convection nanofluid flow using Al_2O_3 nanoparticles with water and ethylene glycol as the base fluids for both laminar and turbulent regimes. They employed conventional single-phase model and used finite volume method for numerical investigation. Their results were compared with experimental values in which a cogent agreement was gained. Behzadmehr and M. S. [1] implemented the two-phase mixture model for studying the turbulent forced convection heat transfer in a circular tube containing nanofluid. They used the conventional single-phase model and also corresponding experimental results for comparison. They claimed that the mixture model is more accurate in predicting Nusselt number than the single-phase model. Mirmasoumi and A. B. [12] investigated the effect of nanoparticle mean diameter on the heat transfer coefficient. Nanoparticles of Al_2O_3 were considered and two-phase approach was employed in this study. As a result, with decreasing the nanoparticle mean diameter, a significant augmentation in heat transfer coefficient was shown, however the effect of particle size on hydrodynamic parameters was negligible. He and Y. M. [18] conducted a numerical study of convective heat

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transfer of TiO_2 nanofluid using both single-phase and two-phase approaches. The aim of this study was to investigate the effect of Reynolds number and nanoparticles concentration and aggregation size on heat transfer and nanofluid characteristics. The authors have carried out the simulation for two values of Reynolds number using pure water and nanofluid with different diameters and concentrations. Gained results have stated that with an increase in concentration of nanoparticles, heat transfer coefficient will increase significantly. They reported significant heat transfer enhancement, particularly in entrance region. Bianco and F. C. [16] employed both single-phase and two-phase models with either constant or temperature dependent properties to study convective heat transfer of Al_2O_3 nanofluids. They reported that heat transfer increases by increasing both nanoparticle concentration and Reynolds number; however, it is accompanied by increasing wall shear stress. The maximum difference in their studies is 11% between two approaches, and temperature dependent properties lead to a more precise result. Sahin and A. B. [3] surveyed convective heat transfer in a circular tube under constant heat flux using two different nanofluids. Two-phase mixture model has been employed in their work. The turbulent heat transfer behavior has been investigated and the obtained results have been compared with those of experimental studies. Augmentation of heat transfer characteristics has been shown. The researchers have also concluded that CuO nanoparticles have a more significant effect on heat transfer than Al_2O_3 when used in a nanofluid. Haghshenas Fard and M. N. [6] implemented both single and two-phase models for laminar convective flow in a tube under constant wall heat flux in order to calculate heat transfer coefficient. They investigated the effect of nanofluid parameters such as volume fraction on heat transfer characteristics. A better agreement with experimental results has been shown in the results of two-phase model. It has also been shown that there is a direct correlation between heat transfer coefficient and particle concentration. Lotfi and Y. S. [11] considered a horizontal tube under constant heat flux to study forced convection of a water–Al_2O_3 nanofluid. Two-phase Eulerian and mixture models have been used and the results compared with a single-phase model. The comparison with experimental results has revealed that the mixture model is more accurate. It has also been shown that with an increase in the volume fraction of nanoparticles the heat transfer enhancement will significantly decrease. Bianco and O. M. [17] have employed both single and two-phase models with constant and temperature dependent properties. Their study for a volume fraction of 1% had the same results for both single and two-phase models, but for higher volume fractions these results had significant differences. According to this study the two-phase mixture model is a suitable model for investigations of heat transfer of nanofluids. Shariat and A. A. [7] studied laminar mixed convection of a water-based nanofluid flow in an elliptical tube using two-phase mixture model. The finite volume approach was used to discretize the three dimensional Navier Stokes equations. Brownian motion of nanoparticles was considered and a cogent agreement with previous numerical results was obtained. The main aim of this work was to determine the influence of aspect ratio in elliptical tubes on local Nusselt number and skin friction. In order to compare single and two-phase models, Akbari and N. G. [8] studied laminar mixed convection flow of aluminum oxide–water nanofluid flow in a horizontal tube under constant heat flux. Significant difference between thermal results of single and two-phase models obtained, however the hydrodynamic results were reasonably identical. It was shown that the problem which considers the two-phase models will have a more accurate prediction of the results. Allahyari and A. B. [15] investigated laminar mixed convection in a tube which was heated at the half top surface and was adiabatic at the bottom half wall. In their study, two-phase mixture model was employed using three dimensional governing equations. The effect of the nanoparticle volume fraction was studied on thermal and hydrodynamic properties of the system. Augmentation in heat transfer was verified by increasing the particle concentration. Sharifi and A. E. [2] studied laminar forced convective heat transfer of Al_2O_3/water nanofluid numerically and experimentally. They reported remarkable enhancement of convective heat transfer, which increases by increasing of nanoparticle concentration and flow Reynolds number. Moraveji and S. M. [10] studied convective heat transfer of non-Newtonian nanofluid containing Al_2O_3 and Xanthan, and the effect of particle size and concentration of Xanthan solution was investigated in different Reynolds numbers. They reported heat transfer enhancement by increasing concentration of Xanthan solution, and also obtained an equation for Nusselt number prediction using dimensionless numbers. Three different two-phase models and single-phase model are compared in the work of Akbari and N. G. [9]. Recently, a numerical study based on computational fluid dynamics method, with a single-phase approach, has been done by Moraveji and M. H. [5] to determine the effects of nanoparticle concentration and flow rate on the convective heat transfer and friction factor of Fe_3O_4 magnetite nanofluid in a turbulent regime. Two correlations are developed for Nusselt number and friction factor. The maximum error of their model with experimental data has been reported 10%. Göktepe and K. A. [14] surveyed the hydrodynamic and thermal behavior of nanofluid using single and two-phase models. Two-phase models are claimed to have more accurate predictions for convective heat transfer coefficient and friction factor.

In this paper three different two-phase models accompany with four different single-phase models have been comprehensively considered for modeling of forced convective heat transfer of Fe_3O_4–water nanofluid in both developing and fully developed regions of a tube. The results have been examined with the obtained experimental data to select the best method for prediction and modeling of nanofluid heat transfer in a horizontal tube.

2. Experimental setup

In order to validate numerical models, an experimental setup is designed and fabricated. The simulated geometry is exactly the same as that used in the experimental study. The test section is a 2680 mm long straight aluminum tube with inner and outer diameters of 9.8 mm and 11.8 mm, respectively. The tube has a heat transfer section of 2380 mm. The 100 mm entry and 200 mm exit lengths of the tube are unheated in order to eliminate the entry and end effects in the measurements. The experimental setup is presented schematically in Fig. 1. A constant heat flux is provided by passing electric current through a 3 mm thick flat-wire element. The heater has been wounded on the entire tube surface and is connected to an AC power supply through a variac. The tube and heater are insulated with low thermal conductivity elastomeric foam of 10 mm thickness. The surface temperature of the tube at the heat transfer section is measured by 20 thermocouples installed on the aluminum tube surface with an equal spacing of 125 mm. The inlet and outlet temperatures of flow are also measured by two K-type thermocouples. All thermocouples are connected to a data logger such that all temperature values can be monitored and recorded simultaneously on the PC. Magnetite ferrofluid with volume fractions of $\varphi = 1$, 1.5 and 2% is synthesized using the conventional coprecipitation process and used in the test procedures separately. Experiments are conducted for five different Reynolds numbers in the laminar flow range of 400–1200. Ferrofluid is circulated in a loop from a reservoir tank with a 24 volt DC pump driven by a DC power supply. Volumetric flow rate passing through the loop is measured using a calibrated flow meter, and can be varied by changing the voltage of the DC power supply of the pump.

There is also a fluid collection tank for measuring and calibrating flow rates. The constant temperature bath (F10-Hc Julabo) is located upstream of the pump to control the inlet temperature. The exit heated ferrofluid from the tube passes through a spiral copper tube which is submerged in the thermal bath reservoir. Ferrofluid is cooled due to the heat transfer to the cold water inside the constant temperature bath. Therefore, nanofluid inlet temperature of the tube can be controlled by the thermal bath reservoir temperature. The viscosity and