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Refinements in Thermal Conductivity Measurements Using Platinum Resistance Wire

by

Erkan Gokmen

A Thesis

Presented to the Graduate and Research Committee

of Lehigh University

in Candidacy for the Degree of

Master of Science

in

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Refinements in Thermal Conductivity Measurements Using Platinum Resistance Wire

Erkan Gokmen

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Date Approved

____

Dr. Alp Oztekin
Thesis Advisor

____

Dr. Sudhakar Neti

Thesis Co-Advisor

____

Dr. D. Gary Harlow

Chairperson of Department

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LIST OF NOMENCLATURE

ΔT Temperature rise (°C)

q Heat generation per unit unit length of hot wire (W/m),

r Radial distance in (m)

a Radius of wire (m)

γ Euler's constant

κ Thermal diffusivity (m2/s)

t Time (s)

λ Thermal conductivity of test liquid (W/mK)

λ_w Thermal conductivity of hot wire (W/mK)

ρ_w Density of hot wire (kg/m3)

ρ Density of test liquid (kg/m3)

c_{p_w} Specific heat of hot wire (J/kgK)

c_p Specific heat of test liquid (kg/m3)

F_o Fourier number

T Temperature (°C)

R Resistance (Ω)

α Electrical resistivity of hot wire (Ωm)

A Cross sectional area of hot wire (m2)

l Length of hot wire (m)

ABSTRACT

Binary and ternary mixtures of molten salt nitrates ($LiNO_3$ -$NaNO_3$ and KNO_3) are ideal candidates as large scale phase change thermal energy storage materials and as heat transfer fluids for concentrating solar power systems. They have higher specific heat capacities and wider operating temperature ranges (150-600°C) compared to the silicon based oils which are currently used in parabolic trough type plants. For design considerations related to power plant and equipment, it is critically important to know the thermo-physical properties of molten salt nitrates; as thermal conductivity being one of the most important. In this regard, the measurements of thermal conductivity of molten salt nitrates are of interest in the present study. A modified version of the hot wire device designed by an earlier research has been used as a transient method to measure the thermal conductivity of fluids. The method has been validated with test liquids with known thermal conductivities such as water, 20 weight % sucrose solution and 40 weight % sugar solution at a variety of temperatures. Finally, the thermal conductivity of ternary mixture of 30:21:49 mol % $LiNO_3$ -$NaNO_3$-KNO_3 has been measured at 134°C. This composition is commonly used in the industry since it is close to the eutectic point. The average value and standard deviation of the measured thermal conductivities of the 15 experiments on the ternary mixture are 0.438 W/mK and 8.27E-4 W/mK, respectively. This value of thermal conductivity is inside the range for single and binary components of nitrate salts published in the literature previously. The observed uncertainty in the validation experiments is around 5 % which determines the overall uncertainty of the measurement of thermal conductivity of the ternary mixture in consideration.

1 INTRODUCTION

Concentrated solar power (CSP) plants are based on the principle of concentrating a large area of sunlight onto a smaller area, which is called a receiver, by mirrors. Two of the most common types of CSP plants are parabolic troughs and power towers. The reflecting mirrors are called heliostats in power tower type plants and troughs in parabolic trough type plants. The mirrors are capable of tracking the sunshine during the day. The receiver has heat transfer fluid circulating inside.

Particularly in power towers, molten salts have significant advantages as heat transfer fluids. They have high specific heat capacity and low melting points. In binary and ternary mixtures of molten salt nitrates, the melting point decreases down around 130°C depending on the composition. The low melting point requires less power to be supplied at night to keep salts in liquid state. Thermal conductivities of single component molten salt nitrates are typically akin to the thermal conductivity of water.

In order to estimate the heat transfer performance of power plant equipment such as steam generator, thermo-physical properties of cycle fluids must be known. One of the most important is the thermal conductivity. For this purpose, the transient hot wire method is used in the present research to measure the thermal conductivities of ternary mixtures of molten salt nitrates at elevated temperatures. The hot wire method is a standard transient regime technique based on the measurement of the rising temperature of a linear heat source embedded in the test material over a certain range of time. The line heat source is usually a metallic wire and also called hot wire in this method. The heat supplied electrically to the wire is assumed to be constant and uniformly distributed around and along the wire [1]. The line heat source is thin and has a high thermal conductivity allowing that the temperature is nearly the same everywhere on and inside the wire. For this reason, in the present research, the measured temperature of the platinum wire is assumed to be equal to the interface (or wire surface) temperature. The current passing through the wire causes the wire to heat up. The experimental data of interface temperature vs. time plot can be used to determine the thermal conductivity of test liquid by the model given by Carslaw and Jaeger, 1959 [2].

An experimental setup which utilizes the fundamental features of conventional transient hot wire method is designed. The setup has been designed to operate and measure the thermal conductivity at elevated temperatures up to 600°C and in corrosive environments as the case in molten salts. The accuracy of the setup has been validated on four sample test liquids with documented thermal conductivities. Finally, experiments to measure the thermal conductivity of ternary mixture of 30 mol % $LiNO_3$, 21 mol % $NaNO_3$ and 49 mol % KNO_3 are conducted at 134°C.

2 LITERATURE REVIEW

2.1 Literature Survey

The transient hot wire method is a widely used technique that has been accepted as the most precise and reliable method for the measurement of thermal conductivity of fluids [3]. It has the ability to eliminate the convective heat transfer when the measurement time is sufficiently low depending on the experimental setup. The temperatures involved in the present research are relatively low for radiation to be effective. For those reasons and because of the relatively simple design of setup, the transient hot wire method was preferred in an attempt to measure the thermal conductivity of binary and ternary mixtures of molten salt nitrates.

Nagasaka and Nagashima [4] claimed that steady state methods yield significant error due to the existence of convection and radiation. Furthermore, when used with mixtures such as binary and ternary mixtures of molten salt nitrates, steady state methods may cause the separation of components because of long term existence of temperature gradient or thermal diffusion in the mixture. Some of the commonly used transient regime methods in the literature for the measurement of thermal conductivity of liquids including molten salts are transient hot wire method, concentric cylinder, optical interferometry and parallel plate method.

Transient hot wire method utilizes a theoretical one-term series solution which corresponds to the problem statement of infinitely long, thin line heat source in an infinite medium of sample fluid. The thin line heat source is of metallic nature due to the need for a high thermal conductivity and commonly made of platinum. Platinum is an ideal material for hot wire for high temperature corrosion resistance. In order to create a temperature rise of about a few Kelvin in the hot wire, a constant heat production is generated electrically by a circuit. The temperature of the test liquid in the proximity of wire increases by heat diffusion in a transient state. Since the metallic wire is assumed to be infinite, its length over diameter ratio must be as big as possible (much bigger than 200, [5]) in order to minimize the end effects. The problem reduces to one dimensional heat conduction in the radial direction. The solution to this problem for the temperature of wire averaged over its volume is given by [6],

$$\Delta T(t) = \frac{q}{4\pi\lambda}\left\{\left[1 - a^2 \frac{(\rho c_p)_w - \rho c_p}{2\lambda t}\right] \ln\left(\frac{4\kappa t}{a^2 c}\right) + \frac{a^2}{2\kappa t} - \frac{a^2}{2\kappa_w t} + \frac{\lambda}{\lambda_w}\right\} \quad (2\text{-}1)$$

where T is the temperature of test or sample liquid, t is the time, q is the heat production per unit length of wire, λ is the thermal conductivity of test liquid, κ is the thermal diffusivity of sample liquid, α is the radius of heat source, $c = e^{\gamma-1}$ and γ is the Euler's constant (0.5772). Index w denotes the wire, while parameters without any index denote the test liquid. Fourier number is defined as

$$F_o = \frac{\kappa t}{a^2} \quad (2\text{-}2)$$

The assumptions leading to the above solution are (1) infinitely long and thin, linear heat source, (2) infinitely large liquid region, (3) only diffusive transfer of heat and (4) uniform properties of sample liquid. When Fourier number is much larger than 1, all the terms in the series expansion (2.1) except for the first term can be neglected. As a result, the equation (2.1) reduces to

$$\Delta T = \frac{q}{4\pi\lambda}\left[ln\left(\frac{4\kappa t}{a^2}\right) - \gamma\right] \qquad (2\text{-}3)$$

The differentiation of equation (2.3) with respect to ln(t) leads to the following solution for the thermal conductivity of test liquid.

$$\lambda = \frac{q}{4\pi\frac{d\Delta T}{dln(t)}} \qquad (2\text{-}4)$$

Equation (2.4) is the fundamental model used in the transient hot wire method to calculate the thermal conductivity of liquids by using the slope of ΔT vs ln(t) curve.

A linear relationship between the resistance and temperature of hot wire is obtained by a calibration process. The resistance data of metallic wire is measured and recorded over a short time period (usually less than 10s). It is then converted to temperature data by calibration calculations. In a stable system meeting the assumptions, the plot of ΔT vs ln(t) of experimental data is a straight line.

For t << 1, Fourier number is very low and more terms from the expansion (2.1) is required for an accurate solution [3]. The onset of convection is observed by a curvature in the ΔT vs ln(t) plot at later times. The optimal range of time is selected to fit a linear curve to the experimental data. The slope of this line is used to calculate the thermal conductivity using equation (2.4).

Nagasaka and Nagashima [7] used the transient hot wire method to measure the thermal conductivity of electrically conducting liquids. Figure 1 is the hot wire assembly used by Nagasaka and Nagashima. Unlike the traditional hot wire method, the metallic wire is covered by an electrical insulation in order not to include the whole cell in the electrical circuit. The designed apparatus was used to measure the thermal conductivity of an aqueous solution of NaCl between 0-45°C at the atmospheric pressure. The accuracy of the measurements was claimed to be ±0.5%.

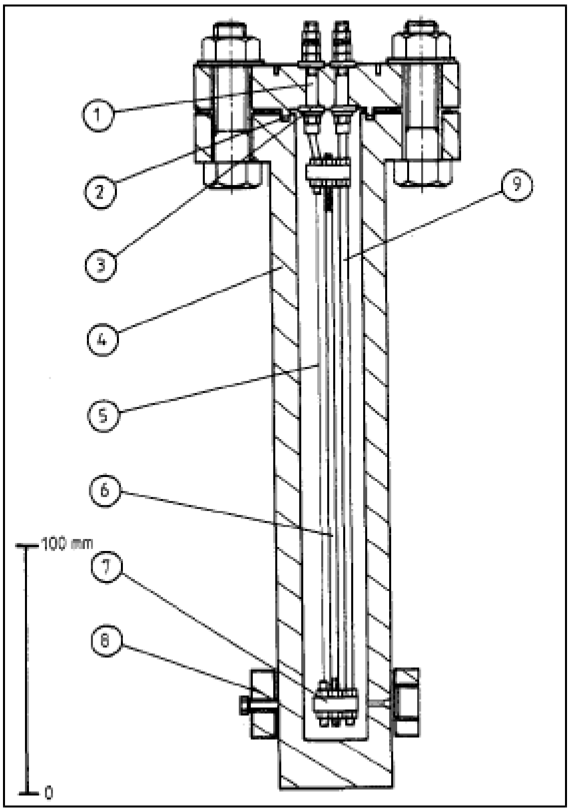


Figure 1: Hot Wire Assembly. The Components are 1- Terminal, 2- Cu Packaging, 3- Teflon Packing, 4- Pressure Vessel, 5- Insulated Pt Wire, 6- Sus Rod, 7- ABS Disk, 8- Grand Retaining Ring, 9- Insulated Cu Rod

Turnbull [8] (1961) used the transient hot wire method with a bare platinum wire without electrical insulation to determine the thermal conductivity of molten salts of pure $NaNO_3$ at 582°C and KNO_3 at 606°C. Based on Smythe's analysis, Turnbull claimed that the current through the salt was negligible and therefore the wire was not insulated. The range of error was reported to be ±2.8%. However, Turnbull's results were analyzed by Nagasaka and Nagashima [4] and 1 min duration for each measurement was implied to be too long to achieve proper conditions for this method. It was also pointed out by Omotani et al. [9] that there were serious electrical conductivity effects for the heat transfer salt of KNO_3-$NaNO_3$-$NaNO_2$, 44-7-49 mol %.

2.2 The Effect of Finite Diameter of Platinum Wire

The conventional hot wire method assumes that an infinitely thin wire is used and thus heat diffusion is only in the radial direction as discussed in the chapter 2.1: Literature Survey. Since the Fourier number will be very large, all the other terms in Equation 2.1 is neglected except for:

$$\Delta T = \frac{q}{4\pi\lambda}\left[\ln\left(\frac{4\kappa t}{a^2 c}\right)\right] \tag{2-5}$$

which corresponds to Equation 2.3. However, if the diameter of wire is not small enough, the other terms of the approximation still needs to be considered. Here, we have investigated the effect of all terms of the expansion for different diameters of wire and water as the test liquid as presented in Table 1. The time selected for the calculations is 3 sec as an average of total measurement time.

Table 1: Contribution of all terms of the Equation 2.1 for three different diameters of Pt wire and water as the test liquid

		Diameter of Platinum Wire		
		127 µm	0.25mm	0.5mm
	Fourier number at 3 sec »	105	27.1	6.78
Term No.	Term			
1	$\frac{q}{4\pi\lambda}\left[\ln\left(\frac{4\kappa t}{a^2 c}\right)\right]$	2.5996	5.6908	2.3402
2	$\frac{q}{4\pi\lambda}\left\{-a^2\frac{(\rho c_p)_w - \rho c_p}{2\lambda t}\ln\left(\frac{4\kappa t}{a^2 c}\right)\right\}$	0.0041	0.0349	0.0574
3	$\left(\frac{q}{4\pi\lambda}\right)\left(\frac{a^2}{2\kappa t}\right)$	0.0019	0.0206	0.0464
4	$\left(\frac{q}{4\pi\lambda}\right)\left(-\frac{a^2}{4\kappa_w t}\right)$	-5.20E-06	-5.57E-05	-1.26E-04
5	$\left(\frac{q}{4\pi\lambda}\right)\left(\frac{\lambda}{2\lambda_w}\right)$	0.0016	0.0045	0.0026
	Summation of second to fifth term as a percentage of first term	**0.29%**	**1.05%**	**4.54%**

Different currents are supplied for each diameter of wire in the experiments. Moreover, the length of wire changes for different wires. Therefore, power per unit length, and thus the first term is different for each diameter of wire.

The contribution of all the other terms, from second term to fifth term, is negligible for diameters of Pt wire less than 0.25 mm. Thus, a linear trend of experimental temperature versus time plots are expected for Pt wires of 127 µm or 0.25 mm diameter. A plot of rise of temperature versus time considering all the terms of Equation 2.1 is shown in Figure 2 for 127 µm diameter Pt wire.

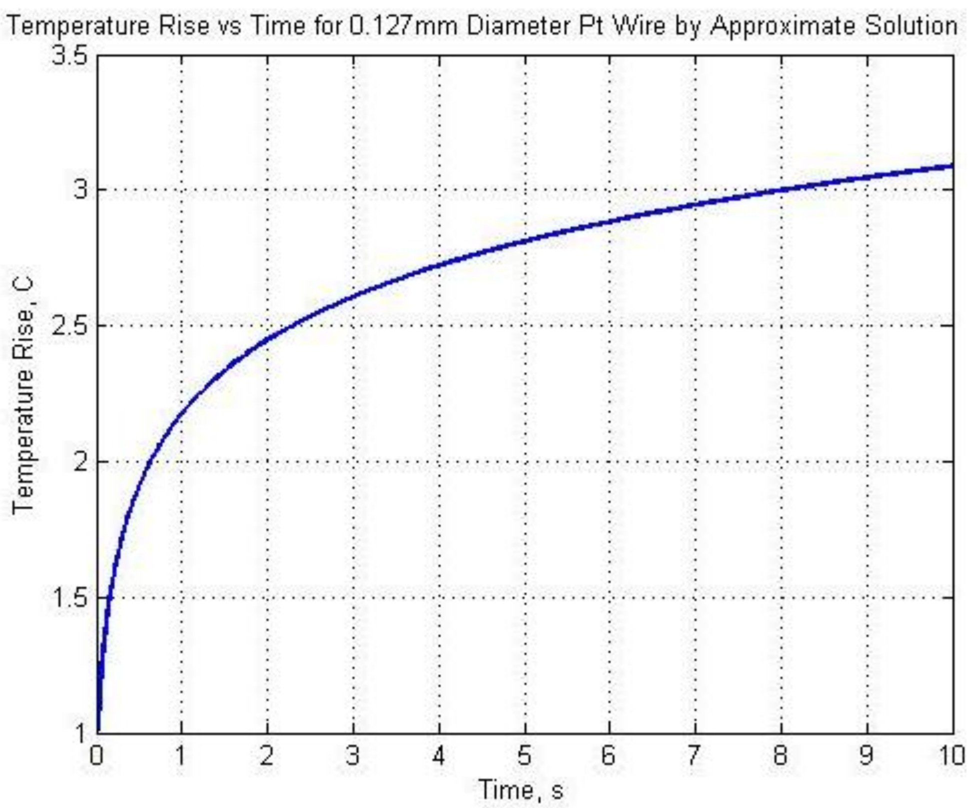


Figure 2: Plot of rise of temperature (°C) vs time (s) by considering all terms of the approximate solution of [6] for a Pt wire of 127 µm diameter and water as the test liquid

3 EXPERIMENTAL SETUP AND CALIBRATION PROCEDURE

3.1 Experimental setup

A modified version of the experimental setup designed and built by Nelle [10] & Rosenzweig [11] is used in the present research. In this setup, the stainless steel cylinder is a cell containing the liquid whose thermal conductivity is to be measured. The hot wire cell consists of a platinum wire with an L-shaped bracket and the resistance thermometer (RTD). Highly accurate and programmable Keithley instruments as Sourcemeter (2440 5A) and Nanovoltmeter (2182 A) are used to supply current to the whole circuit including the platinum wire. The accuracy of the instruments are 10^{-6}A for the sourcemeter and 10^{-8}V for the voltmeter. They are attached to the stainless steel bit and the stainless steel arm through four copper lead wires. A GPIB card is connected to the Keithley Instrument 2440 5A in order to achieve the communication between the Labview sorfware and instruments and to collect the voltage data. The current supply, acquisition of voltage and associated time data of the portion of circuit between the stainless steel bit and the stainless steel arm is achieved by the Keithley instruments. A Labview code has been written in this regard and attached in Appendix B. The selection of the instruments and software is inspired by highly accurate measurements of Merckx et.al [5].

The stainless steel cap on the top of the cell is excluded from the circuitry by using ceramic inserts as isolator parts.

Figure 3 is a picture of the experimental setup. On the top is the data acquisition device for the resistance thermometer (RTD) which measures the equilibrium or initial temperature in the furnace. The other end of DAQ device connections is the USB plug connecting to the laptop. Both Instacal and Tracerdaq software can be used to monitor the temperature inside the cell and the furnace.

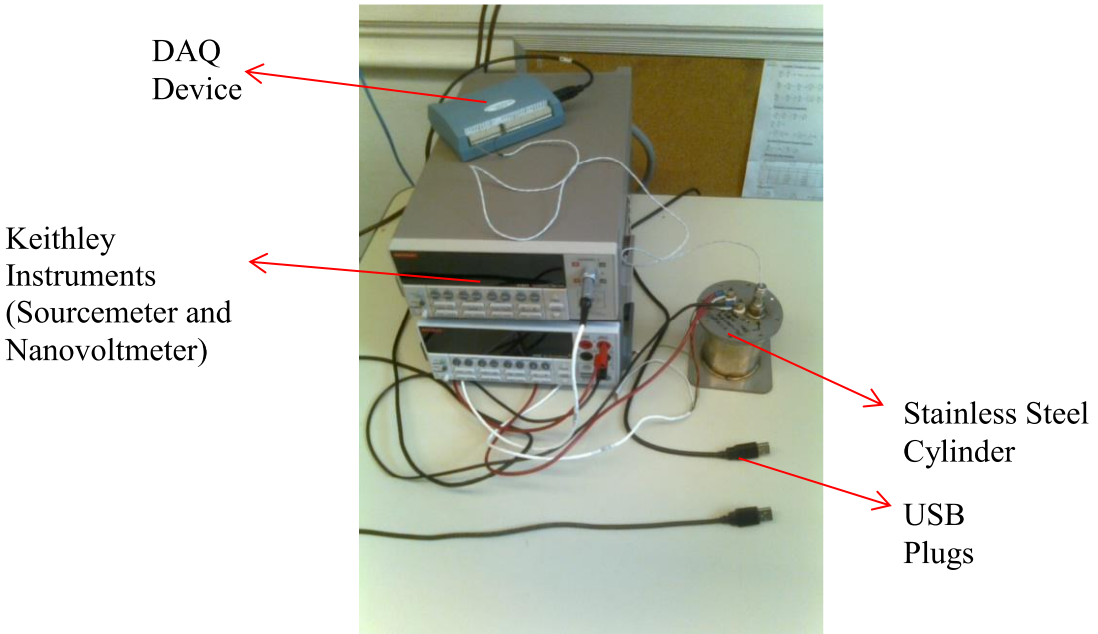


Figure 3: Experimental setup for the transient hot wire device

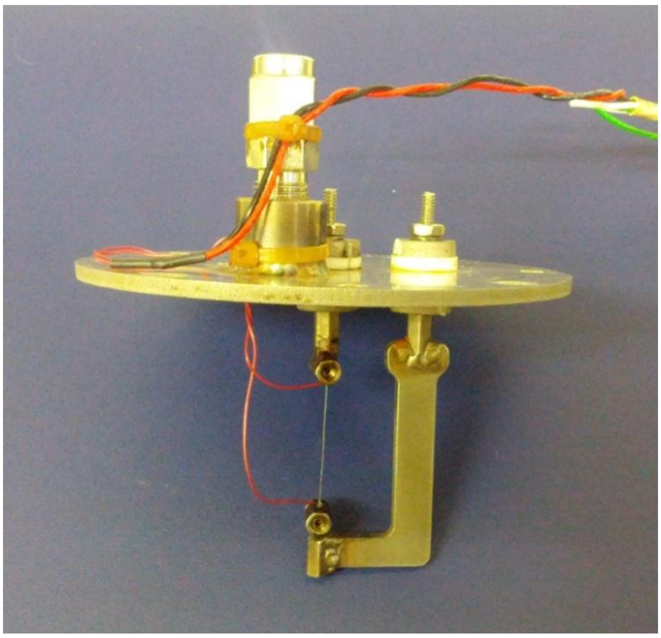


Figure 4: Hot Wire Assembly

A picture of the hot wire assembly including Pt wire, L-shaped bracket and lead wires etc. is presented in Figure 4. The technical drawing of the experimental setup has been presented in the Appendix A.

During the experiments, a current ranging from 0.3 Amps to 5 Amps is supplied to the electrical circuit so as to create a temperature rise of several degrees Celcius. Since the sourcemeter and voltmeter are connected to the stainless steel joiner and the stainless steel arm, the measured voltage and resulting resistance corresponds not only the platinum wire but also to the stainless steel bit and the arm. Therefore, a calibration procedure is conducted to determine the resistance of platinum wire.

3.2 Calibration Procedure

Theoretically, a linear relationship exists between the temperature and resistance of a metallic wire. This relationship is required in order to convert the acquired resistance data to temperature data and eventually obtain the thermal conductivity. The calibration procedure aims to determine the T(R) relationship in the real world conditions.

Three different diameters of platinum wires (1 mm, 0.5 mm, 0.25 mm and 127 µm) with approximately the same length are used during the validation experiments which are based on water, propylene glycol and sugar solutions. The lead wires of nano-voltmeter are soldered to the platinum wire. For this reason, the collected data during the calibration and experiments belongs to the platinum wire only. In order to obtain the T(R) relationship, a small current is supplied to the circuit for a short time (around 0.8 s) and the resulting voltage difference between the two ends of wire is measured, recorded and converted to the resistance. The amount of current is usually 0.03 amps or 0.05 amps depending on the size of Pt wire. The small current causes a negligible heating and thus the average of collected data gives the resistance of Pt wire at that temperature. This is repeated at three different temperatures i.e. 24°C, 55°C and 85°C for an equation valid in 0-100°C range. The procedure is repeated 4 times at each temperature and the results are plotted in Figure 5. A highly linear trend is observed as illustrated in the Figure 5.

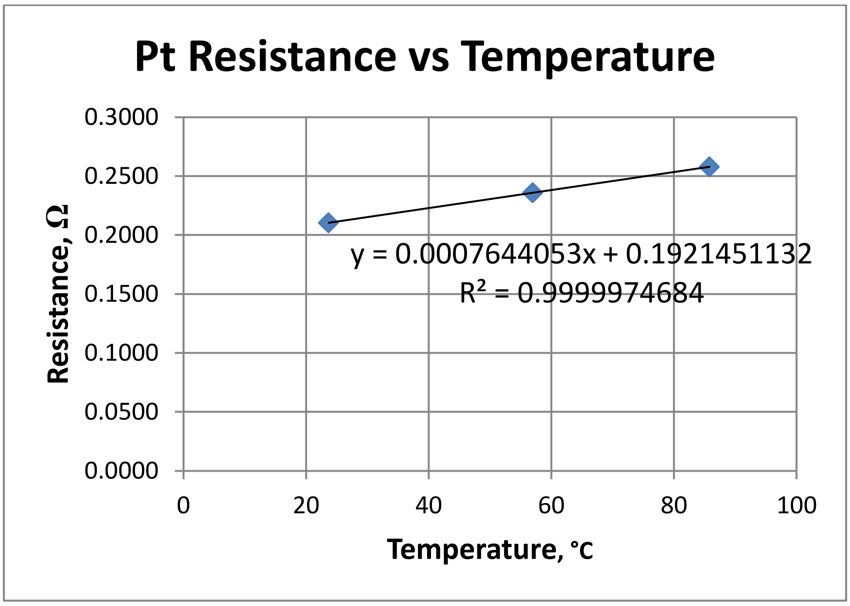


Figure 5: Resistance (Ω) vs. temperature (°C) relationship of a 127 µm diameter Pt wire immersed in distilled water

4 VALIDATION EXPERIMENTS

Repeated measurements of thermal conductivity of water, propylene glycol and sugar solutions have been conducted in order to make sure that the experimental setup is working with various liquids, at a variety of temperatures. This chapter presents the results with different fluids at various temperatures as well as the experiments with different sizes of platinum wires and the analysis of data by two different methods namely a curve fitting and using an average slope.

Every time the wire is replaced, the current flowing in the electric circuit and the voltage measured by nano-voltmeter have been measured and confirmed to be accurate by a multimeter. The supplied current is observed to be constant and equal to the intended current during the experiment except for the initial ramp up trend. This ramp up time is shorter than 10.1 ms depending on the load [12]. The ramp up function is approximately linear but the slope decays close to the set point. Since the ramp up time is very short, its effect on the rise of temperature can easily be neglected.

4.1 Results of Validation Experiments by Linear Curve-Fitting to Experimental Data

The first method used to evaluate the experimental data is linear curve-fitting by least squares regression. This method approximates the experimental data of ΔT vs $\ln(t)$ by a linear equation and allows us interpret how linear the trend of experimental data is.

4.1.1 Water at Room Temperature with a Pt Wire of 1mm Diameter

The room temperature experiments are conducted without using a temperature controlled environment such as furnace. The measurements are taken for distilled water at 23-24°C and compared to the literature value of thermal conductivity of water at 25°C (0.5896 W/mK [13]).

Experiments are conducted using the platinum wire of 1 mm diameter. In this case, the experimental setup, Labview code and calibration equation are the same as those that were designed and used by Nelle & Rosenzweig [10, 11]. Figure 6 illustrates a typical example of the processed data of repeated experiments using 5 Amps current supply.

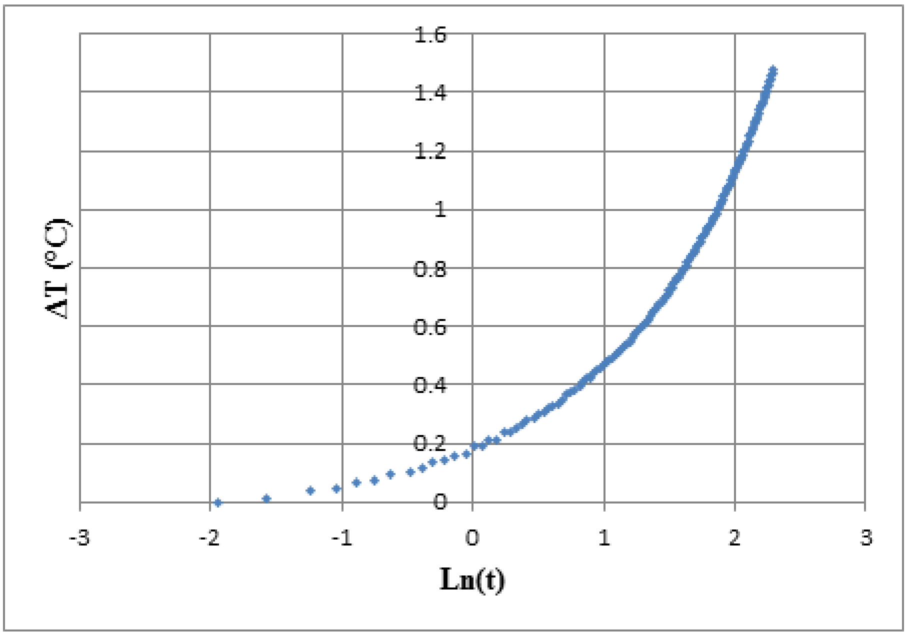


Figure 6: Measured ΔT vs ln(t) for distilled water as test liquid at 23.2 °C with a Pt Wire of 1mm diameter and 5 Amps of current supply

A linear trend of ΔT vs ln(t) is not observed with a platinum wire of 1 mm diameter. After the experiments, it is realized that the bracket and wire connecting to the stainless steel case were loose. In the following examples, all the connections including case, lead wires and hot wire etc. are tight. In addition, a new Labview code that is also capable of acquiring the time data associated with the voltage data has been used. The labview code is presented in the Appendix B.

4.1.2 Water at Room Temperature with a Pt Wire of 0.5 mm Diameter

Replacing the wire requires the calibration procedure to be repeated since a different size wire will have a different slope of T(R) line. The theoretical and experimental resistances of Pt wire at room temperature are obtained and compared. The theoretical resistance of Pt wire of 0.5 mm diameter and 23 mm length is calculated as:

$$R = \alpha \frac{l}{A} = 0.01266\ \Omega \qquad (4\text{-}1)$$

The resistance of the same size wire is measured to be 0.01337 **Ω**. The measured value of the resistance differs 5.6 % compared to the theoretical value. It is concluded that the measured and predicted values of resistance are comparable.

Two lead wires connecting the voltmeter to both ends of Pt wire are soldered to the Pt wire. Two lead wires are inside the test liquid during the measurements. Good connections by soldering have yielded considerable improvement in the measurements. The ΔT vs ln(t) plot exhibits nearly linear relationship as depicted in Figure 7.

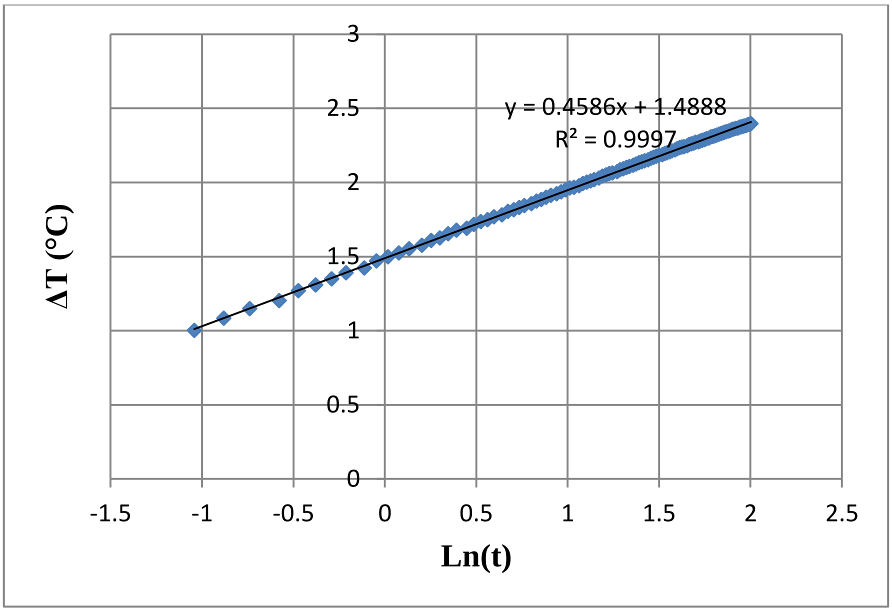


Figure 7: Measured ΔT vs ln(t) for distilled water as test liquid at 23.3 °C with a Pt Wire of 0.5 mm diameter and 3 Amps of current supply

However, the calculation of thermal conductivity based on the slope of ΔT vs ln(t) plot resulted in an average value of water thermal conductivity at room temperature of 0.806 W/mK and an average error of 36.76 %. The least sqaure curve fitting was applied to the data between the time range of $1 < \log(t) < 2$ or $0.35s < t < 7.41s$ to determine the slope. The results of 5 different experiments are shown in Table 2. The thermal conductivity of water is overestimated systematically by 36-37 % as depicted in Table 2.

Table 2: Measured thermal conductivity of distilled water at 23.4°C with a Pt wire of 0.5 mm diameter and 3 Amps of current supply

0.5 MM DIAMETER Pt WIRE (-1 < LN(T) < 2)		
	3 Amps	
Experiment No.	Thermal Conductivity, W/mK	Error, %
1	0.803	36.3
2	0.811	37.5
3	0.809	37.3
4	0.803	36.1
5	0.806	36.7

4.1.3 Optimal Current Supply

Another issue encountered during the experiments with 0.5 mm diameter Pt wire is the amount of optimal current supply as the heat source. When the current is too much for the setup (5 Amps in this case), the onset of natural convection occurs earlier as shown in Figure 8. On the other hand, if the current is too low (2 Amps in this case), the temperature rise is not high enough to be measured accurately as shown in Figure 9.

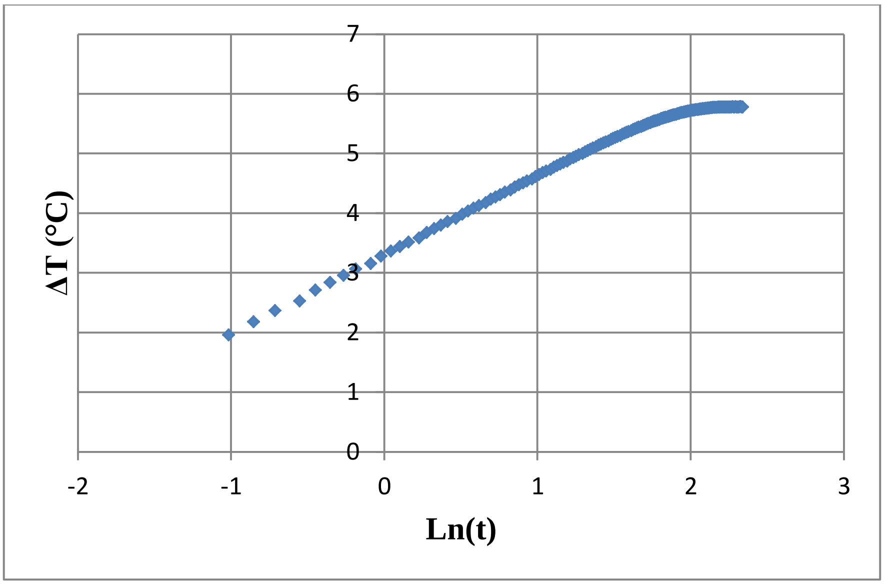


Figure 8: Measured of ΔT vs ln(t) for distilled water at 22.9 °C with a Pt Wire of 0.5 mm diameter and 5 Amps of current supply

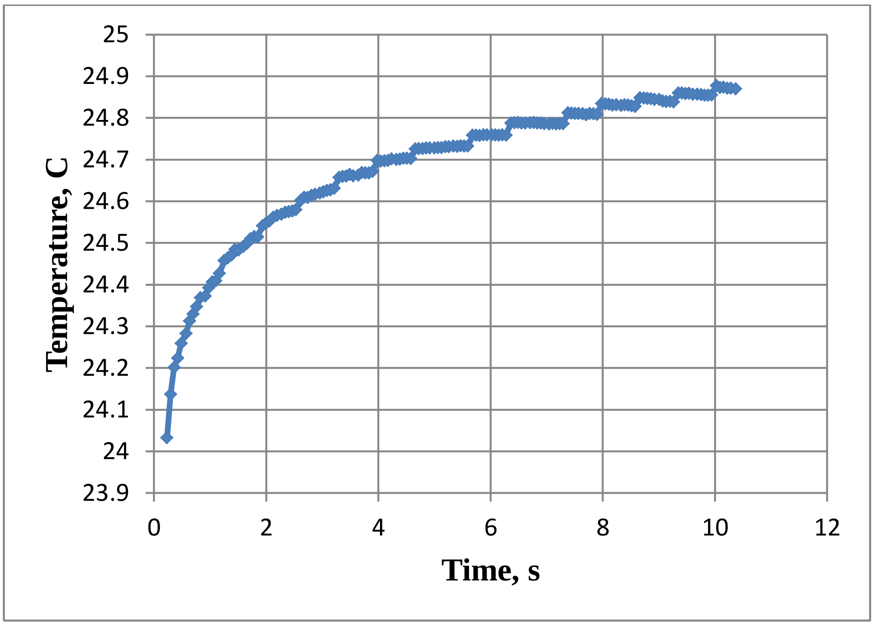


Figure 9: Measured temperature (°C) vs time (s) for distilled water at room temperature with a Pt Wire of 0.5 mm diameter and 2 Amps of current supply

4.1.4 Water at Room Temperature with a Pt Wire of 0.25 mm Diameter

Soldering connections between nano-voltmeter lead wires and Pt wire and firm, threaded connections between nano-sourcemeter and circuit are used with a thinner platinum wire of 0.25 mm diameter. The optimal current supply for this wire is about 2 Amps. To create the same amount of temperature rise, lesser amount of current supply should be used for a thinner wire with a larger resistance.

The platinum hot wire of 0.25 mm diameter yielded considerable decrease in the measurement error. Since the soldering connection occupies certain space, three different measurements of length of wire are considered. Those are; length measured from the inside of one soldering to the inside of the other soldering (23.39 mm), length measured from middle of one soldering to the middle of the other soldering (23.99 mm) and length measured from outside of one soldering to the outside of the other soldering (24.59 mm). The results of 10 different experiments are presented in Table 3 and a representative data is shown in Figure 10. The experimental error is between 10-16% and the thermal conductivity is overestimated. One of the possible explanations for the discrepancy is the diameter of the wire is not small enough and the length of the wire is not long enough to justify the assumption made in chapter 2.1. Because of these two factors, the temperature may not be uniform over the volume of wire in the actual experiments. The experimental temperature is average over the volume of the wire and can be lower than maximum temperature in the wire due to the end effects. In an ideal case, a single temperature value would be generated in the wire and it would be the maximum temperature. Thus, the slope of ΔT vs ln(t) plot is lower compared to the ideal system that leads to the measurements of thermal conductivity above the actual value.

Table 3: Measured thermal conductivity of distilled water at 23.3°C with a Pt wire of 0.25 mm diameter and 2 Amps of current supply

0.25 MM DIAMETER Pt WIRE (-1 < LN(T) < 1)						
	Inside to Inside		Middle to Middle		End to End	
	(23.39 mm)		(23.99 mm)		(24.59 mm)	
Exp. No.	Thermal Conductivity, W/mK	Error, %	Thermal Conductivity, W/mK	Error, %	Thermal Conductivity, W/mK	Error, %
1	0.700	18.7	0.683	15.8	0.666	12.9
2	0.684	16.0	0.667	13.1	0.651	10.3
3	0.674	14.4	0.657	11.5	0.641	8.8
4	0.676	14.7	0.659	11.8	0.643	9.1
5	0.690	17.0	0.673	14.1	0.656	11.3
6	0.686	16.4	0.669	13.4	0.653	10.7
7	0.685	16.3	0.668	13.3	0.652	10.6
8	0.682	15.6	0.664	12.7	0.648	9.9
9	0.683	15.8	0.666	12.9	0.650	10.2
10	0.682	15.7	0.665	12.8	0.649	10.1

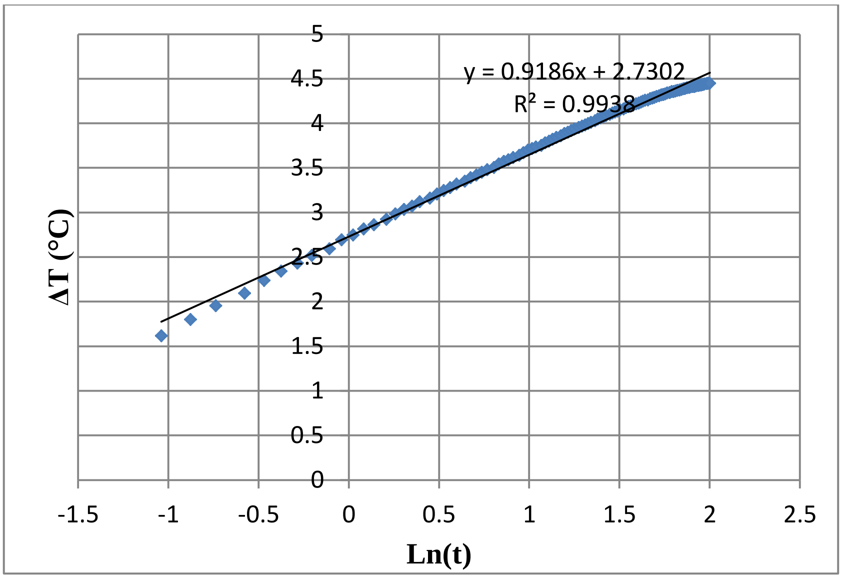


Figure 10: Representative ΔT vs ln(t) measured for distilled water at 23.3 °C with a Pt Wire of 0.25 mm diameter and 2 Amps of current supply

4.1.5 Water at 57°C with a Pt Wire of 0.25 mm Diameter

The experimental data of resistance vs. time for the measurement of thermal conductivity of water is acquired for validation purposes at high temperatures. The relationship between temperature and resistance of wire, which is obtained by calibration procedure, is applied to this data and the figure of ΔT vs ln(t) is plotted by the same manner as room temperature experiments. As observed in this processed data at high temperatures, the curvature in the experimental data starts at an earlier time than the room temperature. Therefore, the optimal time range for a linear curve-fit is observed to be as $-1 < \ln(t) < 1$ for temperatures around 57°C and $-1 < \ln(t) < 0.6$ for temperatures around 86°C. The results of experiments are presented in Table 4 while Figure 11 depicts an example of the representative experimental data.

Table 4: Measured thermal conductivity of distilled water at 56.7 °C using a Pt wire of 0.25 mm diameter and 2 Amps of current supply

0.25 MM DIAMETER Pt WIRE (-1 < LN(T) < 1)						
	Inside to Inside (23.39 mm)		Middle to Middle (23.99 mm)		End to End (24.59 mm)	
Exp. No.	Thermal Conductivity, W/mK	Error, %	Thermal Conductivity, W/mK	Error, %	Thermal Conductivity, W/mK	Error, %
1	0.760	16.2	0.741	13.3	0.723	10.5
2	0.760	16.2	0.741	13.2	0.723	10.5
3	0.759	16.0	0.740	13.1	0.722	10.4

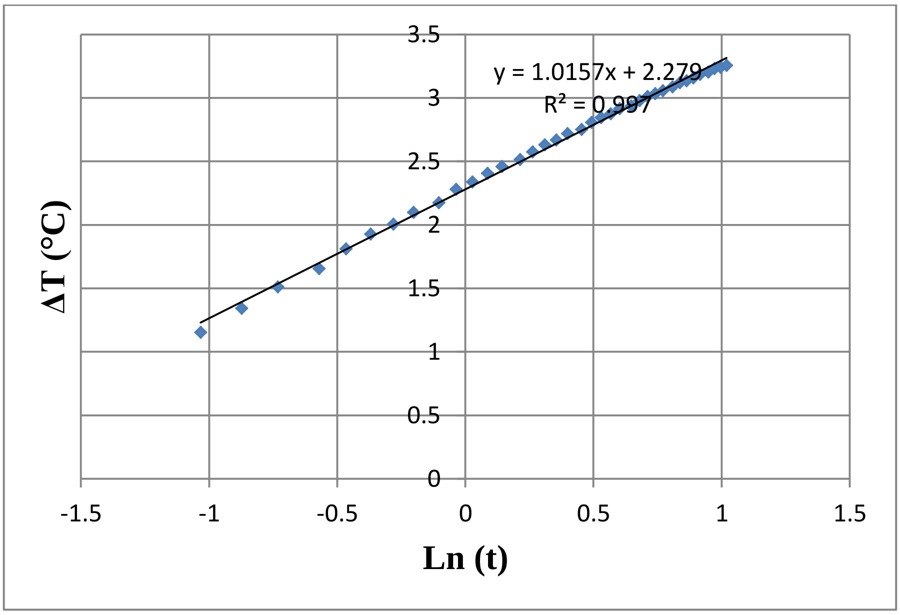


Figure 11: Representative ΔT vs ln(t) measured for distilled water at 56.7 °C using a Pt Wire of 0.25 mm diameter and 2 Amps of current

4.1.6 Water at Room Temperature with a Pt Wire of 127 µm Diameter

The diameter of the hot wire strongly influence the Fourier's number as presented in chapter 2.1. The thinner the wire is, the larger Fourier number is. As a result, one term series expansion can model the temperature rise of the wire. Hence, it is critically important to have a wire that is thin enough.

By using a thinner hot wire of 127 µm diameter, the error in measurements could be reduced significantly. Since the leading ends of the wire are soldering, determining the length of hot wire is an issue during the present experiments. For 127 µm diameter wire, the length measured from inside of one soldering to inside of the other soldering is 24.73 mm, the length measured from middle of one soldering to middle of the other soldering is 25.24 mm and the length measured from outside of one soldering to outside of the other soldering is 25.74 mm. The results of 12 experiments are presented in Table 5 and a typical trend of data is shown in Figure 12.

Table 5: Measured thermal conductivity of distilled water at 23.7 °C with a Pt wire of 127 μm diameter and 0.6 Amps of current supply

127 μm DIAMETER Pt WIRE (-1 < LN(T) < 2)						
	Inside to Inside (24.73 mm)		Middle to Middle (25.24mm)		End to End (25.74 mm)	
Exp. No.	Thermal Conductivity , W/mK	Error , %	Thermal Conductivity , W/mK	Error , %	Thermal Conductivity , W/mK	Error, %
1	0.624	5.77	0.611	3.65	0.599	1.62
2	0.622	5.48	0.609	3.37	0.598	1.34
3	0.621	5.33	0.609	3.22	0.597	1.19
4	0.621	5.31	0.608	3.20	0.597	1.18
5	0.622	5.57	0.610	3.46	0.598	1.43
6	0.623	5.67	0.611	3.56	0.599	1.53
7	0.622	5.56	0.610	3.45	0.598	1.42
8	0.620	5.13	0.607	3.02	0.596	1.00
9	0.620	5.21	0.608	3.10	0.596	1.08
10	0.622	5.47	0.609	3.36	0.597	1.33
11	0.618	4.90	0.606	2.80	0.594	0.78
12	0.625	5.93	0.612	3.81	0.600	1.77

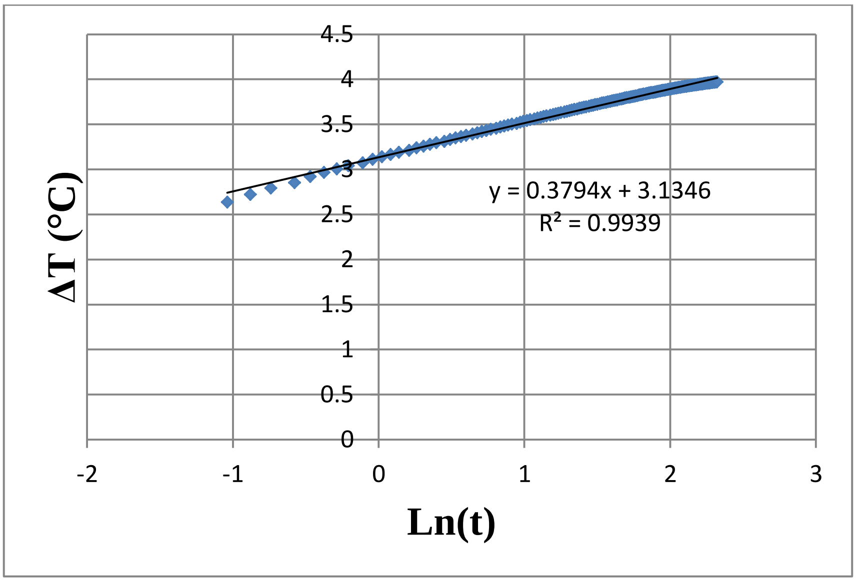


Figure 12: Representative ΔT vs ln(t) measured for distilled water at 23.7 °C with a Pt Wire of 127 μm diameter and 0.6 Amps of current supply

The reference value of thermal conductivity of water is 0.5896 W/mK at 25°C [13]. The measured value of thermal conductivity of water using 127 μm diameter wire differs about 6 %.

4.1.7 Water at 57°C with a Pt Wire of 127 μm Diameter

The same procedure as in chapter 4.1.5 is followed with a platinum wire of 127 μm diameter. The results of validation experiments at 57.1°C are listed in Table 6 with a representative data shown in Figure 13. A comparison between experiments of 0.25 mm diameter wire and 127 μm diameter wire at 57°C indicates a decrease in error more than 50 %.

Table 6: Measured thermal conductivity of distilled water at 57.1 °C using a Pt wire of 127 µm diameter and 0.8 Amps of current supply

127 µm DIAMETER Pt WIRE (-1 < LN(T) < 1)						
	Inside to Inside		Middle to Middle		End to End	
	(24.73 mm)		(25.24mm)		(25.74 mm)	
Exp. No.	Thermal Conductivity W/mK	Error %	Thermal Conductivity W/mK	Error %	Thermal Conductivity W/mK	Error %
1	0.654	-0.07	0.641	-2.07	0.628	-3.99
2	0.650	-0.71	0.637	-2.70	0.624	-4.61
3	0.650	-0.71	0.637	-2.70	0.624	-4.61
4	0.650	-0.63	0.637	-2.62	0.625	-4.53

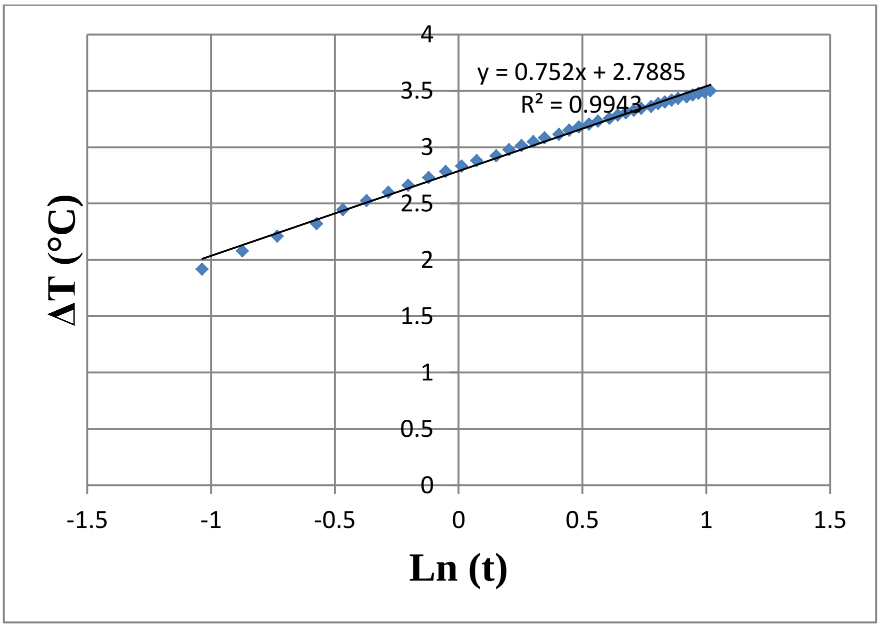


Figure 13: Representative ΔT vs ln(t) measured for distilled water at 57.1 °C using a Pt Wire of 127 µm diameter and 0.8 Amps of current supply

4.1.8 Water at 86°C with a Pt Wire of 127 µm Diameter

The results of validation experiments at 85.7 °C are listed in Table 7 with a representative data shown in Figure 14. Here, a shorter range of time ($-1 < \ln(t) < 0.6$) is used to only consider the linear portion of plot of ΔT vs $\ln(t)$.

Table 7: Measured thermal conductivity of distilled water at 85.7 °C using a Pt wire of 127 µm diameter and 0.5 Amps of current supply

127 µm DIAMETER Pt WIRE (-1 < LN(T) < 0.6)						
	Inside to Inside (24.73 mm)		Middle to Middle (25.24mm)		End to End (25.74 mm)	
Exp. No.	Thermal Conductivity, W/mK	Error, %	Thermal Conductivity, W/mK	Error, %	Thermal Conductivity, W/mK	Error, %
1	0.665	-0.26	0.652	-2.26	0.639	-4.17
2	0.667	0.01	0.653	-1.99	0.641	-3.91
3	0.664	-0.40	0.651	-2.39	0.638	-4.31
4	0.665	-0.21	0.652	-2.20	0.639	-4.12

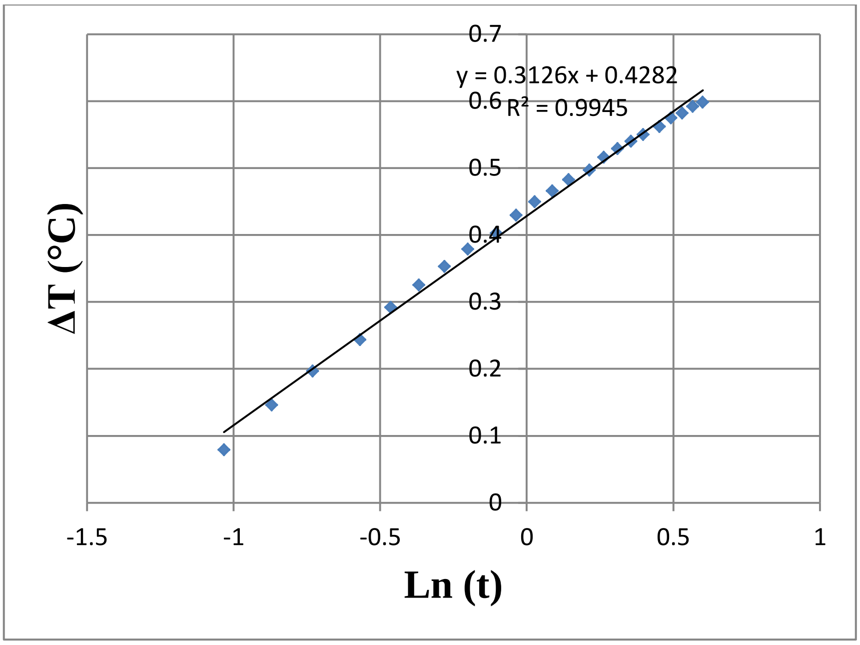


Figure 14: Representative ΔT vs ln(t) measured for distilled water at 85.7 °C using a Pt Wire of 127 μm diameter and 0.5 Amps of current supply

4.1.9 Propylene Glycol at 25°C with a Pt Wire of 127 μm Diameter

After the system yielded highly accurate and repeatable measurements on water at room temperature, the setup is tested with a different type of liquid, propylene glycol. Industrial grade propylene glycol or 1,2 propanediol used in the experiments has a thermal conductivity of 0.206 W/mK at 25°C [14]. In order to obtain a similar temperature rise as water experiments, the optimal current supply should be 0.3 Amps. The experiments have been repeated twice at different dates and the results are presented in Table 8 and Table 9 with a sample of acquired data shown in Figure 15.

Table 8: Measured thermal conductivity of propylene glycol at 24.7 °C with a Pt wire of 127 μm diameter and 0.3 Amps of current supply

127 μm DIAMETER Pt WIRE (-1 < LN(T) < 2)						
	Inside to Inside		Middle to Middle		End to End	
	(24.73 mm)		(25.24mm)		(25.74 mm)	
Exp. No.	Thermal Conductivity, W/mK	Error, %	Thermal Conductivity, W/mK	Error, %	Thermal Conductivity, W/mK	Error, %
1	0.253	22.92	0.248	20.46	0.243	18.1
2	0.254	23.22	0.249	20.75	0.244	18.38
3	0.254	23.2	0.249	20.73	0.244	18.36
4	0.254	23.31	0.249	20.84	0.244	18.47
5	0.253	22.75	0.248	20.3	0.243	17.94
6	0.257	24.61	0.252	22.12	0.247	19.72

Table 9: Another set of measured thermal conductivity of propylene glycol at 24.7 °C with a Pt wire of 127 μm diameter and 0.3 Amps of current supply

127 μm DIAMETER Pt WIRE (-1 < LN(T) < 2)						
	Inside to Inside		Middle to Middle		End to End	
	(24.73 mm)		(25.24mm)		(25.74 mm)	
Exp. No.	Thermal Conductivity, W/mK	Error, %	Thermal Conductivity, W/mK	Error, %	Thermal Conductivity, W/mK	Error, %
1	0.249	20.75	0.244	18.33	0.239	16.01
2	0.250	21.25	0.245	18.82	0.240	16.49
3	0.251	21.64	0.246	19.20	0.241	16.86
4	0.251	21.70	0.246	19.26	0.241	16.92

The amount of error in the second set of experiments (see Table 9) is similar but slightly less than the first set of experiments (see Table 8). Since the same setup yielded accurate results with distilled water, it is investigated whether the calibration liquid has an influence on the calibration procedure. The calibration procedure has been repeated using propylene glycol as the calibration liquid and the resulting equation is used to convert the resistance data to temperature data. The two calibration equations, T(R), are presented in equations 4.2 and 4.3 using water and propylene glycol as calibration liquid, respectively. The effect of the calibration liquid on the calibration procedure is negligible. The experimental data with the propylene glycol as the calibration liquid is presented in Table 10 and yielded slightly improved amount of error.

$$T = 1308.2\, R - 251.4 \qquad (4\text{-}2)$$

$$T = 1348.3\, R - 260.6 \qquad (4\text{-}3)$$

Table 10: Measured thermal conductivity of propylene glycol at 24.1 °C with the propylene glycol as the calibration liquid • 0.3 Amps of current supply is used for the Pt wire of 127 μm diameter

127 μm DIAMETER Pt WIRE (-1 < LN(T) < 2)						
	Inside to Inside		Middle to Middle		End to End	
	(24.73 mm)		(25.24mm)		(25.74 mm)	
Exp. No.	Thermal Conductivity , W/mK	Error, %	Thermal Conductivity, W/mK	Error, %	Thermal Conductivity, W/mK	Error, %
1	0.241	17.17	0.237	14.82	0.232	12.57
2	0.242	17.62	0.238	15.27	0.233	13.01
3	0.243	18.02	0.238	15.66	0.234	13.39
4	0.243	18.08	0.238	15.72	0.234	13.45
5	0.240	16.55	0.235	14.21	0.231	11.97
6	0.244	18.24	0.239	15.87	0.234	13.60
7	0.246	19.44	0.241	17.05	0.237	14.76
8	0.246	19.28	0.241	16.89	0.236	14.60
9	0.247	19.80	0.242	17.40	0.237	15.09

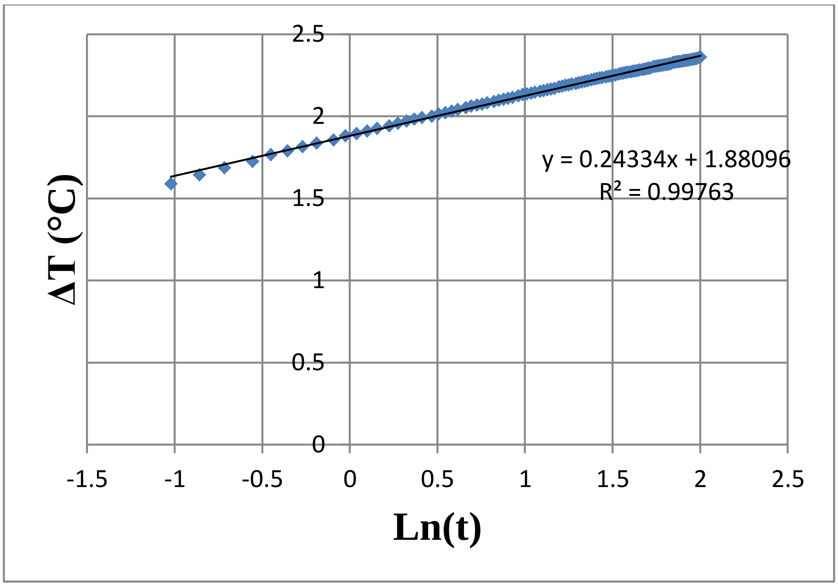


Figure 15: Representative ΔT vs ln(t) measured for propylene glycol at 24.7 °C with a Pt wire of 127 µm diameter and 0.3 Amps of current supply

4.2 Results of Validation Experiments Using Average Slope of ΔT vs ln(t)

After completing the validation experiments using various size wires and different fluids at various temperatures, the thermal conductivity measurements are conducted next with 127 µm diameter wire. The thermal conductivity of fluids is determined by calculating the average value of the slope of ΔT vs ln(t). A comparison of the two methods of determining the slope of ΔT vs ln(t) is presented in chapter 4.3.

Based on the experiments of chapter 4.1, the time range of $-1 < \ln(t) < 1.5$ is a compromise between different ranges that resulted in most accurate measurements. This range of time has been used for processing the data of the following experiments to determine the accuracy of the method.

4.2.1 Water at Room Temperature with a Pt Wire of 127 μm Diameter

The results of experiments using averaged slope of ΔT vs ln(t) plot for distilled water at room temperature are presented in Table 11 with a representative experimental data shown in Figure 16. Note that these results correspond to different experiments than the results presented in chapter 4.1.6. A comparison of the two methods is reported in chapter 4.3.

Table 11: Measured thermal conductivity of distilled water at 23.8 °C by using average slope • 0.6 Amps of current supply is used for a Pt wire of 127 μm diameter

127 μm DIAMETER Pt WIRE (-1 < LN(T) < 1.5)						
	Inside to Inside (24.52 mm)		Middle to Middle (24.96 mm)		End to End (25.39 mm)	
Exp. No.	Thermal Conductivity, W/mK	Error, %	Thermal Conductivity, W/mK	Error, %	Thermal Conductivit y, W/mK	Error, %
1	0.6013	1.98	0.5909	0.21	0.5808	-1.49
2	0.6009	1.92	0.5905	0.15	0.5805	-1.55
3	0.6024	2.17	0.5920	0.41	0.5819	-1.30
4	0.6002	1.79	0.5898	0.03	0.5798	-1.67
5	0.5996	1.70	0.5892	-0.06	0.5792	-1.76

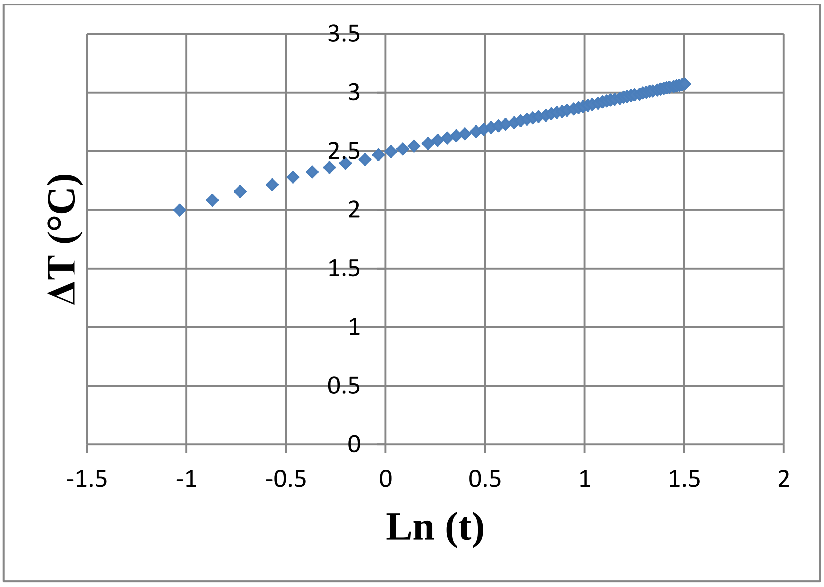


Figure 16: Representative ΔT vs ln(t) measured for distilled water at 23.8 °C using a Pt Wire of 127 μm diameter and 0.6 Amps of current supply

4.2.2 20% Sucrose solution at 52.5°C with a Pt Wire of 127 μm Diameter

The other type of liquid chosen for the validation is solution of sucrose and water. Sugar solutions typically have lower thermal conductivity than pure water [15, 16]. Here, the measurements on a biotechnology grade 20 weight % sucrose solution are presented. The results of the present experiments are compared against those reported by Riedel and others. Riedel [15] claimed that there is 1 % uncertainty in the thermal conductivity measurements at 50°C. The measured thermal conductivities are reported in Table 12 together with a representative experimental data shown in Figure 17.

Table 12: Measured thermal conductivity of 20 weight % sucrose solution at 52.5 °C using average slope with a Pt wire of 127 µm diameter and 0.5 Amps of current supply

127 µm DIAMETER Pt WIRE (-1 < LN(T) < 1.5)						
	Inside to Inside (24.52 mm)		Middle to Middle (24.96 mm)		End to End (25.39 mm)	
Exp. No.	Thermal Conductivity, W/mK	Error, %	Thermal Conductivity, W/mK	Error, %	Thermal Conductivity, W/mK	Error, %
1	0.585	1.83	0.575	0.07	0.565	-1.63
2	0.578	0.69	0.568	-1.05	0.559	-2.73
3	0.581	1.11	0.571	-0.64	0.561	-2.33
4	0.576	0.34	0.566	-1.40	0.557	-3.08
5	0.578	0.61	0.568	-1.13	0.558	-2.81
6	0.575	0.12	0.565	-1.61	0.556	-3.29
7	0.585	1.90	0.575	0.14	0.566	-1.56
8	0.583	1.45	0.573	-0.30	0.563	-2.00

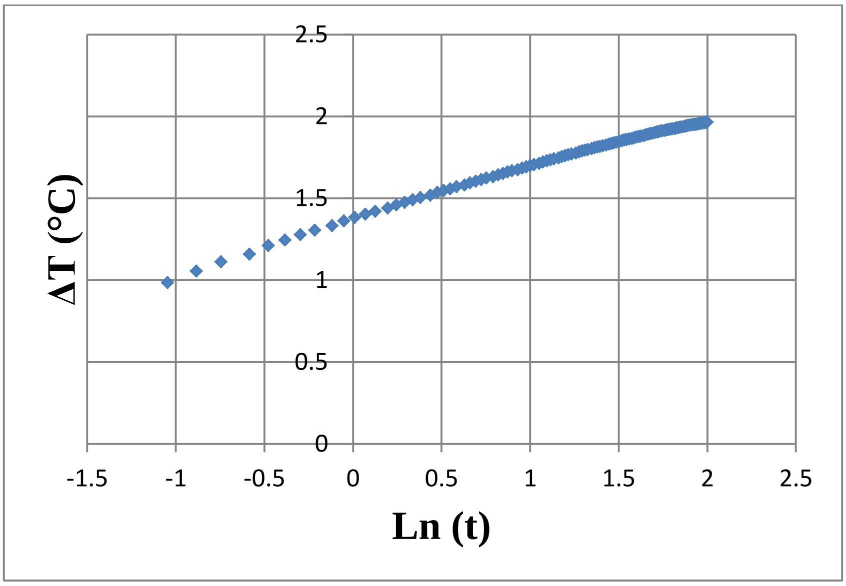


Figure 17: Representative ΔT vs ln(t) measured for 20 wt % sucrose solution at 52.5 °C using a Pt Wire of 127 µm diameter and 0.5 Amps of current supply

4.2.3 20% Sucrose solution at 82.5°C with a Pt Wire of 127 μm Diameter

The validation experiments on the biotechnology grade 20 weight % sucrose solution have been repeated at 82.5°C. The results of the present experiments are again compared with Riedel's measurements, [15]. The error reported in the tables corresponds to the difference between the present measurements and Riedel's measurements. The measured thermal conductivities are listed in Table 13 together with a sample of experimental data shown in Figure 18.

Table 13: Measured thermal conductivity of 20 weight % sucrose solution at 82.5 °C using average slope with a Pt wire of 127 μm diameter and 0.5 Amps of current supply

127 μm DIAMETER Pt WIRE (-1 < LN(T) < 1.5)						
	Inside to Inside		Middle to Middle		End to End	
	(24.52 mm)		(24.96 mm)		(25.39 mm)	
Exp. No.	Thermal Conductivity, W/mK	Error, %	Thermal Conductivity , W/mK	Error , %	Thermal Conductivity , W/mK	Error, %
1	0.634	4.90	0.623	3.09	0.613	1.34
2	0.630	4.21	0.619	2.40	0.609	0.66
3	0.636	5.18	0.625	3.36	0.614	1.60
4	0.627	3.66	0.616	1.87	0.606	0.13
5	0.624	3.25	0.614	1.47	0.603	-0.26
6	0.629	4.07	0.618	2.27	0.608	0.53
7	0.630	4.15	0.619	2.34	0.608	0.60
8	0.628	3.79	0.617	1.99	0.606	0.26

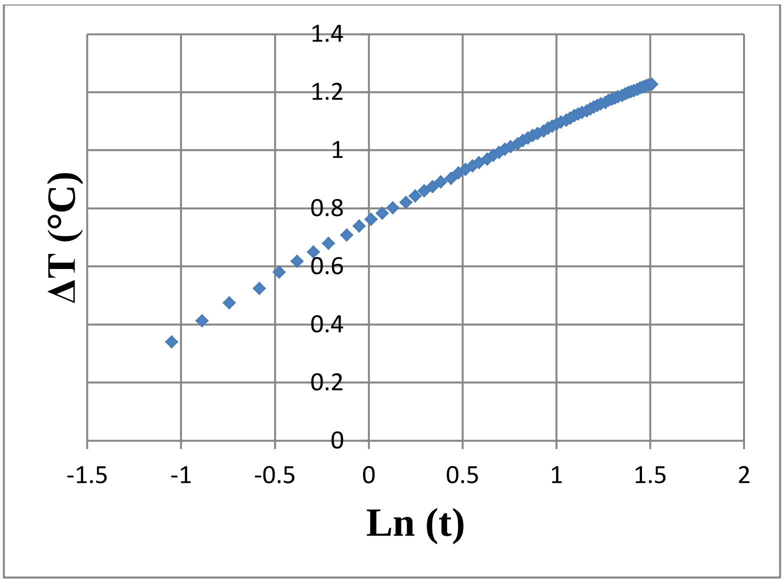


Figure 18: Representative ΔT vs ln(t) measured for 20 wt % sucrose solution as test liquid at 82.5 °C with a Pt Wire of 127 μm diameter and 0.5 Amps of current supply

4.2.4 40% Sugar solution at 51°C with a Pt Wire of 127 μm Diameter

A sugar solution of 39.7 weight % edible Domino regular sugar and water has been prepared and tested at two different temperatures. This percent composition is the same as the sucrose solution tested by Riedel [15]. Firstly, the experiments at 51°C are conducted and the measured thermal conductivities are compared with Riedel's results. The error reported in the tables corresponds to the difference between the present measurements and Riedel's measurements. The measured thermal conductivities are listed in Table 14 together with a sample of experimental data shown in Figure 19.

Table 14: Measured thermal conductivity of 40 weight % sugar solution at 51 °C using average slope with a Pt wire of 127 µm diameter and 0.5 Amps of current supply

127 µm DIAMETER Pt WIRE (-1 < LN(T) < 1.5)						
	Inside to Inside		Middle to Middle		End to End	
	(24.52 mm)		(24.96 mm)		(25.39 mm)	
Exp. No.	Thermal Conductivity, W/mK	Error, %	Thermal Conductivity, W/mK	Error, %	Thermal Conductivity, W/mK	Error, %
1	0.533	5.90	0.524	4.07	0.515	2.30
2	0.532	5.56	0.522	3.73	0.514	1.97
3	0.530	5.19	0.521	3.37	0.512	1.61
4	0.528	4.94	0.519	3.12	0.510	1.37
5	0.527	4.70	0.518	2.89	0.509	1.14
6	0.530	5.18	0.521	3.36	0.512	1.60

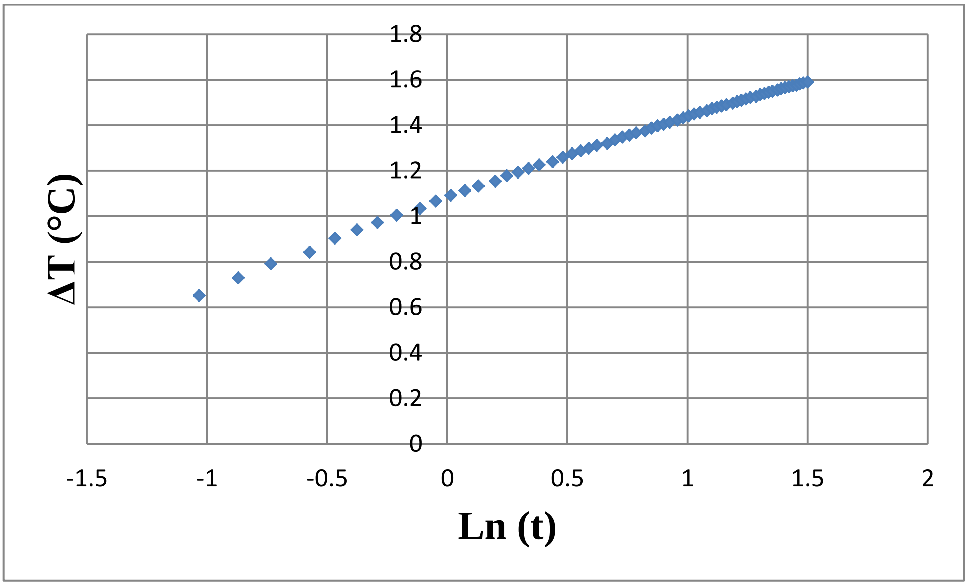


Figure 19: Representative ΔT vs ln(t) measured for 40 wt % sugar solution as test liquid at 51 °C with a Pt Wire of 127 µm diameter and 0.5 Amps of current supply

4.2.5 40% Sugar solution at 81.5 °C with a Pt Wire of 127 μm Diameter

Secondly, the experiments on the 40 wt % sugar solution at 81.5 °C are conducted and the measured thermal conductivities are compared with Riedel's results. The error reported in the tables corresponds to the difference between the present measurements and Riedel's measurements. The measured thermal conductivities are listed in Table 15 together with a sample of experimental data shown in Figure 20.

As indicated by the unusual 20-25 % overestimation, there is a dramatic issue of early start of natural convection with the sugar-water solution at this temperature. This trend has also been observed in the water experiments at 86°C as presented in chapter 4.1.8.

Table 15: Measured thermal conductivity of 40 weight % sugar solution at 81.5 °C using average slope with a Pt wire of 127 μm diameter and 0.5 Amps of current supply

127 μm DIAMETER Pt WIRE (-1 < LN(T) < 1.5)						
	Inside to Inside (24.52 mm)		Middle to Middle (24.96 mm)		End to End (25.39 mm)	
Exp. No.	Thermal Conductivity, W/mK	Error, %	Thermal Conductivity, W/mK	Error, %	Thermal Conductivity, W/mK	Error, %
1	0.657	24.16	0.646	22.02	0.635	19.94
2	0.664	25.56	0.653	23.39	0.642	21.29
3	0.656	24.00	0.645	21.86	0.634	19.78
4	0.656	23.95	0.645	21.81	0.634	19.74
5	0.654	23.67	0.643	21.53	0.632	19.47
6	0.656	23.87	0.644	21.72	0.633	19.65
7	0.653	23.47	0.642	21.33	0.631	19.27

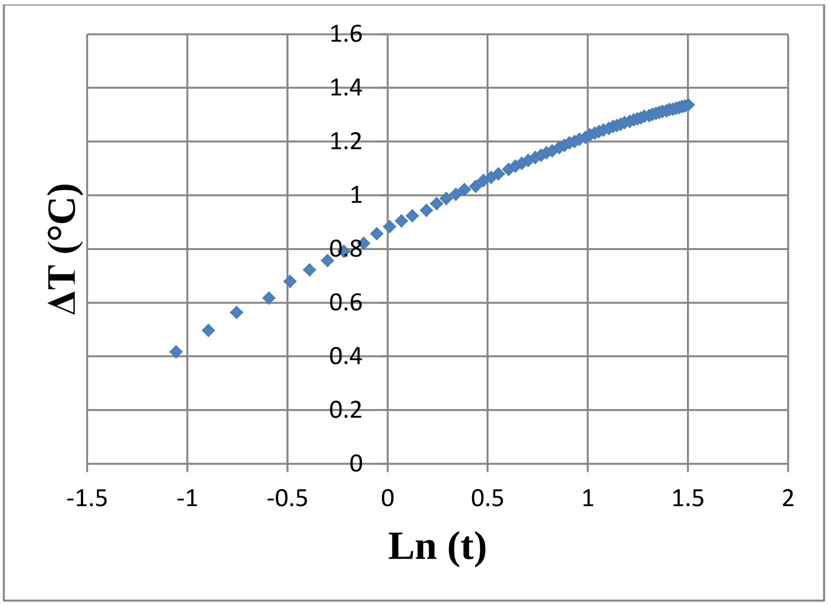


Figure 20: Representative ΔT vs ln(t) measured for 40 wt % sugar solution as test liquid at 81.5 °C with Pt Wire of 127 μm diameter and 0.5 Amps of current supply

4.3 Comparison of two methods of determining the slope of ΔT vs ln(t): Curve-Fitting and Average Slope

Two methods have been considered for the estimation of slope of experimental data of ΔT vs ln(t). The method of linear curve-fitting by least squares method is based on determining the slope and intercept of ΔT vs ln(t). On the other hand, the method of averaged slope is based on calculating the slope at every single data point and using the average of all these slope values. Two neighboring data points are used to calculate the slopes at each time. In an ideal case, the experimental data will be perfectly linear resulting in the same slopes by both methods.

The experiments of water at room temperature with a Pt wire of 127 µm diameter (chapter 4.2.1) have been reprocessed by estimating the slope using a least squares linear curve-fitting. The results are presented in Table 16 for comparison with the results by averaged slope in Table 11. The maximum error by curve fitting is 3.5 % for inside to inside measurement of length, while it is 2.2 % by the method of averaged slope for again inside to inside measurement of length. Although the method of average slope is used for the ternary mixture in chapter 5, both methods yield very close results and this uncertainty could be incorporated in the overall uncertainty of the present experimental setup.

Table 16: Measured thermal conductivity of distilled water at 23.8 °C using a linear curve-fitting with a Pt wire of 127 µm diameter and under 0.6 Amps of current

127 µm DIAMETER Pt WIRE (-1 < LN(T) < 2)						
	Inside to Inside (24.52 mm)		Middle to Middle (24.96 mm)		End to End (25.39 mm)	
Exp. No.	Thermal Conductivity, W/mK	Error, %	Thermal Conductivity, W/mK	Error, %	Thermal Conductivity, W/mK	Error, %
1	0.6076	3.051	0.5971	1.268	0.5869	-0.455
2	0.6086	3.216	0.5980	1.431	0.5879	-0.295
3	0.6103	3.513	0.5998	1.722	0.5895	-0.008
4	0.6083	3.172	0.5978	1.386	0.5876	-0.338
5	0.6083	3.171	0.5978	1.386	0.5876	-0.339

5 EXPERIMENTS ON TERNARY MIXTURE OF $LINO_3$ -$NANO_3$ -KNO_3 AT 134°C

For the measurement of thermal conductivity of ternary molten salts, a mixture with a composition of 30 mol % $LiNO_3$, 21 mol % $NaNO_3$ and 49 mol % KNO_3 is prepared by Dynalene Inc. This composition is commonly used in the industry [17] and close to the eutectic composition which is 37.5:18:44.5 mol % Li-Na-K NO_3 [18]. The melting point of the ternary composition used in this research (127 °C [17]) is slightly higher than the melting point of the eutectic composition (120 °C [18]). On the other hand, a cost analysis reveals the following unit prices of individual components [17]:

$LiNO_3$: $ 5/kg

$NaNO_3$: $ 0.75/kg

KNO_3: $ 1.30/kg

Using 30 mol % of $LiNO_3$ instead of 37.5 mol %, reduces the costs in mass scale production considerably while the melting point of the composition increases only 7 °C. For this reason, the composition of 30:21:49 mol % Li-Na-K NO_3 is preferred by Dynalene Inc. for industrial scale production. [17]

The same experimental setup and method of average slope described in chapter 4.2 has been used to measure the ternary mixture of molten salt nitrate of Li-Na-K NO_3. The hot wire is a Pt wire of 127 μm diameter and the wires connecting the sourcemeter and voltmeter to the cell are again plastic coated. A thermocouple with a sufficiently long probe has been used to observe the equilibrium temperature.

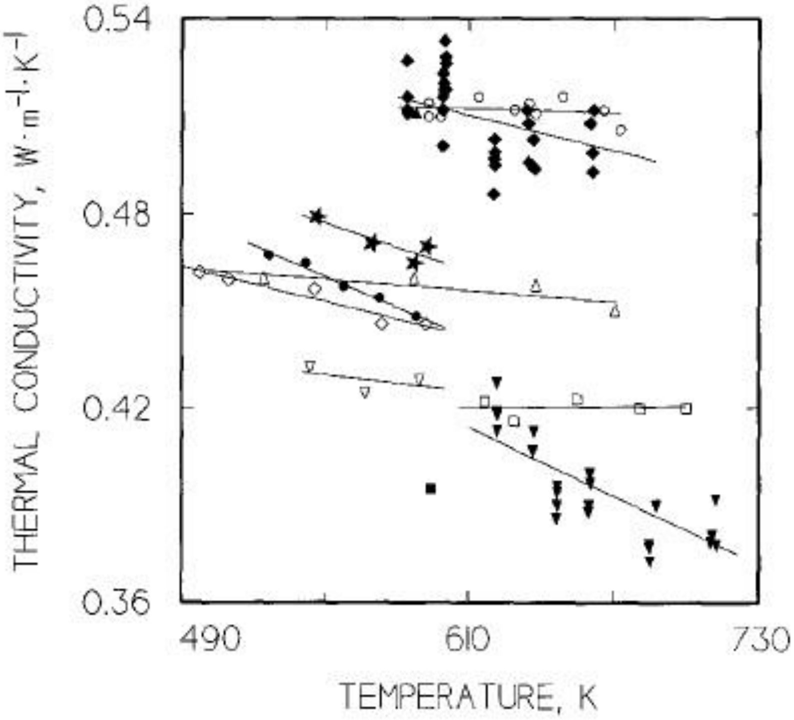
The results of experiments are presented in Table 17 for the measurement of length from middle of one soldering connection to the middle of the other soldering connection (24.96 mm). This length is preferred since it is a compromise between inside to inside and end to end measurement of length. The estimated uncertainty in the measurement of thermal conductivity with the present apparatus is around 5 %. This is the uncertainty observed in the validation experiments and also includes the uncertainty due to the different measurements of length.

Table 17: Measured thermal conductivity of ternary mixture of 30:21:49 mol % $LiNO_3$-$NaNO_3$-KNO_3 at 134°C with several repeated experiments

Exp. No	Measured thermal conductivity, W/mK
1	0.439
2	0.439
3	0.439
4	0.436
5	0.438
6	0.438
7	0.437
8	0.438
9	0.439
10	0.438
11	0.439
12	0.438
13	0.438
14	0.438
15	0.438

The average value and standard deviation of the measured thermal conductivities of the 15 experiments are 0.438 W/mK and 8.27E-4 W/mK.

The thermal conductivity data of ternary mixtures of molten salt nitrates is rather scarce in the literature. Therefore, the measured thermal conductivity of the present research is compared to the thermal conductivity of the binary mixtures of the same components reported in earlier studies. DiGuilio et.al compiled the literature data for the thermal conductivity of single components and binary mixtures of $NaNO_3$ and KNO_3 as shown in Figure 21. The thermal conductivity of binary mixture of $NaNO_3$ - KNO_3 is documented to be between 0.42 W/mK and 0.48 W/mK over the temperature range from 217°C to 337°C depending on the composition. Thus, the measured thermal conductivity of 0.438 W/mK of ternary mixture of 30:21:49 mol % $LiNO_3$-$NaNO_3$-KNO_3 is regarded as plausible and suggested within the accuracy of 5 %.



The thermal conductivity of $NaNO_3$–KNO_3 mixtures: (●) 46 mol% $NaNO_3$, this work; (◆) $NaNO_3$ and (▼) KNO_3, Kitade et al. [28]; (○) $NaNO_3$, (△) 50 mol% $NaNO_3$, and (□) KNO_3, Tufeu et al. [29]; (▲) $NaNO_3$, (★) 75 mol% $NaNO_3$, (◇) 50 mol% $NaNO_3$, (▽) 30 mol% $NaNO_3$, and (■) 10 mol% $NaNO_3$, Omotani et al. [2].

Figure 21: Comparison of literature for thermal conductivity of single components and binary mixtures of $NaNO_3$ and KNO_3 by [19]

6 CONCLUSIONS

Binary and ternary mixtures of molten salt nitrates have vital applications as heat transfer fluids in solar power tower plants. However, the thermal conductivity data of ternary mixtures of molten salt nitrates is very limited in the literature. The measurement of thermal conductivity of ternary mixture of 30:21:49 mol % $LiNO_3$-$NaNO_3$-KNO_3 is conducted in the present study. This composition is preferred for cost effectiveness since its melting point is only 7°C higher than the melting point of the eutectic mixture of 37.5:18:44.5 mol % $LiNO_3$-$NaNO_3$-KNO_3.

The transient hot wire method assumes that the hot wire is infinitely long and thin in order to eliminate the end effects and validate the one term series solution. To understand the characteristics of the measurement system, four platinum wires of different diameters (1 mm, 500 µm, 250 µm and 127 µm) and same length (~25 mm) have been employed in the device. A nonlinear trend for 1 mm diameter wire and linear trends with the other wires have been observed. Significant decreases in the overall level of experimental uncertainty have been observed for wires with a smaller diameter. On the other hand, the effect of the neglected terms of the series solution has been investigated for the Fourier number at 3 sec. Least contribution from the neglected terms has been found for 127 µm diameter wire as expected.

The optimal current supply for the experimental conditions has been found. When a larger current than the optimal current is supplied, the onset of natural convection occurs earlier. A smaller current supply than the optimal one causes environmental disturbances to interfere in the voltage measurement. As an example, for the platinum wire of 127 μm diameter, the optimal current supply is around 0.6 Amps for water and 0.3 Amps for propylene glycol.

Four different test liquids have been tried in order to verify the accuracy of the experimental system including the Pt wire of 127 μm diameter. In the validation experiments with distilled water, the onset of convective heat transfer has been observed to start earlier as the temperature of the sample increases. However, an uncertainty level of around 5 % has been maintained by adjusting the time range used in determining the slope of temperature rise vs logarithm of time (ΔT vs $\ln(t)$). Eventually, the effective time range has been decided to be $-1 < \ln(t) < 1.5$ as a compromise between different range that resulted in high accuracy. Propylene glycol experiments conducted at room temperature suffer considerable error. This situation has been attributed to the low thermal conductivity of propylene glycol (0.206 W/mK at 25°C) which, as a result, behaves more like an insulation. 20 wieght % sucrose and 40 weight % sugar solutions have been tested at 52°C and 82°C. Once again, highly repeatable results with 5 % accuracy have been obtained. Determining the length of wire resulted in most of the uncertainty (~3.5 %). The end effects due to the finite length of wire might constitute a second major source of error.

Finally, thermal conductivity of ternary mixture of 30 mol % $LiNO_3$, 21 mol % $NaNO_3$ and 49 mol % KNO_3 has been measured at 134°C. This composition of molten salt nitrates is commonly used in solar power industry since it is close to the eutectic composition and more cost-effective than the eutectic mixture in large scale production. The experiments have been repeated 15 times to reduce the level of random error in the measurements. The average thermal conductivity is measured to be 0.438 W/mK with a standard deviation of 8.27E-4 W/mK. The literature survey revealed little information on the thermal conductivity of ternary mixtures. The thermal conductivity of binary mixture of $NaNO_3$ - KNO_3 is reported to be between 0.42 W/mK and 0.48 W/mK depending on the composition, over the temperature range from 217°C to 337°C. Thus, the value of 0.438 W/mK is evaluated to be plausible for the thermal conductivity of ternary mixtures of molten salt nitrates.

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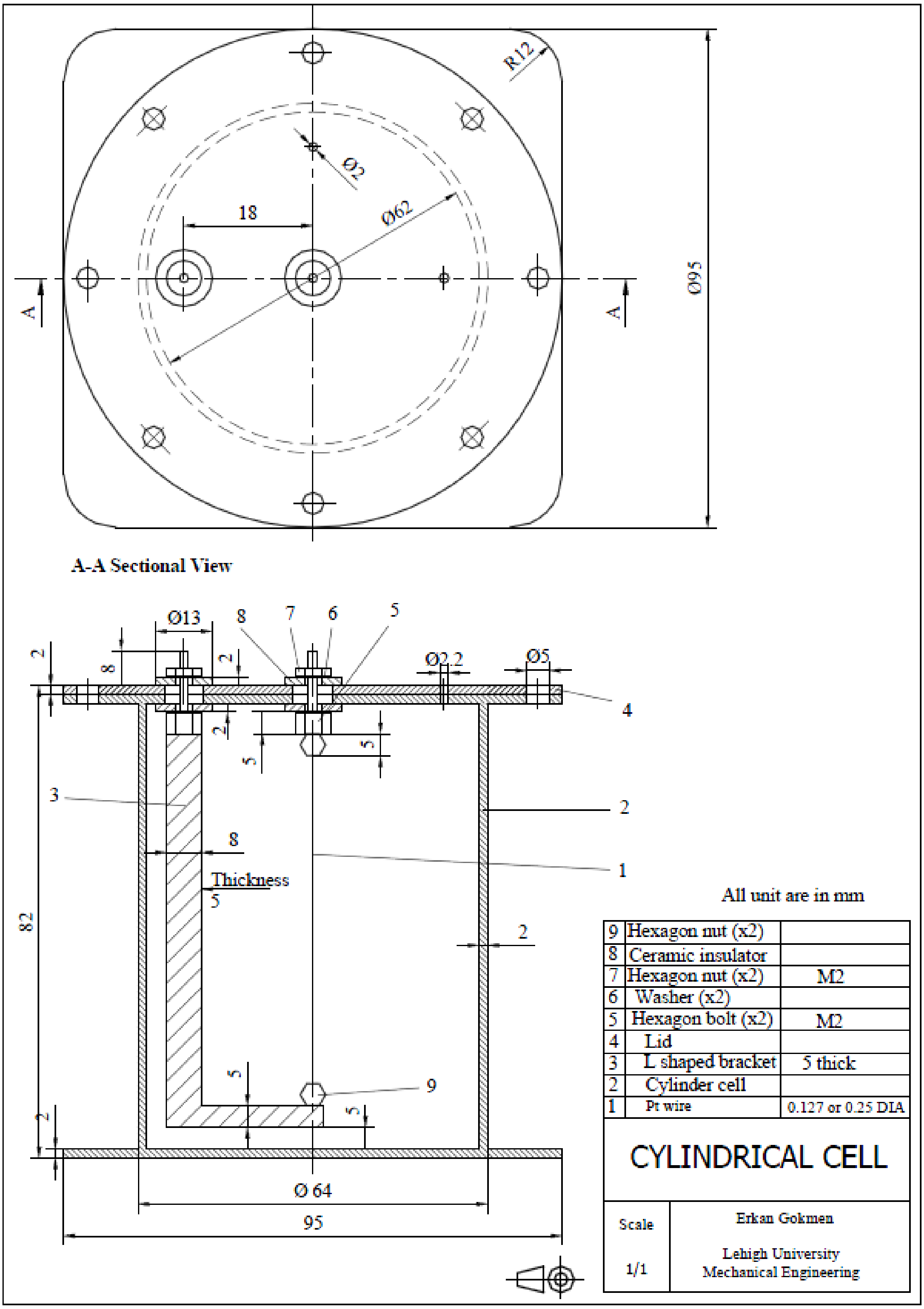
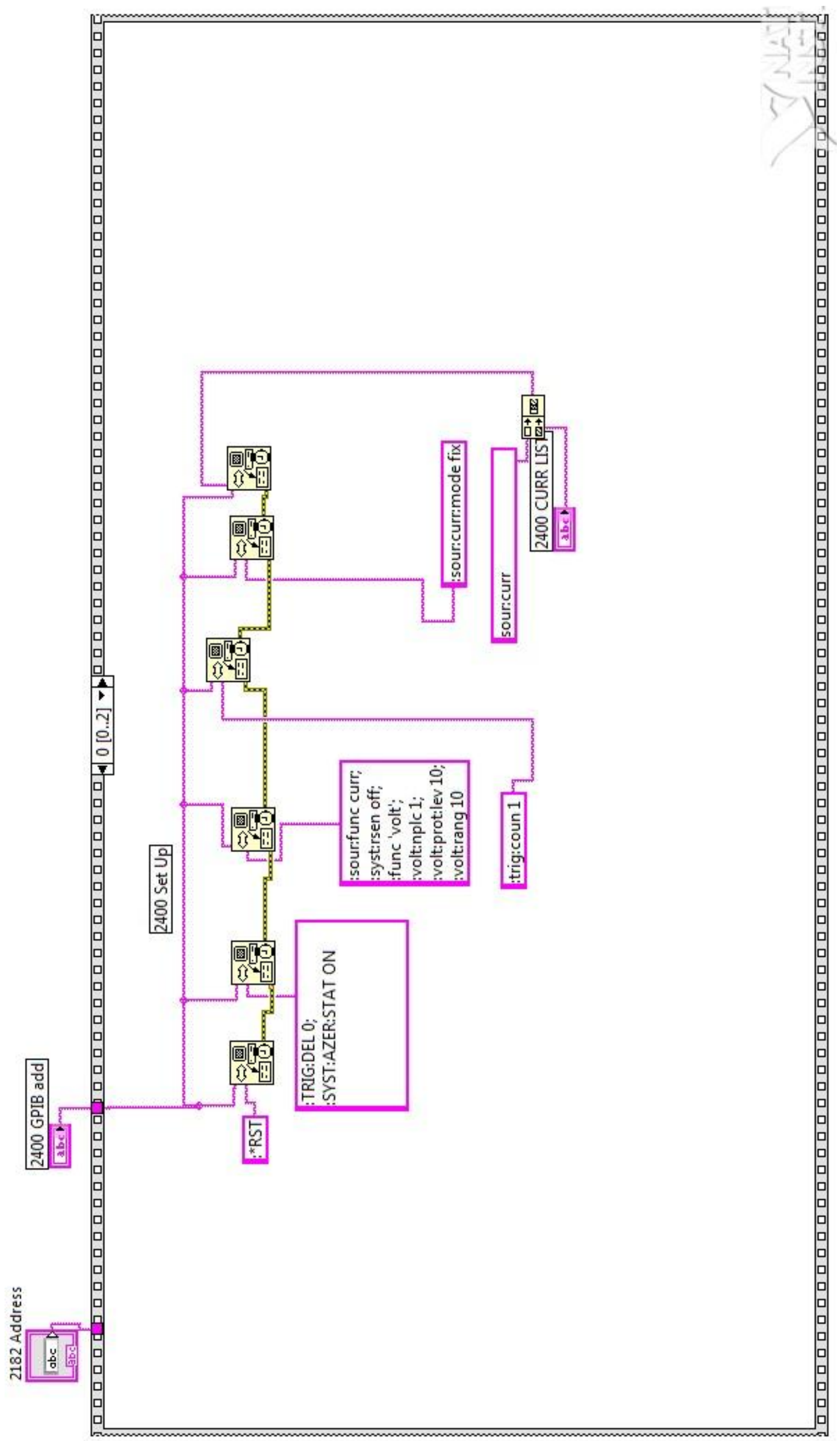
APPENDIX A

Technical Drawing of the stainless steel cell and wire fixture



APPENDIX B

Frame number 0 of the block diagram of Labview code



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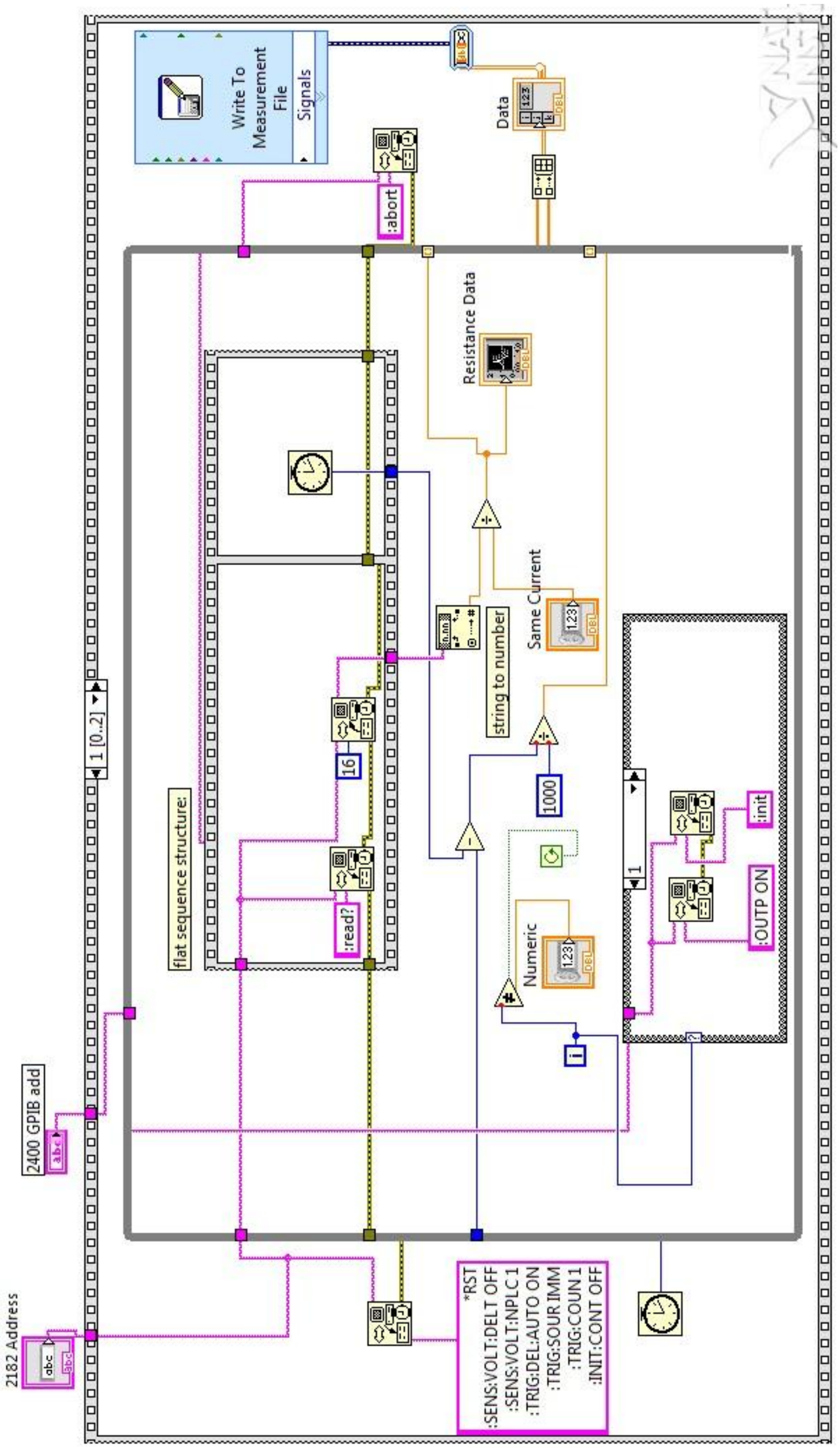

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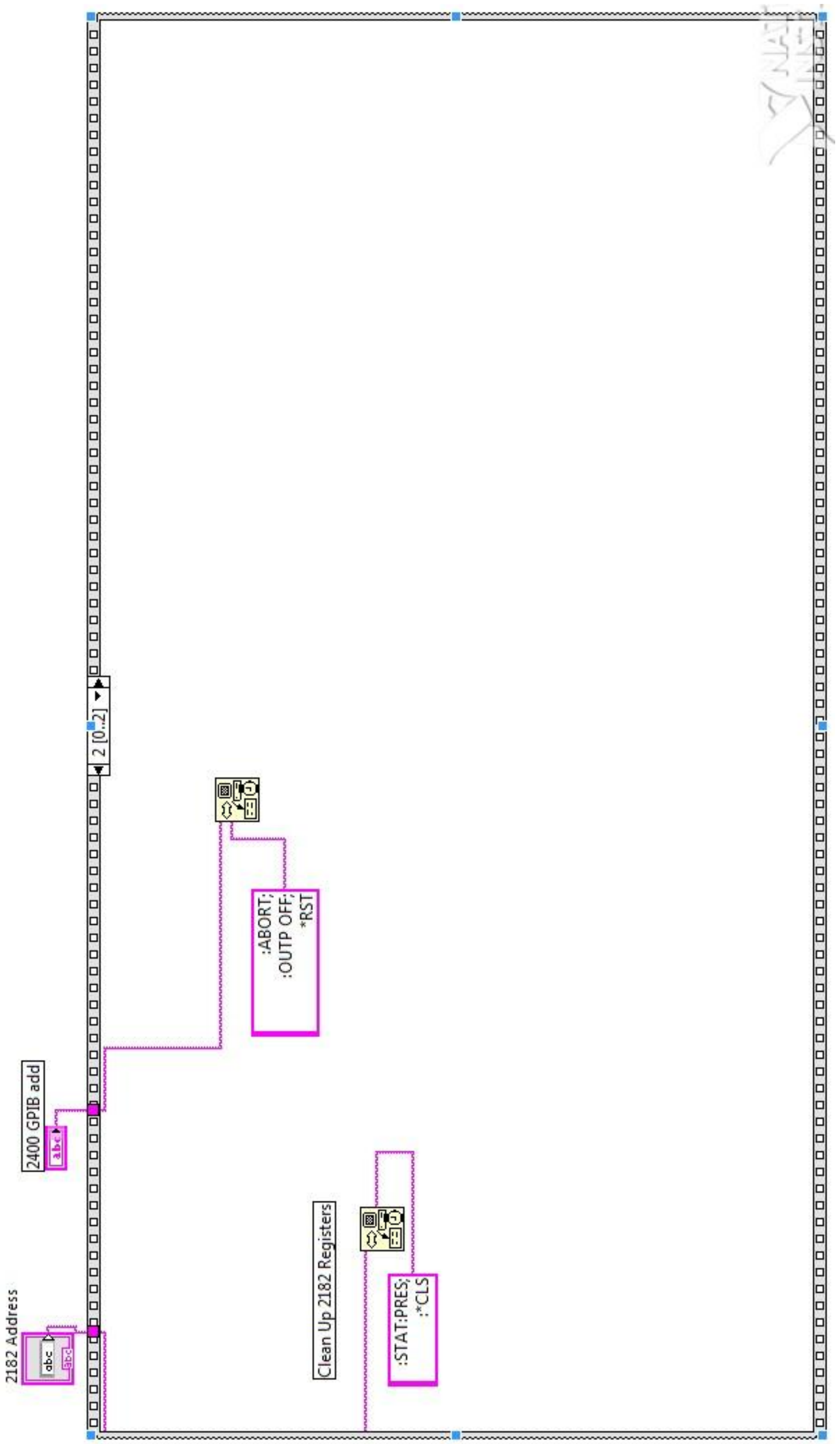
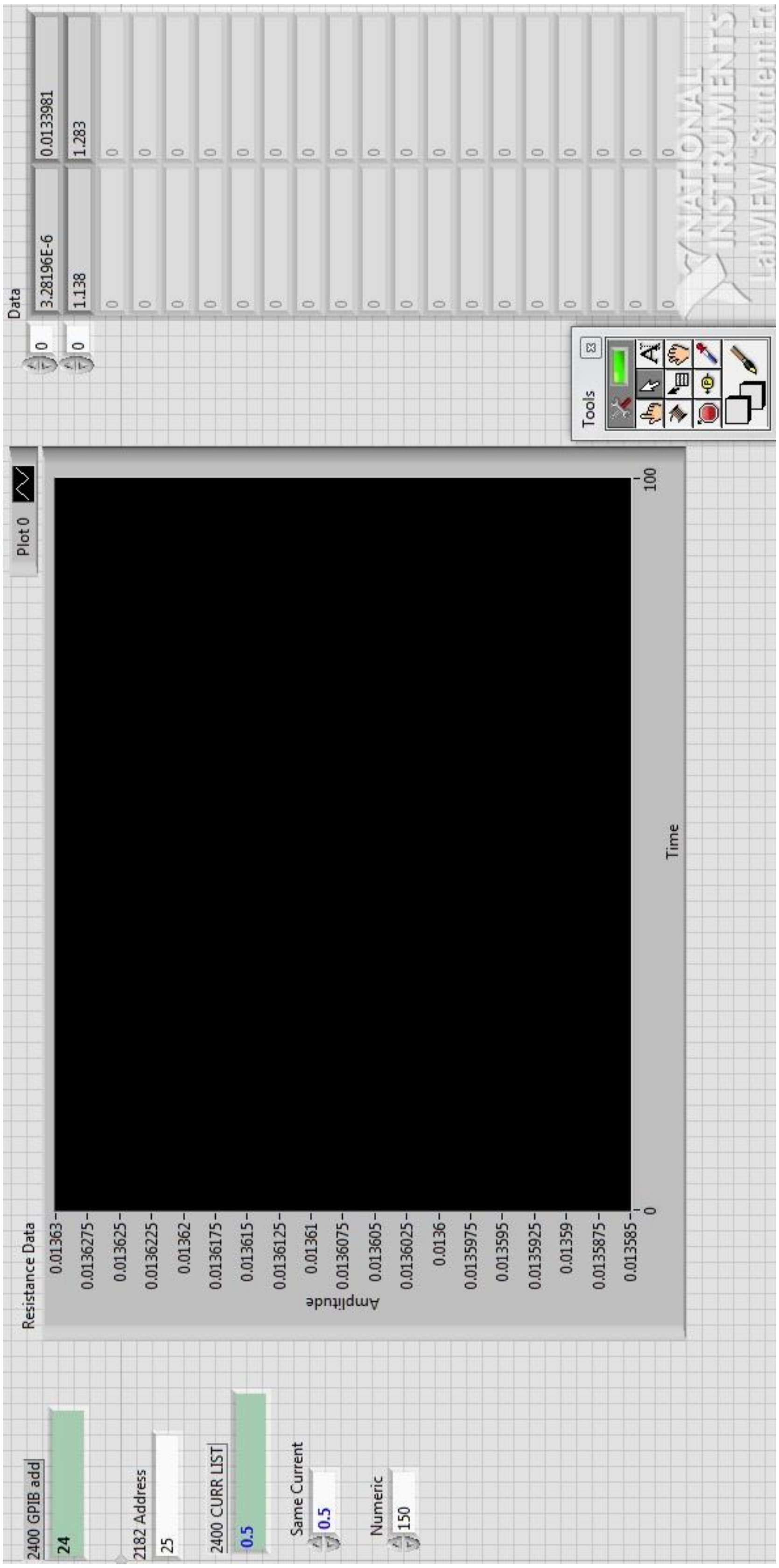


Front panel of the Labview code



VITA

Erkan Gokmen was born in 1988 in Bulgaria. Raised in Bursa, Turkey, he graduated with honors from the Department of Mechanical Engineering at Istanbul Technical University in June, 2011. He continued the Master of Science Program in Mechanical Engineering and Mechanics at Lehigh University. He is currently submitting this thesis as part of requirements of a Master of Science Degree. His primary areas of interest in Mechanical Engineering are energy topics including fluid mechanics, heat transfer, thermodynamics, power plants, turbomachinery etc.