Fabrication, Calibration and Testing of a Transient Hot-Wire Thermal Conductivity Apparatus for Nanosilica-in-Fluid Dispersion (Nanofluids)

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ABSTRACT

The field of nanotechnology is developing at an increasing rate, and studies have been focused in characterizing the properties of nanomaterials in order to further their applications. In this study, a Wheatstone bridge network was incorporated along with a thermal conductivity cell setup in order to determine the thermal conductivity of nanofluids with a certain degree of accuracy and precision. The Wheatstone bridge is balanced using a DC electronic load, and with the measured voltage output and resistance values, the temperature change of a platinum hot-wire is calculated using voltage divider rule. The slope of the temperature change with respect to time in the logarithmic scale is used to compute the thermal conductivity of the fluid. The fabricated apparatus is calibrated using distilled water, with the obtained percent error between measured and standard values ranging from 0.0019% to 1.015%. Further validation of the apparatus was done statistically, with the results supporting the accuracy of the fabricated apparatus. Finally, the apparatus was tested to determine the conductivity of several test fluids composed of ethylene glycol (EG), water and nanosilica (NS), and its precision was validated with repeated measurements on a specific nanofluid 25 EG, 75 H2O 0.25% NS.

Keywords: nanofluids, transient hot-wire, thermal conductivity, Wheatstone bridge

INTRODUCTION

Nanofluids are colloidal suspensions of nanoparticles in a base fluid such as ethylene glycol (EG), water (H_2O), or oil. These nanoparticles are usually made of metals, oxides, carbides, or carbon nanotubes and have at least one of their principal dimensions smaller than 100nm. Nanofluids are known and used for their enhanced thermo-physical properties which are thermal diffusivity, viscosity, convective heat transfer coefficient, and thermal conductivity (Dharmalingam et. al., 2014). However, inconsistencies in the results of different studies keep unresolved the true behavior of nanofluids (Ramires, 1994).

One of the thermal properties of nanofluids is thermal conductivity, defined as the ability of the material to conduct heat. Manipulating thermal conductivity on a nanoscale level would revolutionize how we tackle engineering areas such as the automotive industry, bio-medical technology, power plant cooling systems, and computer technology among others (Codreanu et al., 2006).

Thermal conductivity cannot be directly measured by any instruments and thus, different methods of obtaining the thermal conductivity of the nanofluids were developed. The classical model points to Maxwell's mean-field theory, wherein the effective thermal conductivity is estimated by combining a set of well-dispersed "spheres" into one equivalent sphere. The theory follows that the thermal conductivity of a nanofluid is given by the ratio of nanoparticle volume fraction and the difference of the thermal conductivity of the nanoparticle and the base fluid (Eapen et. al., 2008).

The classical model, however, was not able to sufficiently justify the enhanced thermal conductivity of nanofluids (Tillman and Hill, 2006), leading to the development of further techniques to determine the thermal conductivity of nanofluids. Most methods incorporate the use of hot-wire, specifically: (1) vertical, single wire, hot-wire method; (2) the horizontal, single wire, hot-wire method; (3) the two wire, hot-wire method; and (4) the transient hot-wire method.

Among the four methods, the transient hot-wire method has the advantage of simplicity and comparatively economical in assembly than by other methods (Kostic and Simham, 2009). The basic concept of the method uses a wire as both the heat source of the fluid and the temperature sensor, while incorporating a Wheatstone bridge. The measurement of the thermal property is attained by using a medium's (a platinum wire) resistance and its proportionality to temperature, which is then implemented to a bridge circuit using voltage divider rule as calibrator.

This study aimed to fabricate and test a transient hot-wire apparatus that would determine an accurate thermal conductivity of a fluid. Specifically, it aimed to design the Wheatstone bridge circuit and a transient hot-wire cell for the thermal conductivity apparatus, calibrate the apparatus with respect to a fluid with known thermal conductivity, and test the apparatus by determining the thermal conductivities of base fluids and nanofluids.

METHODOLOGY

The study closely followed the development of the transient hot-wire method as studied by Reddy and Rao (2013) and Kostic and Simham (2009) for measuring the thermal conductivity of a fluid. This section is divided into two major parts, the construction and testing of the thermal conductivity apparatus.

Transient Hot-Wire Method

The transient hot-wire method is comprised of the following: Wheatstone bridge circuit, an insulated platinum wire as the hot-wire, thermocouples for temperature measurements, and voltage measuring devices (Hammerschmidt, 2000). This is the most widely used method because of its static and linear-source technique in determining thermal conductivity.

The hot-wire could be any metal, however previous studies such as that of Kostic (2009) have suggested the use of platinum, for the following reasons: (1) it is a noble metal; (2) its thermophysical properties can handle temperatures up to 200^{o}C without breaking or deforming, (3) it is highly resistant to corrosion, (4) it is one of the least reactive metals, and (5) its change of resistance remains linear over the temperature range.

The hot-wire must have an insulating coating applied in order to prevent the induced current from spreading through the fluid it is submerged it. A previous study by Yu, Wenhua and Choi (2006) suggested polytetrafluoroethylene, more commonly known as Teflon, due to its high heat resistance. In addition, it is also an electrical insulator, and can serve as protection from physical scratching.

Wheatstone bridge

The Wheatstone bridge is the electrical foundation of the thermal conductivity apparatus. It consists of four resistive elements arranged in a bridge network. Following the transient hot-wire method described in the previous section, platinum wire was chosen as the sensor for the thermal conductivity apparatus, and is one of the four resistive elements of the Wheatstone bridge. Any changes in the temperature would lead into corresponding changes in the resistance of the platinum wire.

The Wheatstone bridge must be balanced at all times, hence during calibration it is desired to have an adjustable resistive element to facilitate said balance. For this study, A BK Precision 8540 150-W DC electronic load is used as the second resistance of the bridge.

A carbon resistor and a power resistor were used to complete the rest of the resistances in the Wheatstone bridge circuit. The power resistor was selected as it can maintain its resistance despite the effects of heat on the bridge circuit.

Working Equations

The following equations from the study by Kostic and Simham (2009) were used to determine the resistance across the platinum wire at a given instant in time:

$$R_{WT} = \frac{R_3\left[R_1 + (R_1 + R_2)(V_{OUT} / V_{IN})\right]}{\left[R_2 - (R_1 + R_2)(V_{OUT} / V_{IN})\right]}$$

Equation 1

Where R_{WT} is the resistance across the platinum wire, R_1, R_2, and R_3 are the resistances (in ohms) as shown in Figure 1, and the voltage levels V_{IN} and V_{OUT} are the input and output voltages as measured from the test circuit, respectively.

The resistance R_{WT} is then carried over to compute the voltage (in volts) across the platinum wire, using Equation 2.

$$V_{WT} = \frac{V_{IN} R_{WT}}{R_{WT} + R_3}$$

Equation 2

The heat flux per length, ***q***, is then computed using the results of Equation 2.

$$q = \frac{(V_{WT})^2}{L_W R_{WT}}$$

Equation 3

In equation 3, L_w is the length of the platinum wire (meters).

The change in temperature, and finally, the thermal conductivity, is calculated using Equations 4 and 5, as shown below:

$$\Delta T = \frac{\Delta R_{WT}}{R_{Wo}\sigma}$$

Equation 4

$$k_f = \frac{q}{4\pi} \frac{d \ln(t)}{d\Delta T}$$

Equation 5

Where, in Equation 4, R_{wo} is the initial resistance of the platinum wire (ohms), σ is a constant equal to 0.02656, and ΔT is the change in temperature. Equation 5 computes the thermal conductivity, k_f, introducing the natural logarithm of time as well as the heat flux per length determined from Equation 3.

Fabrication of Thermal Conductivity Cell

The thermal conductivity cell - also the fluid reservoir - must be designed such that the amount of fluid sample it holds is both large enough to obtain the fluid characteristics, yet small enough such that it only needs a small amount of heating power from the platinum wire to change its temperature.

The basis of the working equations in the previous section is Fourier's law for one-dimensional radial transient conduction with a line heat source at the axis of the cylindrical domain. Hence, the heat source must also be placed in the center of a cylindrical reservoir.

The hot-wire cell design is also based on the cell proposed in the study of Kostic and Simham (2009), and adjusted to fit market availability. The entire cell was constructed by the Metals Industry Research and Development Center of the Department of Science and Technology in Taguig, Philippines.

The half-pipe, which holds the platinum wire and separates the fluid from the electrical wirings, is shown in Figure 1. Holes for thermocouples are drilled at the top 75° to the right of the platinum wire, and at the bottom 15° to the left of the wire. The actual diameter used for the half pipe is 1 inch.

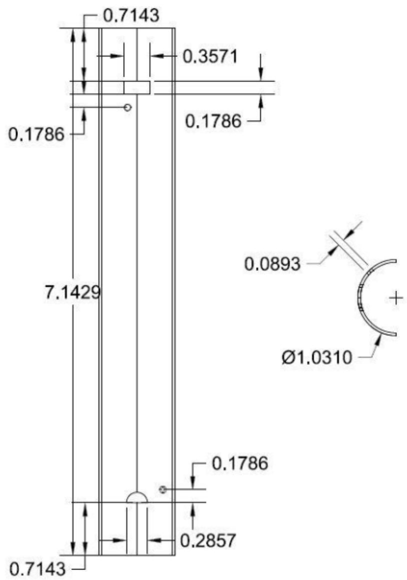

Figure 1. Half-pipe dimensions

Two identical off-centered alignment rings are attached to the top and bottom of the half-pipe. These are used to fasten the off-centered half pipe while also leaving space for the electrical wiring.

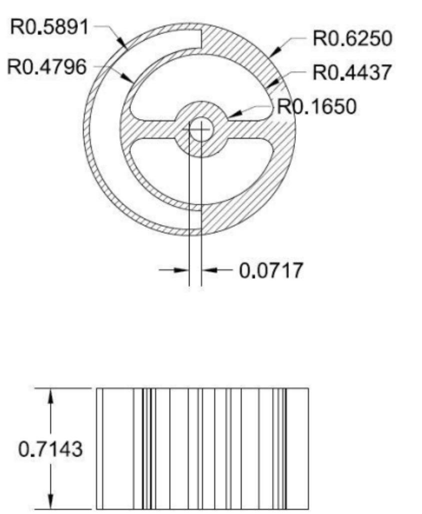

Figure 2. Alignment ring dimensions

The rings are made of a solid stainless steel shaft. Its actual diameter is 1.25 inches. As seen in Figure 2, there is an opening in the left side for the electrical wiring, in the off-center to provide a visual of the fluid, and in the center for the pin which holds the hot wire. The cell base is a 2-inch diameter solid stainless steel shaft welded to a steel stand.

The platinum wire used has a diameter if 76µm. To keep the current in the wire from dispersing through the fluid sample, the wire must be insulated. The temperature rise will be taken over logarithmic time at large time values, because doing so will minimize measurement errors due to insulation (Yu et al., 2006). The wire was insulated using high heat resistant Teflon spray.

Data Gathering, Calibration and Verification

The temperature across the hot-wire was determined using its current resistance. Changes in resistance disturb the balance of the Wheatstone bridge, producing an output voltage which is proportional to the resistance. Therefore data gathering was done using a device which can measure voltage in a given period. A digital power meter was used for this purpose.

The resistance across the hot-wire can be determined from the output voltage using Wheatstone bridge equations. Using the solved resistance, one can solve for the voltage across the hot-wire, and the resulting heat flux and change in temperature due to it.

The temperature conductivity of distilled water was tested. The initial temperature was at 30°C, and the input voltage was switched to 10V. The output voltage is measured and sampled every second. This process is repeated at temperatures 40°C, 50°C, 60°C, 70°C. The corresponding output values were calculated and plotted over logarithmic time, and the slope of the curve is acquired in order to compute for thermal conductivity. The computed value was compared to the standard value of thermal conductivity for distilled water. If the percent error is less than 5%, the setup is concluded to be reliable.

The summarized values of the calibration test were also subjected to statistical verification via ANOVA F-Test, with the null hypothesis "*Ho: there is no systematic relationship between the measured and standard thermal conductivity values*".

Determination of nanofluid thermal conductivity

Once the test apparatus had been calibrated with the test fluid, the same process of testing was applied to three test fluids and nine nanofluids, each with a unique combination of ethylene glycol (EG), water (H_2O) and nanosilica (NS) for the nanofluids.

The results were tabulated and trends were investigated for the different nanofluids tested. A precision test was also performed on one nanofluid to check for the consistency of the determined thermal conductivities.

RESULTS AND DISCUSSION

The results section is divided into the following sections: (1) fabricated thermal conductivity apparatus; (2) calibration of apparatus; and (3) reference thermal conductivity measurements.

Thermal Conductivity Apparatus

The schematic diagram of the completed transient hot-wire thermal conductivity apparatus is shown in Figure 3.

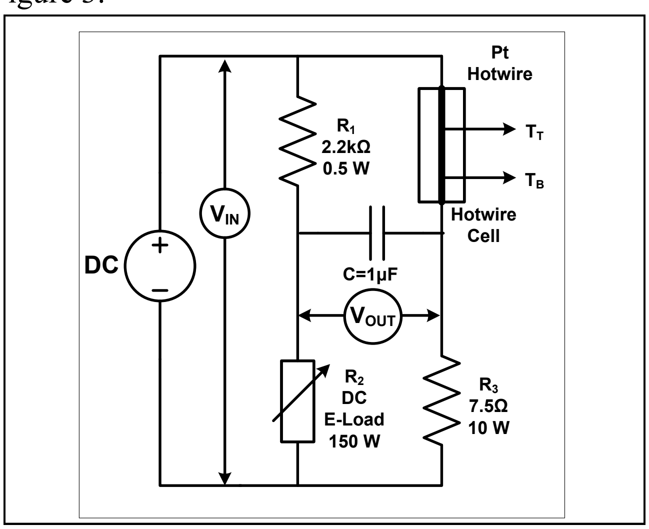

Figure 3. Schematic diagram of the thermal conductivity measurement apparatus.

The Wheatstone bridge was completed using two constant resistors, a ½-Watt, 2.2 kΩ carbon resistor, and the other one a 10-Watt, 7.5Ω power resistor. The other two components consisted of the variable resistance, provided by a 150-Watt DC electronic load, and the platinum hotwire contained in its fabricated cell. Measurements V_{in} and V_{out} were taken using a voltmeter and a digital power meter, respectively, while temperatures T_T and T_B were taken using a T-type thermocouple and a digital thermometer, respectively. A capacitor was connected across the bridge to act as a low-pass filter for the bridge output.

The fabricated hotwire cell is shown in Figures 4 and 5, in both assembled and disassembled form. After considering the merits of the available insulation coating materials, the selected coating was Teflon spray paint.

Figure 4. Disassembled hotwire cell.

Calibration of Test Apparatus

The test apparatus was then calibrated using distilled water as a test fluid. The thermal conductivity obtained from the measurement of the apparatus and the standard thermal conductivity of distilled water were taken, and the percent error was computed.

Table 1 presents the summary of the obtained thermal conductivities, from T=30°C to T=70°C in increments of 10°C. The values obtained for the test apparatus are the average of two experimental runs, while the values of the standard thermal conductivity of water were taken from the standard reference data for thermal conductivity of water, by Ramires et al.

The values at Table 1 reveal that the maximum percent error obtained is at 60°C, equivalent to 1.0149%, and the smallest percent error at 70°C, just over one-thousandths of a percent.

The summarized values were also subjected to statistical verification via ANOVA F-Test, with the null hypothesis *"Ho: there is no systematic relationship between the measured and standard k_f values"*. The results of the ANOVA F-Test are shown in Table 2.

The results of Table 2 allow the conclusion that the values measured from the test apparatus are reliably close to the standard values; hence the setup is concluded valid.

Thermal Conductivity Measurements using Test Apparatus

With the thermal conductivity apparatus calibrated and validated, the apparatus was then used to perform thermal conductivity measurements of various base fluids and nanofluids.

Each fluid's thermal conductivity was calculated from the results of the test apparatus, at three different temperature levels: 30°C, 50°C, and 70°C. Results were then compared to established trends regarding the behavior of nanofluids at said temperature variations, as well as with respect to changing the concentrations of ethylene glycol (EG), hydrogen oxide/water (H_2O), and the percent nanosilica (%NS). Table 3 summarizes the test results.

The results presented in Table 3 indicate that a higher EG content in the base fluid lowers the thermal conductivity. Meanwhile, for the same amounts of EG and H_2O content, increasing the concentration of nanosilica also increased the thermal conductivity of the nanofluid.

With respect to temperature, all nanofluids exhibited increased thermal conductivity with increasing

Table 1. Summary of standard and calculated thermal conductivities.

TEMPERATURE, °C	TEST k_f, W/m°C	STANDARD k_f, W/m°C	% ERROR (%)
30	0.612635	0.61440	0.2872
40	0.632164	0.62940	0.4391
50	0.647999	0.64281	0.8073
60	0.659345	0.65272	1.0149
70	0.660947	0.66096	0.0019

Table 2. ANOVA F-test results.

	Test k_f values	Standard k_f values
Mean	0.640058	0.642618
Variance	0.00034418	0.000413
# of Observations	5	5
df	4	4
F	0.832883064	
P(F≤f), one-tail	0.43180668	
$F_{Critical}$, one-tail	0.156537812	

Figure 5. Assembled hotwire cell.

temperature, maintaining the trend that has been established during the calibration of the test setup with distilled water.

Thermal Conductivity Measurements: Precision of Measurement

Among the 12 nanofluids, the nanofluid 25 EG: 75 H_2O, 0.25% NS was subjected to repeated tests in order to verify the precision of the thermal conductivity apparatus.

Table 4 summarizes five test runs of measurements for the thermal conductivity of 25 EG: 75 H_2O and 0.25% NS at the same three different temperature points: 30°C, 50°C, and 70°C to check for the consistency of the test apparatus' measurements.

Each test run as shown in Table 4 verifies the same trend regarding the proportionality of thermal conductivity with temperature. In addition, the average of the five test runs maintained the same trend. The standard deviations at the three temperature points also show the precision of the test apparatus.

Table 3. Summary of thermal conductivities of various nanofluids, using the thermal conductivity apparatus.

NANOFLUID	THERMAL CONDUCTIVITY (W/m°C)		
	30°C	50°C	70°C
25 EG: 75 H_2O	0.3716	0.3731	0.3752
50 EG: 50 H_2O	0.3386	0.3494	0.3592
75 EG: 25 H_2O	0.3162	0.2757	0.2335
25 EG: 75 H_2O 0.25% NS	0.4225	0.4459	0.4504
25 EG: 75 H_2O 0.25% NS	0.4444	0.4586	0.4777
25 EG: 75 H_2O 0.25% NS	0.4724	0.4858	0.5024
25 EG: 75 H_2O 0.25% NS	0.3996	0.4112	0.4317
25 EG: 75 H_2O 0.25% NS	0.3785	0.3819	0.3843
25 EG: 75 H_2O 0.25% NS	0.4236	0.4327	0.4419
25 EG: 75 H_2O 0.25% NS	0.3007	0.3157	0.3517
25 EG: 75 H_2O 0.25% NS	0.3282	0.3425	0.3613
25 EG: 75 H_2O 0.25% NS	0.3621	0.3825	0.3999

CONCLUSION

In this study, an apparatus for measuring the thermal conductivity of various nanofluids was developed, fabricated, and tested for reliability and precision. The fabricated apparatus consists of three main elements: a Wheatstone bridge network, a thermal conductivity cell for holding the nanofluid, and a platinum wire within the thermal conductivity cell.

Table 4. Test summary of thermal conductivity measurements for nanofluid 25 EG, 75 H_2O 0.25% NS

TEST #	THERMAL CONDUCTIVITY (W/m°C)		
	30°C	50°C	70°C
1	0.4225	0.4459	0.4504
2	0.4242	0.4439	04605
3	0.4187	0.4322	0.4522
4	0.4278	0.4398	0.4528
5	0.4213	0.4488	0.4474
Average	0.4229	0.4422	0.4526
St. Dev	0.0034	0.0058	0.0043

The Wheatstone bridge circuit's four resistances were as follows: (1) a carbon resistor with a rated resistance of 2.2kΩ and actual measured resistance of 2.234 kΩ; (2) a power resistor with a value of 7.5Ω, a DC electronic load as a variable resistance, and (4) the platinum wire to serve as the heat source to the nanofluid sample.

The platinum wire has a length of 0.11 m and thickness of 0.76 µm, stationed inside its fabricated thermal conductivity cell. The thermal conductivity cell is coated with Teflon spray paint to serve as insulation. In addition, the thermal conductivity cell was based from a previous study by Kostic &

Simham, and adjusted to fit the market availability of materials. The final design of the cell was made of stainless steel and is cylindrical, with a half-pipe holder for separation of the fluid from the electrical connections, while allowing space for thermocouple placements.

The fabricated test apparatus was successfully calibrated with distilled water as the test fluid, with validation coming from the standard thermal conductivity of distilled water at five different temperatures, as well as the results of the ANOVA F-test.

The test apparatus was also determined to be precise with consistent measurements performed on a specific nanofluid, and was also tested to determine the thermal conductivities of 3 base fluids and nine nanofluids. It was established that the thermal conductivity increases with temperature and the addition, of increasing concentrations of nanosilica.

RECOMMENDATIONS

While the minimum objectives of the study were met, there is a need for further testing of the device to get more conclusive results. Also, there are several steps that can be taken to further enhance the results of the study aside from:

Increased Repetitions for Nanofluids

The test apparatus proved precise given 5 replicates for a test nanofluid. Increasing repetitions for other nanofluids could further establish the reliability of the test apparatus, or provide a range of nanofluid concentrations where yielded measurements are reliable.

Automation of Data Collection

Data gathering during the course of the study proved tedious due to the available equipment. Given the opportunity, automation of the data collection can be implemented for further testing in order to increase the sampling rate of the required values, thus improving the slope of the ΔT - $\ln(t)$ graphs needed in the course of computing the thermal conductivity.

Test Apparatus Construction Improvement

The fabricated cell used Teflon spray paint due to the limitations on availability. While it yielded successful results, Teflon spray coating is still the ideal protection medium. Finally, the ceramic power resistor used in the Wheatstone bridge can also be replaced by a 25-Watt power resistor for increased durability.

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