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A hot-wire method based thermal conductivity measurement apparatus for teaching purposes

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Abstract

The implementation of an automated system based on the hot-wire technique is described for the measurement of the thermal conductivity of liquids using equipment easily available in modern physics laboratories at high schools and universities (basically a precision current source and a voltage meter, a data acquisition card, a personal computer and a high purity platinum wire). The wire, which is immersed in the investigated sample, is heated by passing a constant electrical current through it, and its temperature evolution, ΔT, is measured as a function of time, t, for several values of the current. A straightforward methodology is then used for data processing in order to obtain the liquid thermal conductivity. The start point is the well known linear relationship between ΔT and $\ln(t)$ predicted for long heating times by a model based on a solution of the heat conduction equation for an infinite lineal heat source embedded in an infinite medium into which heat is conducted without convective and radiative heat losses. A criterion is used to verify that the selected linear region is the one that matches the conditions imposed by the theoretical model. As a consequence the method involves least-squares fits in linear, semi-logarithmic (semi-log) and log–log graphs, so that it becomes attractive not only to teach about heat transfer and thermal properties measurement techniques, but also as a good exercise for students of undergraduate courses of physics and engineering learning about these kinds of mathematical functional relationships between variables. The functionality of the experiment was demonstrated by measuring the thermal conductivity in samples of liquids with well known thermal properties.

(Some figures may appear in colour only in the online journal)

1. Introduction

In the last years we have witnessed increasing interest in the measurement of thermal conductivity of liquids due to the development of special heat transfer fluids such as colloidal suspensions of nanometric size particles (the so-called nanofluids) [1] and thermal wave fluids, e.g. certain emulsions [2], among others. From the several methods proposed for the measurement of thermal conductivity, the hot-wire technique (for a time line of its historical evolution see the recent published paper by Assael *et al* [3]) is one of the most popular and well established. The majority of the published works make use of this technique, which can be considered a standard method with whose results the results obtained with any new developed method should be compared. Therefore, the hot-wire method is a valuable technique in any laboratory dedicated to heat transfer studies and it has gained impetus from the familiarization of students with its basic principles and applications.

Although several works have been published to promote familiarization and interest of students in heat transfer phenomena [4–13] and many undergraduate laboratory experiments have been proposed for thermal characterization of materials [5, 14–16], to the authors' knowledge there are only a few reports in the educational literature on thermal characterization of fluids (gases and liquids) by the hot-wire technique [17–20]. However, as will be seen later, there are still some aspects concerning this method that should be exploited in detail for teaching purposes from both the experimental point of view and the data processing procedure.

In this paper an experiment for teaching purposes based on the hot-wire method will be described, which can be easily implemented in undergraduate laboratories. It is based on the measurement of the temporal history of the temperature rise caused by a linear heat source (hot wire) embedded in a test material. If the wire is heated by passing a constant electrical current through it, i.e. by Joule's effect, the rise in its temperature will be dependent on the thermal conductivity of the surrounding material. In the most used approach this parameter can be determined straightforwardly from the linear part of a graph of the temperature rise, ΔT, as a function of the natural logarithm of the measurement time, t. In the majority of the published works [3, 17] the temperature rise is determined from the measurement of the induced resistance changes in the hot wire located in place of the unknown resistance of a resistance bridge (for example, a Wheatstone bridge), and using the well known (or previously measured) temperature coefficient of resistance of the wire. In these works the linear region in a semi-log plot is often selected arbitrarily, without attention to the well known fact that one can always find in a nonlinear curve a narrow enough data interval in which a linear relationship between the involved variables can be established. Taking this into account, in this paper we describe a methodology for the accurate determination of the sample's thermal conductivity that includes a criterion to select the correct work region in the ΔT versus $\ln(t)$ curve [21], i.e. the region for which the initial conditions and hypotheses of the theoretical model are well fulfilled. Our experimental approach uses a current source and a nanovoltmeter instead of the above mentioned resistance bridge allowing measurements of the voltage drop across the heated wire, which is proportional to the temperature changes, as a function of time for different heating electrical current values. The usefulness of the method is proved with measurements in various test liquids. The experimental system is fully automated using a low cost data acquisition card from National Instruments and software developed with LabVIEW.

The proposed experiment can be used in graduate and/or advanced courses of chemistry, physics and engineering to learn about heat transfer theoretical fundamentals (that involve the use of linear and partial differential equations), thermal properties measurement techniques, electronic instrumentation, automatic experiment control and data acquisition techniques, among related topics. As the proposed experimental methodology makes use of linear, exponential and potential dependences between the measured variables, and because linear fits in linear, semi-log and log–log plots are needed for data processing, the experiment can also be used to learn about these kinds of mathematical functional relationships between variables. The experiment also involves both direct and indirect measurements so that it can also permit students to learn about experimental uncertainty analysis techniques such as error propagation.

This paper is organized as follows. In the next section the theoretical details behind the proposed methodology will be proposed. In section 3 the experimental setup will be described and in section 4 the experimental results obtained with measurements in various samples of known thermal conductivity will be presented and discussed, with emphasis on data processing details. Finally, in section 5 the conclusions will be drawn.

2. Basic theory and proposed methodology

2.1. The hot-wire technique

The hot-wire technique is part of a group of methods that use a transient flow of heat to determine the thermal conductivity. The use of transient heat flow is advantageous over steady state methods for rapid measurements. The transient methods are based on the transfer of heat from a controlled source to a material and measuring the temperature changes caused by heat dissipation to determine the thermal properties as a function of time. The hot-wire technique, particularly, is a good method to determine the thermal conductivity of materials, such as liquids, that fit well around a thin wire working as both a heat source and a temperature sensor. Therefore, many applications have appeared in the field of liquid characterization.

The mathematical model developed for the hot-wire method considers a thin and infinitely long linear heat source (a wire) with a uniform distribution of temperature, throughout immersed in a homogeneous and infinite test sample. The general assumption is that, as a result of conductive heat transfer to the sample, the temperature of the source varies with time. The governing equation of this phenomenon is derived from the non-stationary heat diffusion Fourier equation with proper boundary conditions. The solution is well known [22]. For large enough measurement times so that $t \gg r^2/\alpha = \tau$, where r is the wire radius and α is the sample thermal diffusivity, and neglecting heat losses by convection and radiation, it leads to

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

Here $\Delta T(t) = T(t) - T_0$, where $T(t)$ is the temperature at any time and T_0 the initial temperature, k is the thermal conductivity of the sample, q is the heat flow per unit length of the source and $\ln(C) = \gamma = 0.5772$ is Euler's constant.

2.2. Methodology for determining the thermal conductivity

It is advantageous to use the heated wire also as the sensor of its temperature. This is possible using the well known relationship existing for metals between their electrical resistivity and the temperature [23] given by the following equation:

$$R(t) = R_0(1 + \sigma\Delta T(t)), \tag{2}$$

where σ is the temperature coefficient of the metallic wire resistivity, R_0 is the initial resistance of the wire at room temperature, T_0, and $\Delta T(t) = T(t) - T_0$. Suppose that we heat a metallic wire by passing an electrical current, I, through it, thus converting electrical energy into heat by the Joule effect. A steady flow of heat is established into the sample so that the wire's temperature will change with time. As a result the electrical resistance, R, of the wire changes causing a time varying potential difference, V, between the ends of the wire that is given by the following equation:

$$V(t) = R(t)I = R_0(1 + \sigma \Delta T(t))I. \tag{3}$$

Here we neglected higher order terms in the resistance dependence on temperature [23]. Substituting equation (1) in equation (3), the potential difference between two points separated by a distance L in a straight and infinite cylindrical wire is

$$V(t) = IR_0 \left\{ 1 + \sigma \left[\frac{q}{4\pi k} \ln \frac{4t}{\tau C} \right] \right\}, \tag{4}$$

where $q = I^2 R_0/L$. Equation (4) may be rewritten as

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

Here $\Delta V(t) = V(t) - V_0$, where $V(t)$ is the voltage at any time and V_0 the initial voltage, $m = IR_0 \sigma q/4\pi k$ and $B = m \; \ln \left({}^{4}\!/_{\tau C} \right)$. Differentiating equation (5) with respect to ln(t), we obtain

$$\frac{\mathrm{d}\Delta V(t)}{\mathrm{d}(\ln t)} = m = \frac{I^3 R_0^2 \sigma}{4\pi L k}, \tag{6}$$

where the slope m can be obtained by making a least-squares fit in the linear region of the curve ΔV versus ln(t). If R_0, σ and I are known then the thermal conductivity (k) can be calculated from the value of m. This is the methodology usually used by the majority of authors [21]. But here the following question arises: is the selected linear region the one that matches the criteria involved in the physical model?

2.2.1. Verification of the linearity of the curve ΔV versus ln*(t).* Equation (6) can be rewritten as follows:

$$m = bI^3, \tag{7}$$

where

$$b = \frac{R_0^2 \sigma}{4\pi L k}. \tag{8}$$

Taking the natural logarithm of equation (7), it leads to

$$\ln(m) = 3 \ln(I) + \ln(b). \tag{9}$$

Thus, the experiment described in the previous subsection can be performed for different values of the electrical current, I, so that m can be plotted versus I in a double logarithmic scale graph. If according to equation (9) the slope of this graph is equal to 3, then one can be sure that the selected linear regions in the curves of ΔV versus ln(t) are the correct ones. This verification criterion could be unsatisfied in the regions of the curves ΔV versus ln(t) where transient phenomena are present at the beginning of the measurement or when convection heat losses become important, as will be seen later.

2.2.2. Determination of the thermal conductivity. From equation (7) it can be seen that a linear dependence exists between the slopes m and the values of I^3. In other words, the curve m versus I^3 is a straight line with slope equal to b, from which the thermal conductivity can be calculated using equation (8). The value of R_0 in equation (8) is taken as an average of the values measured for this parameter at very low current levels before each experiment.

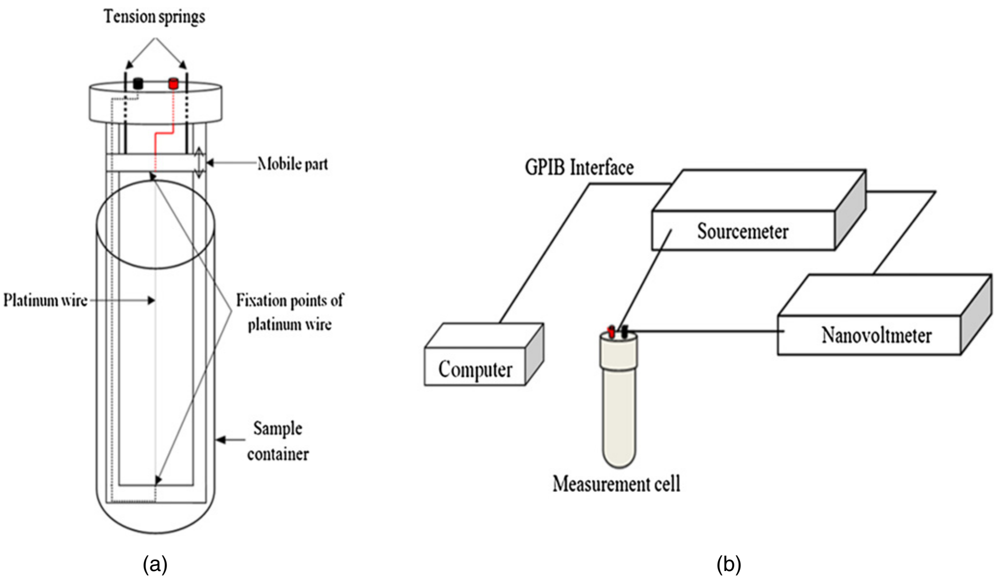

Figure 1. (a) The entire assembly of the hot-wire cell. The mobile part permits us to adjust the tension of the platinum wire and this tension is regulated with a pair of springs. On the top of the supporter are two connectors for the electrical connections. (b) Experimental setup scheme. The current source is a sourcemeter Keithley 2400 and the voltage drops are measured with a nanovoltmeter Keithley 2182A. They communicate with a computer through a GPIB interface (NI GPIB-USB-HS) using the software 'Hot-Wire' developed in LabView®.

3. Experimental apparatus

In our experimental setup the heat source is a 76.2 μm diameter platinum wire (Alfa Aesar Platinum wire www.alfa.com) whose length L is 0.12 m. It is mounted on a support manufactured in Nylamid® M and the entire assemble is introduced into a 15.5 cm long and 3.81 cm diameter copper test tube as shown in figure 1(a). Thus the volume of fluid required to cover the platinum wire is about 152 ml. This can be a large volume for some research applications but appropriate for teaching purposes where measurements will be mainly carried out with low cost easily available fluids.

The whole experimental arrangement is represented in figure 1(b). In our experimental arrangement the current values were varied from 50 to 110 mA and better accuracy was achieved using four-wire remote sensing, which eliminates the resistance of connection cabling. The measurement speed of the nanovoltmeter was fixed by setting the integration time of the A/D converter. In the experimental setup a medium (1 PLC) integration time has been selected for which the compromise between noise performance and speed is acceptable and the number of measurement points is enough for calculations.

The software made in LabView® allows the automatic control of the instrument, data acquisition and storage of the obtained data. The parameters controlled with the software were the voltage and current supplied by the source, the name assigned to the data file for storage and the number of measurements and the speed with which they are obtained by the nanovoltmeter.

The sample container is thermally stabilized using a homemade system (not shown in the figure), but a commercial thermal bath can be used as well. Although the experiment can be

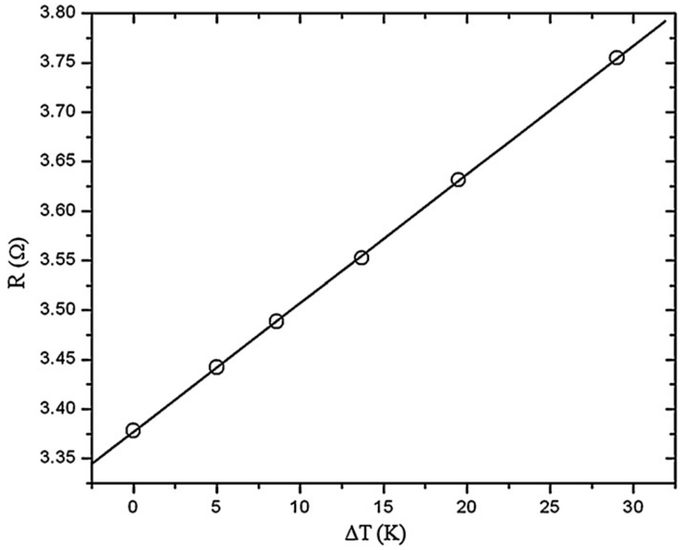

Figure 2. Typical plot of wire resistance versus temperature for determining the temperature coefficient of resistivity. The solid line is the best least-squares fit.

performed at room temperature, careful control of its value is recommended in order to avoid undesirable fluctuations in the voltage versus time curves.

Our experimental device provides fast and accurate data collection with precise instrument control and automated data collection. The automation of the experiment significantly reduces the amount of time spent by a student in collecting data, and provides digitalized formats that lend themselves to easy display, analysis and comparison of the data. The acquired data can be saved in a data file, permitting detailed data analysis and display using software such as Microcal ORIGIN.

4. Results and discussion

The first step in the calibration of the instrument is the determination of the temperature coefficient of resistance of the platinum wire, σ, which, as can be seen in equation (8), is a parameter necessary for the calculation of thermal conductivity (k). Furthermore, the student can see the relationship between the electrical resistance of a metal and its temperature.

From equation (2), for determining the value of the coefficient σ, the electrical resistance of the wire was measured at different temperature values. A corresponding graph is shown in figure 2. The slope (s) and the intercept (R_0) are given by the least-squares fit of the curve $R(t)$ where $s = \sigma \cdot R_0 = (1.300 \pm 0.007) \times 10^{-2}\ \Omega\ \mathrm{K}^{-1}$ and $R_0 = (3.377 \pm 0.001)\ \Omega$. (Here a discussion with students about the concepts of electrical resistivity and resistance is useful. While the latter depends on the wire length, the former parameter is a material intrinsic property independent of dimensions and geometry.)

Using the slope and intercept the value $\sigma = (0.003\,85 \pm 0.000\,02)\ \mathrm{K}^{-1}$ was calculated, in agreement with the value reported by other authors for this temperature range [23].

To continue with the calibration and verification of the correct operation of this instrument, the thermal conductivity of the following liquids was measured: glycerin, ethylene glycol, water, methanol and motor oil SAE 50, commonly used as test samples [24–26], because they

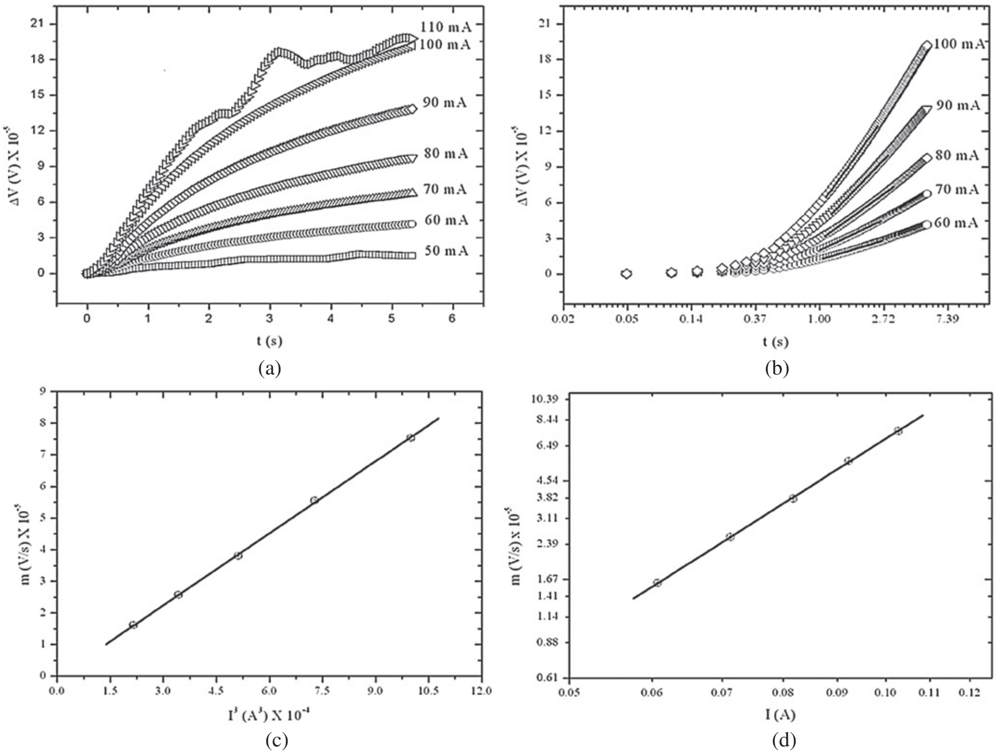

Figure 3.(a) Voltage increase versus time for different heating electrical current values. (b) Semi-log plot of the voltage increase versus time for different current values showing with solid lines the results of the best least-squares linear fit over the linear regions of the curves. (c) Linear plot of the slopes (m) versus cubic current values (I^3). The solid line represents the best least-squares linear fit; from it the value of the parameter b is equal to 0.0758 ± 0.0007, giving a value for the thermal conductivity of 0.208 ± 0.009 W m^{-1} K. (d) Plot of the slopes ln(m) versus ln(I). The solid line represents the results of the best least-squares linear fit and it has a slope of 3.03 ± 0.02 (see table 1).

have well known thermal properties. Measurements were carried out at a temperature of the thermal bath of (290 ± 1) K.

Figure 3 shows typical results obtained for a methanol sample. As mentioned above the theoretical model of the hot-wire technique considers only heat transfer by conduction, and a great advantage of this technique is the easy way to identify when convection appears. This mode of heat dissipation causes appreciable deviations in the behaviour of the ΔV versus t curve when the heating current exceeds a certain value. This can be appreciated in figure 3(a) for the measurement carried out with 110 mA, where deviations are found in the path of the curve revealing the presence of convection. Thus this measurement will not be used to determine the thermal conductivity. The 50 mA curve is also discarded because the temperature variation is very small and the electrical noise present is significant in that case. Figure 3(b) shows a plot of ΔV versus ln(t). The solid lines represent the best least-squares linear fits following equation (6) from which the slopes m are obtained. The linear regions in the graph of figure 3(b) have been selected by trial and error according to the discussion in section 2.2.1. Figure 3(c) shows that the slope of the least-squares fit of the graph ln(m) versus ln(I) is equal to 3.03 ± 0.02, close to 3, the value required by equation (9). Finally,

Table 1. Experimental results. Reported values of the thermal conductivities were taken from [27].

Sample	Slope of the ln(m) versus ln(I) curve	k (measured) (W m^{-1} K)	k (reported) (W m^{-1} K)
Ethylene glycol (J T Baker 99.90%)	3.01 ± 0.01	0.252 ± 0.009	0.256
Distilled water Q.P.	3.010 ± 0.007	0.59 ± 0.03	0.609
Methanol (J T Baker 99.90%)	3.03 ± 0.02	0.208 ± 0.009	0.202
SAE 50 Oil (QUAKER STATE)	3.02 ± 0.03	0.141 ± 0.006	0.145
Glycerin (J T Baker 99.90%)	3.03 ± 0.01	0.288 ± 0.006	0.286

from the graph of m versus I^3 shown in figure 3(d), the value of coefficient b is obtained from a least-squares linear fit using equation (7) and it is equal to 0.0758 ± 0.0007.

Then using equation (8) the thermal conductivity is obtained, giving for methanol a thermal conductivity of $k = (0.208 \pm 0.009)$ W m^{-1} K. Applying the same procedure for the other investigated liquids the results shown in table 1 were obtained.

It is important to mention before concluding that although thermal diffusivity (α) is involved in the principal equation of the hot-wire technique (equation (1)), the uncertainty in its determination can be about an order of magnitude higher than that of the thermal conductivity, as discussed by other authors [17]. The thermal diffusivity can be determined following equation (5) of this paper as

$$\alpha = \frac{r^2 C}{4} \exp\left(\frac{B}{m}\right), \tag{10}$$

where the intercept B can be determined from the linear fit of the selected linear region of the ΔV versus ln(t) plot. From equation (10) the uncertainty in the thermal diffusivity determination can be calculated following the expression [17]

$$\frac{\delta\alpha}{\alpha} = \sqrt{\left(\frac{2\delta r}{r}\right)^2 + \left(\frac{B}{m}\right)^2 \left[\left(\frac{\delta m}{m}\right)^2 + \left(\frac{\delta B}{B}\right)^2\right]}, \tag{11}$$

where δi denotes the absolute uncertainty of the ith variable. Taking into account only the orders of magnitude involved in each parameter and neglecting any uncertainty in the radius of the wire, the following result follows from equation (11):

$$\frac{\delta\alpha}{\alpha} = \frac{B}{m}\sqrt{\left(\frac{\delta m}{m}\right)^2 + \left(\frac{\delta B}{B}\right)^2} \approx \frac{10^{-5}}{10^{-5}}\sqrt{\left(\frac{10^{-6}}{10^{-5}}\right)^2 + \left(\frac{10^{-6}}{10^{-5}}\right)^2} \approx 15\%. \tag{12}$$

This is about five times the uncertainty obtained here for the thermal conductivity. (Making a statistical analysis from their measurements, Fox *et al* [17] reported a value of 20% and estimated an uncertainty of 50% in the results reported in [28].) Therefore we have decided not to calculate the thermal diffusivity. However the above analysis can be used to discuss with students the importance of the accuracy that must accompany experimental measurements. A more detailed discussion about this point can be found elsewhere [17, 29, 30].

Note that in this technique by applying a constant electric current through the wire, a constant amount of heat per unit time and unit length is released by the wire and propagates throughout the sample. In practice, the theoretical infinite linear source is approached by a thin resistive wire and the infinite sample is replaced by a liquid with finite radial dimensions determined by the container. In the plot of the recorded temperature (in our case a voltage proportional to it) as a function of time (see figure 3(a)), the early part of the curve diverges considerably from the theoretical predictions because of the non-vanishing contact resistance between wire and sample and the finite heat capacity of the former [31]. In order to avoid these effects the condition $t \gg r^2/\alpha$ mentioned above must be fulfilled. It is a good exercise for students to verify that this condition is satisfied for liquids with typical thermal diffusivities of about 10^{-6} m^2 s^{-1} and for a wire of $r = 76.2 \times 10^{-6}$ m used in our experiments. On the other hand, a limit to the maximum measuring time is imposed not only due to the convection effects but also because of the finite sample size: when heat reaches the outer surface of the sample, heat exchanges between the sample and the environment make the theoretical model no longer valid. The time necessary for the heat flux to reach the outer surface can be estimated as $t = d^2/\alpha$, where d is the radius of the container. Students can also verify that this time becomes about 10^4 s in this experiment, being much longer than the total measurement time. The correct determination of the minimum and maximum times to be considered in the calculations is of fundamental importance for getting accurate and consistent results. One way to account for the correct region is the multi-current analysis described here.

Equation (1) is a result of approximations based on the above analysis. Some authors [31–33] use a more general formula that takes into account some of the above mentioned end effects and use a nonlinear least-squares fitting method with which both thermal conductivity and diffusivity are obtained by comparing the recorded experimental curve and the one predicted by the theoretical model. But this analysis is far beyond the objectives of an undergraduate experiment and thus beyond the scope of this paper.

5. Conclusions

We described a simple experimental setup of a technique that plays an important role in the field of thermal characterization of materials, in particular thermal conductivity, namely the hot-wire technique. Our system does not make use of the resistance bridge as was usual in many previous works. Instead it involves high precision instruments that are often available in teaching laboratories that simplify the experimental arrangement. The methodology used for data processing is very useful from the instructive point of view, because it allows familiarization with the techniques of data processing that make use of linear, semi-log and log–log graphs that appear very often in the scientific praxis. Contrary to other experiments proposed for teaching, the methodology proposed here also permits the correct selection of the linear part of the ΔT versus $\ln(t)$ graphs, where the theoretical model associated with the hot-wire technique is fulfilled. The experiment is an instructive exercise for the students because it allows learning about heat transfer theoretical fundamentals, thermal properties measurement techniques, electronic instrumentation, automatic experiment control and data acquisition techniques, among related topics. It has been used with success by students taking the course on heat transfer lectured by some of the authors as part of the Program on Advanced Technology (PTA) at CICATA-Legaria, IPN.

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