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Influence of particle properties on convective heat transfer of nanofluids

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ABSTRACT

An experimental study is performed in order to examine how particle properties such as size and thermal conductivity affect the convection heat transfer of nanofluids. For this purpose, we prepare and study self-synthesized water-based nanofluids with different kinds of particles: polystyrene, SiO_2, Al_2O_3 and micelles. Concentrations of the nanofluids vary in the range of 0.1–1.8 vol-% and particle sizes between 8 and 58 nm. Full-scale convective heat transfer experiments are carried out using an annular tube heat exchanger with the Reynolds numbers varying in the range of 1000–11000. The pressure losses are also taken into account in the analysis in order to assess the feasibility of the nanofluids for practical forced convection heat transfer applications. The fluids are thoroughly characterized: viscosities, thermal conductivities, densities, particle size distributions, shapes and zeta potentials are all determined experimentally. In many previous studies, anomalous enhancement in convective heat transfer is observed based on comparison of the Nusselt numbers with equal Reynolds numbers. Also in this work, the nanofluids exhibit Nusselt numbers higher than water when compared on this basis. However, this comparison neglects the impact of differences in the Prandtl numbers, and therefore the altered thermal properties of nanofluids are not properly taken into account. In this study, no difference in Nusselt numbers is observed when the Prandtl number is properly considered in the analysis. All nanofluids performed as the Gnielinski correlation predicts, and the widely reported anomalous convective heat transfer enhancement was not observed with any nanoparticle types. Instead, we show that the convection heat transfer behavior of nanofluids can be explained through the altered thermal properties alone. However, addition of any type of nanoparticles was observed to change the fluid properties in an unfavorable manner: the viscosity increases significantly, while only moderate enhancement in the thermal conductivity is obtained. The more viscous nanofluids reach lower Reynolds numbers than water with equal pumping powers resulting in lower heat transfer coefficients. However, the increase in viscosity, and therefore also the deterioration of the convective heat transfer, is less pronounced for the nanofluids with smaller particle size indicating that small particle size is preferable for convective heat transfer applications.

1. Introduction

Nanofluids are a modern class of heat transfer fluids, in which typically solid particles with diameters of 1–100 nm are suspended in a liquid medium. The concept of nanofluids was first proposed by Choi et al. in 1995 [1] and since then nanofluid research has been thriving. According to the literature, addition of nano-sized particles has been claimed to cause anomalous enhancement in thermal conductivity and convective heat transfer performance of the base fluid. Several experiments suggest that the increment of thermal conductivity is significantly larger than the predicted enhancement according to the well-known Maxwell equation for thermal conductivity of heterogeneous solutions [2–5]. In addition, the convective heat transfer performance of nanofluids has been stated to increase even beyond the effect of the enhanced thermal conductivity [6–11].

The thermal properties of nanofluids are very different from those of conventional heat transfer fluids even with relatively low particle concentrations of only a few vol-%. Typically, the addition of nanoparticles has been observed to increase the following three properties by tens of percents: thermal conductivity, convective heat transfer and viscosity. However, an ongoing debate about the magnitudes of these changes exists, since the results of different groups are often

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contradictory. In some publications, an anomalous behavior in convective heat transfer has not been observed at all [12–17]. In spite of the large body of research, no theory has been able to provide a solid and well-established explanation for the physical basis of the possible anomalous heat transfer enhancement of nanofluids.

The aim of this study is to experimentally scrutinize the influence of particle properties such as size and thermal conductivity on convective heat transfer of nanofluids. Nine water-based nanofluid samples are prepared, characterized, measured and analyzed. The convective heat transfer is studied with an annular tube heat exchanger with Reynolds numbers varying in the range of 1000–11000. In addition to the convective heat transfer, the analysis includes the change in the required pumping power due to increased viscosity and friction factor caused by the nanoparticles. The nanofluids are also thoroughly characterized; particle sizes, shapes, fluid stabilities, viscosities, densities and thermal conductivities are all determined experimentally.

2. Materials and methods

Several different types of water-based nanofluids were investigated in the present study. The thermal properties of the particle materials studied varied in a wide range (Table 1). For example, the thermal conductivities varied in the range of 0.16–36 W/mK and the specific heats in the range of 745–2090 J/kgK. The influence of thermal properties of the particle material on the convective heat transfer behavior of nanofluids was evaluated by measuring and comparing two equal concentrations (0.5 vol-% and 1.0 vol-%) of Al_2O_3 and polystyrene nanofluids (PS2) with similar particle size distributions (~10 nm). Thus, the influence of concentration and particle size was attempted to be kept similar in order to obtain a fair comparison between the two types of nanofluids with different thermal properties of particle materials. The polystyrene nanofluids were self-prepared using a method adopted from Kaiyi and Zhaoqun [18], and a commercial dispersion of Al_2O_3(aq) (Nanostructured & Amorphous Materials Inc.) was used for the Al_2O_3 nanofluid preparation. In addition, a polystyrene nanofluid sample with slightly larger particle size of ~17 nm was prepared and measured (PS1). The influence of concentration on convective heat transfer of nanofluids was evaluated by preparing and measuring three different concentrations of SiO_2 nanofluids. The particle size of the SiO_2 nanofluids (~50 nm) was also significantly larger than those of the other nanofluids (~10 nm) thus providing means to evaluate the influence of the particle size on convective heat transfer. The SiO_2 nanoparticles were self-synthesized using the Stöber method [19]. In addition to these solid-particle nanofluids, a micelle-in-water fluid (~10 nm) was prepared in order to evaluate the influence of the differing particle structure. The micelles were formed using polysorbate20 (Tween20, 81.9 w-%) and sorbitan trioleate (Span85, 18.9 w-%) surfactants.

Particle size distributions were determined with Dynamic Light Scattering (DLS) method using the Malvern Zetasizer Nano ZS apparatus. The results were also verified with the Tecnai F-20 G2 200 kV FEG transmission electron microscope (TEM). The DLS measurements were conducted at temperatures of 20 °C and 60 °C in order to study the stability of the fluids in the temperature range used in the convective heat transfer measurements. The size distribution of each sample was also verified with DLS after the convective heat transfer measurements. In addition to the particle size distributions, DLS was used to determine zeta potentials of the nanofluids. The zeta potentials were also measured at 20 °C and 60 °C.

The viscosities were measured with two different types of viscometers in order to ensure the measurement reliability and to compare the functionality of the different measurement methods. The two measurement devices were a Haake falling ball type C viscometer and a Brookfield DV3TLVCJ0 cone/plate rheometer. Based on measurement repetition, the maximum errors for these two measurement methods were estimated to be 0.5% and 1.5%, respectively. The temperature range in both viscosity measurements was 20°C–60 °C, which was roughly equal to the temperature range of the convective heat transfer measurements.

The thermal conductivities were determined with the C-therm TCi-3-A thermal conductivity analyzer, based on modified transient source plane technique. According to the manufacturer, the uncertainty of the device was 3%. The thermal conductivities were measured at room temperature.

The specific heats of the nanofluids $c_{p,nf}$ were obtained according to Eq. (1) as mass-weighted averages of specific heats of the nanoparticles $c_{p,s}$ and the base fluid (water) $c_{p,bf}$.

$$c_{p,nf} = \frac{1}{\rho_{nf}}[\rho_s \phi c_{p,s} + \rho_{bf}(1-\phi)c_{p,bf}], \tag{1}$$

where ϕ is the volume fraction of the nanoparticles and ρ_s and ρ_{bf} are the densities of the particles and the base fluid, respectively. The densities of the nanofluids were determined using VWR Hydrometers.

3. Convective heat transfer measurements

The convective heat transfer experiments were conducted using an annular type heat exchanger, in which the nanofluid samples flowed in the inner tube and hot water flowed in the outer section (Fig. 1). The inner and outer tubes of the heat exchanger were 1.47 m long acid-resistant steel pipes with inner diameters of d_i = 6 mm and d_o = 13 mm, respectively. The thickness of the inner pipe, which corresponds to the wall separating the two fluids, was 1 mm. Thus, the outer diameter of the inner tube was d_{io} = 8 mm. The temperature of the incoming nanofluid was set to 15–20 °C. The cooling was arranged using a heat exchanger with cold water flowing in the external side. The outlet temperature of the heated sample varied between 45 °C and 78 °C, depending on the flow rate. The volumetric flow rate of the nanofluids was varied in the range of 0.13–2.17 l/min. The flow rates were controlled with pump frequency controllers. The hot water in the outer section entered into the heat exchanger at the temperature of 80 °C and cooled to 75–80 °C, depending on the flow rate of the

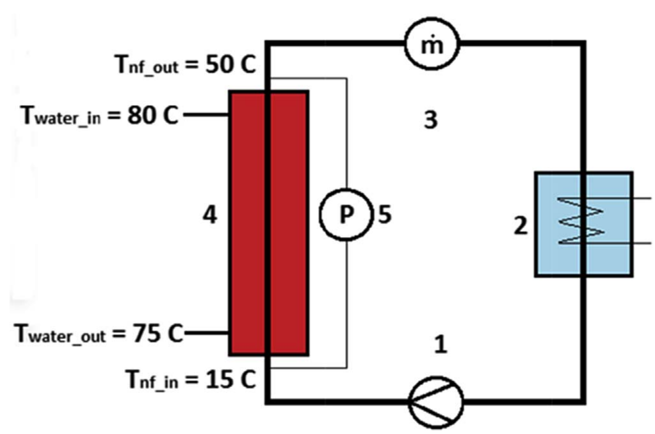

Fig. 1. A schematic of the convection heat transfer measurement apparatus: pump (1), cooler (2), flow meter (3), tube-in-tube type heat exchanger (4) and pressure meter (5).

Table 1
The particle materials and their thermal properties.

Material	Thermal conductivity (W/mK)	Density (kg/m^3)	Specific heat (J/kgK)
Polystyrene	0.16 [20]	1053 [21]	1210 [22]
SiO_2	1.38 [22]	2220 [22]	745 [22]
Al_2O_3	36.0 [22]	3970 [22]	765 [22]
Tween20	0.20	1100	2010
Span85	0.17	1000	2090 [23]