Effect of alumina nanoparticles in the fluid on heat transfer in double-pipe heat exchanger system

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(*Received 5 October 2007 • accepted 5 March 2008*)

Abstract−This study was performed to investigate the convective heat transfer coefficient of nanofluids made of several alumina nanoparticles and transformer oil which flow through a double pipe heat exchanger system in the laminar flow regime. The nanofluids exhibited a considerable increase of heat transfer coefficients. Although the thermal conductivity of alumina is not high, it is much higher than that of the base fluids. The nanofluids tested displayed good thermal properties. One of the possible reasons for the enhancement on heat transfer of nanofluids can be explained by the high concentration of nanoparticles in the thermal boundary layer at the wall side through the migration of nanoparticles. To understand the enhancement of heat transfer of nanofluid, an experimental correlation was proposed for an alumina-transformer oil nanofluid system.

Key words: Convective Heat Transfer, Heat Transfer Coefficient, Nanofluid, Alumina Nanoparticle, Laminar Flow

INTRODUCTION

The addition of solid particles into heat transfer media has long been known as one of the useful techniques for enhancing heat transfer, although a major consideration when using suspended millimeter- or micrometer-sized particles is that they have the potential to cause some severe problems, such as abrasion, clogging, high pressure drop, and sedimentation of particles. Compared with heat transfer enhancement through the use of suspended large particles, the use of nanoparticles in the fluids exhibited better properties relating to the heat transfer of fluid. This is because nanoparticles are usually used at very low concentrations and nanometer sizes. These properties prevent the sedimentation in the flow that may clog the channel. From these points of view, there have been some previous studies conducted on the heat transfer of nanoparticles in suspension. Since Choi et al. wrote the first review article on nanofluids [1], several research papers and journal articles have shown that with low particle concentration, the thermal conductivity can increase by more than 20% [2-5]. Some other efforts have been made to understand the heat transfer coefficient changes in heat exchangers [6-10] and the mechanism for the enhancement of thermal conductivity [11,12]. The heat transfer coefficients of nanofluids are much higher than that of base fluids with low volume fraction of nanoparticles, and the change of friction factor and viscosity of the fluids is very small. Xuan and coworkers have argued that the random movement of the nanoparticles in a nanofluid increases the energy transfer rate in the fluid and results in thermal dispersion in the flow [13]. Recently, Khanafer et al. have performed a more detailed analysis and simulation, and come to the same conclusion [14].

However, in spite of their great potential, these nanofluids are still in the early stages of development. To investigate extensively the effect of nano-sized particles on convective heat transfer of fluid, more experimental data for fluids containing different kinds of nano-sized particles are necessary. Additionally, many other important factors such as the surface structure and shape of nanoparticles, non-uniform particle concentration, movement of nanoparticles in the flow, which may play important roles on the heat transfer of nanofluids, have not yet been studied. Understanding the role of these factors in the base fluid is extremely important in understanding the mechanism of heat transfer enhancement in nanofluids. It is clear that many additional studies to effectively predict the heat transfer properties of nanofluids need to be performed.

An 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 alumina particles on heat transfer were performed in double-pipe heat exchanger systems. Alumina particles are very interesting materials with broad applicability as adsorbents, coatings and catalysts [15].

EXPERIMENT

1. Experimental Equipment

The experimental system constructed for our study, shown in Fig. 1, mainly consisted of two double-pipe heat exchangers for heating and cooling of nanofluids, a circulation pump, solution tank and mass flow meter. The test section was a 5 m length of stainless steel tube (SS 304) with 0.00635 m inner tube diameter, 0.0127 m outer tube diameter, respectively. All double-pipe heat exchangers were made of a non-corrosive stainless steel with thickness of 0.1 cm. Eight K-type thermocouples were inserted into the input and output lines of the heating fluid (hot water) and that of the cooling fluid (nanofluid). The temperature and flow rates of input nanofluids were controlled by external cooling water bath before flow in the test section and a by-pass valve installed in the output line of the circulation pump. Each temperature and flow rate measured by the thermocouple and mass flow meter were stored by the data acquisition systems.

2. Materials

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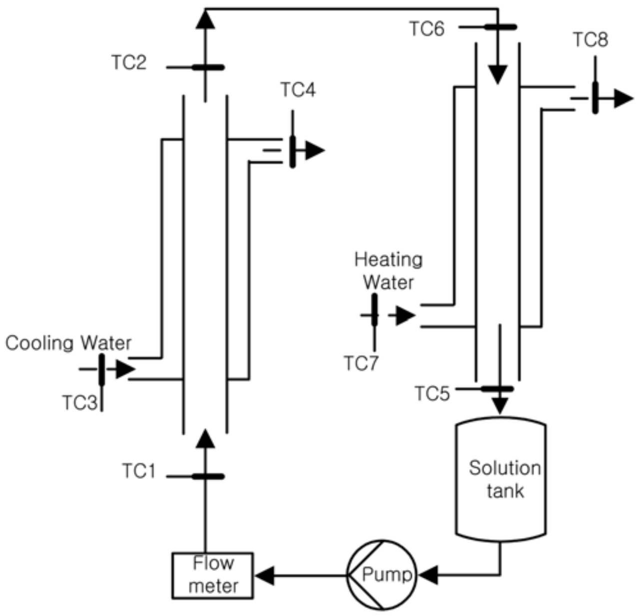

Fig. 1. Experimental apparatus.

Three kinds of alumina nanoparticles were used to investigate the convective heat transfer characteristics of the nanofluids by using water and transformer oil as the base fluids. The dispersion of particles was performed by mixing the particles with the base fluids and then subjecting them to ultrasonic vibration. The samples of AK, AR, AF alumina have different manufacturer, surface properties, shape, and size. Comparing AK alumina nanofluid with AR alumina nanofluid illustrates the effects of surface properties of nanoparticles. Comparing AK alumina nanofluid with AF alumina nanofluid shows the effects relating to the shape of the nanofluid. The material properties of used alumina and those of nanofluid are illustrated in Tables 1 and 2.

3. Data Analysis

The following procedure was used to calculate the heat transfer coefficient of the nanofluids. Heat transfer rate from hot fluid to cold fluid can be easily calculated from the measured temperature change and flow rate with specific heat of a fluid. The heat transfer rate is:

$$q_{HW}=\dot{m}_{HW}C_{p,HW}(T_{HW,in}-T_{HW,out})=q_{NF} \tag{1}$$

where q_{HW} and q_{NF} are the heat transfer rates of hot water and nanofluid, $\dot{m}_{HW}$ is the mass flow rate of water, $C_{p,HW}$ is the heat capacity of hot water, $T_{HW,out}$ and $T_{HW,in}$ are the temperatures of water at the entrance and exit of the tube. The overall heat transfer coefficient (U) is related with a log mean temperature difference (LMTD), of the overall heat transfer coefficient and heat transfer area, which can be expressed as the following equation:

$$U=\frac{q}{A\cdot\Delta T_{LMTD}}=\frac{\dot{m}_{HW}C_{p,HW}[T_{HW,in}-T_{HW,out}]}{A\cdot\Delta T_{LMTD}} \tag{2}$$

where, the definition of a log mean temperature difference is shown in the following equation [9]:

$$\Delta T_{LMTD}=\frac{(T_{NF,in}-T_{HW,out})-(T_{NF,out}-T_{HW,in})}{\ln\frac{(T_{NF,in}-T_{HW,out})}{(T_{NF,out}-T_{HW,in})}} \tag{3}$$

The relation of overall and individual heat transfer coefficients is represented as an approximation in a double-pipe heat exchanger as follows:

$$\frac{1}{U}=\frac{1}{h_i}+\frac{\delta_w}{k_w}+\frac{1}{h_o} \tag{4}$$

where, h_i and h_o is the individual heat transfer coefficients of the inside and outside fluids, respectively. And δ_w is the thickness of the inner pipe, and k_w is the thermal conductivity of the inner pipe wall.

It can be transformed to the overall heat transfer coefficient of fluid in the tube as follows:

$$\frac{1}{U}=\frac{1}{h_i(A_i/A_o)}+\frac{D_o}{2k}\ln\frac{D_o}{D_i}+\frac{1}{h_o} \tag{5}$$

Table 1. Material properties of used alumina particles

Alumina	AK	AR	AF
Company	Degussa	N&A Materials	
Size	~43 nm	27-43 nm	~7 nm
Shape	Spherical	Spherical	Rod like (Aspect ratio 50-200)
Surface	Hydrophobic	Hydrophilic	Hydrophilic
Specific heat (KJ/Kg K)	20	20	20
Density (Kg/m^3)	3970	3970	3970
Thermal conductivity (W/m K)	36	36	36

Table 2. Material properties of fluids

Liquid	Viscosity (Pa s)	Heat capacity (KJ/Kg K)	Density (Kg/m^3)	Thermal conductivity (W/m K)	Note
Transformer oil	0.0141	2.1	900	0.112	
AR 0.5%	0.0143	2.49	915	0.114	calculated
AK 0.5%	0.0145	2.49	915	0.116	calculated
AF 0.5%	0.0151	2.49	915	0.117	calculated

where, D_i and D_o are the diameter of inside tube and outside tube, A_i and A_o are the area of inside tube and outside tube.

To estimate the individual heat transfer coefficient of a nanofluid, data of the individual heat transfer coefficient of hot water are necessary. In this study, h_o can be obtained by Monrad and Pelton's equation [16], which is generally used under the turbulent condition in annuli,

$$Nu = \frac{h_o D}{k_{HW}} = 0.02 Re^{0.8} Pr^{0.33} \left(\frac{D_2}{D_1}\right)^{0.53} \tag{6}$$

where, k_{HW} is the thermal conductivity of hot water, Re is the Reynolds number, Pr is the Prandtl number, and D_1, D_2 are the inner and outer diameter of annulus.

Experiments were performed to measure the overall heat transfer coefficient as a function of the Reynolds number at constant flow rate for hot water. U and Re can be obtained from experimental data. The thermal conductivity and thickness of stainless steel pipe used in this study were 14.9 W/m K and 0.001 m, respectively.

Furthermore, in this study, a heat transfer correlation for alumina nanofluid has been developed. Fundamentally, nanofluids are multi-component systems, so the material properties and amounts of nanoparticles will affect the ability of heat transfer. This means that a new correlation for nanofluids must be developed. Recently, Li and Xuan proposed a new correlation for the convection heat transfer coefficient of nanofluids as [17]:

$$Nu = 0.4328(1 + 11.285\Phi^{0.754} Pe^{0.218}) Re^{0.333} Pr^{0.4} \tag{7}$$

where, Pe is Peclet number.

But, if we assume the particle sizes are very small and the fraction of particles is so low, the fluid is regarded as a homogeneous fluid. Under these circumstances, the general correlation form might be applied to nanofluids. The individual heat transfer coefficient can be expressed as a function of Reynolds number and Prandtl number as follows:

$$h_i = \alpha \frac{k}{D} Re^{\beta} Pr^{\gamma} \tag{8}$$

To decide the heat transfer correlation of an alumina nanofluid, α, β and γ was determined by non-linear regression of experimental data.

4. Estimation of Physical Properties of Nanofluids

By assuming that the nanoparticles are well dispersed in the fluid, the concentration of nanoparticles may be considered uniform throughout the tube. Although this assumption is not true in real systems because of particle migration in the tube, it can be a useful tool to estimate the physical properties of a nanofluid. The effective properties of nanofluids can be estimated by the classical formulas that are well known for the fluid of two-phase mixtures. In the following equations, the subscripts 'NP', 'BF', and 'NF' refer to the nanoparticle, the base-fluid, and the nanofluid.

$$\rho_{NF} = \rho_{BF}(1-\Phi) + \rho_{NP}\Phi \tag{9}$$

$$C_{p\,NF} = C_{p\,BF}\frac{\rho_{BF}(1-\Phi)}{\rho_{BF}(1-\Phi)+\rho_{NP}\Phi} + C_{p\,NP}\frac{\rho_{NP}\Phi}{\rho_{BF}(1-\Phi)+\rho_{NP}\Phi} \tag{10}$$

To estimate the thermal conductivity of nanofluid, the effective particle volumes were calculated from the measurement of viscosity.

In the dilute suspension of nanoparticles, the viscosity is expressed as follows:

$$\mu = \mu_{BF}(1 + a\Phi) \tag{11}$$

where a is a constant, i.e., it is 2.5 in Einstein relation but it is lager than 2.5 in the nanofluid generally. It means that the nanoparticles have large effective volume in the fluid, which is expected in a microparticle suspension. Kang and coworkers proposed that the thermal conductivity of nanofluid can be expressed by using effective particle volume or constant a [18]:

$$k = k_{BF}\left(\frac{k_{NP} + 2k_{BF} - \frac{a}{1.25}\Phi(k_{BF} - k_{NP})}{k_{NP} + 2k_{BF} + \frac{a}{2.5}\Phi(k_{BF} - k_{NP})}\right) \tag{12}$$

In this study, the viscosity of nanofluid was measured, and the thermal conductivity of the nanofluid was estimated by the above equation.

RESULTS AND DISCUSSION

A number of experiments were conducted to measure the overall heat transfer coefficients of nanofluids that consisted of nano-sized alumina particles and transformer oil as base fluid. Pre-experiments were performed to check the stability of nano-sized particles in base fluids and the energy balance of the double-pipe heat exchanger systems in our previous work [10]. The difference of heat transfer rates of two fluids in both sides of the heat exchanger was very small. This result means that there is only a little energy loss in the double-pipe heat exchanger system.

Fig. 2 shows the viscosity of the nanofluid as a function of particle volume fraction. From the result, the slope was calculated. For the case of AK alumina nanofluid, the slope of the relative viscosity to the particle volume fraction (a) was 5.3. Finally, the effective thermal conductivity of nanofluid was estimated by Eq. (12).

Fig. 3 shows the effects of the hydrophilic properties of alumina

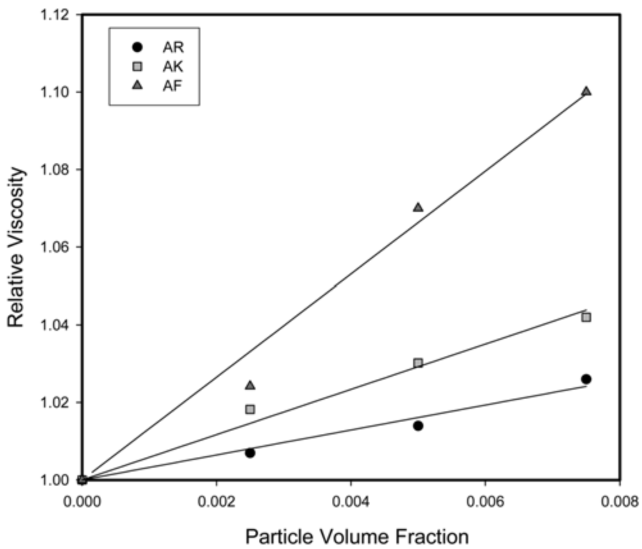

Fig. 2. Viscosity of the nanofluid as a function of particle volume fraction.

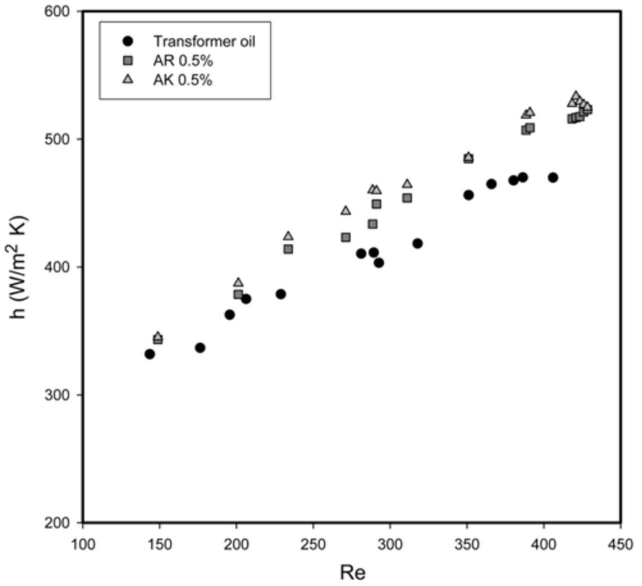

Fig. 3. Plot of heat transfer coefficient versus Reynolds number caused by the surface properties.

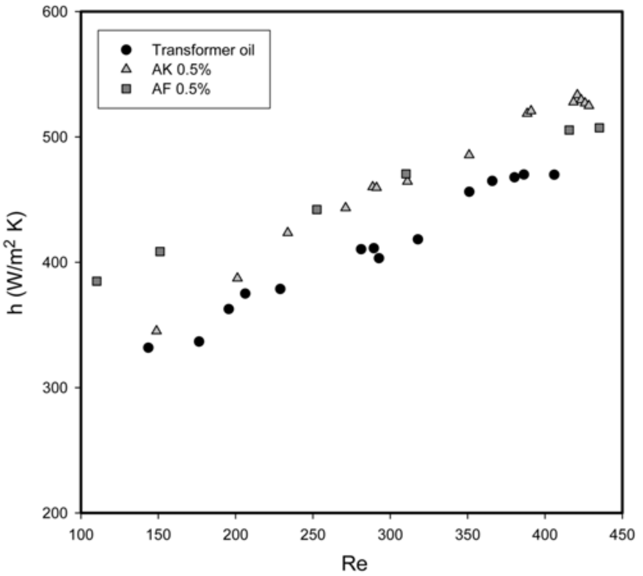

Fig. 4. Plot of heat transfer coefficient versus Reynolds number caused by the shape of nanoparticles.

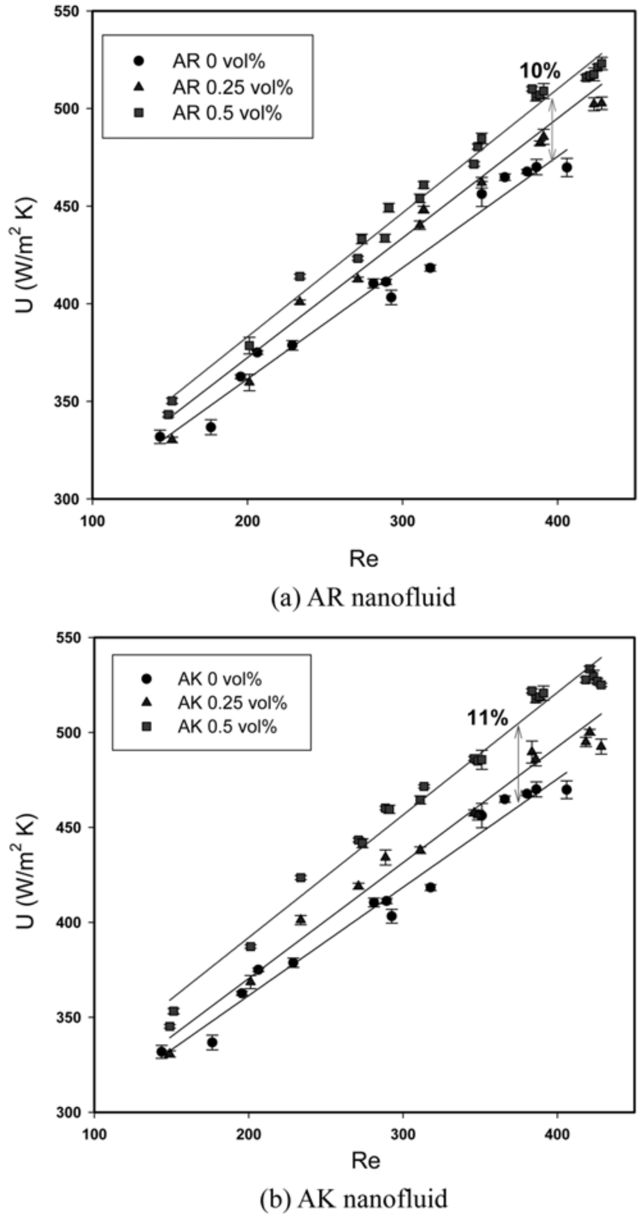

Fig. 5. Plot of heat transfer coefficient versus Reynolds number caused by the nanoparticle loadings.

surface on the heat transfer of nanofluids. As shown in Table 1, AK and AR alumina have almost the same size and shape. The important difference between the two types of alumina is the hydrophilic properties of the surfaces. The surface of AK alumina was hydrophobic, while that of AR alumina was hydrophilic. This difference may affect the stability of dispersion in a hydrophobic base fluid. Though both AK and AR alumina nanofluids show an increase of heat transfer relative to that of the base fluid, the enhancement of the AK nanofluid was larger than that of the AR nanofluid. The AK nanofluid with 0.5 vol% showed a typical increase in average heat transfer coefficient of 13% over the base fluid, and the AR nanofluid exhibited an increase of 10%, while the estimated thermal conductivity was about 2% higher than that of the base fluid. These results indicate that the contact between nanoparticles and base fluid is one of the important parameters in the heat transfer of a nanofluid.

The effect of the particle shape is shown in Fig. 4. The shape of AF alumina nanoparticles was rod-like, and the aspect ratio was about 50 to 200. Compared with AK nanofluid, the AF nanofluid displayed different heat transfer properties. It was greater than that of the AK nanofluid in the region of low Reynolds numbers, and smaller in the region of high Reynolds number. Although the average heat transfer coefficients increase with the Reynolds number, the slope was smaller than that of the AK nanofluid. The difference in high Reynolds number was caused by the high viscosity of the AF nanofluid, as shown in Table 2. In general, the fluid with rod-like particles has high viscosity because of their strong interaction and aggregation under the shear flow. The high viscosity of AF nanofluid in the region prevented the enhancement of heat transfer by the convection. On the other hand, in the low Reynolds number region, the AF nanofluid showed very high average heat transfer coefficients. It represented an increase in the average heat transfer coefficient of 25% relative to that of the base fluid at a low Reynolds number (Re<200). This may have been caused by the high thermal conductivity of the AF nanofluid and the arrangement of long rod-like particles around the thermal boundary layer in the pipe. From these results, we can say that a nanofluid with these rod-like nanoparticles will be very useful in the heat exchanger under a low Reynolds number condition.

Fig. 5 shows the effect of particle loadings. At this condition, the nanofluid with AK or AR nanoparticles (0.5 vol%) had a typical increase in average heat transfer coefficient of 10% over the transformer oil. Both the AK and AR nanofluids exhibited an increase in proportion to the particle loadings.

The comparison of average heat transfer coefficient between pure base fluid and nanofluids shown in Figs. 3, 4 and 5 also shows that the average heat transfer coefficients of nanofluids are superior to that of base fluid under the same Reynolds number. These results can be explained by 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. There are some mechanisms for the enhancement of thermal conductivity of nanofluids including the liquid layering on the surface of nanoparticles, Brownian motion, clustering of nanoparticles, ballistic transport of phonon in the nanoparticles, etc. In addition, there will be one important mechanism for this enhancement on thermal conductivity of nanofluid in the piping flow. That is the non-uniform particle concentration in the cross-section of the tube. Ding and Wen investigated that the particle migration by shear rate gradient, viscosity gradient, and Brownian motion causes non-uniformity in particle concentration for large particles [19]. They showed the concentration of nanoparticles in the wall side of the tube is much larger than that of microparticles in the wall side of the tube. It means that the enhancement in the thermal conductivity of fluid by the addition of nanoparticles in the wall side of tube will be much larger than that by the addition of microparticles. This enhancement in thermal conductivity may cause an increase of the heat transfer coefficient in the thermal boundary layer around the wall side of tube. On the other hand, since the microparticles tend to move toward the center of the tube, the enhancement of thermal conductivity of micro-particle suspension in the thermal boundary layer is low, so the heat transfer coefficient does not change much.

By non-linear regression of experimental data, the correlation was decided as follows:

$$h_i = \frac{k}{D} \times 1.7 \times Re^{0.4} \tag{13}$$

As can be seen in Fig. 6, the predicted values for heat transfer coefficient of transformer oils by correlation of this study are almost exactly identical to the experimental results. The Prandtl number does not play an important role in our correlation. Therefore, when the transformer is designed, this correlation can be used to predict the individual coefficient of nanofluids for alumina concentrations.

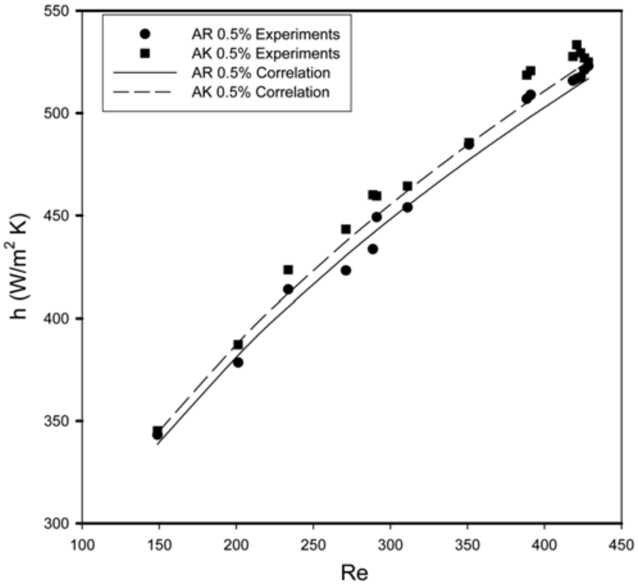

Fig. 6. Correlation of heat transfer coefficients of alumina-transformer oil nanofluid.

CONCLUSIONS

This paper is concerned with the convective heat transfer of nanofluids made of transformer oil and alumina nanoparticles in laminar flow through a circular pipe. The experimental data show that the addition of nanoparticles in the fluid increases the average heat transfer coefficient of the system in laminar flow. The surface properties of nanoparticles, particle loading, and particle shape are key factors for enhancing the heat transfer properties of nanofluids. These increases of heat transfer coefficients may be caused by the high concentration of nanoparticles in the wall side by the particle migration. But more investigation is needed to develop an appropriate heat transfer correlation for the nanofluids.

ACKNOWLEDGMENTS

This work is supported by research grants from the Korea Science and Engineering Foundation through the Applied Rheology Center (ARC), an official ERC, at Korea University, Seoul, Korea.

REFERENCES

1. S. U. S. Choi, *Development and applications of non-newtonian flows*, ASME, New York (1995).
2. S. U. S. Choi, Z. G. Zhang, W. Yu, F. E. Lockwood and E. A. Grulke, *Appl. Phys. Lett.*, **79**, 2252 (2001).
3. J. A. Eastman, S. U. S. Choi, S. Li, W. Yu and L. J. Thomson, *Appl. Phys. Lett.*, **78**, 718 (2001).
4. H. Xie, J. Wang, T. G. Xi, Y. Liu and F. Ai, *J. Appl. Phys.*, **91**, 4568 (2002).
5. T. H. Cho, S. D. Park, Y. S. Lee and I. H. Baek, *Korean Chem. Eng. Res.*, **42**, 624 (2004).
6. Y. Xuan and Q. Li, *ASME J. Heat Transfer*, **125**, 151 (2003).
7. G. Roy, C. T. Nguyen and P. R. Lajoie, *Superlattices and Microstruc-*

tures, **35**, 497 (2004).
8. D. Wen and Y. Ding, *Int. J. Heat and Mass Trans.*, **47**, 5181 (2004).
9. Y. Yang, Z. G. Zhang, E. A. Grulke, W. B. Anderson and G. Wu, *Int. J. Heat and Mass Transfer*, **48**, 1107 (2005).
10. C. H. Lee, S. W. Kang and S. H. Kim, *J. Ind. Eng. Chem*., **11**, 152 (2005).
11. P. Keblinski, S. R. Phillpot, S. U. S. Choi and J. A. Eastman, *Int. J. Heat and Mass Transfer*, **45**, 855 (2002).
12. S. P. Jang and S. U. S. Choi, *Appl. Phys. Lett.*, **84**, 4316 (2004).
13. Y. Xuan and W. Roetzel, *Int. J. Heat Mass Trans*., **43**, 3701 (2000).
14. K. Khanafer, K. Vafai and M. Lightstone, *Int. J. Heat Mass Trans.*, **46**, 3639 (2003).
15. K. Pansanga, O. Mekasuwandumrang, J. Panpranot and P. Praserthdam, *Korean J. Chem. Eng*., **24**, 397 (2007).
16. C. C. Monrad and J. F. Pelton, *Trans. Am. Inst. Chem. Eng.*, **38**, 593 (1942).
17. Q. Li and Y. Xuan, *Science in China E*, **45**, 408 (2002).
18. H. U. Kang, J. M. Oh and S. H. Kim, *Exp. Heat Transfer*, **19**, 181 (2006).
19. Y. Ding and D. Wen, *Powder Technology*, **149**, 84 (2005).