CHAPTER 4

THERMAL CONDUCTIVITY AND VISCOSITY MEASUREMENTS

4.1 INTRODUCTION

In the development of any energy-efficient heat transfer fluids for enhanced heat transfer performance, in practical applications, a detailed study of the thermo-physical properties such as thermal conductivity, viscosity, density and heat capacity, is necessary. The nanofluids’ thermo-physical properties, such as thermal conductivity and dynamic viscosity are of great importance in every heat transfer application involving a fluid system. Improving the thermo-physical properties is the key idea to improve the heat transfer characteristics of conventional fluids. This chapter deals with the experimental techniques, working principle, measurement devices and the actual experimental procedure for measuring the thermal conductivity and viscosity of silver/water nanofluids.

4.2 THERMAL CONDUCTIVITY MEASUREMENT

The thermal conductivity of nanofluids is an important transport property in practical heat transfer applications. Generally, there are two types of methods for measuring the thermal conductivity of any liquids: the steady state method and the transient method. In the present study, the transient hot-wire method is used for measuring the thermal conductivity of silver/water nanofluids. This method was first introduced by Nagaska and Nagashima (1981). This method is preferred because of its accuracy, speed and ability to
minimize the effects due to natural convection. This method, however, is normally restricted to electrically non-conducting fluids such as noble gases and organic liquids. Nanofluids are electrically conducting fluids. Thus, the Nagaska and Nagashima technique is modified, in which a platinum wire is coated with a thin electrical insulation layer, instead of a bare wire to measure the thermal conductivity of nanofluids. Hence, in the present study, the transient hot-wire (Teflon coated platinum wire) technique is used for measuring the thermal conductivity of silver/water nanofluids.

### 4.2.1 Transient hot-wire method

The transient hot wire method is the most appropriate and widely used method to measure the thermal conductivity of liquids. In this method, a thin platinum wire is used both as a line heat source and as a temperature sensor. The wire is surrounded by the liquid (nanofluid) whose thermal conductivity is to be measured. The wire is then heated by sending electrical current through it. Now, the higher the thermal conductivity of the surrounding liquid, the lower will be the temperature rise of the wire. This principle is used to measure the thermal conductivity. This experiment lasts for a maximum of up to 4 seconds and eliminates the effects of natural convection; hence, it is very fast and accurate. This method is called transient because heat is supplied suddenly, and the readings are taken before reaching steady state when natural convection currents get set. The working equation is based on a specific solution of Fourier’s law for radial (one dimensional) transient heat conduction with a line heat source at the axis of the cylindrical domain. From the solution presented by Carslaw and Jaeger (1967), the temperature distribution equation for a line heat source is obtained by integrating it over the radial (r) direction from hot-wire radius (assumed zero) using r-zero and r-infinity boundary conditions and is given in equation 4.1. The infinite-series solution is then approximated with the first term only since the higher order terms virtually vanish after short initial transiency period.
\[ T = \frac{q}{4\pi k} \ln \frac{4kt}{r^2 \rho c_p} - \frac{\gamma q}{4\pi k} \]  

(4.1)

where, \( \gamma \) is the Euler’s constant, \( q \) = the heat liberated per unit time per unit length of the line source in W/m and \( k_f = \) the conductivity of the liquid in Wm\(^{-1}\)K\(^{-1}\). If temperatures of the heat source at time \( t_1 \) and \( t_2 \) are \( T_1 \) and \( T_2 \) respectively, then putting these conditions in equation (4.1) gives the conductivity of the liquid (nanofluid) as:

\[ k_N = \frac{q}{4\pi(T_2 - T_1)} \ln \frac{t_2}{t_1} \]  

(4.2)

### 4.2.2 Transient hot wire apparatus

A schematic diagram of the typical transient hot-wire apparatus, made for measuring the thermal conductivity of the silver/water nanofluid is shown in Figure 4.1. A platinum wire is placed along the axis of a glass container, which is filled with the silver/water nanofluid whose thermal conductivity is to be measured. As the wire is to be used for both heating and temperature sensing, a platinum wire is chosen, since platinum has stable (noble) thermo-physical properties. Also, it has a temperature coefficient of resistance which is much higher than that of the other metals. It is an ideal metal for temperature sensing because of its resistance change being linear over a large temperature range. In the measurement, the platinum wire is to be used as a line heat source. Hence, the wire diameter is usually kept within 100 µm (Das et al 2007). Therefore a platinum wire of 75 µm diameter is used in the present study. Teflon spray is used for easy and convenient coating of the platinum wire to act as an electric insulation. The thickness of the coating on the wire is estimated to be around 7.5 µm. The length of the wire chosen is 150 mm, representing an infinitely long line heat source, assuring one directional (radial) heat transfer.
Figure 4.1 Schematic diagram of the transient hot-wire apparatus

The main experimental cell which is shown in Figure 4.2 is actually a part of the Wheatstone bridge circuit since the wire (hot-wire) is used as one arm of the bridge circuit. In the bridge $R_1$ and $R_2$ are the fixed resistors having 1000 $\Omega$ and 15 $\Omega$ resistance; and $R_3$ is the variable resistor with a maximum of 1000 $\Omega$ resistance connected to the Wheatstone bridge circuit; and $R_w$ is the resistance of the wire which is to be measured. A 100 ml glass tube having a cylindrical cavity of 2.9 cm diameter and 23 cm length, is used as the nanofluid container, which is filled with silver/water nanofluid whose thermal conductivity is to be measured. The dimensions of the cylinder and wire are selected based on the study reported by Das et al (2008). The Platinum wire is placed at the center of the nanofluid container kept inside a constant temperature cylindrical water bath. The bath is 17.5 cm in diameter and 24.5 cm long. The constant temperature bath consists of a heater, a stirrer and temperature sensors to ensure that constant temperature is maintained inside. The constant temperature bath is thermally insulated. A photographic view of the transient hot-wire experimental apparatus is shown in Figure 4.3.
Figure 4.2 Wheatstone bridge circuit and details

Figure 4.3 Photographic view of the transient hot-wire apparatus
4.2.3 **Experimental procedure for measuring thermal conductivity**

The nanofluid with chosen volume concentration is heated to the desired temperature after sonication. Then, the Wheatstone bridge circuit is balanced before starting the experiment (i.e. till the galvanometer shows zero deflection) by adjusting the variable resistor $R_3$. As discussed in the previous section, the platinum wire has to work simultaneously as line-heating source and temperature sensor; it is made as an arm of a Wheatstone bridge circuit. Subsequently, the direct current (DC) supply is given to the bridge which causes the change of voltage in the bridge through the Platinum wire. As the current flows through the circuit, due to the resistance the temperature of the wire increases, which in turn increases the resistance again this produces an emf between the arms, causing an unbalanced condition in the circuit. This change in voltage over time is recorded by the data logger with 0.001% accuracy at the sampling rate of 10 readings per second. The change in the resistance of the wire is calculated from the measured voltage change over time and the Ohm’s law. From the temperature/resistance relation of the platinum wire, the temperature variation of the wire is calculated. This temperature variation is plotted against the natural logarithm of time $(t)$ which gives a linear curve as shown in Figure 4.4. The initial transients are ignored for the calculated temperature points up to 2.7 seconds. The calculated temperature points for the time step ranging between 2.7 seconds and 5 seconds as mentioned in the graph, which is a straight line, is chosen and its slope $[\ln(t_2/t_1)/(T_2-T_1)]$ is measured to calculate the thermal conductivity from the formula described earlier in equation (4.3). The time step greater than 5 seconds is also ignored due to the natural convection effect. The flow chart shown below in Figure 4.5 gives the step by step procedure for measuring the thermal conductivity.
Figure 4.4 Variation of wire temperature with respect to logarithmic time

Roder (1981) reported that the timing of the experiment could be as small as possible (3.012 ms); and the use of large time increments simply reduces the number of useful points for thermal conductivity analysis, since for nearly all fluid conditions the onset of convection occurs at around one second in this apparatus. Therefore, in the present study the experiment is conducted and the readings are recorded up to 6 seconds, and the actual calculation is carried out for a time length less than 5 seconds in order to avoid natural convection of the wire and fluid. Measurements are taken at different temperatures ranging from 50°C to 90°C. It took nearly 15 to 20 minutes to reach each temperature range chosen for the study. After taking the reading for each concentration, the nanofluid is taken out and sonicated well before conducting the experiment for the next concentration. The above procedure is repeated for different temperatures and volume concentrations of the silver/water nanofluid. The uncertainty in the value of the thermal conductivity of the silver/water nanofluid measured by this equipment is less than 1.6 % of its mean value. Then, the experimentally estimated thermal conductivity of nanofluid is used for comparison with that obtained from the existing correlations.
Figure 4.5 Flow chart for thermal conductivity measurement
4.3 VISCOSITY MEASUREMENT

Generally, various methods are used for the experimental determination of viscosity, namely, concentric cylinders, or cone and plate methods; and they are very similar to the parallel plate visualization for measuring shear viscosity, which can be found in textbooks describing the meaning of shear viscosity. The method chosen for the present study is the capillary viscometer, and more specifically the Cannon-Fenske Opaque, also called as the Reverse-Flow Viscometer. As shown in Figure 4.6, this is used to measure the kinematic viscosity of the silver/water nanofluid. This viscometer is preferred, because the meniscus of the silver/water nanofluid is not clearly visible due to the opacity of the fluid. The kinematic viscosity is calculated by multiplying the time taken for the fluid sample to pass between the two specified marks on the viscometer with the coefficient of calibration value given by the manufacturer. This is then converted into dynamic viscosity by multiplying it with the density of the fluid.

An investigation of the dependence of viscosity on temperature and particle loading for the nanofluids is conducted using the Cannon-Fenske Opaque capillary viscometer. With this instrument it is possible to measure the kinematic viscosity of the fluid in a range from 0.1 to 15 mPa.s with an uncertainty of 0.5 %.
4.3.1 Experimental procedure for measuring viscosity

In the present study, the measurements are taken at different temperatures ranging from 50°C to 90°C with 0.3 %, 0.4 %, 0.6 %, 0.8 %, 0.9 % and 1.2 % volume concentrations. The experimental apparatus for measuring the viscosity is shown in Figure 4.7. In order to have the experimental data at different temperatures, the viscometer is placed in a constant temperature bath. The constant temperature bath consists of a heater and temperature sensors to ensure that constant temperature is maintained in it. Water is used as the heating fluid in the bath, which is thermally insulated.
Initially the viscometer is cleaned using suitable solvents and made dry by passing clean, dry, filtered air through the instrument to remove the final traces of the solvents. After cleaning, the sample is charged into the viscometer by inverting the instrument and immersing the tube D in the liquid sample; and suction is applied to the tube arm E, and the sample liquid is drawn up to the mark C. After charging the sample, the instrument is turned back to its normal vertical position. Then the sample is allowed to flow through the capillary tube B, approximately till the bulb A is half-filled. A rubber stopper is used in the tube arm E in order to stop the liquid sample meniscus in bulb A. Before taking the readings, the rubber stopper is removed from the tube arm E and the liquid sample is allowed to travel upwards into the bulb H, and the efflux time is measured for the meniscus to pass from mark I to mark G. From the measured efflux time in seconds, the kinematic viscosity of the liquid sample is calculated by multiplying the viscometer constant for bulb H (the viscometer constant is given as 0.015 mm$^2$s$^{-2}$).

Figure 4.7 Apparatus for measuring the viscosity
Finally, the dynamic viscosity is calculated by multiplying the kinematic viscosity and the density of the fluid. For every concentration the viscometer is cleaned and kept for some time to be dried before filling the sample. Then the measurements are taken and the same procedure is repeated for different temperatures and volume concentrations. The uncertainty in the value of viscosity of silver/water nanofluid measured by this equipment is less than 1.5% of its mean value for the entire range. Then, the measured viscosities of nanofluids are compared with those obtained from the existing well-known models.

The obtained results of nanofluid thermal conductivity and viscosity, the mechanisms involved in the enhancement of thermal conductivity, and the comparison of the measured data with the published correlations are discussed in detail in Chapter 7.