Experimental Study on Convective Heat Transfer of Aqueous Suspensions of Nano-Diamond Particles

Shuichi Torii

Department of Mechanical System Engineering, Kumamoto University, Kumamoto, Japan

Abstract: This paper aims to study the convective heat transfer behaviour of aqueous suspensions of nano-diamond particles flowing through a horizontal tube heated under constant heat flux condition. Consideration is given to the effects of particle concentration and Reynolds number on heat transfer enhancement. It is found that (i) significant enhancement of heat transfer performance due to suspension of nano-diamond particles in the circular tube flow is observed in comparison with pure water as the working fluid, (ii) the enhancement is intensified with an increase in the Reynolds number and the nano-diamond concentration, and (iii) substantial amplification of heat transfer performance is not attributed purely to the enhancement of thermal conductivity due to suspension of nano-diamond particles.

Keywords: Nanofluid, Heat Transfer, Nano-diamond

1. INTRODUCTION

Crystalline solids have thermal conductivities higher than fluids by one to three orders of magnitude. By intuition, one expects that thermal conductivities of particle-fluid mixtures are higher than those of pure fluids, as pointed out by Maxwell [1] more than a century ago. The conventional solid-liquid mixtures in which millimeter and/or micrometer-sized particles are added are known as slurries. It is known that slurries settle rapidly, clog flow channels, erode pipelines and cause severe pressure drop and other undesirable problems. Therefore, fluids with suspended large particles have little practical application in heat transfer enhancement.

Modern technology makes it possible to produce particles <100 nm in diameter for suspending in conventional fluids such as water, engine oil, and ethylene glycol. This new class of fluids is referred to as “nanofluids”, whose term is first named and used by Choi [2]. Compared with micron-sized particles, nano-particles have much larger relative surface areas and a great potential for heat transfer enhancement. Based on this idea, many studies were conducted to explore superior properties of nanofluids, such as large surface-area-to-volume ratio, stable suspension, and no flow passage clogging, which are suitable in heat transfer applications.

Eastman et al. [3] demonstrated that oxide nanoparticles, such as Al2O3 and CuO have excellent dispersion properties in water, oil, and ethylene glycol and form suspensions. Lee et al. [4] measured thermal conductivity of fluids containing Al2O3 and CuO particles so that for the copper oxide/ethylene glycol system, thermal conductivity can be enhanced by more than 20% at 4 volume percentage. In particle, they disclosed that the thermal conductivity of nanofluids depends on the thermal conductivities of both the base fluids and particles. Using the measured thermal conductivity and viscosity data, Wang et al. [5] concluded that the increase in pressure drop is about the same as the increase in heat transfer for both laminar and turbulent flow in a circular tube for all of the fluid-particle mixtures. Most of these studies are on the effective thermal conductivity under macroscopically stationery conditions. There are very few studies on the other aspects related nanofluids such as phase change behavior (for example, Das et al. [6] and convective heat transfer.

Lee and Choi [7] estimated the performance of micro-channel heat exchangers with water, liquid nitrogen and nanofluids as the working fluid and showed the superiority of a nanofluid-cooled microchannel heat exchanger. Pak and Cho [8] investigated convective heat transfer in the turbulent flow regime using the mixing fluids of water-Al2O3 and water-TiO2. As for the mechanism of heat transfer enhancement of the nanofluid, Xuan and Roetzel [9] found that the effects of transport properties of the nanofluid and thermal dispersion are included. Xuan and Li [10] measured convective heat transfer of water-Cu nanofluids and found substantial heat transfer enhancement. Wen and Ding [11] reported an experimental work on the convective heat transfer of nanofluids made of water and g-Al2O3 nanoparticles in the laminar flow region. They proposed that the enhancement of convective heat transfer is attributed to a non-uniform distribution of thermal conductivity and viscosity field and an attenuation of the thermal boundary layer thickness. The heat transfer behavior of aqueous suspensions of multi-walled carbon nanotubes (CNT) in the laminar tube flow is experimentally studied by Ding et al. [12]. They proposed that enhancement of the convective heat transfer is ascribed to particle re-arrangement, shear induced thermal conduction enhancement, reduction of thermal boundary layer thickness, and the higher aspect ratio of CNTs.

The purpose of the present study is to investigate heat transfer characteristics of circular pipe flow including nano-diamond particles. Emphasis is placed on the effect of the suspension with the particles, i.e., the volume fraction of particles and Reynolds number on heat transfer performance in the turbulent flow.

2.EXPERIMENTAL SETUP and MEASUREMENT METHODS

In general, the heat transfer coefficient of the thermal
fluid flow including nanofluids is affected by the Reynolds number, thermal properties and so on. In this work, the viscosity and thermal conductivity of nano-diamond fluids are considered here to study the effect of convective heat transfer. Nanoparticle suspensions are far more stable than suspensions of larger particles [13]. One of a few methods of assessing nanofluid stability is to visually inspect fluid sample over an extended period of time. Figures 1(a) and (b) depict picture of 0.4% and 1% nano-diamond fluids after 60 days later, respectively. The corresponding pH for two nanofluids is 6.62 and 6.35, respectively. One observes that no concentration gradient appears in both nanofluids. It implies long-term degradation in thermal performance due to setting inside the cooling system’s reservoir.

The viscosity is measured by using the Cannon-Fenske viscometer. The measurements are done on nanofluids of different nano-diamond concentrations. For reference, a TEM image of the sample is depicted in Fig. 2. The electron micrograph shows that the particles are dispersed in the fluid and some are in the format of agglomerates.

The experimental system for measuring the convective heat transfer coefficient is illustrated schematically in Fig. 3. It consists of a flow loop, a power supply unit, a cooling device, and a flow measuring and control unit. The flow loop includes a pump, a digital flowmeter, a reservoir, a collection tank and a test section. A straight seamless stainless tube with 1000 mm length, 4.0 mm inner diameter, and 4.3 mm outer diameter is used as the test section. The whole test section is heated with the aid of the joule heating method through a electrode linked to a DC power supply. The power supply is adjustable and had a maximum power supply of 1000W. Six K-type thermocouples (0.01mm in diameter) are mounted on the test section at axial position of 150mm from the inlet of the test section to measure the wall temperature distribution, and two further K type thermocouples are inserted into reservoir and collection tank at the inlet and exit of test section to measure the bulk temperatures of nanofluid, respectively. The maximum flow rate that the pump can deliver is 25 l/min. In the heat transfer experiments, the temperature readings from the 8 thermocouples are recorded by a data logger system with a personal computer.

The local heat transfer coefficient, \( h_x \), is defined as

\[
h_x = \frac{q}{(T_{wx} - T_{mx})} \tag{1}
\]

where \( x \) represents axial distance from the entrance of the test section, \( q \) is the heat flux, \( T_{wx} \) is the measured wall temperature, and \( T_{mx} \) is the mixed mean temperature, i.e., the fluid temperature estimated by the following energy
balance:

\[ T_{\text{out}} = T_{\text{in}} + \frac{Q}{c_p W} \quad (2) \]

Here, \( c_p \) is the heat capacity, \( T_{\text{in}} \) is the fluid temperature at the inlet. And \( Q \) and \( W \) are respectively the heat rate from the heat wall surface and the average fluid velocity over the cross-section. Note that Eq. (2) is taken a heat loss through the insulation layer into account.

The local heat transfer coefficient, \( h_x \), in Eq. (1) is usually expressed in the form of the Nusselt number \( Nu_x \), as:

\[ Nu_x = \frac{h_x D}{k}, \quad (3) \]

where \( D \) is the tube diameter, and \( k \) is the fluid thermal conductivity. In general, the \( Nu \) number is related to the Reynolds number, \( Re \), and the Prandtl number, \( Pr \). Thus, \( h_x \) is arranged in the form of \( Re \) versus \( Nu_x \) in the following section, because only the nano-diamond nanofluid is employed. Notice that the thermal conductivity of nanofluid is strongly dependent on the nano-particle volume fraction. Hamilton and Crosser [14] proposed a model for liquid-solid mixtures in which the ratio of conductivity of two phases is larger than 100, as:

\[ k = k_s \left[ \frac{k_s + (n-1)k_f - (n-1)V(k_f - k_s)}{k_s + (n-1)k_f + V(k_f - k_s)} \right], \quad (4) \]

where \( k_s \) is the thermal conductivity of the discontinuous particle, \( k_f \) is the thermal conductivity of the fluid, \( V \) is the volume fraction of particle, and \( n \) is the empirical shape factor. \( V \) and \( n \) are defined by

\[ V = \frac{V_s}{V_f + V_s}, \quad (5) \]

and

\[ n = \frac{3}{\psi}, \quad (6) \]

respectively. Here \( \psi \) is the sphericity defined as the ratio of the surface area of a sphere with a volume equal to that of the particle to surface area of the particle. \( \psi = 1 \) is assumed in the present study, because the nanoparticles are seen like a sphere, as seen in Fig. 2.

Three volumetric concentrations of nano-diamond fluid, 0.1\%, 0.4\% and 1\% are tested in the present study. The Reynolds number is ranged from 3000 to 6000. An uncertainty analysis [15] yields the following results: the uncertainty in nanofluid flowrate is estimated to be ±1.5\%, the uncertainty in the physical properties is less than 1\%, and the uncertainty in the temperature measurement is estimated to be ±1.5\%. The thermocouples were calibrated in a thermostat water bath and the accuracy was found to be within 0.1 K.

3. RESULTS AND DISCUSSION

3.1. Viscosity of nanofluid

The viscosity of nano-diamond fluid was measured under various conditions. Figure 4 shows results for different concentrations. For comparison, the corresponding viscosities for different concentrations are theoretically estimated using the Batchelor Model. The viscosity of nanofluids increases with increasing nano-diamond concentration. Such behavior is also observed by Kinloch et al [16] for highly concentrated aqueous suspensions of multiwalled carbon nanotubes. The results have an important implication to nano-diamond fluids flowing through the tubular geometry used in this work. In other words, the viscosity of nano-diamond fluid is higher than the theoretical value over the wide range of volume fraction. Using the measured value, the Reynolds number is determined in the following.

Figure 4 Experimental and theoretical results for different volume fractions

3.2. Convective heat transfer coefficient

Having established confidence in the experimental system, systematic experiments were performed at different flow conditions (Reynolds numbers), and different nano-diamond concentrations.

Figure 5 shows the effect of nano-diamond concentration on the local heat transfer coefficient at various axial distances from the entrance of the test section at \( Re = 6000 \). Here, local heat transfer coefficient is divided by the heat transfer coefficient for the thermally and hydrodynamically fully-developed region in the pure fluid pipe flow. It is observed that (i) the presence of nano-diamond particles increases the convective heat transfer coefficient significantly, and the increase is more considerable at high nano-diamond concentration, and (ii) at a given nano-diamond concentration, the heat transfer coefficient decreases with axial distance because of the entrance region effect. A similar trend but with less significant enhancement was obtained at different lower Reynolds numbers (not shown) and was also observed by Xuan and Li [10] in the turbulent flow regime and Wen and Ding...

[11] at the entrance region in the laminar glow regime. It is observed in Fig. 5 that the local heat transfer coefficient approaches the constant value along the axial direction, that is the thermally fully-developed region appears in the downstream region. In the following section, consideration is given to effects of Reynolds number and nano-diamond concentration on heat transfer performance in the thermally fully-developed region, i.e., at $x/D=180$. Notice that a comparison of nanofluid with pure fluid indicates that the enhancement of the local heat transfer coefficient is much more dramatic than that purely due to the enhancement of effective thermal conductivity. For reference, an increase in the thermal conductivity is depicted in Fig. 6 in the form of volume fraction versus dimensionless thermal conductivity with difference nano-particle materials as a parameter. Here, each thermal conductivity is normalized by one of the pure fluid. It is seen that the effective thermal conductivity increase with increasing nano-particle concentration and maximum enhancement is about 16% at 5% of volume fraction.

Figure 7 depicts the enhancement of the heat transfer coefficient with reference to pure fluid. It can be seen that the heat transfer enhancement increases with increasing Reynolds number. This trend becomes larger with an increase in the nano-diamond concentration. Figure 7 illustrates the effect of the Reynolds number on the heat transfer coefficient at $x/D=180$. The measured values are summarized in Fig. 7 in the form of $Re$ versus $Nu$ with the nano-diamond concentrations, as the parameter. For comparison, the following well-known Gnielinski’s correlation equation [17] under the constant heat flux boundary condition is superimposed in Fig. 7 as a solid line.

Next is to investigate the mechanisms of heat transfer enhancement. The heat transfer coefficient, $h$, is a macroscopic parameter describing heat transfer when a fluid flows across a solid surface of different temperature. The boundary layer increases with axial distance until fully developed after which the boundary layer thickness and hence the convective heat transfer coefficient is constant. This theory suggests that both an increase in the thermal conductivity, $k$, and/or a decrease in the thermal boundary layer thickness cause an amplification of the convective heat transfer coefficient. The maximum enhancement of the thermal conductivity under the conditions of the convective heat transfer experiments in this work does not exceed 16% for 5.0% nano-dimamond fluid, as seen in Fig. 6. Meanwhile, Fig. 7 shows that the enhancement of the convective heat transfer coeffi-
cient is much greater than that due to the increase in the thermal conductivity, particularly at high nona-diamond concentrations and high Reynolds numbers. One may therefore simply attribute the large enhancement purely to a decrease in the thermal boundary layer thickness. No doubt, the reduction in the thermal boundary layer thickness could be an important factor, but further enhancement on the thermal conduction under dynamic conditions could be another important factor.

4. SUMMARY
Experimental study has been performed to investigate the heat transfer behaviour of aqueous suspensions of nano-diamond particles. Experimental and theoretical methods are employed to obtain the effective thermal conductivity, viscosity and convective heat transfer coefficient. Consideration is given to the effect of particle concentration and Reynolds number on heat transfer enhancement. The effective results are summarized as follows:
(1). Significant enhancement of heat transfer performance due to suspension of nano-diamond particles in the circular tube flow is observed in comparison with pure water as the working fluid.
(2). The enhancement depends on the Reynolds number and the nano-diamond concentration. In other words, the maximum heat transfer enhancement in the thermally and hydrodynamically fully-developed flow region takes places with an increase in the Reynolds number and nano-diamond concentration.
(3). Substantial amplification of heat transfer performance is not attributed purely to the enhancement of thermal conductivity due to suspension of nano-diamond particles.

The above discussion is mostly from the macroscopic point of view. Microscopically, particle migration and re-arrangement due to non-uniform shear rate over the pipe cross-section could also be a reason for the observed large heat transfer enhancement. Thus further work is needed to disclose mechanisms of heat transfer enhancement.

NOMENCLATURE
Cp specific heat
D pipe diameter
f friction factor, Eq. (8)
hx local heat transfer coefficient, Eq. (1)
k thermal conductivity, Eq. (4)
kf thermal conductivity of the fluid
ks thermal conductivity of the discontinuous particle
n empirical shape factor in Eq. (4)
Nu Nusselt number, Eq. (7)
Nux local Nusselt number, Eq. (3)
Pr Prandtl number
Qx heating rate
Q heat flux
Re Reynolds number
Tmo inlet fluid temperature
Tmx mixed mean temperature, (2)
V volume fraction of particle
W mean velocity of fluid
x coordinate, m

Subscripts
f fluid
mx mean
s solid or surface
wx axial

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