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Effect of nanofluid on heat transfer in double-pipe heat exchanger system

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1. Introduction

Due to an increasing need for more efficient heat transfer fluids in many industries, the heat transfer fluids containing particles have attracted an increasing interest in recent years. Some approaches which used solid particles suspensions as the heat transfer fluids were introduced to increase heat transfer efficiency. Unfortunately, the suspended particles of micrometer or millimeter dimensions may cause some severe problems such as abrasion and clogging in small passages [1]. Furthermore, the stability of all large-sized particle suspensions are very poor, because the coarse-grained solid particles in suspensions settle out eventually [2]. Fluids containing nano-sized particles have a unique feature which is quite different from those of the conventional solid-liquid mixtures of micro-sized particles. Experimental studies show that the solid nanoparticle colloids are extremely stable and exhibit no significant settling under static conditions, even after weeks or months. Futhermore, the enhancement of thermal conductivity of nanofluids was even greater than that of suspensions of coarse-grained materials. In order to apply the nanofluids as a new type of heat transfer fluids for thermal engineering process, many kinds of nano-sized particles were synthesized and the experimental measurements for the thermal conductivity of fluids containing nano-sized particles such as Cu, Al, CuO and Al_2O_3 have been reported by various authors [3,4,5,6,7]. However, there are few studies for effects of nano-sized particles on convective heat transfer performance of fluid. Though Xuan and Li [8] measured the heat transfer coefficient of Cu-water nanofluids, to investigate extensively an effect of nano-sized particles on convective heat transfer of fluid, more experimental data for fluids containing different kind of nano-sized particles are necessary. And it is difficult for water to improve heat transfer performance because that of water is good for itself. Due to electrical conductivity of water, insulating oil was used for roles of insulation and cooling in transformer. In this study, the experimental apparatus was made to measure the heat transfer coefficient of fluids containing nano-sized particles. The experimental analyses for the effects of nano-sized particles on heat transfer were performed in double-pipe heat exchanger systems.

2. Experiment

2-1. Experimental equipments

The schematic diagram of experimental systems for the convective heat transfer of nanofluids in the double-pipe heat exchanger is given in Figure 1. The experimental system consisted of two double-pipe heat exchangers for heating and cooling of nanofluids, circulation pump, solution tank and mass flow meter. Pre-experiments were performed to obtain experimental consistency. Four kinds of double-pipe heat exchangers were made and tested; outside diameters of inner pipe and outer pipe and lengths of heat exchanger are 0.635cm/1.27cm/60cm, 0.9525cm/1.905cm/30cm, 0.635cm/1.27cm/30cm and 0.635cm/1.27cm/500cm, respectively. The heat exchanger which have length of 500cm have the best experimental consistency of the four ones. The photograph of that is shown in Figure 2. All double-pipe heat exchangers are made of a non-corrosive stainless steel with thickness of 0.1cm. Eight thermocouples (K-type) were equipped in input and output lines of coolant and that of fluids. Input fluids were preheated by external heating water bath and flow rates were controlled by the by-pass valve equipped in output line of circulation pump (HYDRA-CELL Corp. G13XDBTHHECA). Each temperature and flow rates measured by thermocouple and mass flow meter (KROHNE Corp. MFM 3081 F) were stored by the data acquisition systems (YOKOGAWA Corp. DA100).

SiO_2 (DEGUSSA Corp. Aerosil R7200) and Al_2O_3 (DEGUSSA Corp. Aeroxide Alu C) nano-sized particles were used to investigate the convective heat transfer characteristics of nanofluids. The dispersion of particles was done by mixing the particles with water and insulating oil (MICHANG OIL IND. CO. KS C 2310) as base fluids and ultrasonic vibration.

2-2. Data analysis

Heat transfer rate from fluids to coolant is equal to enthalpy variation of coolant in the heat exchanger which can be easily calculated from the measured temperature change and flow rate with specific heat of coolant. It is related with a log mean temperature difference (LMTD), overall heat transfer coefficient and heat transfer area. The overall heat transfer coefficient can be expressed as the following equation.

$$U = \frac{m_c C_{p,c} \Delta T_c}{A \Delta T_{LMTD}} \tag{1}$$

Where definition of a log mean temperature difference is as following equation [9].

$$\Delta T_{LMTD} = \frac{[T_{f,i} - T_{c,o}] - [T_{f,o} - T_{c,i}]}{ln[(T_{f,i} - T_{c,o})/(T_{f,o} - T_{c,i})]} \tag{2}$$

A relation of overall and individual heat transfer coefficients is represented approximately in a double-pipe heat exchanger as follows:

$$\frac{1}{U} = \frac{1}{h_i} + \frac{\delta_w}{k_w} + \frac{1}{h_o} \tag{3}$$

To estimate the individual heat tansfer coefficient (h_i) of fluids, data of individual heat transfer coefficient (h_o) of coolant are necessary. In this study, h_o can be obtained by Dittus-Boelter Equation (4) which is generally used under the turbulent condition.

$$Nu = \frac{h_i D}{k} = 0.023 Re^{4/5} Pr^{1/3} \tag{4}$$

Experiments were performed to measure the overall heat transfer coefficient as a function of the solution Reynolds number at constant coolant flow rate. U and Re can be obtained from experimental data. Thermal conductivity and thickness of stainless steel pipe are k_w=14.9W/m^2 · ℃ and δ_w=0.001m.

Furthermore, in this study, heat transfer correlation for nano insulating oils have been developed using general correlation form which can be expressed as a function of Reynolds number and Prandtl number as follows:

$$h_i = aRe^b Pr^c \tag{5}$$

To decide heat transfer correlation of nano insulating oils, a, b and c was determined by non-linear regression of experimental data. Prandtl number of insulating oil containing SiO_2 nano-sized particles is given in Table 1.

3. Results and discussion

3-1. Overall heat transfer coefficients (U) of nanofluids

A number of experiments were conducted to measure the overall heat transfer coefficients of nanofluids that consisted of nano-sized SiO_2 and Al_2O_3 particles with water and insulating oil as base fluids. Pre-experiments were performed to check the stability of nano-sized particles in base fluids and the energy balance of double-pipe heat exchanger systems. SiO_2 nano-sized particles are more stable than Al_2O_3 in both of water and insulating oil. Because heat transfer rate of water is almost exactly identical to that of coolants, there is little energy loss in the convective heat transfer from water to coolants in the double-pipe heat exchanger system of this study. The overall heat transfer coefficient of water, insulating oil, fluids containing SiO_2 and Al_2O_3 nano-sized particles are shown as a function of fluid flow rate in Figure 3, 4 and 6. The overall heat transfer coefficients of three kinds of nanofluids increase with fluid flow rate. The comparison of overall heat transfer coefficient between pure base fluid and nanofluids in Figure 3, 4 and 6 also show that the overall heat transfer coefficients of nanofluids are superior to that of pure base fluid under the same Reynolds number. The reason of this result is possible to guess with the increase of heat transfer efficiency due to the enhancement of thermal conductivity, the activation of convective heat transfer or the thinning of thermal boundary layer. The effects of base fluid on heat transfer enhancement by SiO_2 nano-sized particles are shown in Figure 3 and 6. Enhancement of overall heat transfer coefficient of insulating oil is superior to that of water because heat transfer performance of water is good for itself. As Al_2O_3 is more unstable than SiO_2 in insulating oil, effects of resuspension of fluids on heat transfer enhancement by Al_2O_3 nano-sized particles are shown in Figure 4 and 5. Heat transfer enhancement by resuspended Al_2O_3 due to stirring of tank is an almost half of that of well suspended Al_2O_3 nanofluids under same Reynolds number of 370. As suspension of SiO_2 and Al_2O_3 is stable, comparison of heat transfer enhancement by different kind of nano-sized particles are shown in Figure 4 and 6. Though the thermal conductivity of two nano-sized particles are different, the heat transfer enhancement of both nanofluids is similar to each other. Therefore the reason of heat transfer enhancement is not the thermal conductivity but·the activation of convective heat transfer or thinning of thermal boundary layer.

3-2. Individual heat transfer coefficients (h_i) and correlation of SiO_2 nano insulating oil

The individual heat transfer coefficient of insulating oil and nanofluids is shown as a function of fluid flow rate in Figure 7. Due to the activation of convective heat transfer or thinning of thermal boundary layer by SiO_2 nano-sized particles, the individual heat transfer coefficients of nanofluids are superior to that of insulating oil. By non-linear regression of experimental data, correlation is decided as follows:

$$h_i = 3.79 Re^{0.4237} Pr^{0.5339} \tag{6}$$

As can be seen in Figure 8, the predicted values for heat transfer coefficient of insulating oils by correlation of this study is almost exactly identical to experimental results. Therefore, when the transformer is designed, the correlation can be used to predict the individual coefficient of nanofluids according to SiO_2 concentrations.

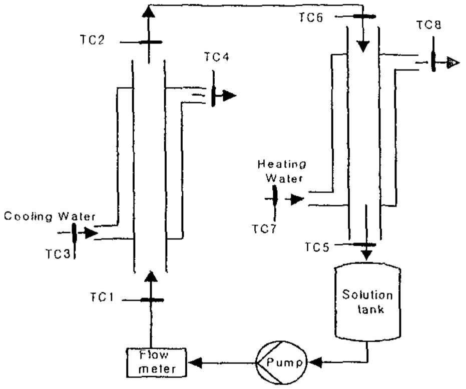

Figure 1. Experimental apparatus

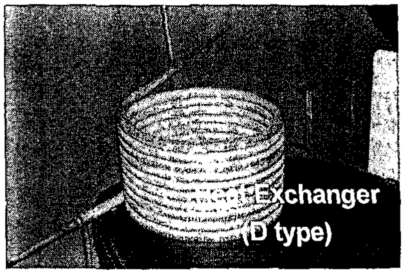

Figure 2. 0.635cm/1.27cm/500cm
Heat Exchanger

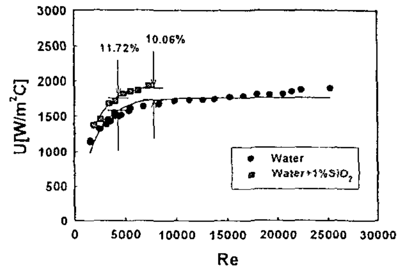

Figure 3. Increase of overall heat transfer coefficient of 1wt% SiO_2 nano particle in water

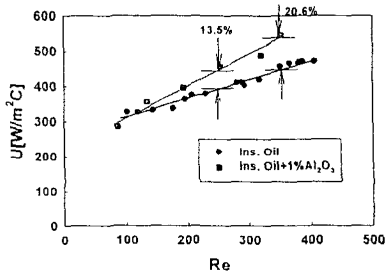

Figure 4. Increase of overall heat transfer coefficient of 1wt% Al_2O_3 nano particle in insulating oil

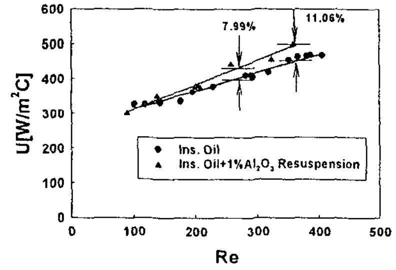

Figure 5. Increase of overall heat transfer coefficient of resuspended Al_2O_3 particle in insulating oil

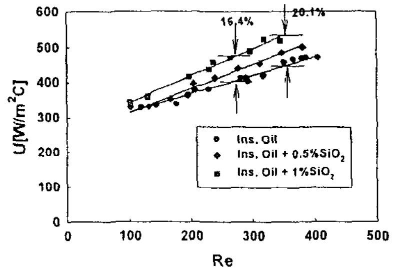

Figure 6. Overall heat transfer coefficient as a function of SiO_2 weight conc. in insulating oil

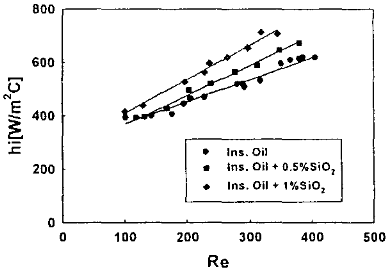

Figure 7. Individual heat transfer coefficient as a function of SiO_2 weight conc. in insulating oil

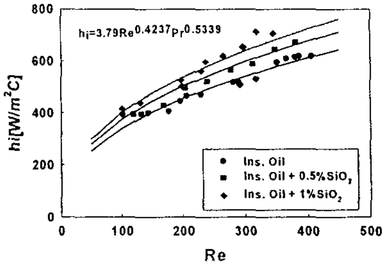

Figure 8. Comparison relation with data

Table 1. Prandtl number of nano insulating oil containing SiO_2 nano particles

	C_p(Btu/lb°F)	μ($cP=10^{-2}g/cm \cdot s$)	k(Btu/ft · h · °F)	Pr
0%	0.464	14.4	0.137	117.9
0.5%	0.497	16.2	0.137	142
1.0%	0.548	16.7	0.137	161

4. Conclusions

Overall and individual heat transfer coefficients of water or insulating oil containing nano-sized SiO_2 or Al_2O_3 particles are superior to those of pure base fluids. The reason of result is the increase of heat transfer efficiency due to the activation of convective heat transfer and the thinning of thermal boundary layer. And heat transfer correlation of nano insulating oils have been reported to predict the individual heat transfer coefficient of fluids according to SiO_2 concentrations in procedure of transformer design.

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