



Thermophysical properties of carbon-based material nanofluid



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ABSTRACT

Nanoparticle dispersed fluids, nanofluids, have been widely investigated. Yet, there have been discussions of interpreting changes in nanofluid thermal conductivity, and heat conduction mechanism in nanofluids. However, changes in the thermal conductivity by mixing nanoparticles are relevant to a characteristic length of the nanoparticles. Therefore, we in the present study employed soot fine particles, which can be produced by means of combustion method at relatively low cost, and investigated them for nanofluids. As the soot fine particles, we employed carbon black (CB). For comparison with them, we also used carbon nanopowder (CNP), which was one of carbon-based materials. We experimentally measured effective thermal conductivity, and specific heat of each nanofluid by means of transient hot-wire method, and adiabatic method. We found that the CB and the CNP nanofluids thermal conductivities depended on their fluid temperature at almost identical increase rate. In addition, we found that the CB and the CNP nanofluids enhanced their own thermal conductivities by approximately 7%, and 19% respectively, at particle volume fraction of 1.5%. Our results indicated the nanoparticle geometry influenced its own thermal conductivity. Regarding the specific heat, our results were that each of the nanofluid specific heat decreased with increase in their nanoparticle volume fractions. Our results were consistent with a prediction model of nanofluid specific heat.

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1. Introduction

Nanoparticles suspended fluids, so called nanofluids, have been widely investigated since Choi et al. [1] reported that the nanofluids are able to change their own physical properties from their base fluid. As for carbon-based materials, carbon nanotubes [2,3], fullerene [3], and graphite [4] have been employed for suspending materials of nanofluids. Those previous experimental investigations confirmed that the nanofluids thermal conductivities changed. The carbon nanotube and the graphite nanofluids enhanced their thermal conductivities. On the other hand, the fullerene nanofluid decreased its thermal conductivity. This difference in thermal conductivity change arose from difference in their molecular structures. Including the carbon-based material nanofluids, amounts of nanofluid thermal conductivity change [5], and heat conduction mechanism in nanofluids [6,7] also have been investigated and discussed until now. However, they are still open question. Although, what we can conclude is that changes in the thermal conductivity and engineering advantages by mixing nanoparticles are relevant to a nanoscale characteristic length of the particles. We in the present study focused on soot fine particles, initial diameters of which

are nanoscale. Another advantage of the soot fine particles is that they can be industrially produced at relatively low cost by means of an incomplete combustion method of hydrocarbons, or by means of thermal decomposition of oils [8]. The soot fine particles may work as nanofluid suspension particles. Therefore, we experimentally investigated changes in thermal properties of the soot fine particle suspended fluid. As the soot fine particles, we employed carbon black (CB). Commercial CB is less expensive by a factor of approximately 400 than other commercial carbon-based nanoparticle products. For comparison with CB, we also employed a carbon nanopowder (CNP), which was one of carbon-based materials. We evaluated thermal conductivity of those nanofluids by means of transient hot-wire method, and specific heat by means of adiabatic method.

2. Sample and methodology

We employed a CB from Mitsubishi Chemical (Product number: MA100). Its nominal diameter is 24 nm. In addition, we employed a CNP from Sigma Aldrich (Product number: 63310). Its nominal diameter is 100 nm. The CNP was produced by a laser method. In a previous study, Raman spectroscopy confirmed that the CNP had a graphitic nature in its structure [9]. The CNP morphology observed by scanning electron microscopy was shown in Ref. [9].

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To enhance the carbon particles suspension, we dissolved 0.5 wt% surfactant of polyvinylpyrrolidone (PVP) into a distilled water, and added a few drops of ammonia solution so that each of those base fluids was approximately 9.0 in pH. The above mentioned pH value employed in the present study was based on a previous study of a graphite nanofluid stability and zeta potential [4]. We mixed a certain amount of sample particles with the base fluid at a certain volume fraction, and sonicated the fluids to enhance the particle suspension. By means of the procedure, we produced carbon black fluid (CBF), and carbon nanopowder fluid (CNPF), and then evaluated the thermal properties as a function of fluid temperature and particle volume fraction.

In the case of CNPF, the sample fluid had been opaque for more than 7 days since it was prepared. However, in the case of CBF, a dispersion time was shorter than that of CNPF. Differently from CNP, CB molecular structure has hydroxyl and carboxyl groups. Because of this, the most stabilizing pH value for CB might differ from that of graphite. Nevertheless, the following measurements were performed while the sample fluids were opaque.

We evaluated the CB density employed in the present study since it had been unknown. We added the CB into the base fluid in a graduated cylinder until the particles mixed with the fluid in the cylinder. From this, we evaluated the CB particle volume. Besides, we measured weight change in the sample in the cylinder. From them, we evaluated the CB density at multiple times. Our result was $1.70 \pm 0.07 \text{ g/cm}^3$, which was close to the CNP density. Available physical properties of CB, CNP, and graphite are summarized in Table 1.

2.1. Thermal conductivity measurement

As for thermal conductivity measurement, we employed transient hot-wire method with electrically insulated two wires (e.g. [2]). Working principle of the transient hot wire method is to heat up a target fluid through flowing electric current in small-diameter Pt wires, and evaluate change in Pt-wire temperature from change in electrical resistivity so that the target fluid thermal conductivity is evaluated from heat flux from the Pt wires and the change in the electrical resistivity. The evaluation equation is expressed as follows:

$$k = \frac{(R_L - R_S) I^2}{4\pi A} \frac{d\rho_e}{dT} \bigg/ \frac{d\Delta V}{d \ln t} \quad (1)$$

k denotes the thermal conductivity of the target fluid. ρ_e denotes the electrical resistivity of Pt. R_L denotes the electrical resistance of a long Pt wire, and R_S denotes the electrical resistance of a short Pt wire. T denotes the wire temperature. ΔV denotes voltage difference in the long and short wires, corresponds to $V_L - V_S$. I denotes the electric current through the Pt wire. t denotes the time, and A is the cross-section of the wire. The electric current the Pt wire was evaluated from the voltage across a shunt resistor in the circuit. Fig. 1 illustrates the electric circuit we employed. Fig. 2 illustrates the measurement cell, where Cu electrodes equipped with the long and short Pt wires were immersed in the sample fluid. The Pt wires were 50 μm in diameter, and fixed on the Cu electrodes. The Pt wire

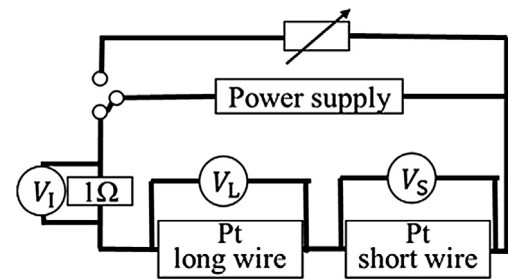


Fig. 1. Electric circuit.

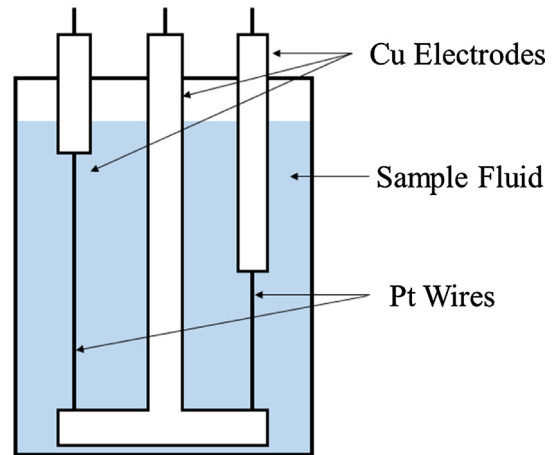


Fig. 2. Measurement cell.

lengths were 50 mm and 100 mm, which were longer than the length to eliminate wire end effects [2]. To insulate electrical conduction from the Pt wires and the Cu electrodes to the sample fluid, parylene coating of approximately 5 mm was deposited on the wires and the electrodes. In addition, silicone coating was applied on them. To eliminate effects of unstable initial electricity through the wires and of natural convection associated with the wire heating, we evaluated the logarithmic time change in the voltage difference $d\Delta V/d \ln t$ from data of the heating time domain of 2.00–4.25 s from the beginning. With the evaluation procedure, we confirmed that temperature increase in the Pt wires were 4–5 K, which were comparable with that recommended for precise measurement [2]. Moreover, the time domain were able to eliminate the natural convection influence on $d\Delta V/d \ln t$.

To validate measurement apparatus accuracy, with the apparatus and the procedure we measured thermal conductivity of 5.0 wt% NaCl solution at sample temperature of 20 °C. 5-time measurement result was $0.595 \pm 0.007 \text{ W/m}\cdot\text{K}$. 0.593 W/m·K is a reference value of thermal conductivity of 5.0 wt% NaCl solution at 20 °C calculated from a literature [12]. Its relative error was 0.3%. We confirmed that no electricity leaked into the sample fluid based on that no fluctuations of the wire electricity were observed after the electricity got stable during the measurement. According to the literature [12], electrical conductivity of 5.0 wt% NaCl solution is estimated to be 6.72 S/m. A previous study [13] reported that electrical conductivity of carbon nanotube (CNT) nanofluid at weight fraction of 1.0 and 5.0 wt% was 43.0, and 91.4 mS/m. Compared with the NaCl solution, the CNT nanofluid electrical conductivity was low by a factor of tens. CB, CNP, and CNT all are carbon based materials. Therefore, it is expected that the CB and the CNP nanofluid electrical conductivities are comparable with the CNT nanofluid, or even lower than that. Based on them, we concluded that the electrical insulation coating was at a workable level. Besides,

Table 1
Physical properties of carbon black, graphite, and carbon nanopowder.

	Density [g/cm ³]	Thermal conductivity [W/m·K]	Specific heat [J/g·K]
Carbon Black (MA100)	1.70 ± 0.07	N/A	N/A
Graphite [10]	N/A	100	0.72
Carbon Nanopowder (63319) [11]	1.8–2.1	N/A	N/A

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