Study of the dependence the thermal conductivity of nanofluids on different parameters

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Abstract. The paper presents the results of systematic measurements of the thermal conductivity coefficient of nanofluids at room temperature. It is shown that the thermal conductivity of all considered nanofluids depend on concentration, nanopartical size, as well as the base fluid properties. It was revealed that thermal conductivity coefficient of nanofluids increases with increasing concentration and size of nanoparticles.

1. Introduction

The first use of a fluid with microparticles for the purpose of heat-transfer intensification has been known since the mid-1970s (e.g., Ahuja, 1975 [1]). However, it failed to obtain substantial results. This is due to the fact that large disperse particles sediment quite rapidly and cause the channel walls to erode. Fluids in which the dispersed component is represented by nanoparticles are free from this drawback. The idea of using nanoparticles to enhance the heat conduction of a carrier fluid emerged about two decades ago. A two-phase medium whose carrier component is a regular liquid and whose dispersed component is represented by nanoparticles is currently referred to as a nanofluid (this term appeared for the first time in the work of Choi [2]). At present, one important fundamental issue is understanding mechanisms of transfer of heat in nanofluids. To explain the anomalous heat conduction of nanofluids one analyzes a few mechanisms: Brownian motion of nanoparticles (diffusion), the formation of a high-thermal-conductivity liquid layer on the "liquid–particle" interface, classification of nanoparticles, thermal diffusion (transfer of nanoparticles by the action of a temperature gradient), ballistic transfer of thermal energy in an individual particle and between nanoparticles occurring in the case of their contact, and others. The issue as to the contribution of these mechanisms to the effective thermal conductivity of various nanofluids remains open. Due to this, no general theory capable of predicting reliably the heat conduction of nanofluids has been created to date. Therefore, a reliable experimental procedure of measurement of the thermal-conductivity coefficient of nanofluids is required.

Despite the great number of works in which the heat conduction of nanofluids and their heat transfer are studied, the results obtained are often erratic. This is true of, e.g., heat transfer under natural-convection conditions [3]. Although an enhancement of the heat transfer in the case where nanoparticles are used is noted in most works [4], there are publications where a decrease in the heat transfer on adding them is demonstrated [5]. In addition to experimental investigations of the heat

conduction of nanofluids, there are numerous theoretical works; however, a review of results of works by different researchers shows that it is impossible to closely predict the heat conduction of nanofluids at present. Therefore, comprehensive investigations of the heat transfer of nanofluids require a reliable procedure of measurement of the thermal-conductivity coefficient.

The present work we used hot-wire method. This method is widely employed to measure the thermal-conductivity coefficient of liquids.

2. Measurement technique

Thermal conductivity measurements were performed by non-stationary hot-wire method. Detailed description of the test bench and testing technique is given in [6]. Wheatstone bridge was used as the basis of the test bench instrumentation to measure an unknown electrical resistance of hot wire. A copper wire with a length of 150 mm and a diameter of 75 microns was used in the experiments. The wire serves one of the measuring bridge resistors R_w. The bridge includes also two other resistors: R_1=2 kOhm and R_3=1 Ohm as well as the resistance box R_2, needed to balance bridge. Initially the bridge is balanced and the output voltage does not exceed 10 µV. Balancing of the measuring circuit is carried out by a voltage of 0.1 V from a lab power source GWInstek GPC-3060D applied within a short period of time. Further, the circuit is energized by measuring voltage to record the out-of-balance voltage change of the bridge circuit over time. Voltage measurement is carried out using a precision voltmeter GWInstek GDM-78261 with increments of 10 ms. In addition, the test fluid temperature was measured by means of chromel-copel thermocouples connected to the TRM-138 meter.

Data processing was made in a following way. The initial resistance of the wire is found from the condition of the bridge circuit balance: $R_{w0} = R_1 R_3 / R_2$. The change in wire resistance is determined by the ratio

$$R_{wt} = R_3 \left[R_1 + \frac{V_o(R_1 + R_2)}{V_i} \right] \left[R_2 - \frac{V_o(R_1 + R_2)}{V_i} \right]^{-1},$$

where V_i – is the input voltage of the bridge, V_o – is out-of-balance bridge voltage. Given the dependence of electrical resistance of copper on temperature, we can determine the temperature change of wire:

$$\Delta T = (R_{wt2} - R_{wt1})(\alpha R_{w0})^{-1} = \Delta R_{wt}(\alpha R_{w0})^{-1},$$

where $\alpha = 0.000383 1/K$ – is the temperature coefficient, predetermined from measurement series of used copper wire resistance at different temperatures. The voltage drop on the wire is given by formula: $V_{Rw} = V_i R_{wt} / (R_{wt} + R_3)$. Then, the linear density of heat flux on the wire is defined as $q = V_{Rw}^2 / (L_w R_{wt})$: where L_w – is the length of the wire. In the experiments, a typical value of q was around 10 W/m.

Eventually, the heat conductivity coefficient of a fluid is defined as follows: $\lambda = \alpha q R_{w0} / (4\pi G)$, where G – is the angular coefficient of the linear section taken from the dependence of the wire resistance on the logarithm of time. The coefficient G was calculated by the least squares method. The value of thermal conductivity coefficient was obtained by averaging over ten measurements. During the measurements, the nanofluid temperature was maintained constant. In the presented measurements it was equal to 25°C. The resultant relative measurement error of fluid thermal conductivity coefficient does not exceed 3 %.

Preparation of nanofluids was carried out based on standard two step process. After adding to the base fluid the required amount of nanopowder, the nanofluid was first thoroughly mixed mechanically, and then was placed for the half-hour into an ultrasonic disperser "Sapphire" to destruct conglomerates of particles. The nanoparticles were purchased from "Plasmoterm" company (Moscow).

3. Dependence of thermal conductivity on particle concentration

The first question that arises in the study of thermal conductivity of any dispersed fluid is formulated quite simply: how thermal conductivity depends on the particle concentration φ. The answer to this question for coarse liquids with spherical particles was given by Maxwell [7], who obtained the following relation between the thermal conductivity coefficient of the suspension and base fluid:

$$\lambda = \lambda_f \frac{\lambda_p + 2\lambda_f + 2\varphi(\lambda_p - \lambda_f)}{\lambda_p + 2\lambda_f - \varphi(\lambda_p - \lambda_f)} \qquad (1)$$

where λ_p, λ_f – is the thermal conductivity coefficient of particle material. Formula (1) is obtained for spherical particles non interacting with each other. Later Bruggemann [8] proposed a model, which took into account the interaction of the randomly distributed particles. This model, unlike (equation (1)), has no restrictions on particle concentration, though within the low concentration range it leads to the same results as the Maxwell model. Hamilton and Crosser [9] generalized the model (equation (1)) for the case of non-spherical particles. There are still quite a lot of models, a short list of which can be found, for example in [10], however, the model (equation (1)) satisfactorily describes numerous experimental data obtained in coarse fluids at not too high concentrations.

In all cases, increasing the particle concentration leads to significant enhancement of nanofluid thermal conductivity. The enhancement of nanofluid thermal conductivity over that of pure water at 6% concentration of nanoparticles reaches 5-28% that is greater than the values defined by equation (1). For illustration, figure 1 shows nanofluids thermal conductivity coefficients along with the values calculated by equation (1).
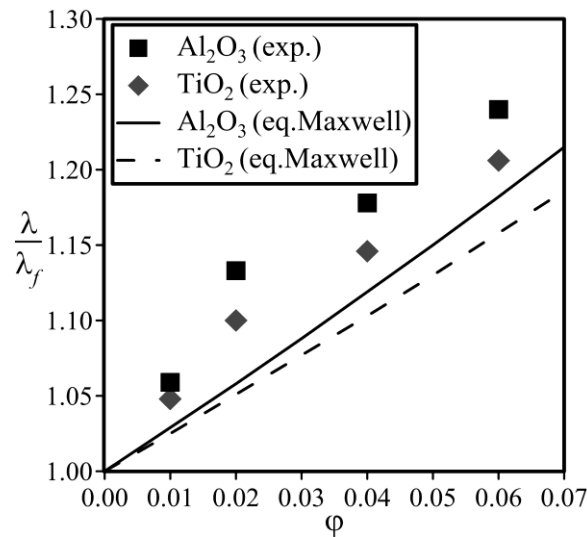

Figure 1. Relative thermal conductivity of water based nanofluids with 150 nm particles of TiO_2, Al_2O_3 depending on particle concentration.

4. Dependence of thermal conductivity on particle size

In order to clearly answer the question about the nature of this dependence, it was necessary to perform thermal conductivity measurements in nanofluids with particles of different size, though at the same volumetric concentration. We have performed these measurements using nanofluids with silicon, aluminum, zirconium, and titanium oxides particles. The particle sizes ranged from 10 to 150 nm. Pure water was used as the base fluid in all cases, while volumetric concentration of the nanoparticles was

equal to 2%. The measurements were carried out at a temperature of 25°C. The data obtained are presented in figure 2 and allow us to unambiguously assert that the nanofluid thermal conductivity coefficient depends on the particle size; at that, the more particle size the higher thermal conductivity.

However, the degree of enhancement of thermal conductivity coefficient is very different. It is characteristic that for nanofluids containing SiO_2 and Al_2O_3 particles, the obtained relative thermal conductivity coefficients are lower than those defined by equation (1). This fact was noted in the literature before, though was not associated with the relationship between the thermal conductivity and particle size.
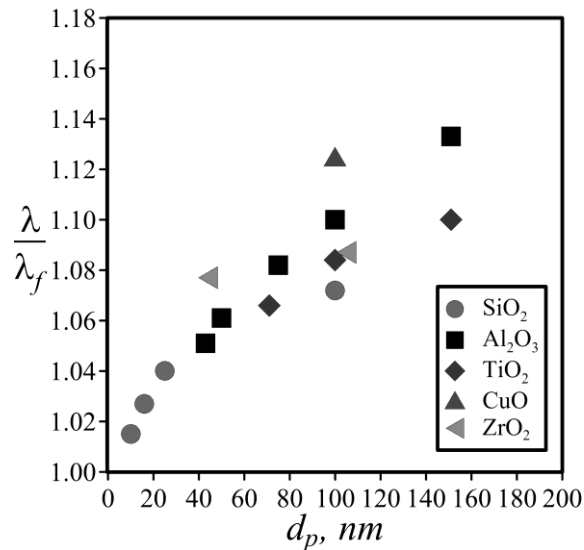

Figure 2. Relative thermal conductivity coefficients of nanofluids depending on nanoparticle size at volumetric concentration of 2%.

5. Dependence of thermal conductivity on the properties of the base fluid

To date, just a few works are known, where the effect of base fluid properties on nanofluid thermal conductivity was studied. This was first done in [11], which deals with nanofluids based on water, ethylene glycol, vacuum pump oil, and engine oil. It was noted that the highest thermal conductivity of the nanofluid was revealed in ethylene glycol based nanofluids. Later, the influence of the base fluid was studied by Xie and colleagues [12]. They developed a method to create a stable nanofluids, based on deionized water, ethylene glycol, and decene with multiwalled carbon nanotubes. It was found that the thermal conductivity coefficient enhancement decreases with increasing thermal conductivity of the base fluid. This conclusion is not consistent with the data presented in work [11], though, certainly, the studied nanofluids were quite specific. Therefore, it was extremely important to test the applicability of this conclusion with regard to the conventional nanofluids.

The complexity of studying the effects of the thermal conductivity of the base fluid on the thermal properties of nanofluids consists in the necessity to compare the data, at least of two nanofluids with the same concentration of nanoparticles and their size, though different base fluids. In the present work, the measurement series was carried out with nanofluids based on water and ethylene glycol, containing TiO_2 particles 150 nm in size. The data obtained differ systematically, though not much (see figure 3). In all cases, thermal conductivity enhancement of ethylene glycol based nanofluids is higher than that of water based nanofluids. At that, thermal conductivity coefficient of water is almost two and a half times higher than that of ethylene glycol.
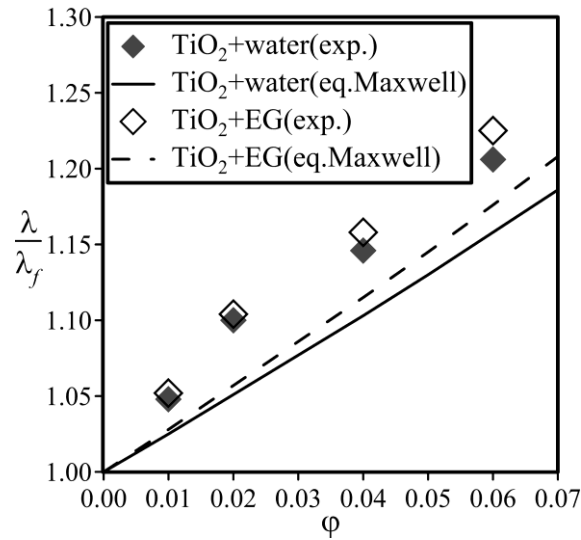
Figure 3. Relative thermal conductivity coefficient of water and ethylene glycol based nanofluids depending on TiO_2 particle concentration.

6. Conclusion

First of all, it should be noted that the nanofluid thermal conductivity is not described by the classical theories, including the Maxwell theory (equation (1)) for coarse fluids. The main difference is that the nanofluid thermal conductivity coefficient is a complicated function not only of the particle concentration, but also the particle size, material, and type of base fluid.

Measured thermal conductivity coefficients almost always exceed the values calculated by equation (1), though nanofluids with sufficiently small particles may have thermal conductivity coefficients even lower than those predicted by the Maxwell theory. However, in all cases, the nanofluid thermal conductivity coefficient enhances with increasing particle size. Starting with a certain particle size, the measured nanofluid thermal conductivity coefficients exceed the values predicted by classical theories (in particular, by equation (1)).

By definition, nanoparticles are particles sized from 1 to 100 nm. In the present work we studied the thermal conductivity of both nanofluids and dispersed fluids with larger particles. At that, in all cases we observed a monotonic enhancement of thermal conductivity with increasing particle size. However, as already mentioned, noted enhancement of thermal conductivity coefficient with increase in particle size cannot be unlimited. Determining the nature of dependence of the thermal conductivity coefficient in dispersed fluids on size of the particles larger than 100 nm requires further systematic study.

The base liquid also significantly influences the effective thermal conductivity of the nanofluid. In this work we have confirmed that the lower the thermal conductivity of the base fluid, the higher the relative thermal conductivity coefficient of the nanofluid. This is quite naturally explained by the fact that in the base fluid with the highest thermal conductivity the enhancement of thermal conductivity is weaker, at other conditions being equal. This, in particular, means that the supplement of the nanoparticles into the fluid will be most effective for the base fluid with low thermal conductivity. Nevertheless, the effect of base fluid properties on the effective thermal conductivity of nanofluid is still poorly studied.

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