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An experimental apparatus measuring convective heat transfer coefficient from a heated fine wire traversing in nanofluids [†]

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Abstract

Most of the previous convection experiments for nanofluids have been performed for internal tube flow with constant heat flux boundary condition. In contrast, a simple experimental apparatus measuring convective heat transfer coefficient from a heated wire to external nanofluids is proposed and its working principles are explained in detail. The convective heat transfer coefficient provided by the present system might be used as a useful indication justifying the adoption of prepared nanofluids as new efficient heat transfer fluids. Validation experiments by comparing convective heat transfer coefficients between the conventional correlation and measured values are carried out for base fluids. Also the effect of increased thermal conductivity of nano lubrication oil on the enhancement of convective heat transfer coefficient is investigated.

Keywords: Nanofluids; Thermal conductivity enhancement; Convective heat transfer coefficient; Cylinder in cross flow

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1. Introduction

Nanofluids have attracted research interest during the past decade due to their potential advantage in increasing the heat transfer performance of a thermal system. The idea of nanofluids was proposed by Choi [1] about 15 years ago as a colloidal mixture of pure heat transfer fluids and nanometer-sized metallic particles. Metal particles have orders of magnitude larger thermal conductivities than pure fluids, from which we can easily expect that the thermal conductivity of a mixture of particles and fluids may be much higher than that of pure fluids only.

Early researches mainly focused on the enhancement of thermal conductivity of nanofluids. Lee et al. [2] reported maximum increase in thermal conductivity of 20% in the study for 4% CuO particles with average diameter 35nm dispersed in ethylene glycol by using a transient hot wire method. An even greater enhancement was reported for pure metal Cu nanofluids, where only a 0.3% volume concentration of 10nm particles led to an increase of 40% in thermal conductivity [3]. Choi et al. [4] observed that the dispersion of a very small amount of carbon nanotubes produces a remarkable change in the effective thermal conductivity of the base fluid, with the thermal conductivity ratio exceeding 250% at just 1% volume concentration. Das et al. [5] examined the effect of fluid temperature on the enhancement of thermal conductivity. Other papers [6-8] discussed that the level of increase in thermal conductivity is more than an order of magnitude above the increase predicted by the traditional macroscopic theories of Hamilton and Crosser [9].

Convection researches of nanofluids have discussed the relations between the enhancement of thermal conductivity and the increased convection heat transfer. Yang et al. [10] performed a laminar flow convective heat transfer experiment through a circular tube with graphite nanoparticles in water. The experimental results show that the nanoparticle increases the heat transfer coefficient, but the increase is much less than that predicted by the correlation of Xuan and Li [11]. Wen and Ding [12] showed 47 % increase in the convective heat transfer coefficient for an aqueous based 1.6% of alumina nanofluids. This value is also greater than the thermal conductivity increase of 10%. Ding et al. [13] studied the heat transfer behavior of aqueous suspensions of multi-walled CNT nanofluids flowing through a horizontal tube. They observed 350% increase of the convective heat transfer coefficient and this enhancement depends on the Reynolds number and CNT concentration.

Most of the previous convection experiments were performed in the internal tube flow with constant heat flux boundary condition. They show similar conclusions that the use of nanofluids significantly enhances the heat transfer performance and this enhancement increases along with the flow ve-

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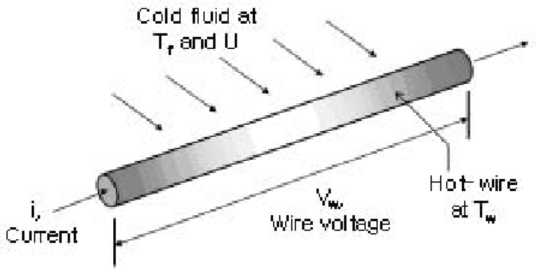


Fig. 1. Convection from a heated cylinder in cross flow.

locity and the volume concentration of particles. Moreover, the amount of this convective heat transfer enhancement always exceeds the thermal conductivity increase of nanofluids.

On the other hand, the related research of the convection from a heated surface by the external flow of nanofluids is relatively scarce, despite the importance of engineering applications such as cooling in high power electronics or high speed rotational machinery. To diversify the application of nanofluids to real industrial fields, the related researches need to be expanded in the near future.

Based on the above-mentioned literature review, the objective of this paper is to find the relationship between the enhancement of thermal conductivity of nanofluids and the increase of convective heat transfer coefficient where this convection happens from a heated fine wire to external nanofluids. Operating principles of the apparatus are explained in detail and typical measurements for base fluids are carried out for the validation of the proposed system. Comparisons between convective heat transfer coefficient and thermal conductivity are made for base as well as nanofluids and the relation of those two variables is investigated.

2. Working principles of experimental apparatus

The present experimental apparatus employs forced convection heat transfer from a heated cylinder to ambient fluid (see Fig. 1 for schematic). The heated cylinder in this paper is actually a platinum fine wire whose diameter is 25 μm. Similar use of metal fine wire as a sensor can be found for a hot-wire anemometer, where the sensor works both as a heater and a temperature sensor [14].

Joule heating is generated if some electric current i is applied across this resistive fine wire. If the flow velocity is kept constant, there exists a heat balance between the heat generation from the wire and the heat dissipation by convection. Under this condition, the working temperature of the wire would have the constant value which satisfies Eq. (1).

$$i^2 R_w = hA\left(T_w - T_f\right) \tag{1}$$

Here i, R_w, h, A, T_w and T_f designate the electric current, the working resistance of the wire, convective heat transfer coefficient, surface area of the sensor, working temperature of the wire and fluid temperature respectively. Any changes in the above variables will lead to some variation in T_w. For example, if the flow velocity increases, the convection instantaneously exceeds the heat generation; as a result, T_w decreases. Similarly, if the heat dissipating ability of a nanofluid is better than that of a base fluid, then the wire working temperature of the sensor T_w will have a lower value.

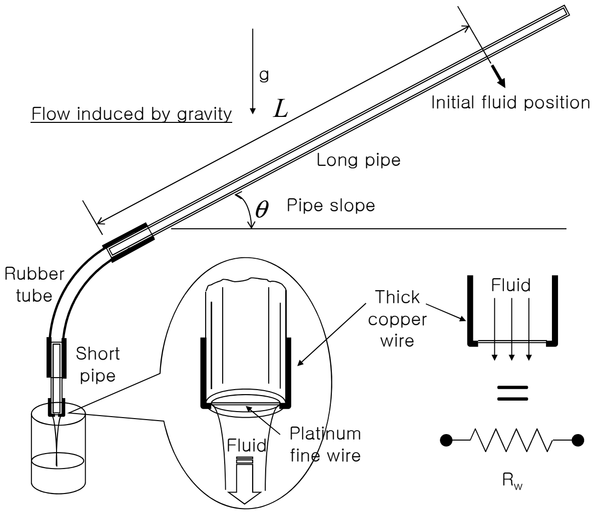


Fig. 2. Experimental apparatus composed of a tube and a heated wire.

It is possible to calculate the heat generation from a wire with high accuracy by measuring current and voltage across the wire. Also T_w can be estimated by the temperature-resistance relation (Eq. (2) below) if the working resistance of the wire R_w is known. Inserting i, R_w, A, T_w and T_f into Eq. (1) finally gives the convective heat transfer coefficient h.

$$R_w = R_0\left(1 + \alpha T_w\right) \text{ or } T_w = \frac{\left(R_w - R_0\right)}{R_0 \alpha} \tag{2}$$

The convective heat transfer coefficient changes depending on the properties of the fluids (density, viscosity, thermal conductivity and specific heat, etc.) and also the flow parameters (velocity, fluid temperature, pressure, etc.). In addition to these variables, h of nanofluids may vary depending on the particle material, particle size, particle concentration and base fluids. If h from a nanofluids proves to be higher than that obtained from the base fluid experiment at the same speed, adopting nanofluids as a new heat transfer fluid will give more plausible possibility of enhanced heat transfer performance in a real system than just expecting its effectiveness based on the thermal conductivity k alone.

3. Operational features of two types of experimental apparatus

A typical example of convective heat transfer experimental system would be the internal tube flow composed of pipes, pumps, reservoirs and so on. In general, the system is sometimes complex and large. Perhaps it needs a large amount of fluid for operation. Producing nanofluids at lab-based level is still expensive and time consuming. In case the introduction of newly developed nanofluids proves to be useless, it will retard the whole development plans. Hence, this approach is not suitable for the early stage of test level of nanofluids development.

Therefore, it is necessary to develop a new type of convection apparatus for nanofluids, which should be simple, accurate and it does not need a large amount of fluid. The present author proposes two different experimental apparatuses. They operate under the principle of external convection cooling over a heated cylinder in cross flow as discussed in Sec. 2. However, the working principles are slightly different from each other. While the first one has a stationary heated wire with the fluid flow over it, the second one has a moving heated wire in the stationary fluid. Therefore the net effects that the wire experiences are identical. A schematic diagram of the first apparatus is shown in Fig. 2 [15].

This apparatus can be divided into two main parts: tube and sensor part. The heated wire is located at the end of the sensor part. It is soldered to the thick copper wires so that the sensor is kept fixed at that location and maintained stationary during experiments. The fluid in the tube begins to flow downward by gravity with the start of experiment and takes heat away from the wire by convection. The long and short pipe are 1000mm and 150mm, respectively, with the same inside diameter of 7mm. The diameter of the wire sensor is 50μm and its length is 7mm.

A hot-wire sensor indicated as R_w is connected in series with the standard resistor R_{std}. Ends of this resistor circuit are connected to a DC power supply, which supplies electric current to the wire sensor. The schematic of the circuit is shown in Fig. 3 and it satisfies following Eq. (3) at every moment. Here V_p, V_{std} and V_w denote the power supply voltage, the voltage from the standard resistor and voltage from the wire sensor respectively.

$$V_p = V_{std} + V_w \tag{3}$$

This circuit is often called the voltage divider because two resistors R_{std} and R_w divide the constant voltage V_p into V_{std} and V_w depending on their magnitude of resistance. The standard resistor has a fixed value of resistance: here it is 10 ohms. However, the sensor resistance R_w changes according to several factors such as current, fluid temperature, and most importantly the convective heat transfer coefficient h in the present study. This can be easily expected by the use of Eqs. (1)-(2). When R_w rises, the voltage from this sensor V_w also rises. Accordingly, the voltage across the standard resistor V_{std} should be decreased since the total voltage V_p is kept constant. Current i can be calculated by measuring V_{std} as explained below in Eq. (4). Since it is a serial circuit, the same current i flows through both the standard resistor and the wire sensor, so the working resistance of the wire can be obtained as indicated in Eq. (5), which is Ohm's law.

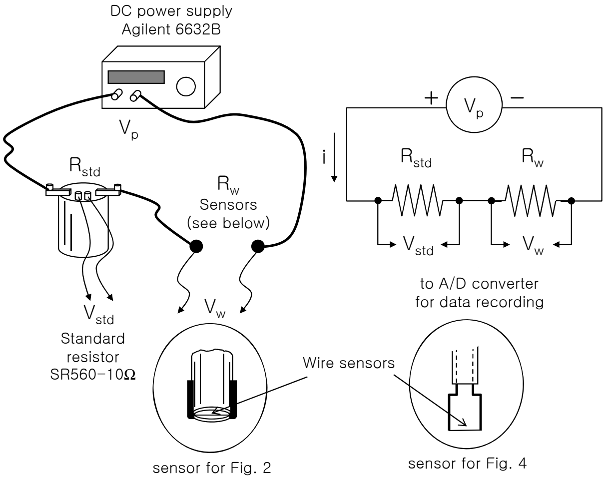


Fig. 3. Voltage divider circuit detecting the temperature variation of the wire sensor.

$$i = \frac{V_{std}}{R_{std}} = \frac{(V_p - V_w)}{R_{std}} \tag{4}$$

$$R_w = \frac{V_w}{i} \tag{5}$$

With this R_w, the wire working temperature T_w can be calculated by Eq. (2). Inserting all these data into Eq. (1) finally gives the convective heat transfer coefficient h. The flow velocity in the tube can be changed by varying the slope of the tube. When a pure fluid and a nanofluid are tested at the same slope and if h of the nanofluid shows greater value than that of the pure fluid, it could be said that the nanofluid has better heat transfer capability than the pure fluid. The higher h results in the lower working temperature of the wire T_w; it also appears as a reduced sensor resistance R_w and reduced voltage of V_w. Since R_w or T_w are secondary variables converted from V_w, measured voltage V_w can be regarded as a primary or direct indicator of heat transfer augmentation in practice. More details of experimental procedures and comparisons of h between nano and pure lubrication oils are found in reference [15]. Though this apparatus works as a useful tool to directly compare the thermal performance of fluids in terms of convection, it has several technical inconveniences. Since the viscosity of nanofluids varies along with the concentration of particle loading, the flow velocity of each nanofluid with different concentration shows different value though the tube is set at the same slope. Accordingly setting the flow velocity exactly to a specific value is difficult. In addition to this, a nanofluid becomes stickier at thicker concentration. Some of the fluid adheres to the inside wall of the tube after an experiment so, it is difficult to clean out all the remains from the inner wall for the next test.

To avoid the above-mentioned inconveniences, another improved experimental apparatus is proposed as indicated in Fig. 4. This apparatus consists of a linear traversing system (con-

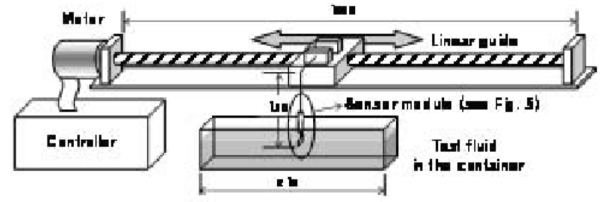


Fig. 4. Experimental apparatus composed of a traversing mechanism and a heated wire.

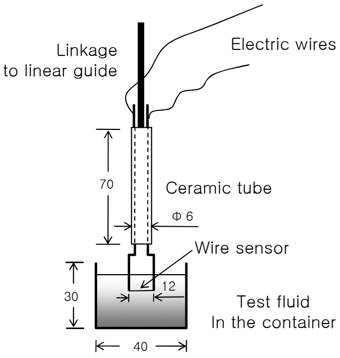


Fig. 5. Enlarged schematic of the sensor part.

troller, motor, linear guide from Robostar, Korea) the sensor, stationary test fluid and fluid container. Fig. 5 is a detailed drawing of the sensor part, which includes the wire sensor, sensor supporter, the ceramic tube holding the wire supporter, linkage to the linear guide and electric wires. The sensor length is 12mm and its resistance is 2.573 ohm at 18°C. The sensor can move exactly at the preset value of velocity because the servo motor and the controller enable the linear guide to move precisely. The sensor can be cleaned easily after an experiment by moving the sensor several times in the ethyl alcohol. The same electric circuit in Fig. 3 and the same data processing steps to obtain the convective heat transfer coefficient *h* are used again for the new system.

The design concept of the present sensor is based mainly on the dimension of the sensor used for hot-wire anemometry, where the most common configuration includes 2mm of the sensor length, 5μm of the sensor diameter, so its length to diameter ratio is 400. Considering this aspect ratio, commercially available 25μm platinum wire (OMEGA, SPPL-001) with a length of 12mm has been used as a sensor. The length-to-diameter ratio is 480 (> 400), so it can be accepted large enough to insure 2-dimensional external flow. However, the aspect ratio of the sensor for the previous tube apparatus is 140 (< 400), which is not enough to guarantee 2-dimensional flow. To overcome this weakness, I designed a new sensor module with large aspect ratio and applied it to the new system shown in Fig. 4. All experimental data of this paper were obtained by using the second apparatus. The principle of the second apparatus is similar to that of the first one. However, to explain the improvement from the first system to the second one, the working principles and its technical difficulties of the previous system are explained in detail.

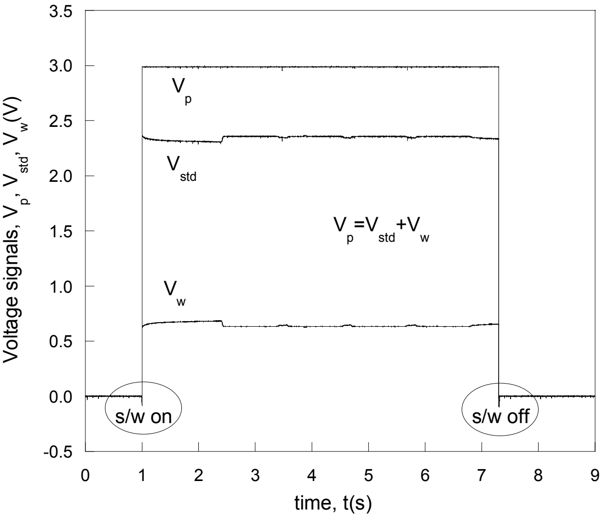
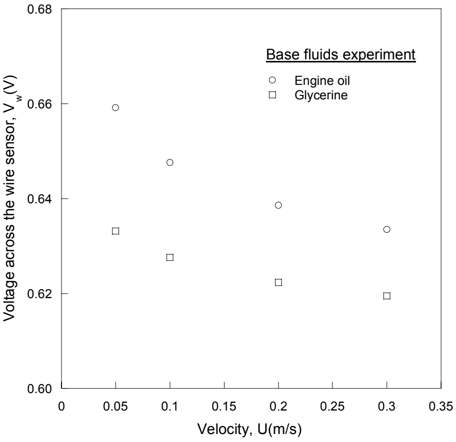


Fig. 6. Voltage signals from power supply, standard resistor and wire sensor.



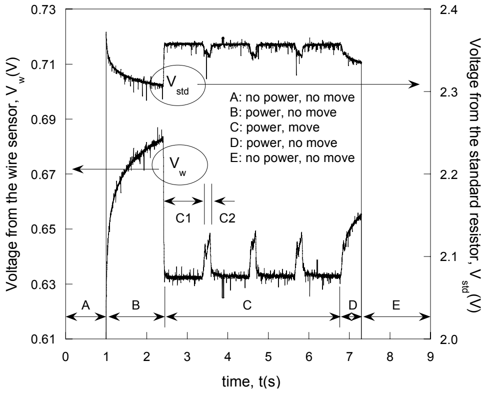


Fig. 7. Magnified signals of V_w and V_{std}.

4. Results and discussion

Fig. 6 shows a typical example of voltage signals from power supply, standard resistor and the wire sensor when the sensor travels back and forth two times in a nanofluids. From s/w on to s/w off, the power supply applies constant voltage V_p to the series resistor circuit. Fig. 7 is a magnified drawing of

V_{std} and V_w of Fig. 6, where the left and right vertical axes are for

V_w and V_{std} respectively. It is interesting to note that as V_w goes up, V_{std} goes down and the opposite happens at every moment. Moreover, it can be realized that the sum of two signals always becomes constant voltage V_p as predicted by Eq. (3).

Section A in Fig. 7 indicates the period without power to the circuit. Section B is the period of no motion of traversing system while the electric current is being applied to the circuit after period A. Joule heating raises the temperature of the wire, which makes the rise of wire voltage V_w up to about 0.68V. At the end of period B, the traversing system begins to move and V_w falls down to 0.63V. This indicates that the motion of the wire cools the heated wire and results in lowered value of V_w. V_w is maintained nearly constant during C1, which means that the sensor moves at constant speed but it rises again during C2, which indicates that the speed of the sensor is reduced due to the change of direction. Fig. 7 shows that section C has two round trip movements of the sensor in 4 seconds. Therefore it is possible to evaluate the sensor speed accurately based on this signal. The total number of movements of the sensor and its speed can be set by programming the controller of the servo motor. Section D shows that V_w rises again due to the electric heating after stopping of the traversing system.

Fig. 8 shows the variation of wire voltage according to the change of sensor velocity and the kind of base fluids (glycerin and engine oil). The V_w from the glycerin experiment always has lower value than that of engine oil for the range of tested velocity. Twofold higher thermal conductivity of glycerin than engine oil might be attributed to more efficient cooling of the wire sensor at the same power supply voltage. Fig. 9 shows the variations of convective heat transfer coefficients of the base fluids with the flow velocity. Glycerin has about 1.89 times higher value of h than that of engine oil. The ratio of thermal conductivities of glycerin and engine oil is 1.97 at 300K [16], which coincides almost with the above ratio of h of the two fluids. Here again, the fluid with higher k shows better convective performance than the other one as previous papers discussed [1-5]. The tested velocity range of this article (0.05m /s to 0.3m /s) corresponds to Re number range from 0.002 to 0.013. Churchill and Bernstein's equation [17], which has been widely adopted for predicting external convective heat transfer from a heated cylinder, was used to confirm the

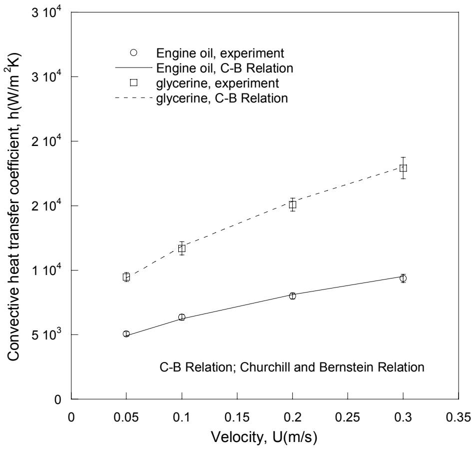


Fig. 8. Variation of wire voltages from the test of base fluids.

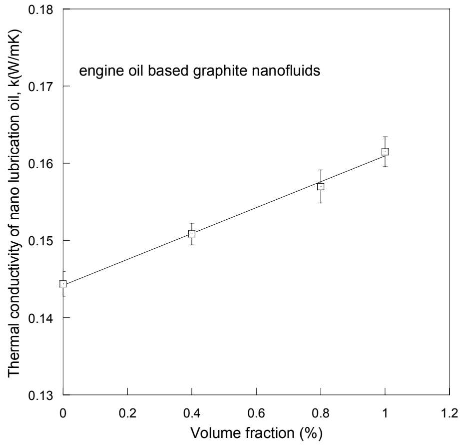


Fig. 9. Convective heat transfer coefficients from the test of base fluids.

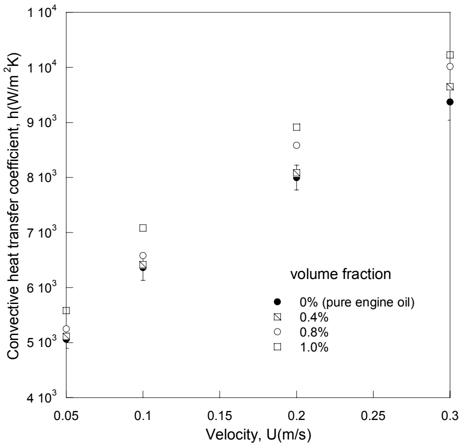


Fig. 10. Thermal conductivity data of nano oil by transient hot-wire technique.

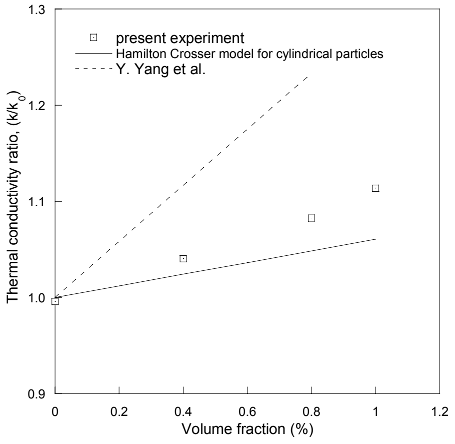


Fig. 11. Comparison of the ratio of thermal conductivity enhancement.

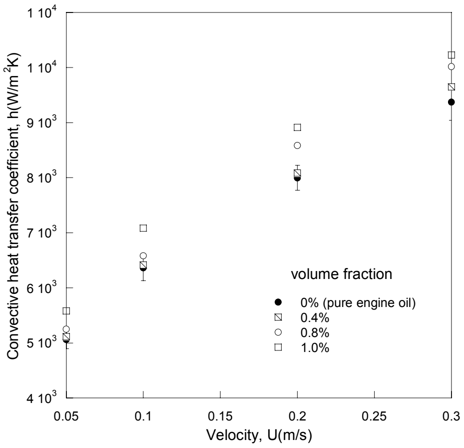


Fig. 12. Comparison of convective heat transfer coefficients of the base and nano oil.

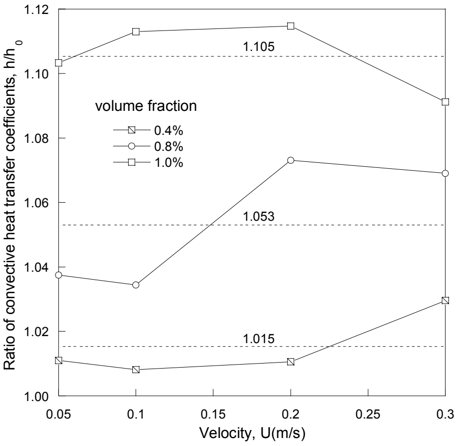


Fig. 13. Ratio of convective heat transfer coefficient between the base and nano oil.

validity of the present experimental measurement. The criterion for application of the relation is RePr>0.2. Though the Re itself is less than 0.013, its multiplication with Pr covers from 14.5 to 87.2, which is large enough to satisfy the application criterion. Moreover, the experimental results coincided well with the prediction of Churchill and Bernstein's relation. Therefore, I inferred that the current apparatus is satisfactory to the external convective heat transfer phenomena.

Fig. 10 shows the measured value of the thermal conductivity of graphite nano lubrication oil at 295K together with the associated standard deviations. The measurement was performed by the transient hot wire method [2]. The average size of graphite particle is 55nm and the base fluid is Supergear EP220 from SK energy, Korea. Technical information for base lubricant oil and graphite particles can be found in Lee et al. [18]. The thermal conductivity of nanofluids increases almost linearly with volume fraction of particle loading, which agrees well with previous results [2-5]. Fig. 11 compares the present ratio of thermal conductivity enhancement with the conventional theory by Hamilton-Crosser model [9] and recent experimental results of graphite nanofluids by Yang et al. [10]. Measured thermal conductivities lie above the prediction of the Hamilton-Crosser model for cylindrical shape of particle but lie far below the value presented by Yang et al.

To use nanofluids as successful engineering heat transfer fluids, it is necessary to maintain the volume concentration of the nano particles as low as possible. The viscosity of nanofluids rises rapidly with the increase in the concentration of particle mixing, which leads to the increase in pumping power for fluid flow in heat exchanger. Based on the previous researches, the nanofluid with 1% concentration is already regarded as a thick or high viscose fluid. For this reason, nanofluids samples under 1% concentration (pure, 0.4%, 0.8%, 1.0%) were tested in this paper.

Comparisons of the enhancement of convective heat transfer coefficient between base and nano oil are made as shown in Fig. 12. It explains that there exists distinct tendency of increase in h according to the increase in volume fraction at each tested velocity. Fig. 13 represents the results of quantitative estimation of increase of h shown in Fig. 12. It is a different presentation of the same data from Fig. 12 in terms of the ratio of heat transfer coefficients h/h_0 instead of h itself. The ratio of h/h_0 was made by dividing the heat transfer coefficient of nanofluids (h) from the concentrations of 0.4%, 0.8%, 1% with that of pure fluid (h_0) at a specified velocity. For example, there are four convective heat transfer coefficient data (from three nanofluids and one pure fluid) at 0.2m/s in Fig. 12. The three ratios of h/h_0 at 0.2m/s in Fig. 13 were made by dividing the three heat transfer coefficient data of nanofluids with that of the pure fluid. Fig. 13 shows the final results of h/h_0 after repeating a similar calculation for the other velocities. The ratio h/h_0 has greater value as the increase of the concentration of nanofluids; however, it is hard to find a tendency of any increase or decrease of h/h_0 with velocity for a given concentration. In conclusion, h/h_0 is irrelevant to the velocity and varies only with the volume concentration.

Since the thermal conductivity of nanofluids changes linearly with the particle volume fraction as indicated in Fig. 10, it can be restated that h is simply proportional to the thermal conductivity in this study. This finding looks somewhat different from the previous researches [10-13] which claim that the enhancement of h grows bigger as velocity increases. However, it should be realized that the experimental condition of the present study is at the range of low velocity, where the effect of velocity on h is not so strong than that at high velocity. Therefore the result of present study can be accepted as a limiting case of convection experiment of nanofluids where h shows strong dependency on k but shows weak dependency on fluid velocity. The convective heat transfer coefficient provided by the present system might be used as a primary indicator which guarantees the minimum enhancement of heat transfer by nanofluids.

Final representative value of h was obtained by averaging 50 instantaneous measured data of convective heat transfer coefficient. It can be justified that the random error might be ignored because 50 data are used in the averaging process of h.

The calculating formula for convective heat transfer coefficient can be derived from Eq. (1), where the current i, resistance R_w and the wire working temperature T_w (derived from these i, R_w) are very accurate, so these variables do not seem to cause a serious amount of uncertainty. However, the fluid temperature T_f seems to be the major source of the error because it is difficult to measure T_f accurately; moreover it is hard to keep the fluid temperature at a constant value independent of environmental variation. The uncertainty related with the variation of T_f can be obtained as follows;

$$\frac{\Delta h}{h} = \sqrt{\left(\frac{\Delta T_f}{\left(T_w - T_f\right)}\right)^2} \tag{6}$$

This equation tells us that the uncertainty from the drift of the fluid temperature can be minimized when the variation of the fluid temperature is small and the temperature difference between the wire working temperature and fluid temperature is large. From Fig. 13, it can be estimated that the uncertainties of convective heat transfer coefficients from the 0.4% and 1.0% nanofluids are about 1% however, 2% for 0.8%.

5. Conclusions

A simple experimental apparatus measuring convective heat transfer coefficient from a heated wire to nanofluids is proposed in this article. Experimental data provided by the present apparatus with base fluids agree well with the empirical correlation, which verifies the secure operation of the present system. The present apparatus has the feature that it does not need a large volume of working fluid in contrast to traditional convection equipment. Comparison of convective heat transfer coefficients from base and nanofluids has been made in terms of the ratio of those two values. There exists a strong dependence of this ratio on the volume fraction of nanoparticles but it is hard to find any meaningful variation of this ratio with velocity. This finding looks somewhat different from the previous results; however, this result can be accepted as a limiting case of convection experiment of nanofluids where h shows strong dependency only on k. The convective heat transfer coefficient h or as a more practical variable, the wire voltage V_w provided by the present system might be used as a primary indicator which guarantees the minimum enhancement of heat transfer by nanofluids.

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Nomenclature

A : Surface area of a wire sensor
h : Convective heat transfer coefficient
i : Electric current
k : Thermal conductivity
Pr : Prandtl number
Re : Reynolds number
R_0 : Resistance of a wire sensor at 0°C
R_{std} : Resistance of a standard resistor
R_w : Working resistance of the wire sensor
t : Time
T_w : Working temperature of the wire sensor
T_f : Fluid temperature
U : Fluid velocity
V_p : Power supply voltage
V_{std} : Voltage from the standard resistor
V_w : Voltage from the wire sensor

Greek symbol

α : Temperature resistance coefficient of the wire sensor

References

[1] U. S. Choi, Enhancing thermal conductivity of fluids with nanoparticles, *Development and Applications of Non-Newtonian Flows*, 66 (1995) 99-105.

[2] S. Lee, U. S. Choi, S. Li and J. A. Eastman, Measuring thermal conductivity of fluids containing oxide nanoparticles, *Journal of Heat Transfer*, 121 (1999) 280-289.

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

[4] U. S. Choi, Z. G. Zhang, W. Yu , F. E. Lockwood and E. A. Grulke, Anomalous thermal conductivity enhancement in nanotube suspensions, *Applied Physics Letters*, 79 (2001) 2252-2254.

[5] S. K. Das, N. Putra, P. Thiesen and W. Roetzel, Temperature dependence of thermal conductivity enhancement for nanofluids, *Journal of Heat Transfer*, 125 (2003) 567-574.

[6] S. P. Jang and U. S. Choi, Role of Brownian motion in the enhanced thermal conductivity of nanofluids, *Applied Physics Letters*, 84 (2004) 4316-4318.

[7] S. H. Kim, S. Choi, J. Hong and D. S. Kim, Measurement of the thermal conductivity of Alumina/Zinc-Oxide/Titanium-Oxide nanofluids, *Journal of KSME B*, 29 (9) (2005) 1065-1073.

[8] C. Chon, K. D. Kihm, S. Lee and U. S. Choi, Empirical correlation of finding the role of temperature and particle size for nanofluid (Al2O3) thermal conductivity enhancement, *Applied Physics Letters*, 87 (2005) 153107.

[9] R. L. Hamilton and O. K. Crosser, Thermal conductivity of heterogeneous two-component systems, *I & EC Fundamentals*, 1 (3) (1962) 187-191.

[10] Y. Yang, Z. G. Zhang, E. A. Grulke, W. B. Anderson and G. Wu, Heat transfer properties of nanoparticle-in-fluid dispersions (nanofluids) in laminar flow, *International Journal of*

Heat and Mass Transfer, 48 (2005) 1107-1116.

[11] Y. Xuan and Q. Li, Investigation on convective heat transfer and flow features of nanofluids, *Journal of Heat Transfer*, 125 (2003), 151-155.

[12] D. Wen and Y. Ding, Experimental investigation into convective heat transfer of nanofluids at the entrance region under laminar flow condition, *International Journal of Heat and Mass Transfer*, 37 (2004) 5181-5188.

[13] Y. Ding, H. Alias, D. Wen and R. A. Williams, Heat transfer of aqueous suspensions of carbon nanotubes (CNT nanofluids), *International Journal of Heat and Mass Transfer*, 49 (2006) 240-250.

[14] H. H. Bruun, *Hot-Wire Anemometry*, Oxford University Press (1995).

[15] S. Lee, Measuring convective heat transfer coefficient around a heated fine wire in cross flow of nanofluids, *Journal of KSME B*, 32 (2) (2008) 117-124.

[16] F. P. Incropera and D. P. DeWitt, *Fundamentals of Heat and Mass Transfer*, John Wiley & Sons, USA (1996).

[17] S. W. Churchill and M. Bernstein, A correlating equation for forced convection from gases and liquids to a circular cylinder in cross flow, *Journal of Heat Transfer*, 99 (1977) 300-306.

[18] C. Lee, Y. Hwang, Y. Choi, M. Park, J. Lee, C. Choi and J. Oh, Comparative study to the tribological characteristics of graphite nano lubricants after thermal degradation, *Journal of the KSTLE*, 24 (4) (2008) 190-195.

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