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Research Paper

Forced-convective heat-transfer coefficient and pressure drop of water-based nanofluids in a horizontal pipe

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HIGHLIGHTS

- Convective heat transfer and pressure drop of six water-based nanofluids studied.
- Different nanoparticle material, concentration and shape included.
- Thermal conductivities, specific heat, cluster size and viscosities reported.
- Results compared in constant Reynolds number and constant pressure drop basis.
- Classical correlations are valid if measured thermophysical properties are used.

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ABSTRACT

In this paper the heat transfer performance of Al_2O_3, SiO_2 and multi-walled CNTs (MWCNTs) in a closed loop were investigated. Heat transfer coefficient and pressure drop were measured in a horizontal thermal-insulated test-section. Special care was taken in the loop calibration and the estimation of measurement uncertainties. The results show that the Gnielinski correlation can be used to predict the turbulent heat transfer coefficient as long as the proper experimental values for the thermophysical properties of each nanofluid are used. Also, the Colebrook–White correlation for the friction factor showed good agreement with the experimental results for pressure drop. The nanofluids showed an increased heat transfer coefficient with respect to that of water on a constant Reynolds number basis, but a reduced performance when compared on a constant pumping power basis. Note that some authors treat CNTs as nanofluids because one of their dimensions is in the nanoscale, but strictly speaking this dimension is not the one that is actually contributing to the changes in the thermal properties of the mixture. We include them in our analysis to demonstrate that this kind of suspension also follows conventional correlations.

1. Introduction

It is difficult to overemphasize the importance of heat transfer enhancement for modern technology as many industrial applications rely on heating and/or cooling processes. This is the case for air conditioning systems, chemical processes, industrial ovens, microelectronics or transportation among others. As the heat transfer performance of conventional fluids, i.e. those present in nature, is actually poor, several techniques have been proposed to enhance it. For instance, the working fluids are usually placed in a loop so that a pumping system makes them pass through the heat source (or sink). The heat transfer in these forced-convective systems can be up to several orders of magnitude higher than for natural convection systems. Also, the design of a proper geometry for the heat exchanger is of primary importance in order to improve the efficiency of these processes.

Another approach consists in the change of the thermophysical properties of the working fluids. This technique was first proposed by Maxwell in 1873 [1], who proposed the addition of solid microparticles to fluids as the thermal conductivity of most solids is much higher than that of conventional fluids. The resulting mixture is expected to have an increased thermal conductivity with respect to the base fluid. But the application of this technique has been strongly limited due to the significant deposition of the particles, a phenomenon that leads to the clogging of the pipelines. Also, the particles cause erosion on the pipe walls and a huge increase of the pressure drop across the installations.

In 1993, Masuda et al. [2] used nanoparticles for the enhancement of the thermal conductivity of a fluid. Two years later, S.U.S. Choi [3] coined the term nanofluid and defined it as a dilute-stable

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suspension of particles with sizes below 100 nm. These suspensions present higher specific surface than conventional colloidal suspensions and are more stable than conventional slurries. Given that it is possible to adjust the thermophysical properties of the nanofluids by modifying the interpaticle interactions [4], most of the published works have focused on the thermal conductivity enhancement by controlling the particle volume fraction, nanoparticle sizes and shapes, and by changing the pH of the nanofluid or adding surfactants. All these factors have some influence on the degree of nanoparticle agglomeration, which has been found to be the most influential factor in changing thermal conductivity [5–9]. A complete reference of recent works can be found in References 10 and 11.

It is important to note that a proper preparation of the nanofluid suspensions is of vital importance for their use, as the preparation process influences the agglomeration of nanoparticles. Two methods have been proposed for a proper nanofluid ellaboration [10]. In the single-step method, the nanoparticles are generated by physical vapor deposition directly onto the working fluid. In the two-step method, the nanoparticles are produced as a dry powder. Then, the nanoparticle powder is dispersed into the working fluid. More information on nanofluid preparation can be found in References 12–14.

Experimental data available show a signficant enhancement of convective heat transfer in parallel channels [15], tubes [16–18] and annular flow channels [19]. Despite the fact that the theoretical models for nanofluid heat-transfer coefficients are quite limited, several studies point out that there is strong implication that particle size and shape could play an important role in the level of heat transfer enhancement on a constant Reynolds number basis. Under similar conditions, the enhancement of heat transfer coefficient is much higher for carbon nanotubes [20] than that for disc-shaped nanofluids [18]. Thus, the addition of nanoparticles improves the thermal conductivity of the working fluids and enhances the efficiency in systems that require to be functioning at a given Reynolds number. But for those industrial applications whose efficiency relies on the pumping power that is needed to make the working fluids move inside the loops, one must take into account that the addition of nanoparticles also increases the viscosity of the resulting nanofluid with respect to that of the base fluid. This results in an increase of the pressure drop and the required pumping power, so an analysis on a constant pressure drop basis is also desirable. In this case, the efficiency analysis consists in a balance between energy consumption and the heat transfer rate. At the moment, there is no agreement on the result of this balance. Some authors observe that the energy consumption is not balanced by heat transfer rate enhancement, but others propose an optimal concentration of nanofluids for the heat transfer enhancement [21,22] so that this balance can be overcome. So more experimental work is needed in this sense. In particular, more research is needed in order to clarify whether the nanofluids verify conventional correlations for heat transfer or not.

At present, the convective transport models proposed for nanofluids can be classified in the following three types [23].

1.1. Homogeneous flow models

These models consider that nanofluids behave like single-phase fluids. Then, correlations available for single-phase flows such as the ones proposed by Dittus–Boelter or Gnielinski can be extended to nanoparticle suspensions provided that the nanofluid thermophysical properties are used in the calculations. Correlations accurately reproduce the convective heat transfer coeffcient, the friction factor and viscous pressure drop in tubes, but proper models involving thermal conductivity, viscosity and specific heat are needed [22,24–26].

1.2. Dispersion models

In this approach, an empirical dispersion coefficient is introduced to describe the heat transfer enhancement that is caused by the slip velocity between the nanoparticles and the base fluid [27].

1.3. Non-homogeneous equilibrium models

The heat transfer enhancing mechanism is accounted for by Brownian-motion induced diffusion and thermophoresis [23,28].

This variety in models is in part produced by the discrepancies found between different experimental works. We note here that, in order to determine the proper model, the thermophysical properties for the resulting nanofluids should be experimentally measured as well, and more specifically at the testing temperature. In many previous works, a combination of measured and modeled set of properties is used, or the room temperature measured properties are taken into account [16,21,29–31]. Only few works using water as base fluid measure some relevant properties (thermal conductivity, viscosity, etc.) of the resulting nanofluid at the temperature of the heat transfer experimental data [32–34]. The work by Ferrouillat et al. [32] collected bibliography on experimentally forced convective heat transfer with nanofluids until 2011 (a total of 24 references). According to their review, many studies found that in laminar flow, nanoparticles enhance heat transfer beyond expectation only by thermal conductivity alone. Most of their reviewed works for turbulent flow showed increased heat transfer results for nanofluids when compared to than predicted by the pure fluid correlation. However, some works also proved that this increase was eliminated when the temperature dependent measured nanofluid were used in the correlations. Prabhat et al. [35] performed a critical analysis of 12 databases of published works (8 laminar and 4 turbulent flows) comparing predicted and measured heat transfer coefficients. The predicted values were calculated according to the established correlations (Dittus–Boelter's for turbulent flow and Shah's for laminar flow), and the uncertainties were also evaluated. Although increase for nanofluid heat transfer in laminar flow was demonstrated for the entrance region (beyond uncertainties), the lack of measured temperature dependence of the nanofluid viscosity could not confirm the results for turbulent flow.

Also, the available literature shows little information on the measurement uncertainties, either for the heat transfer coefficient or the pressure drop. This lack of information makes it difficult to determine whether the differences between theory and experiments are statistically significant or not. In this regard, the review of 12 different nanofluid databases reported in Reference 35 gathers or calculates uncertainties of the data to compare predicted and measured heat transfer coefficient values with their corresponding uncertainties. They also showed that, for turbulent flow, the lack of information about temperature dependence of nanofluid viscosity made it impossible to conclude (within differences among several experiments) the anomalous convective heat transfer enhancement in nanofluids. In this work, a set of thermophysical properties (thermal conductivity, viscosity and heat capacity) that was experimentally measured is employed. Also, the uncertainty of the reported measurements is included. We note that more details on nanofluid preparation and the stability of the water-based nanofluids of Al_2O_3, SiO_2 and multi-walled CNTs (MWCNTs) that have been used in this work can be found in a previous work of the same authors [14]. Subject-matter experts shall notice that CNTs cannot be strictly included within the nanofluids, as the dimension that falls in the nanoscale range is not the one that is actually contributing to the changes in the thermal properties of the compound. CNTs are included in this analysis as many authors in the nanofluid field have studied their thermal properties, and this work shows that they also follow standard correlations for heat transfer and pressure drop.