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A Critical Analysis of the Hot-wire Technique for Thermal Conductivity Measurements of Thermal Nanofluids

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Nanofluids (liquid mixtures with a small concentration of nanoparticles in suspension) have unique properties that make them potentially useful for heat transfer applications. Ceramic and carbon-based nanoparticles as well as nano-sized free metals and metal oxides exhibit good thermal conductivities and heat capacities. When suspended in a carrier fluid (usually with the aid of a dispersant), these materials may potentially improve the heat transfer characteristics of the carrier. The hot-wire technique is a well-developed and widely accepted method for measuring the thermal conductivity of a fluid. The aims of this work were to validate the accuracy of the hot-wire technique for thermal conductivity measurements of metal oxide nanofluids and to determine if the magnetic field that is induced by the current running through the wire influences the measured thermal conductivity. A 3D printed hot-wire cell was used for the experiments. The metal oxide nanoparticles tested were copper oxide and magnetite. The nanofluids were tested at weight loadings of 0.5 %, 1.0 % and 1.5 % and temperatures of 25 ˚C, 30 ˚C and 35 ˚C. To determine the effect of the magnetic field on the measured thermal conductivity additional control experiments were conducted using a double pipe apparatus, using distilled water as a validation medium. The results for the metal oxide nanofluids showed an expected increase in thermal conductivity with temperature and weight percentage of nanoparticles. There was a consistent positive bias in the measurement of the thermal conductivity using the hot-wire cell. Since this consistent bias was present for both the copper oxide (which was diamagnetic) and the magnetite (which was ferromagnetic) it was concluded that the magnetic field induced by the hot-wire was not of a high enough intensity to affect the measured thermal conductivity of the magnetite nanofluids.

1. Introduction

Single phase heat transfer fluids are used extensively in chemical processing plants, in large-scale manufacturing and power generation (Sundar et al., 2017), as well as in niche areas such as automotive applications (Wong and Leon, 2010). These fluids are characterized by relatively poor thermal properties, which translate into poor heat transfer performance. In particular the low thermal conductivity of the fluids impacts negatively on the overall heat transfer in many of these applications (Leong et al., 2017). It is well established that solid materials, particularly metals, have superior heat transfer characteristics. The introduction of both metallic and non-metallic solid microparticles into various heat transfer fluids was observed to improve the overall heat transfer characteristics of the fluids, at the expense of increased erosion and clogging of the heat transfer systems (Tawfik, 2017). These drawbacks were eventually overcome with the development of nanofluids, suspensions of nano-sized metallic and non-metallic particles in a base fluid. The nanofluids offer improved stability, lower erosion rates and significantly better heat transfer performance (Alirezaie et al., 2018). One of the key characteristics of thermal nanofluids is their relatively higher thermal conductivity compared to the base fluids (Tawfik, 2017). In order to establish whether a particular nanofluid can be used as an effective heat transfer medium, the accurate measurement of thermal conductivity is required. Various transient techniques can be used, which include the hot-wire method (Yoo et al., 2007), temperature oscillation method (Czarnetzki and Roetzel, 1995), and 3-ω method (Paul et al., 2010). The hot-wire method is the most common technique employed, since it is relatively simple to carry out and is inexpensive (Tawfik, 2017). A hot-wire cell apparatus consists of a vertical cylinder with a wire running through the centre. Platinum is usually selected as the material for the wire as its resistance/temperature relationship is a linear function, a key parameter that

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allows for simple measurement of temperature changes (Ranjbarzadeh et al., 2019). A current is passed through this wire which generates a constant heat flux. The potential difference across the hot-wire cell is then measured this potential difference is related to the resistance in the wire, which is in turn related to the temperature. By performing an overall energy balance over the system, the thermal conductivity can be determined. Using this technique, the thermal conductivity of a wide variety of thermal nanofluids has been measured (Gupta et al., 2018). Doganay et al. (2019) have shown that the thermal conductivity of magnetic nanofluids, e.g. magnetite-water suspensions, are significantly altered by the action of an external magnetic field. According to Oersted's law, a current flowing through an electric wire induces a magnetic field. The question of whether the magnetic field induced by the current-carrying wire in the hot-wire technique influences the measured thermal conductivity has not been addressed in the open literature. In this work, the thermal conductivity of metal oxide nanoparticle suspensions containing diamagnetic (copper oxide) and ferromagnetic (magnetite) materials were measured using both the hot-wire method and a double-pipe apparatus, at various temperatures and nanoparticle loadings. These measurements were compared in order to quantity the influence of the induced magnetic field.

2. Experimental

2.1 Preparation of nanofluids

For the copper oxide nanoparticles, 50 g of copper shavings were dissolved in 175 ml of 75 % nitric acid (Merck) to produce a copper nitrate stock solution. 10 ml of Oleic acid (Sigma Aldrich) was added to the solution before dropwise addition of a 3 mol L-1 mixture of sodium hydroxide. The resultant copper hydroxide was filtered and placed in an oven to thermally oxidize to copper oxide at 185 °C overnight.

For the preparation of the magnetite nanoparticles, the co-precipitation technique was employed (Lokhat et al., 2015). This involved digesting iron shavings in hydrochloric acid to produce solutions of ferrous and ferric chloride. The solutions were combined in a 1:1 ratio (final volume approximately 32 ml), to which 13 ml of oleic acid was added before precipitation with a 3 mol L-1 mixture of sodium hydroxide. The iron hydroxide was filtered and placed in an oven to thermally oxidize to magnetite at 250 °C overnight.

The mineralogical content of the copper oxide and magnetite samples were confirmed by X-ray powder diffraction (XRD) measurements on a PANalytical Empyrean X-ray diffractometer with a Co Kα (1.789 Å) radiation source (40 kV, 45 mA). In the magnetite sample, distinct diffraction peaks corresponding to the Fe_3O_4 phase were observed. The average crystallite size for the magnetite sample, calculated using the diffraction data and the Scherrer equation, was 34 nm. The major phase present in the copper oxide sample was tenorite, confirming that the sample was in fact cupric oxide and had an average crystallite size of 33 nm.

The copper and magnetite nanoparticles were redispersed in water at various loadings under the action of an ultrasonic probe before the thermal conductivity tests.

2.2 Hot-wire apparatus for measurement of the thermal conductivity

A hot-wire cell was designed and fabricated according to the work of Alvarado et al. (2012). The hot-wire cell apparatus consisted of a copper tube 155 mm long with an inner diameter and wall thickness of 51 mm and 1.5 mm, respectively. This copper tube was sealed at the bottom by a welded copper plate 80 mm in diameter and 1 mm thick. Nickel wire (20 µm diameter) was threaded through a waterproofed PLA support structure that was designed on the SolidWorks (Dassault Systèmes) platform and 3D printed on a Wanhao 3D printer. The support structure allowed both ends of the wire to be accessed from the top of the cell and for only a well-defined length of the wire to be exposed to the fluid inside the cell, with the rest of it insulated. A PVC cap with tension screws was added to ensure that the wire could be drawn taut for the experiment. Figure 1 a shows the 3D printed support structure immersed in the test fluid and Figure 1 b shows the cell fully assembled before being placed in a constant temperature bath. A class A Pt100 temperature probe, connected to an Agilent data acquisition device, was placed inside the water bath to log the temperature. One end of the nickel wire was connected in series to a standard resistor. For this study a 220 Ω resistor was selected. The standard resistor was connected in series to a DC power supply. This power supply was then connected to the Agilent data acquisition module. The circuit was then completed by connecting the Agilent device to the other end of the nickel wire from the hot-wire cell. Using this arrangement the current in the system was measured. Other ports on the Agilent device were used to measure the potential difference across the standard resistor and the hot-wire cell.

2.3 Double-pipe apparatus for measurement of the thermal conductivity

The double-pipe apparatus was constructed from a copper pipe which was again sealed at one end using a copper plate. This cooper pipe had the same dimensions as that present in the hot-wire cell. The copper pipe was placed inside a PVC pipe of diameter 77 mm. The PVC and copper pipes were then bonded using PVC glue. The outside and bottom of the PVC pipe was then insulated using moulded polystyrene. A second temperature probe was connected to the Agilent data logger. A polystyrene cap was then constructed to insulate the top of the apparatus. Two holes were made in this cap to fit the two temperature probes. One temperature probe was place in the centre of the inner copper cylinder while the other was placed 65 mm from the centre in the annulus between cylinders. Each temperature probe was submerged at a depth of 50 mm from the top of the copper tube. Distilled water at 20 °C was placed in the annulus and the nanofluid at each of the investigated temperatures was placed in the central portion of the apparatus. The change in temperature of both fluids was measured as a function of time.

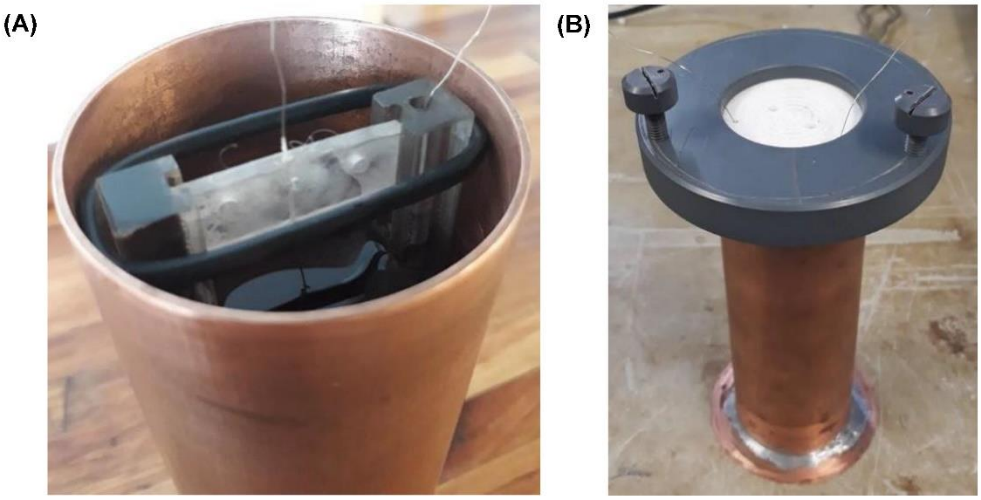

Figure 1: a) 3D printed support structure with nickel wire immersed in test fluid; b) fully assembled hot-wire cell

2.4 Determination of thermal conductivity using the hot-wire apparatus

This method uses transient heat flow to determine the thermal conductivity of a process fluid. In the transient method heat is transferred from a controlled heat source to a sample. The changes in heat dissipated are then observed and this is then used to determine the thermal properties as a function of time (Alvarado et al., 2012). The mathematical model developed for the hot-wire cell technique is shown by Eq. (1). This model considers the wire to be an infinitely long thin wire, with a linear geometry that act as a temperate sensor as well as a heat source. The temperature of the wire along its length is uniform. The wire is also assumed to be immersed in an infinite and homogeneous test fluid.

$$\Delta T(t) = \frac{q}{4\pi k}\ln\left(\frac{4t}{\tau C}\right) = \frac{q}{4\pi k}\ln\left(\frac{4t\alpha}{r^2 C}\right) \quad (1)$$

where ΔT is change in temperature at time t from the initial value, k is the thermal conductivity, q is the heat flow per unit length of the wire, r is the radius of the wire, α is the thermal diffusivity of the sample and ln C is Euler's constant (0.5772). The ratio $r^2/\alpha = \tau$ which should be much smaller than the period of measurement.
When a current is passed through the wire, the temperature and hence resistance change. This causes the potential difference across the hot-wire cell to vary over time. In accordance with Ohm's law, and assuming a linear relationship between the resistivity and temperature, the potential difference is given by Eq. (2):

$$V(t) = R(t)I = \left(R_0\left(1 + \theta\Delta T(t)\right)\right)I \quad (2)$$

where V is the potential difference and R is the resistance at time t, R_0 is the initial resistance, I is the current and θ is the temperature coefficient relating resistance to changes in temperature. By substituting Eq. (1) in (2) we obtain:

$$V(t) = IR_0\left(1 + \theta\,\frac{q}{4\pi k}\ln\left(\frac{4t}{\tau C}\right)\right) \quad (3)$$

The heat flow can be related to the resistance, current and length of wire L, according to Eq. (4):

$$q = \frac{I^2 R}{L} \quad (4)$$

Eq. (3) can be reduced to the simple linear relationship between the voltage over the hot-wire cell and the natural logarithm of time, as shown in Eq. (5). This relationship can be exploited through linear regression to obtain the thermal conductivity from transient measurements of voltage.

$$\Delta V(t) = m\,ln(t) + B \tag{5}$$

2.5 Determination of thermal conductivity using the double-pipe apparatus

A transient model of the heat transfer occurring in the double-pipe apparatus was used to determine the value of the thermal conductivity. The model assumed that there was no heat loss to the surroundings, the fluids were stationary and convective heat transfer effects were not present, there was no heat generation in the system and the low thermal resistivity of the copper cylinder meant that conductive resistance to heat transfer could be ignored. The resultant balance is shown in Eq. (6):

$$Q = \rho_1 C_{p1} V_1 \frac{dT_1}{dt} = -\rho_2 C_{p2} V_2 \frac{dT_2}{dt} \tag{6}$$

where Q is the heat transferred, C_p is heat capacity, ρ is the density and V is the volume of fluid 1 and 2. Integrating both sides of the expression from initial temperatures T_1^0 *and* T_2^0 to T_1 and T_2 respectively, and thereafter eliminating T_2 gives:

$$(\rho_1 C_{p1} V_1)(\rho_2 C_{p2} V_2) \frac{dT_1}{dt} = hA(\rho_2 C_{p2} V_2 T_2^0 + \rho_1 C_{p1} V_1 T_1^0 - (\rho_1 C_{p1} V_1 + \rho_2 C_{p2} V_2) T_1 \tag{7}$$

where h is the heat transfer coefficient and A is the heat transfer area. The relationship between the initial temperatures and the final equilibrium temperature (T_{inf}) can be obtained by solution of the steady-state version of Eq. (6):

$$T_{\text{inf}}(\rho_1 C_{p1} V_1 + \rho_2 C_{p2} V_2) = \rho_1 C_{p1} V_1 T_1^0 + \rho_2 C_{p2} V_2 T_2^0 \tag{8}$$

Substituting this result into Eq. (7), separating variables and integrating finally yields:

$$h = \frac{\ln\left(\frac{T_1 - T_{\text{inf}}}{T_1^0 - T_{\text{inf}}}\right)}{-\left(\frac{1}{(\rho_1 C_{p1} V_1} + \frac{1}{\rho_2 C_{p2} V_2}\right) At} \tag{9}$$

The value of the thermal conductivity can then be obtained by dividing the heat transfer coefficient by the length of the copper cylinder.

3. Results and discussion

The first set of experiments that were carried out on both the hot-wire cell and double-pipe apparatus were for distilled water. These were performed in order to validate both sets of experimental equipment. The results of these tests at three different temperatures (20, 30 and 35 °C) are shown in Figure 2. The hot-wire cell gave excellent agreement with the literature data, with a consistent negative bias of 1.25 % on average. The results of the double-pipe experiments were poorer, with an average negative deviation of 4.7 %, and may be due to some heat loss to the surroundings during the initial part of the experiment. However, the agreement was of satisfactory quality to make comparisons for the nanofluids.

Measurements of thermal conductivity for copper oxide based nanofluids were carried out using the hot-wire apparatus at the same three temperatures and at three loadings of nanoparticles (0.5, 1 and 1.5 wt %). As expected, increases in temperature and loading of the nanoparticles gave an improvement in the thermal conductivity of the fluid. A low loading of 0.5 wt % of copper oxide nanoparticles gave an average increase of 3 % in the thermal conductivity over the base fluid (distilled water) within the temperature range explored. Further increases in loading gave a marginal improvement in thermal conductivity. The results from the double-pipe apparatus were in qualitative agreement, as they also showed that increases in temperature and weight loading of nanoparticles improved the thermal conductivity of the base fluid. Interestingly, all the values of thermal conductivity obtained using the hot-wire apparatus were consistently greater than those obtained using the double-pipe apparatus, as was originally observed for the experiments using distilled water. Again, the suspected loss of heat to the surrounds, especially at the start of the experiment, is believed to be the cause of these lower reported values for the double-pipe apparatus.

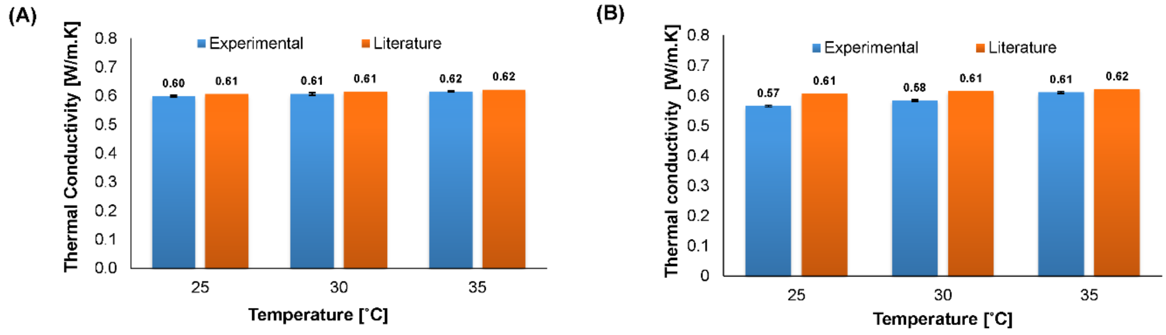

Figure 2: Thermal conductivity of distilled water using a) hot-wire apparatus b) double-pipe apparatus. Literature data from Castelli and Stanley (1974).

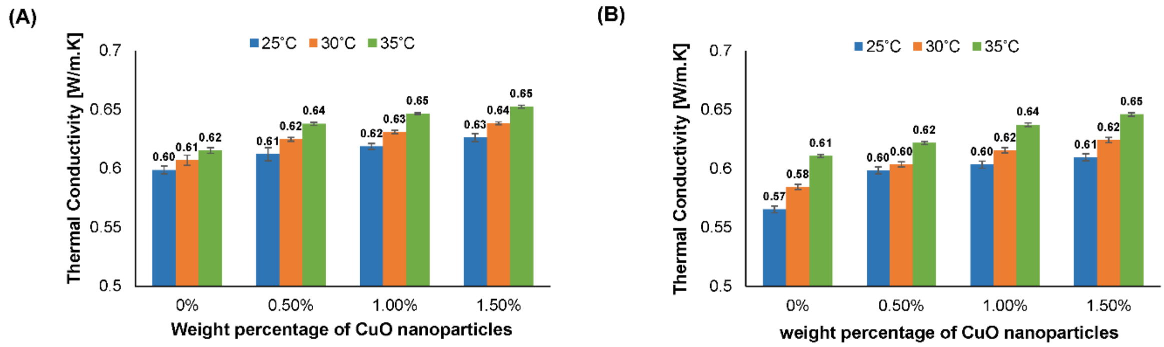

Figure 3: Thermal conductivity of CuO-based nanofluid using a) hot-wire apparatus b) double-pipe apparatus.

The results of thermal conductivity measurements for magnetite nanofluid using both the hot-wire cell and double-pipe apparatus are shown in Figure 4. Both temperature and nanoparticle loading had a beneficial effect on thermal conductivity. Comparing the results in Figures 2,3 and 4, the increase in thermal conductivity using magnetite nanofluid is comparable to that of copper oxide nanofluid (on average 3 %) at the low nanoparticle loadings employed in this work. Once again there was a consistent positive bias in the measurement of the thermal conductivity using the hot-wire cell, when compared to the double-pipe apparatus. In testing whether the induced magnetic field in the hot-wire apparatus significantly increases the thermal conductivity it is necessary to compare the results to the double-pipe apparatus. A direct comparison cannot be made due to the consistent positive bias in the hot-wire cell measurements. However, since this consistent bias was present for both the copper oxide (which is diamagnetic) and the magnetite (which is ferromagnetic) it can be concluded that the magnetic field induced by wire was not of a high enough intensity to affect the measured thermal conductivity of the magnetite nanofluids.

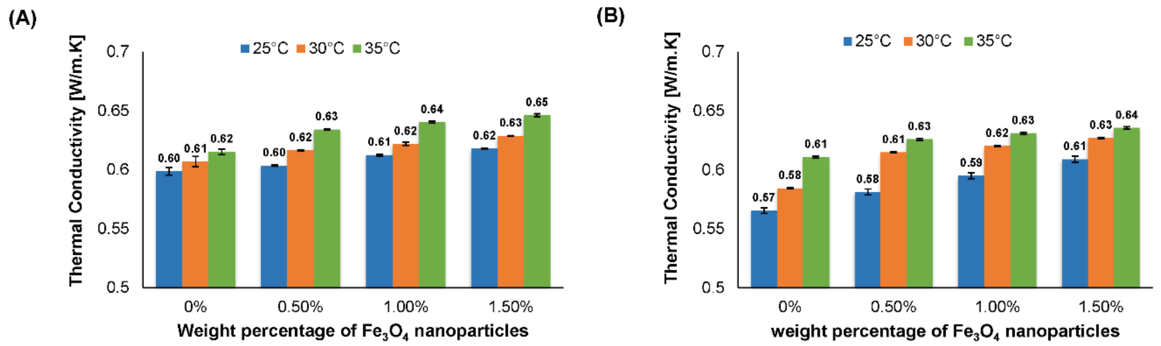

Figure 4: Thermal conductivity of Fe_3O_4-based nanofluid using a) hot-wire apparatus b) double-pipe apparatus.

4. Conclusions

The transient hot-wire technique is a popular method of measuring the thermal conductivity of nanofluids, one of the key parameters that affect its performance as a heat transfer medium. Some metal oxide nanomaterials that are used as the loading component in thermal nanofluids also exhibit strong magnetic properties. In the hot-wire apparatus, the current that flows through the high-resistance wire also induces a magnetic field within the test fluid and magnetic fields are known to enhance the thermal conductivity. In order to test whether the induced magnetic field in the hot-wire apparatus significantly increases the thermal conductivity of nanofluids, experiments were performed using both diamagnetic and ferromagnetic fluids (i.e. copper oxide and magnetite-based fluids, respectively) and using both a hot-wire cell and a double-pipe apparatus for the measurements. The performance of copper oxide and magnetite nanofluids were comparable at the low loadings employed this work. On average, a 3 % increase in thermal conductivity was observed when employing a 0.5 wt % loading of both CuO and Fe_3O_4 nanoparticles. The thermal conductivities obtained from measurements using the hot-wire cell were consistently higher than those obtained using the double-pipe apparatus, mainly due to heat losses at the start of the experiment for the latter. Taking into account this positive bias (averaging 1 % over the entire set of data for all fluids), the experimental errors (as indicated in the figures as error bars and averaging less than 1 %), as well as the fact that the bias was observed for both the diamagnetic and ferromagnetic fluids, it can be concluded that there was no significant increase in thermal conductivity for the magnetite nanofluid when employing the hot-wire technique.

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