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 8–58 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.

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 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.

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 60ºC 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 60ºC.

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) $c_{p,bf}$.

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

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.

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]

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 nanofluid. The flow rate of hot water was kept constant at ~8 l/min in all the measurements. In order to prevent natural convection, the warming nanofluid was arranged to flow upwards in the vertically positioned heat exchanger. Consistently, the water flow on the external side was set to flow downwards.

The temperatures of the nanofluids were measured with two K-type thermocouples (accuracy ±0.05 K) at the inlet point and another two at the outlet. Before reaching the outlet thermocouples, the fluids were strangled in a narrow gap of 1 mm in diameter in order to ensure complete mixing of the fluid. With such an arrangement, cross-sectional temperature gradients were minimized thus improving the quality of outlet temperature measurement. The temperature of the hot water was measured with one thermometer on each side of the tube. The apparatus for measuring pressure losses (Yokogawa DP Harp pressure transmitter, uncertainty 0.04 %) was connected to each side of the inner tube of the heat exchanger, with a distance of 1.68m. The velocities of the nanofluid and water flows were measured with an Optiflux 4000 electromagnetic flow sensor (uncertainty 0.20%). Based on measurement repetition, the maximum experimental errors were estimated to be 1% for both heat transfer coefficients and pumping powers. However, the accuracies of the velocity and pressure loss measurements are limited with very low flow rates (laminar regime) causing the uncertainty for pumping powers to approach 5%.

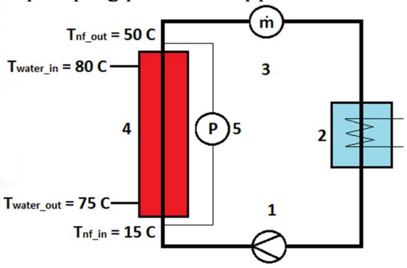

Fig 1. A schematic of the convection heat transfer measurement apparatus: pump (1), cooler (2), flow meter (3), tube-in-tube type heat exchanger (4) and pressure meter (5)

Calculation of heat transfer coefficient

Heat transfer coefficients were determined based on the measured inlet and outlet temperatures, mass flows and fluid properties. First, a logarithmic temperature difference is calculated using the definition.

$$\theta_{ln} = \frac{(T_{water,in} - T_{nf,out}) - (T_{water,out} - T_{nf,in})}{ln\frac{T_{water,in} - T_{nf,out}}{T_{water,out} - T_{nf,in}}}, \quad (2)$$

where T (K) are inlet and outlet temperatures of fluids. The subscript nf refers to the nanofluid. The conductance G of the heat exchanger is defined as the ratio of the heat transfer power ϕ and the logarithmic temperature difference θ_{ln} as

$$G = \frac{\phi}{\theta_{ln}} = \frac{\dot{m} c_p \Delta T}{\theta_{ln}}, \quad (3)$$

where $\dot{m}$ is the mass flow, c_p is the specific heat and ΔT the temperature change of the fluid. Conductance per length can be also expressed as

$$\frac{1}{G/L} = \frac{1}{\pi d_i h_i} + \frac{\ln(\frac{d_o}{d_i})}{2\pi \lambda_{tube}} + \frac{1}{\pi d_{io} h_{io}}, \quad (4)$$

where d_i and d_{io} are the inner and outer diameters of the inner tube, respectively, h_i and h_{io} are the inner and outer heat transfer coefficients, respectively, and λ is the thermal conductivity of the tube material (15 W/mK). The heat transfer coefficient of nanofluid h_i can be calculated after h_{io} is obtained using well-known correlations for the Nusselt number of turbulent flow. In this work, the Dittus-Boelter correlation for cooling fluids [6] was used to determine the Nusselt number of the external water side

$$Nu_{DB} = 0.023 Re^{0.8} Pr^{0.3}, \quad (5)$$

where Re is the Reynolds number and Pr is the Prandtl number of the hot water flow. A hydraulic diameter $d_h = d_o - d_{io}$ is applied to the Reynolds number. The Nusselt number was further corrected to correspond to the geometry of the duct between the annular tubes using a method suggested by Petukhov and Roizen [24].

$$Nu_{ann} = \frac{h_{io} d_h}{\lambda_{water}} = 0.86 Nu_{DB} \frac{d_o}{d_{io}}^{0.16} \quad (6)$$

RESULTS AND DISCUSSION

Nine different nanofluids were characterized and measured to study the effect of particle properties on convective heat transfer performance of the nanofluids. The main properties of the nanofluids are summarized in Table 2.

Table 2. The concentration (C) and the main material properties of the nanofluids. The particle size was measured with DLS and reported as the peak value of the number distribution. The viscosity (η), thermal conductivity (λ), density (ρ) and zeta potential (ζ) values were measured at 25 °C. The specific heats (c_p) were determined using Eq. (1).

Particle material	C (vol-%)	Particle size (nm)	PdI	ζ (mV)	λ_{nf}/λ_w	η_{nf}/η_w	ρ_{nf}/ρ_w	$c_{p,nf}/c_{p,w}$
SiO_2	0.09	52	0.04	-50.2	1.00	1.04	1.00	1.00
SiO_2	0.45	58	0.06	-43.9	0.99	1.08	1.01	0.99
SiO_2	1.81	47	0.08	-32.3	0.99	1.22	1.02	0.97
Micelle	0.5	8	0.40	-10.9	1.00	1.01	1.00	1.00
Polystyrene	1.0	17	0.10	-53.9	1.00	1.03	1.00	0.99
Al_2O_3	0.5	10	0.23	52.3	1.01	1.09	1.01	0.99
Al_2O_3	1.0	10	0.26	50.6	1.02	1.21	1.02	0.97
Polystyrene	0.5	12	0.09	-57.8	0.99	1.04	1.00	1.00
Polystyrene	1.0	12	0.12	-40.9	0.98	1.09	1.00	0.99

Structure

The zeta potentials are presented in Table 2. The zeta potentials of SiO_2, polystyrene and Al_2O_3 samples were considered to be sufficient for stability since the absolute values exceeded the stability limit of 30 mV. However, for the micelle nanofluid a relatively low zeta potential of -10.9 mV was obtained and thus its stability was considered to be uncertain.

The particle sizes and polydispersity indices (PdI) measured with DLS are presented in Table 2. No significant differences were observed in particle size distributions measured at the two temperatures: 25 °C and 60 °C. The size distributions of the fluids were also measured after the convective heat transfer measurements in order to ensure the dispersion stability during the experiments. All nanofluids except for the micelle fluid remained unchanged during the heat transfer measurements. The size distribution of the micelle sample could not be verified after the heat transfer experiments, since parallel measurements yielded inconsistent results. This indicated that the fluid composition had slightly altered during the heat transfer measurements. Micelles are not strongly bound particles but rather loose assemblies of amphiphilic molecules, and therefore their size and shape may change in flowing systems.

Since DLS assumes the particles to be spherical in shape, the size distributions and shapes for the solid-particle nanofluids were also verified with TEM. The TEM images are presented in Fig 2. The SiO_2- and polystyrene particles were observed to be approximately spherical (Figs. 2a-b and d) and alumina particles were somewhat oval-shaped (Fig. 2c). The TEM images of polystyrene and Al_2O_3 particles were in good agreement with the DLS data, thus confirming the particle size distributions measured. However, the SiO_2 particles (Figs. 2a and b) can be divided into two groups in terms of size: small particles with an average diameter of ~10 nm and large particles with an average diameter of ~90 nm. These results differ significantly from the DLS measurements that indicated a distribution with only one peak at a diameter of ~50 nm. However, DLS measures the suspension whereas dry samples are imaged in TEM. Therefore, the differences may have been caused by the drying and storage of the TEM samples.

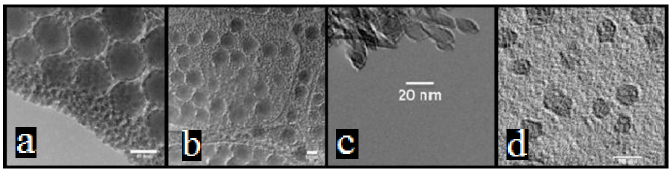

Fig 2. TEM-images of SiO_2 (a,b), Al_2O_3 (c) and polystyrene particles (d). The scale bars are 50 nm (a,b) and 20 nm (c,d).

Viscosity

The relative viscosities measured at 25 ºC are presented in Table 2. In addition, the relative viscosities are plotted as a function of temperature in Fig 3. The viscosities were measured with two measurement devices: a Haake Type C falling ball viscometer and the Brookfield DV3TLVCJ0 cone/plate rotational rheometer. The results differed significantly depending on which measurement technique was used, as can be seen in Fig. 3. In all the measurements except for one (0.09 vol-% SiO_2), the relative viscosities were lower when measured with the rotational rheometer. The relative magnitude of the difference seems to increase with increasing particle concentration. The largest difference of 20.5% was observed for the 1.81 vol-% SiO_2 nanofluid. A definite reason for these differences could not be concluded. Nevertheless, the sensitivity of the falling ball viscometer to any larger particles or agglomerates may result in excessively high values. In addition, micelles may break in the rheometer due to vigorous stirring resulting in anomalously low values. Similar uncertainties in viscosity measurements could be one of the reasons for inconsistent results in the literature [25-49]. Furthermore, errors in viscosity measurements could also distort the analysis of convective heat transfer experiments, since the Reynolds number is heavily dependent on the viscosity. In this work, the rotational viscometer was considered to be a more reliable measurement device and thus these results were used in the data analysis of the convective heat transfer experiments. However, the viscosities of Al_2O_3 nanofluids could not be measured with the rotational viscometer, since the Al_2O_3 particles agglomerated rapidly due to the presence of the chamber material (Aluminium). Therefore, the falling ball viscometer values were used in the analysis of Al_2O_3 and PS2 nanofluids in order to obtain a fair comparison.

The addition of nanoparticles caused the fluid viscosities to increase considerably, as expected. A particle fraction of only 0,5 vol-% resulted in viscosity increase of up to 10 % (rotational viscometer). However, the viscosity increase cannot be explained with the concentration alone, but also the particle properties have an influence. The highest increases in viscosities were measured for the SiO_2 nanofluids with the largest particle sizes of ~50 nm, whereas equal concentrations of very small ~10 nm particles (Al_2O_3, polystyrene, micelle) increased the viscosity significantly less. This indicates that small particle size is preferable in terms of viscosity. In addition, the viscosities of Al_2O_3 nanofluids were higher than those of the polystyrene nanofluids although both the concentrations and particle size distributions were similar. Therefore, the viscosity of nanofluids seems to depend on other parameters as well.

Typically, the relative viscosity of nanofluids was independent on the temperature, as proposed in several publications [25,26,50]. However, the relative viscosity of the 1.81 vol-% SiO_2 nanofluid was observed to decrease with increasing temperature (Fig. 3a). This phenomenon was observed with both measurement devices. Similar behavior was also observed by Sundar *et al.* [27].

The Newtonian behavior of the samples was verified with the rotational viscometer. However, the range of shear rates studied (1125-1875 1/s) was relatively high and narrow, since sufficiently high shear rates are required for low viscosity fluids, such as the water-based fluids studied herein. On the contrary, in the falling ball viscometer the fluid is stationary, and the ball descends slowly through the fluid. Therefore, non-Newtonian behavior with very low shear rates cannot be ruled out as a reason for the differences between the results obtained with the two devices, since the measurement conditions of the devices differ from each other in terms of shear rates. In fact, some previous articles have proposed that nanofluids exhibit shear thinning behavior particularly in the regime of very low shear rates [29,52].

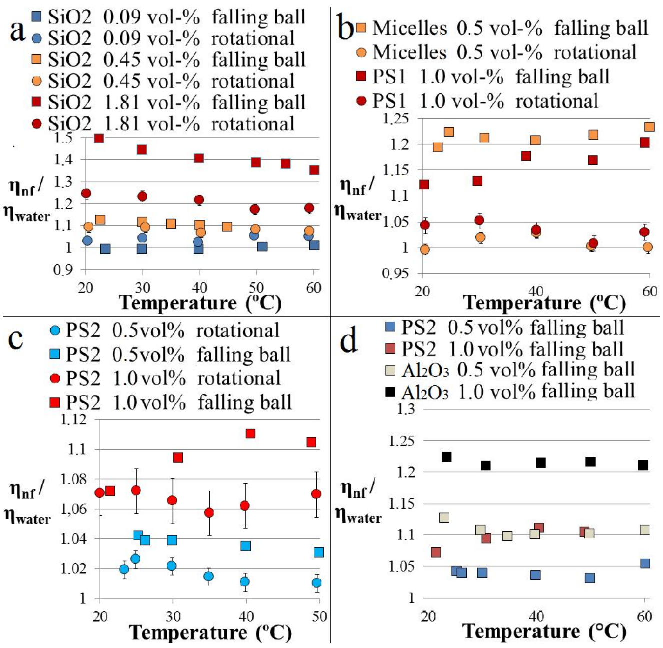

Fig 3. The relative viscosities of the nanofluids. The error bars are estimated based on the differences between parallel measurements. In case of the falling ball viscometer, the differences were insignificant.

Thermal conductivity

The relative thermal conductivities of the samples are presented in Table 2. The addition of the nanoparticles caused the thermal conductivities of the fluids to change in an expected manner. The particle material with the highest thermal conductivity (Al_2O_3) caused the highest enhancement (2%) and the particle material with the lowest thermal conductivity (polystyrene) caused the largest decrease (2%). The change in the thermal conductivity was observed to increase with the particle concentration. However, the differences observed in the thermal conductivities were rather small and, in fact, within the uncertainty of the measurement device (3%). The thermal conductivity enhancements reported in literature for 0.5 – 1 vol-% Al_2O_3 nanofluids are typically higher than those measured herein, but also similar values have been reported [4]. Most of the measured conductivities give slightly lower values than the well-known Maxwell equation for dispersed spheres in a base fluid (Table 3). However, the difference between the measurements and the model is minute.

Table 3. Difference between measured thermal conductivities of solid particle nanofluids (values presented in Table 2) and those from the Maxwell equation.

Particle material	*C* (vol-%)	Particle size (nm)	Difference %
SiO_2	0.09	52	-0.1%
SiO_2	0.45	58	-1.4%
SiO_2	1.81	47	-2.6%
Polystyrene	1.0	17	+1.0%
Al_2O_3	0.5	10	-0.4%
Al_2O_3	1.0	10	-0.9%
Polystyrene	0.5	12	-0.5%
Polystyrene	1.0	12	-1.0%

Convective heat transfer

The Nusselt numbers are plotted as a function of the Reynolds numbers (averaged along the tube length) in Fig. 4. Typically, the nanofluids reached higher Nusselt numbers than water with an equal Reynolds number and the difference increased with increasing concentration. The largest difference of 12.5-20.5% was obtained for the sample with the highest particle fraction: 1.81 vol-% SiO_2 nanofluid. Similar behavior has been reported widely in the literature [6-8,16,52-55]. However, this presentation method has been criticized in several recent publications [14-17,52,56-58]. The standard method does not take the pumping power into account and therefore the suitability of the fluids for practical forced convection applications cannot be properly assessed. In addition, the method disregards the effect of the Prandtl number leaving the altered thermal properties of nanofluids incompletely accounted for. Therefore, the method is also unable to state whether the measured convective heat transfer is truly unexpected, or simply a result of the altered fluid properties. To account for this, a direct comparison between the experimental results and the Gnielinski correlation [7] is presented. The correlation is valid in both the transition and turbulent regimes for $2300 < Re < 5 \times 10^6$ thus covering the majority of the experimental results [7].

$$Nu_{correlation} = \frac{\left(\frac{f}{2}\right)(Re-1000)Pr}{1+12.7\left(\frac{f}{2}\right)^{1/2}\left(Pr^{2/3}-1\right)} \qquad (7)$$

Experimental friction factors were not used in Eq. (7), since purely correlation-based reference values were desirable. Instead, the friction factors for this purpose were determined based on the Blasius Law for turbulent flow in a pipe [59].

$$f = 0.316Re^{-0.25} \qquad (8)$$

In Fig. 5, the measured *Nu* (Nu_{exp}) are presented as a function of *Nu* calculated based on the Gnielinski correlation ($Nu_{correlation}$). The correlation seems to be able to explain the heat transfer behavior of all the nanofluids regardless of the different particle properties. In particular with higher Nusselt numbers, where the flow is approaching a fully turbulent regime, the experimental values agree with the predicted values accurately. In addition, the nanofluids and water behave almost similarly when presented with this method that takes both *Re* and *Pr* into account. The Nusselt numbers of all nanofluids were within 5% from that of water, and no anomalous heat transfer behavior was observed. In Fig. 5d, the experimental results do not follow the correlation very well, but the nanofluids show slightly deteriorated heat transfer performance instead. However, the same deterioration of the heat transfer performance can be observed for the reference water sample as well. The difference between the predicted and measured values in Fig. 5d can be attributed to a thin thermal resistance layer on the surface of the measurement tube caused by an earlier measured unstable polystyrene sample. However, regardless of the resistance layer, the measurements are comparable within the same measurement set. Due to the similar results between the nanofluids and the water reference, no anomalous heat transfer behavior was observed for these fluids either.

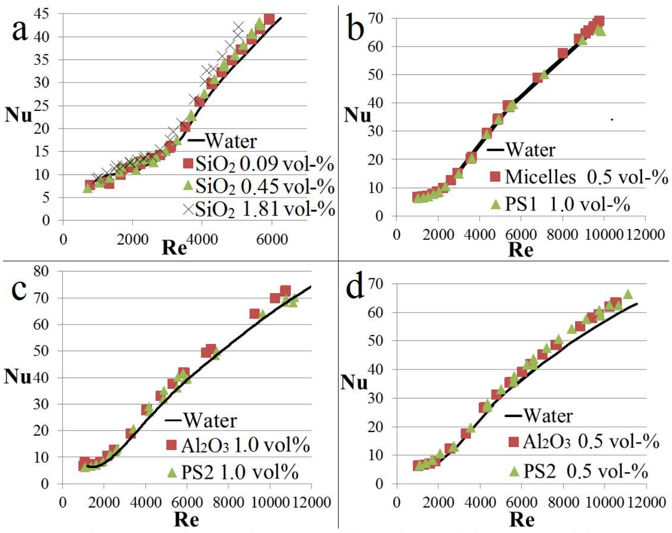

Fig 4. The Nusselt numbers as a function of the Reynolds numbers.

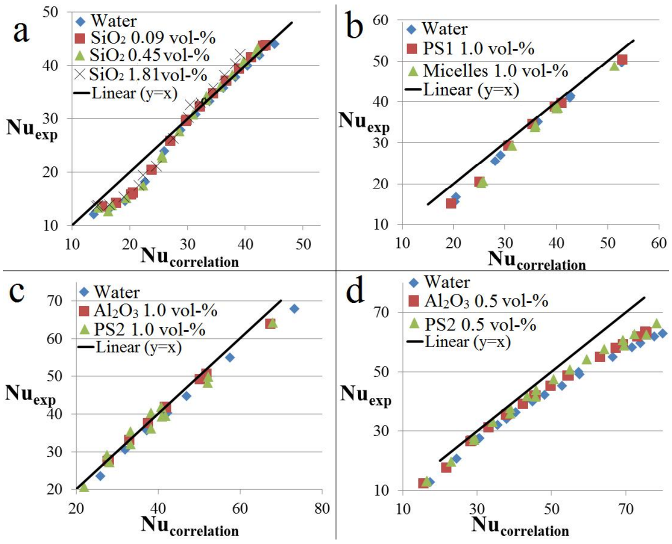

Fig 5. The experimental results compared to the Gnielinski correlation.

Friction factors

The Darcy friction factors are presented in Fig. 6. In all cases, the friction factors of the nanofluids were approximately equal to those of water with equal *Re*. In the turbulent flow regime, all the data are in agreement. Likewise, the behavior in the laminar and transition flow regimes is similar for all fluids measured. The pressure loss measurements of 1 vol-% polystyrene nanofluid (PS2) failed due to the aforementioned fluid instability and these results are not presented here. Also the subsequently measured 0.5 vol-% Al_2O_3 and polystyrene fluids exhibited increased pressure losses (Fig. 6d). Therefore, the friction factors of these fluids can be compared only with each other and with the corresponding water reference. Overall, the differences in the friction factors of the nanofluids and water were rather small and thus, all differences were interpreted to be within the measurement uncertainty. Therefore, the nanofluids were observed to behave as conventional fluids in terms of the friction factors.

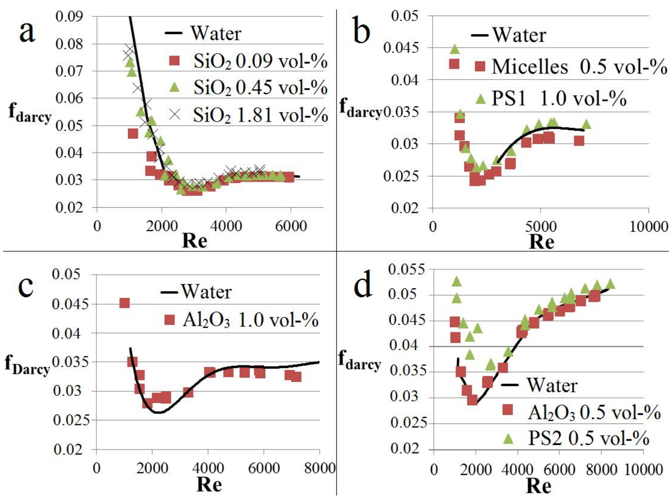

Fig 6. The friction factors of the nanofluids.

Convective heat transfer efficiency

Figure 7 describes the effective heat transfer performance of the fluids: the heat transfer coefficients (HTC) are presented as a function of the pumping power. On this basis, the addition of nanoparticles seems to deteriorate the heat transfer performance. In all cases, the nanofluids showed lower or similar performance to that of water. The differences in convective heat transfer efficiencies arise from the differences in fluid properties, since all the nanofluids were observed to perform as conventional fluids in terms of both the convective heat transfer and the friction factors. The addition of nanoparticles was observed to change the fluid properties in an unfavorable manner regardless of the particle type: the viscosities increased significantly in all cases, while only moderate enhancements in the thermal conductivities were observed. With equal pumping powers, the more viscous nanofluids reach lower Reynolds numbers than water resulting in lower heat transfer coefficients (Fig. 7). The viscosity increases with concentration, which causes the heat transfer efficiency to deteriorate further. Similar decrease of heat transfer efficiency with increasing concentration has been also reported in some earlier publications [50,60,61]. The SiO_2 nanofluids with the highest viscosities (and the largest particle sizes) show the most notable deterioration in the heat transfer performance, whereas the other fluids with slightly lower viscosities perform almost equally with water. In some previous publications, small particle size has been reported to be preferable for the convection heat transfer of nanofluids, and these results show partial support on the claim [28,29,53,62]. However, the SiO_2 nanofluids differ from the other samples in terms of the particle material as well, and thus no firm conclusions of the particle size effect can be drawn. The alumina and polystyrene nanofluids performed roughly equally and therefore, the thermal conductivity of the particle material does not seem to have a notable impact on the convection heat transfer efficiency with the rather small concentrations studied herein ($\leq$ 1 vol-%).

Although anomalous enhancement in forced convection heat transfer of nanofluids was not observed, enhancement in thermal conductivity caused by the nanoparticles could still be harnessed to improve the heat transfer fluids. Significant increment in thermal conductivity might be obtained for instance by using metallic nanoparticles [62]. However, the addition of the nanoparticles would result in practical enhancement only if the negative effects caused by increasing viscosity and decreasing specific heat could be retained low.

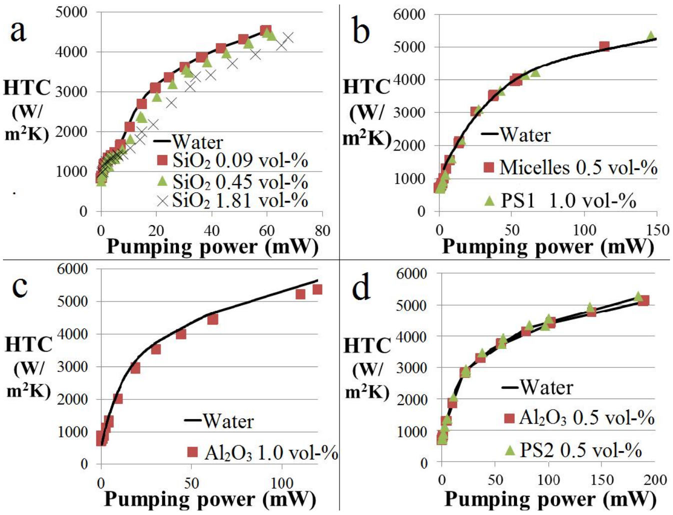

Fig 7. Effective heat transfer performance of the nanofluids.

CONCLUSIONS

Influence of particle properties on convective heat transfer of nanofluids was experimentally studied. Nine different nanofluids were prepared and measured with an annular tube heat exchanger. The nanofluids were also thoroughly characterized: particle size distributions, shapes, fluid stabilities, viscosities, densities and thermal conductivities were all determined experimentally.

The standard analysis method of presenting the Nusselt numbers solely as a function of the Reynolds numbers indicates enhancement in the convection heat transfer. However, since the Nusselt number is dependent on both the Reynolds and Prandtl numbers, the standard method is found to be questionable and to favor more viscous nanofluids excessively. Indeed, the convection heat transfer enhancement that the standard method suggests can be explained by considering also the Prandtl numbers in the analysis. The convection heat transfer of all the nanofluids followed the well-known Gnielinski correlation for turbulent flow, and no anomalous heat transfer enhancement was observed for any nanofluids regardless of the particle type. In addition, the nanofluids were observed to behave similarly to conventional fluids in terms of friction factors. Therefore, both the convection heat transfer and the friction behavior of nanofluids can be explained through the altered thermal properties.

The addition of any type of nanoparticles was observed to change the fluid properties in an unfavorable manner in terms of forced convection heat transfer applications: the viscosity increases significantly due to the nanoparticles. The viscosity of nanofluids was observed to depend mainly on the concentration and the particle size, but also other parameters seem to have an influence. In addition, the two devices used in the viscosity measurements were observed to yield contradictory results. The values obtained with the falling ball viscometer were typically higher than those obtained with the rotational viscometer. The relative magnitude of the difference increased with increasing particle concentration, and the largest difference observed was 20.5%. Only moderate enhancements in the thermal conductivities were obtained (up to 2%), depending on the particle type. The influence of particle material on the thermal conductivity of nanofluids was observed to be as expected: the highest conductive particle materials cause the highest enhancement, and vice versa.

The nanofluids exhibited heat transfer efficiency similar or lower than water, when compared with equal pumping powers. The differences in the heat transfer efficiencies were analyzed to be caused mainly by the differences in the viscosities. Increasing the nanoparticle concentration decreased the convective heat transfer efficiency in all cases. However, the decrease in the heat transfer efficiency was less pronounced for nanofluids with smaller particle size indicating that a very small particle size would be preferable for forced convective heat transfer applications. The thermal conductivity of particle material did not have a notable impact on the convection heat transfer efficiency with the relatively low concentrations studied herein (≤ 1 vol-%).

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