CONVECTIVE HEAT TRANSFER PERFORMANCE OF POLYSTYRENE, SiO₂, Al₂O₃ AND MICELLE NANOFLUIDS

Mikkola V.[1]*, Puupponen S.[1], Granbohm H.[2], Saari K.[1], Ala-Nissila T.[3,4] and Seppälä A.[1]

*Author for correspondence

[1]Aalto University School of Engineering, Department of Mechanical Engineering, Thermodynamics and Combustion Technology, P.O. Box 14400, FI-00076 Aalto, Finland

[2]Aalto University School of Chemical Technology, Department of Materials Science and Engineering, Advanced and Functional Materials, P.O. Box 16200, FI-00076 Aalto, Finland

[3]Aalto University School of Science, Department of Applied Physics and COMP CoE, P.O. Box 11000, FIN-00076 Aalto, Finland

[4]Brown University, Department of Physics, P.O. Box 1843, Providence, RI 02912, USA

E-mail: valtteri.mikkola@aalto.fi

ABSTRACT

In this study, influence of concentration, particle size and thermal conductivity of particle material on convective heat transfer of nanofluids is experimentally examined. Water-based nanofluids containing SiO₂, micelle, polystyrene or Al₂O₃ particles are self-synthesized (apart from Al₂O₃) and measured with an annular tube heat exchanger. Concentrations of the nanofluids studied vary in the range of 0.1–2.2 vol-% and particle sizes between 8–58 nm. The heat transfer measurements cover both laminar and turbulent regimes with the Reynolds numbers varying in the range of 1000-11000. The measurements also include pressure losses in order to study the suitability of 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. No difference is observed when the effect of Prandtl number is taken into account. All nanofluids studied performed as Gnielinski correlation predicts, and anomalous behavior was not observed. When compared by using equal pumping powers, the nanofluids show equal or poorer performance than water. Increase in the particle concentration lowers the heat transfer performance in all cases. However, the magnitude of this deteriorating effect is smaller for nanofluids with smaller particle size indicating that small particle size is beneficial for heat transfer of nanofluids. The thermal conductivity of the particle material does not have a notable impact on the convection heat transfer with the relatively low particle concentrations studied herein (≤ 1 vol-%).

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 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, such anomalous behavior in convective heat transfer has not been observed at all [12-15]. In spite of the large body of research, no theory has been able to provide a solid and well-established explanation for physical basis of the possible heat transfer enhancement of nanofluids.

The aim of this study is to experimentally examine the influence of concentration, particle size and thermal conductivity on convective heat transfer of nanofluids. Nine nanofluid samples are prepared, characterized, measured and analyzed for this purpose. The convective heat transfer performance is studied with an annular tube heat exchanger. The measurements cover both the laminar and turbulent regimes 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 nanofluids were investigated in this study. The measurements were divided into three sets according to their objectives. In the first measurement set, three different concentrations of SiO_2 nanofluids with average particle sizes of ~50 nm were measured in order to study the effect of concentration on convective heat transfer of nanofluids. The SiO_2 nanoparticles were self-synthesized using the Stöber method [16]. In the second set, nanofluids with very small particle sizes of ~10 nm were studied and compared with the previous fluids with larger particle sizes in order to study the influence of the particle size on the convective heat transfer. Two different nanofluids were prepared and measured for this purpose: polystyrene-in-water nanofluids (PS1) and micelle-in-water fluids. The polystyrene nanofluids were self-prepared using a method adopted from Kaivi and Zhaoqun [17] and micelles were formed using polysorbate20 (Tween20, 81.9 w-%) and sorbitan trioleate (Span85, 18.9 w-%) surfactants. In the third set, the influence of thermal conductivity of the particle material on the convective heat transfer behavior of nanofluids was studied. Two equal concentrations of Al_2O_3 and polystyrene nanofluids (PS2) with similar particle size distributions were compared. 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 conductivities of particle materials. A commercial dispersion of $Al_2O_3(aq)$ (Nanostructured & Amorphous Materials Inc.) was used for the Al_2O_3 nanofluid preparation.

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 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 temperatures of 20°C and 60ºC.

The viscosities were measured with two different types of viscometers 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 the Brookfield DV3TLVCJ0 cone/plate rheometer. Based on measurement repetition, maximum errors for these two 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.

Thermal conductivities of the nanofluids were determined with the C-therm TCi-3-A thermal conductivity analyzer, based on modified transient source plane technique. According to the manufacturer, the error 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) $c_{p,bf}$.

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

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.

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 6 mm and 13 mm, respectively. The thickness of the inner pipe, which corresponds to the wall separating the two fluids, was 1 mm. The temperature of incoming nanofluid was set to 15-20°C. Cooling was arranged using a heat exchanger with cold tap 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 thermometers 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) was connected to each side of the inner tube of the heat exchanger, with a distance of 1.68m. Velocities of nanofluid and water flows were measured with the Optiflux 4000 electromagnetic flow sensor. Based on measurement repetition, the maximum experimental errors were estimated to be 1% for both heat transfer coefficients and pumping powers.
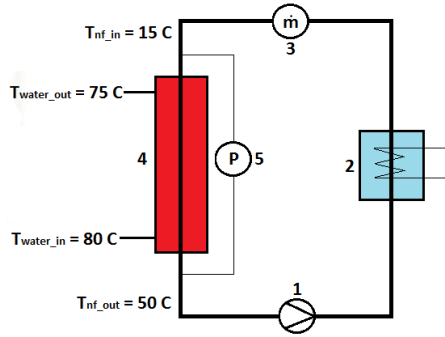
Fig 1. A schematic of the convection heat transfer measurement apparatus: pump (1), cooler (2), flow meter (3), tube-in-tube type heat exchanger (4) and pressure meter (5)

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.

$$\theta_{ln} = \frac{(T_{water,in}-T_{nf,out})-(T_{water,out}-T_{nf,in})}{ln\frac{T_{water,in}-T_{nf,out}}{T_{water,out}-T_{nf,in}}}, \qquad (3)$$

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

$$G = \frac{\phi}{\theta_{ln}} = \frac{\dot{m}c_p\Delta T}{\theta_{ln}}, \qquad (4)$$

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

$$\frac{1}{G/L} = \frac{1}{\pi d_i h_i} + \frac{ln(\frac{d_o}{d_i})}{2\pi \lambda_{tube}} + \frac{1}{\pi d_o h_o}, \qquad (5)$$

where d_i and d_o are the inner and outer diameters of the tube, respectively, h_i and h_o 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_o 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

$$Nu_{DB} = 0{,}023Re^{0{,}8}Pr^{0{,}3}, \qquad (6)$$

where Re is the Reynolds number and Pr is the Prandtl number of the hot water flow. 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 [18].

$$Nu_{ann} = \frac{h_o d_o}{\lambda_{water}} = 0{,}86Nu_{DB}\frac{d_o}{d_i}^{0{,}16}. \qquad (7)$$

RESULTS AND DISCUSSION

Nine different nanofluids were characterized and measured to study the effect of concentration, particle size and thermal conductivity of particle material on effective convective heat transfer of nanofluids. The main properties of the nanofluids studied are summarized in Table 1.

Table 1. The concentration (C) and the main material properties of the nanofluids studied. The Particle size is measured with DLS and reported as the peak value of the number distribution. Viscosity (η), thermal conductivity (λ) and density (ρ) values are measured at 25 °C.

Particle material	C (vol-%)	Particle size (nm)	PdI	Zeta pot.	λ_{nf}/λ_w	η_{nf}/η_w	ρ_{nf}/ρ_w
SiO$_2$	0.09	52	0.04	-50.2	1	1.04	1.00
SiO$_2$	0.45	58	0.06	-43.9	0.99	1.08	1.01
SiO$_2$	1.81	47	0.08	-32.3	0.99	1.22	1.02
Micelle	0.5	8	0.40	-10.9	1.00	1.01	1.00
Polystyrene	1.0	17	0.10	-53.9	1.00	1.03	1.00
Al$_2$O$_3$	0.5	10	0.23	52.3	1.01	1.09	1.01
Al$_2$O$_3$	1.0	10	0.26	50.6	1.02	1.21	1.02
Polystyrene	0.5	12	0.09	-57.8	1.03	1.04	1.00
Polystyrene	1.0	12	0.12	-40.9	1.04	1.09	1.00

Structure

The zeta potentials are presented in Table 1. The zeta potentials of SiO$_2$, polystyrene and Al$_2$O$_3$ 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 1. 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 different 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 they may deform in flowing systems.

Since DLS assumes the particles to be spherical in shape, the size distributions and shapes 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$_2$O$_3$ 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.
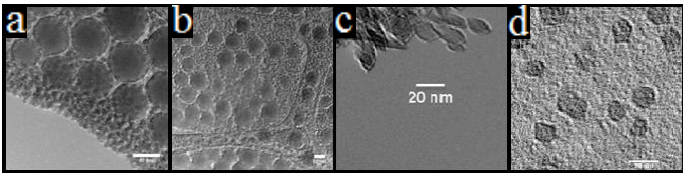
Fig 2. TEM-images of SiO₂ (a,b), Al₂O₃ (c) and polystyrene particles (d). The scale bars are 50 nm (a,b) and 20 nm (c,d).

Viscosity

The relative viscosities measured at 25 ℃ are presented in Table 1. 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, unstable 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 [19-43]. 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 Al₂O₃ nanofluids could not be measured with the rotational viscometer, since the Al₂O₃ particles agglomerated rapidly due to the presence of the chamber material (Aluminium). Therefore, the falling ball viscometer values were used in the analysis of the third measurement set (Al₂O₃ and PS2 fluids).

Typically, the relative viscosity of nanofluids measured was independent on the temperature, as proposed in several publications [19,20,44]. 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.* [21].

The Newtonian behavior of the samples was verified with the rotational viscometer. However, the studied range of shear rates (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.
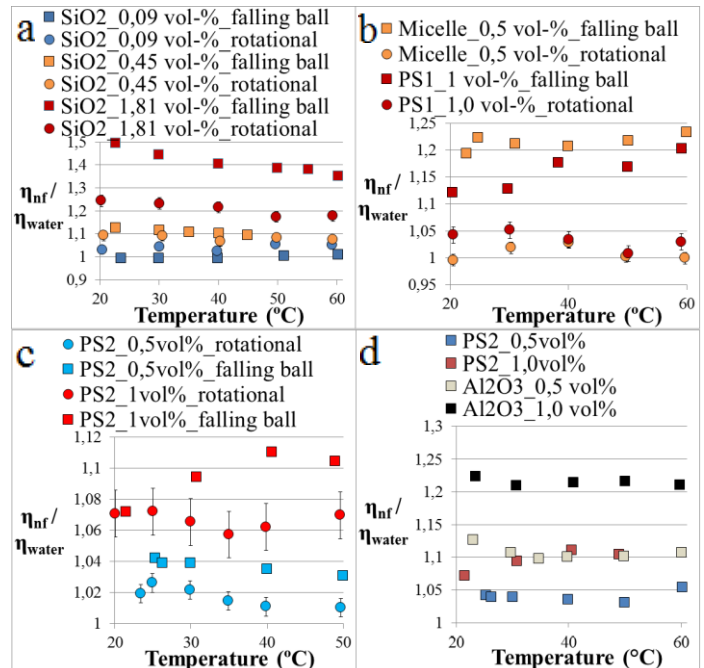
Fig 3. The relative viscosities of the nanofluids measured. The error bars are estimated based on the differences between parallel measurements. In case of the falling ball viscometer, the differences were insignificant.

Thermal conductivity

Relative thermal conductivities of the samples are presented in Table 1. The addition of nanoparticles caused slight changes in thermal conductivities. However, the differences observed were relatively small; the maximum enhancement of 3.5 % was obtained with 1 vol-% polystyrene nanofluid. Thermal conductivities of Al₂O₃-nanofluids were observed to be slightly lower than those of polystyrene nanofluids with corresponding concentrations. Such a result is unexpected since the reported value of the thermal conductivity of bulk Al₂O₃ is 12.1 W/mK [45], whereas the value for bulk polystyrene is only 0.14 W/mK [45]. One explanation could be the sodium dodecyl sulfate surfactant used for the preparation of PS nanofluids. The ionic surfactant may enhance the ordering of H_2O molecules in the vicinity of nanoparticles, and thus increase the thermal conductivity. No surfactant was used in the preparation of the Al₂O₃ nanofluids. However, the observed differences in the thermal conductivities were rather small and no large deviations were even expected, since the particle concentrations of the studied fluids were relatively low (≤1 vol-%).

Convective heat transfer

The Nusselt numbers are plotted as function of the Reynolds numbers in Fig. 4. Typically, the nanofluids reached higher Nusselt numbers than water with an equal Reynolds number. 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 widely reported in literature as well [6-8,46-49]. However, this presentation method has been criticized in several recent publications, since it does not take pumping power into account [14,15,46,50,51]. Therefore, the

standard method is unable to assess the suitability of fluids for practical forced convection applications. In addition, the method disregards the effect of the Prandtl number and thus it is also unable to state whether the performance of the fluids follow the conventional heat transfer correlations. Thus, a direct comparison between the experimental results and the Gnielinski correlation [6] is presented.

$$Nu_{correlation} = \frac{\left(\frac{f}{2}\right)(Re-1000)Pr}{1+12,7\left(\frac{f}{2}\right)^{1/2}(Pr^{2/3}-1)} \qquad (8)$$

Since purely correlation-based reference values were desirable, experimental friction factors were not used in Eq. (8). Instead, the friction factors for this purpose were determined based on the Blasius Law for turbulent flow in a pipe [52].

$$f = 0.316 Re^{-0,25} \qquad (9)$$

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 the nanofluids. In particular with higher Nusselt numbers, where the flow is approaching fully turbulent regime, the values measured 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 in this measurement set either.
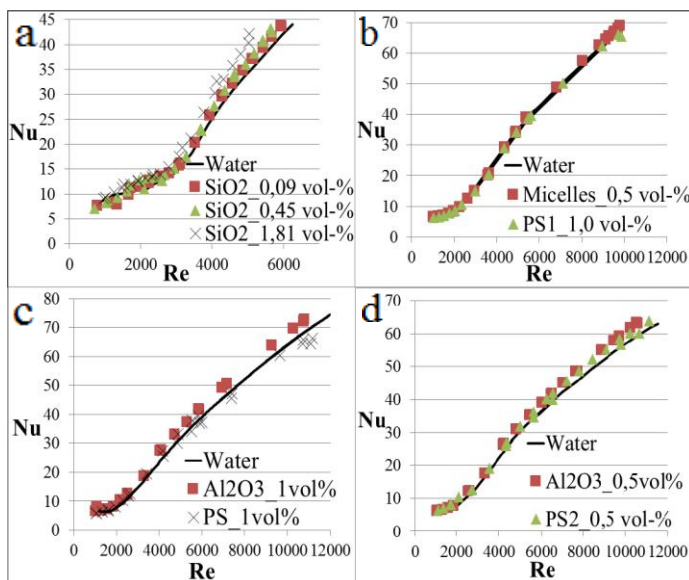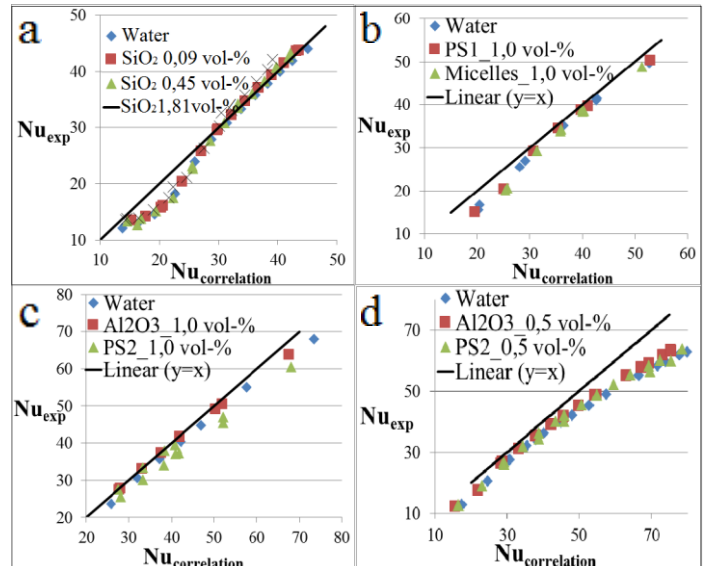

Fig 5. The experimental results compared to the Gnielinski correlation.

Friction factors
The Darcy friction factors are presented in Fig. 6. In all three measurement sets, the friction factors of the nanofluids were approximately equal to those of water. In the turbulent flow regime, all the data are in agreement. Likewise, the behavior in the laminar and transition flow regimes was noticed to be 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-% fluids of the third set experienced 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 between the results were interpreted to be within the measurement errors.
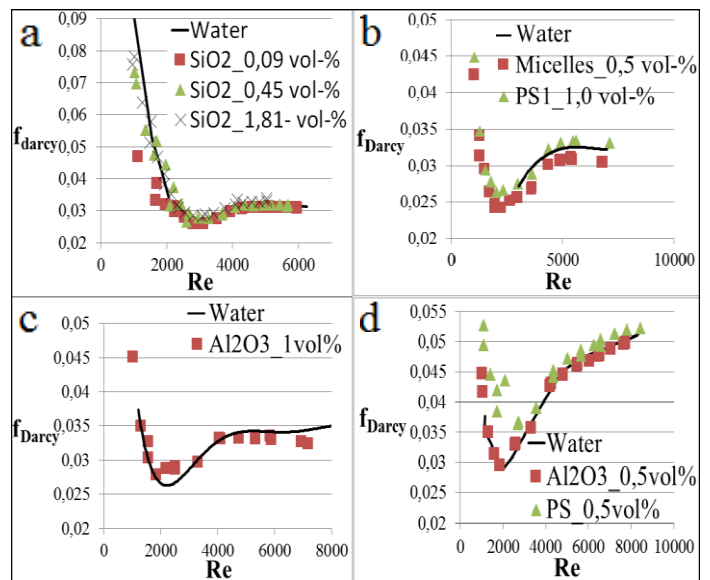

Fig 4. The Nusselt numbers as a function of Reynolds numbers.

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. Furthermore, the effect of concentration seems clear: the effective heat transfer performance decreases with increasing concentration as observed also in some earlier experiments [44,53,54]. In addition to the concentration, the particle size was observed to have an influence on the effective convective heat transfer. Silica nanofluids with the largest particle size of ~50 nm had the lowest performance whereas smaller Al_2O_3, polystyrene and micelle nanofluids composed of ~10 nm particles performed substantially better. These results indicate that a small particle size would be beneficial for effective convective heat transfer performance of nanofluids as suggested earlier in some publications [22,23,47,55]. However, the SiO_2 nanofluids differ from the other samples in terms of the material as well, and thus no firm conclusions of the particle size effect can be drawn. Alumina and polystyrene nanofluids performed roughly equally, and the thermal conductivity of the particle material was not observed to have any significant impact on heat transfer with the 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 conventional heat transfer fluids. Significant increment in thermal conductivity might be obtained for instance by using metallic nanoparticles [56]. 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.
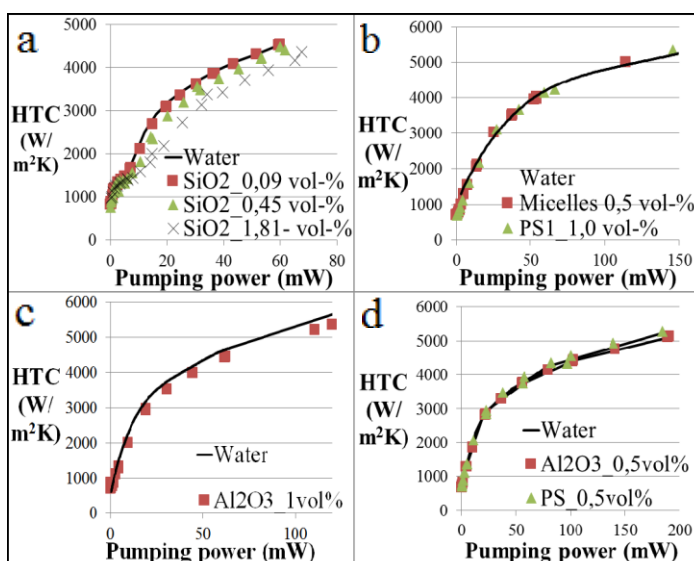

Fig 7. Effective heat transfer performance of nanofluids

CONCLUSIONS

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

A traditional analysis method of presenting the Nusselt numbers solely as a function of the Reynolds numbers indicated increment in the convection heat transfer. However, since the Nusselt number is dependent on both Reynolds number and Prandtl number, the traditional method of presenting results only as a function of Reynolds number was found to be questionable and favor more viscous nanofluids excessively. Indeed, no significant deviations from conventional heat transfer correlations were observed when the samples measured were compared to the well-known Gnielinski correlation for turbulent flow.

The nanofluids exhibited heat transfer performance similar or lower than water, when compared with equal pumping powers. Increasing the nanoparticle concentration decreased the convective heat transfer performance of all fluids measured. However, the decrease in the effective heat transfer performance was weaker for nanofluids with smaller particle size. Therefore, the measurement data indicates that a very small particle size would be beneficial for heat transfer performance of nanofluids. The thermal conductivity of particle material did not have a notable impact on the convection heat transfer with the relatively low concentrations studied herein ($\leq$ 1 vol-%).

The two devices used in the viscosity measurements yielded 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%. The thermal conductivities or Al_2O_3 nanofluids were observed to be slightly lower than those of polystyrene samples. Such a result is unanticipated, since the thermal conductivity of bulk Al_2O_3 is two orders of magnitude higher than that of polystyrenes.

ACKNOWLEDGEMENTS

REFERENCES

[1]Choi, S. U. S. and Eastman, J. A., Enhancing thermal conductivity of fluids with nanoparticles, *ASME International mechanical engineering congress & exposition*, 1995

[2]Sundar, L. S. et al., Investigation of thermal conductivity and viscosity of Fe_3O_4 nanofluid for heat transfer applications, *International communications in heat and mass transfer*, vol. 44, pp. 7-14, 2013

[3]Yu, W. et al., Investigation of thermal conductivity and viscosity of ethylene glycol based ZnO nanofluid, *Thermochimica Acta*, Vol. 491, pp. 92-96, 2009

[4]Yu, W. et al., Review and comparison of nanofluid thermal conductivity and heat transfer enhancements, *Heat transfer engineering*, Vol. 29, 2008

[5]Esfe, M. et al., Thermal conductivity of Cu/TiO$_2$-water/EG hybrid nanofluid: Experimental data and modeling using artificial neural network and correlation, *International communications in heat and mass transfer*, Vol. 66, pp. 100-104, 2015

[6]Michaelides, E. E., Nanofluidics: Thermodynamic and transport properties, *Springer*, 2014. ISBN: 978-3-319-05620-3

[7]Kakac, S. et al., Convective heat transfer (Third edition), *CRC Press, Taylor&Francis Group*, 2014. ISBN: 978-1-4665-8344-3

[8]Sarkar, J., A critical review on convective heat transfer correlations of nanofluids, *Renewable and sustainable energy reviews*, Vol. 15, pp.3271-3277, 2011

[9]Anoop, K. B. *et al.,* Effect of particle size on the convective heat transfer in nanofluid in the developing region, *International journal of heat and mass transfer,* Vol. 52, pp. 2189-2195, 2009

[10]Chen, H. *et al.,* Heat transfer and flow behaviour of aqueous suspensions of titanate nanotubes (nanofluids), *Powder Technology,* Vol. 183, pp. 63-72, 2008

[11]Gupta, M. et al., A comprehensive review of experimental investigations of forced convective heat transfer characteristics for various nanofluids, *International journal of mechanical and materials engineering*, 2014

[12]Akhavan-Zanjani, H. et al., Turbulent convective heat transfer and pressure drop of graphene-water nanofluid flowing inside a horizontal circular tube, *Journal of dispersion science and technology*, Vol. 35, pp. 1230-1240, 2014

[13]Williams, W., Buongiorno, J. and Hu, L., Experimental investigation of turbulent convective heat transfer and pressure loss of alumina/water and zirconia/water nanoparticle colloids (nanofluids) on horizontal tubes, *Journal of heat transfer*, Vol. 130, pp. 2008

[14]Haghighi, E. B., Single phase convective heat transfer with nanofluids: An experimental approach (Doctoral thesis), *KTH industrial engineering and management, Department of energy technology, Division of applied thermodynamics and refrigeration*, 2015. ISBN: 978-91-7595-414-1

[15]Mikkola, V.*,* Impact of concentration, particle size and thermal conductivity on effective convective heat transfer performance of nanofluids (Master's thesis), *Aalto University School of Engineering, Department of Energy Technology,* 2015

[16]Stöber, W., Fink, A., Bohn, E., Controlled growth of monodisperse silica spheres in the micron range, *Journal of colloid and interface science*, 26, 62 (1968), DOI:10.1016/0021-9797(68)90272-5

[17]Kaiyi, L., Zhaoqun, W., A novel method for preparing monodispersed polystyrene nanoparticles, *Front. Chem. China* 2007 2(1) 17-20.

[18]Cengel, Y. A., Heat transfer - A practical approach, 2. Edition, *McGraw-Hill*, pp. 444, 2003 ISBN: 0-07-115150-8

[19]Esfe, M. and Saedodin, S., An experimental investigation and new correlation of viscosity of ZnO-EG nanofluid at various temperatures and different solid volume fractions, *Experimental thermal and fluid science*, Vol. 55, pp. 1-5, 2014

[20]Chen, H. et al., Rheological behavior of ethylene glycol based titania nanofluids, *Chemical physics letters*, Vol. 444, pp. 333-337, 2007

[21]Sundar, L. S. et al., Viscosity of low volume concentrations of magnetic Fe$_3$O$_4$ nanoparticles dispersed in ethylene glycol and water mixture, *Chemical physics letters*, Vol. 554, pp. 236-242, 2012

[22]Esfe, M. H. and Saedodin, S., Turbulent convection heat transfer and thermophysical properties of MgO-water nanofluid with concentration of different nanoparticles diameter, an empirical study, *Journal of thermal analysis and calorimetry*, Vol. 119, pp. 1205-1213, 2015

[23]He, Y. et al., Heat transfer and flow behaviour of aqueous suspensions of TiO$_2$ nanoparticles (nanofluids) flowing upward through a vertical pipe, *International journal of heat and mass transfer*, Vol. 50, pp. 2272-2281, 2007

[24]Mishra, P. C. et al., A brief review on viscosity of nanofluids, *International nano letters*, Vol 4, pp. 109-120, 2014

[25]Jarahnejad, M. et al., Experimental investigation on viscosity of water-based Al$_2$O$_3$ and TiO$_2$ nanofluids, *Rheologica acta*, Vol. 54, pp. 411-422, 2015

[26]Corcione, M., Empirical carrelating equations for predicting the effective thermal conductivity and dynamic viscosity on nanofluids, *Energy conversion and management*, Vol. 52, pp. 789-793, 2011

[27]Said, Z. et al., Experimental investigation of the thermophysical properties of AL$_2$O$_3$-nanofluid and its effect on a flat plate solar collector, *International communications in heat and mass transfer*, Vol. 48, pp. 99-107, 2013

[28]Fedele, L. et al., Viscosity and thermal conductivity measurements of water-based nanofluids containing titanium oxide nanoparticles, *International journal of refrigeration*, Vol. 35, pp. 1359-1366, 2012

[29]Suganthi, K. S. et al., Heat transfer performance and transport properties of ZnO - ethylene glycol and ZnO -ethylene glycol - water nanofluid coolants, *Applied energy*, Vol. 135, pp. 548-559, 2014

[30]Pastoriza-Gallego, M. J. et al., CuO in water nanofluid: Influence of particle size and polydispersity on volumetric behavior and viscosity, *Fluid phase equilibria*, Vol. 300, pp. 188-196, 2011

[31]Namburu, P. K. et al., Experimental investigation of viscosity and specific heat of silicon dioxide nanofluids, *IET micro & nano letters*, Vol 2, s. 67, 2007]

[32]Yu, L. et al., Laminar convective heat transfer of alumina-polyalphaolefin nanofluids containing spherical and non-spherical nanoparticles, *Experimental thermal and fluid science*, Vol. 37, pp. 72-83, 2012

[33]Venerus, D. et al., Viscosity measurements on colloidal dispersions (nanofluids) for heat transfer applications, *Applied rheology*, Vol. 20, 2010

[34]Jeong, J. et al., Particle shape effect on the viscosity and thermal conductivity of ZnO nanofluids, *International journal of refrigeration*, Vol. 36, pp. 2233-2241, 2013

[35]Moosavi, M. et al., Fabrication, characterization, and measurement of some physicochemical properties of ZnO nanofluids, *International journal of heat and fluid flow*, Vol. 31, pp. 599-605, 2010

[36]Nguyen, C.T. et al., Viscosity data for Al$_2$O$_3$-water nanofluid – hysteresis: is heat transfer enhancement using nanofluids reliable?, *International journal of thermal sciences*, Vol. 47, pp. 103-111

[37]Said, Z. et al., New thermophysical properties of water based TiO$_2$ nanofluid - The hysteresis phenomenon revisited, *International communications in heat and mass transfer*, Vol. 58, pp. 85-95, 2014

[38]Li, X. et al., Rheological behavior of ethylene glycol-based SiC nanofluids, *International journal of heat and mass transfer*, Vol. 84, pp. 925-930, 2015

[39]Pineiro, M. M. et al., Rheological non-Newtonian behaviour of ethylene glycol-based Fe$_2$O$_3$ nanofluids, *Nanoscale research letters*, Vol. 6, pp. 1-7, 2011

[40]Mariano, A. et al., Thermal conductivity, rheological behaviour and density of nen-Newtonian ethylene glycol-based SnO$_2$ nanofluids, *Fluid phase equilibria*, Vol. 337, pp. 119-124, 2013

[41]Sadri, R. et al., An experimental study on thermal conductivity and viscosity of nanofluids containing carbon nanotubes, *Nanoscale research letters*, Vol. 9, 2014

[41]Pastoriza-Gallego, M. J. et al., Rheological non-Newtonian behaviour of ethylene glycol-based Fe$_2$O$_3$ nanofluids, *Nanoscale research letters*, Vol. 6, pp. 1-7, 2011

[42]Sundar, L. S. et al., Empirical and theoretical correlations on viscosity of nanofluids: A review, *Renewable and sustainable energy reviews*, Vol. 25, pp. 670-686, 2013

[43]Yiamsawas, T. et al., Measurement and correlation of the viscosity of water-based Al_2O_3 and TiO_2 nanofluids in high temperatures and comparisons with literature reports, *Journal of dispersion science and technology*, Vol. 34, pp. 1697-1703, 2013

[44]Saarinen, S. et al., Turbulent heat transfer characteristics in a circular tube and thermal properties of n-decane-in-water nanoemulsion fluids and micelles-in-water fluids, *International journal of heat and mass transfer*, Vol. 81, pp. 246-251, 2015

[45]Kotiaho, V., Lampinen, M. and Seppälä, A., Termodynamiikan ja lämmönsiirto-opin taulukoita, *Aalto University, Department of energy engineering*, 2004. ISBN 951-22-7557-0

[46]Wu, Z. et al., Pressure drop and convective heat transfer of water and nanofluids in a double-pipe helical heat exchanger, *Applied thermal engineering*, Vol. 60, pp. 266-274, 2013

[47]Meriläinen, A. et al., Influence of particle size and shape on turbulent heat transfer characteristics and pressure losses in water-based nanofluids, *International journal of heat and mass transfer*, Vol. 61, pp. 439-448, 2013

[48]Fotukian, S.M. and Esfahany, M. N., Experimental study of turbulent convective heat transfer and pressure drop of dilute CuO/water nanofluid inside a circular tube, *International communications in heat and mass transfer*, Vol. 37, pp. 214-219, 2010

[49]Dalkilic, A. S. et al., Forced convective heat transfer of nanofluids – A review of the recent literature, *Current nanoscience*, Vol. 8, pp. 949-969, 2012

[50]Yu, W. et al., Thermophysical property-related comparison criteria for nanofluid heat transfer enhancement in turbulent flow, *Applied physics letters*, Vol. 96, 2010

[51]Yu, W., Comparative review of turbulent heat transfer of nanofluids, *International journal of heat and mass transfer*, Vol. 55 pp. 5380-5396, 2012

[52]White, F. M., Viscous fluid flow (third edition), *McGraw-Hill*, 2006. ISBN: 007-124493-X

[53]Ferrouillat, S., et al., Influence of nanoparticle shape factor on convective heat transfer and energetic performance of water-based SiO_2 and ZnO nanofluids, *Applied thermal engineering*, Vol. 51, pp. 839-851, 2013

[54]Bayat, J. and Nikseresht, A. H., Thermal performance and pressure drop analysis of nanofluids in turbulent forced convective flows, *International journal of thermal sciences*, Vol. 60, pp. 236-243, 2012

[55]Mehrali, M. et al., Effect of specific surface area on convective heat transfer of graphene nanoplatelet aqueous nanofluids, *Experimental thermal and fluid science*, Vol. 68, pp. 100-108, 2015

[56] Eastman, J. A., Choi, S. U. S., Li, W. Yu., and Thompson, L. J., Anomalously increased effective thermal conductivities of ethylene glycol-based nanofluids containing copper nanoparticles, *Applied Physics Letters*, Vol. 78, 2001, pp. 718-720