

Experimental Set-Up for The Measurement of The Thermal Conductivity of Liquids

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Abstract. The paper describes an in house made experimental set-up that measures the thermal conductivity of liquids. The measurement principle is based on the Transient Hot Wire Method. The theoretical bases of the measurement method are firstly presented, and then our original experimental implementation is described. The hardware as well as the software design reveals the simple configuration of the measurement set-up that contains high performance inexpensive components. It is also simple to use and well suited for research laboratories, data being stored either in text, or in graphical files. Finally, based on experimental results, the measurement accuracy and sensibility performances are discussed and compared with other instruments in literature.

Keywords: measurement and instrumentation, thermal conductivity of liquids, transient hot wire method.

1. Introduction

The huge demand for new advanced materials with improved properties for broad ranges of physical, chemical, biological, and medical applications conducted to a significant development of the science and technology of materials during the past years. As a consequence of this trend, it is obvious the high increase in requirements for

methods and instrumentation for material properties characterization and performance evaluation.

In many situations, the classical characterization methods are too complex and time consuming and need expensive instrumentation. In addition, the volume and the complexity of acquired data need precise control on instrumentation and on measurement parameters, and frequently, data processing, and/or, graphical data representation are required. The introduction of alternative methods that are relatively simple, fast and of good precision would be of great benefit to the scientific and engineering communities by producing reliable data for the growing demand. In addition, implementing these new methods on cheap, easy accessible and computer controlled instrumentation is a stringent need for research laboratories and would be of great benefit to the scientific and engineering communities.

In the thermal engineering field, great efforts are made to construct high efficient heat transfer equipment, where high thermal conductive fluids are needed to enhance the thermal transfer. Also, in many cooling applications ranging from microelectronics to automotive or aero-spatial industries, one of the key elements is the use of advanced fluids, with increased thermal conductivity beside to classical cooling fluids. In such circumstances, the measurement of the thermal conductivity of fluids is very important in evaluating the thermal transfer efficiency in thermal equipment and in cooling systems.

In order to measure the thermal conductivity, a family of techniques named Contact Transient are becoming very attractive and popular for general use in the last years, from which, the Transient Hot Wire has been widely accepted as the most accurate technique over a wide range of fluids. Although the principle of the method is apparent simple, its experimental implementation requires suitable temperature sensing, automatic control, data acquisition, and data analysis systems to be used. Because of the relatively short experimental times and large amounts of parametric data involved in the measurement process, computer control of the measurement is essential.

The experimental set-up described here has been designed to measure the thermal conductivity of nanofluids [1], a class of cooling liquids prepared by suspending very small volume concentrations of nanoparticles in deionized water or ethylene glycol. However, by properly adjusting the test parameters, and by using suitable test cells, it can be adapted to measure any other fluids (liquids or gases), and even powders or solids. The measurement and control are accomplished and integrated by using the MicroConverter Quick Start development system based on MicroConverter ADuC845 from Analog Devices. The data are transmitted to the computer by means of the RS 232 serial, and are processed through the Instrument Control Tool Box in MATLAB or can be exported and processed by Microsoft Excel. The system acquires measured data with high speed and accuracy. It interactively processes/analyzes, and stores measured data either for immediate use or for future post-processing. Data can be displayed in graphical and/or numerical forms. In addition, the system allows for easy modification and enhancement of test parameters and measurement conditions by modification of the circuitry biasing and software programming.

2. Theoretical considerations on transient hot wire method for thermal conductivity of liquids

2.1. Theoretical model

The Transient Hot Wire technique for measurement of the thermal conductivity in fluids is based on detection of the temporal temperature rise in a thin wire immersed in the test material, initially at thermal equilibrium, following the application of a stepwise electrical current [2, 3]. The wire acts as a heat source and produces a time-dependent temperature field within the test material. The theoretical model describing the THW technique is derived from the analytical solution of the heat conduction equation for a line heat source of radius $r \rightarrow 0$ and length $l \rightarrow \infty$ of negligible thermal mass, which is perfectly embedded, with no thermal contact resistance, in an unbounded heat sink, initially at uniform temperature T_0 . The sink is considered of homogeneous and isotropic material with constant thermal transport properties. When a constant electric power is stepwise applied, the wire instantly and totally liberates the heat source output per unit length, q , to the test sample, where it is conducted outwards and stored entirely. The temperature rise at the radial distance r from the heat source is given by [4]:

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

where t is the time, k is the thermal conductivity ($\text{Wm}^{-1}\text{K}^{-1}$), a – thermal diffusivity (m^2s^{-1}) of the test fluid and $C = \exp(\gamma)$, $\gamma = 0.5772157$ is the Euler's constant.

The plot of the temperature $T(r, t)$ on a logarithmic scale of time, $\ln t$, is linear, with the slope $s = q/(4\pi k)$, from which the thermal conductivity can be derived as:

$$k = \frac{q}{4\pi s}. \quad (2)$$

2.2. Deviations from the ideal model

In practice, there are some deviations from the ideal model arising from the effects related to the finite length of the wire and to the non-vanishing heat capacity, as well as from the effects related to the finite dimensions of the sample.

The finite length of the wire together with its support at both ends give rise to longitudinal heat losses or gains that cause deviations from the supposed uniform temperature profile of concentric isotherms around the wire. This source of errors can be eliminated if the temperature is observed at, or near the middle of the wire where its profile is undisturbed. A good solution is to use two wires of different lengths $l_1 > l_2$ connected in series. This way, the difference in voltage drops across the wires is a measure of the temperature of the virtual central section of length $l_1 - l_2$.

On the other hand, the non-vanishing heat capacity of the wire causes a certain fraction of the input power to be stored by the wire itself instead of being liberated to the sample. Thus, the temperature rise is delayed in time. In contrast to the end

effect, which works over the whole measurement period, this disturbance is effective only at small times. At large times, the boundary effect arising from the finite size of the sample gets more effective. For quasi-isothermal boundary conditions, a growing amount of heat flows outward the sample at its exposed surfaces, while for quasi-adiabatic conditions the heat transfer is smaller than for an ideal unbounded sample. In both cases, the temperature excursion is no longer quasi-linear in $\ln(t)$ for longer times. A real sample can additionally give rise to convective heat transport, as well as mass transfer.

Thus, any signal on specimens that transfer heat only by conduction can only be quasi-linear in time as long as the end effect is compensated and the heat dissipated by the wire can be confined to the sample. A time window, which is open for measurements between t_{min} and t_{max} , is necessary to estimate, depending on particular experimental conditions. For expected systematic errors from 0.1% to 0.5 %, it was obtained:

$$t_{min} \geq 10 \frac{r^2}{a} \quad \text{and} \quad t_{max} \leq 0.2 \frac{R^2}{a}, \quad (3)$$

where R is the minimal distance between the wire and an outer surface of the sample.

For time intervals $(t_2 - t_1)$, corresponding to the temperature difference $(T_2 - T_1)$, the working equation (1) is used in the simplified form [4]:

$$k = \frac{q}{4\pi} \cdot \frac{\ln(t_2 - t_1)}{T_2 - T_1}. \quad (4)$$

When implementing the method in a practical scheme, it is convenient to measure the temperature rise in the hot wire, and to extract the value of the thermal conductivity by subsequently processing measurement data.

The graphical representations of the temperature rise as a function of time intervals, as it results from equation 4, are presented in Figs. 1 and 2, considering a linear, and respectively, a logarithmic scale of time.

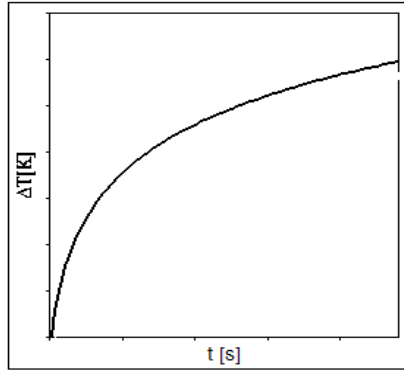


Fig. 1. Theoretical graphical representation of the temperature rise in the hot wire as a function of time intervals, when a step wise heat pulse is applied.

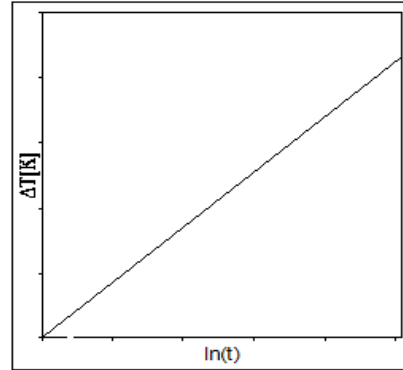


Fig. 2. Graphical representation of the temperature rise in the hot wire as a function of logarithmic time intervals when a step wise heat pulse is applied.

From the temperature rise representation on a logarithmic scale of time in Fig. 2, the thermal conductivity of the sample can be obtained by simply calculating the slope of the curve and considering the heat per unit length liberated by the heating source.

3. Experimental implementation of the transient hot wire method

Following the theoretical considerations presented above, the general configuration of an experimental set-up for measurement of the thermal conductivity in liquids according to the Transient Hot Wire (THW) method is that illustrated in Fig. 3.

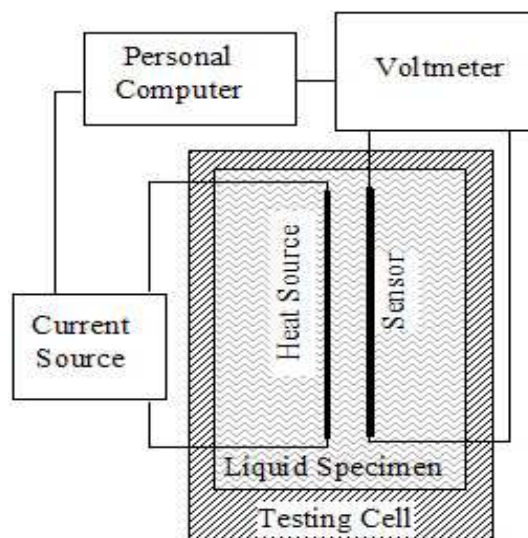


Fig. 3. Basic configuration of the experimental set-up measuring the thermal conductivity of liquids.

It mainly consists of a recipient where the liquid specimen is poured in and the measurement instrumentation. The measurement process is computer controlled. The recipient is thermal isolated from the ambient environment and contains the testing cell formed by the heating source and the temperature sensor. The measurement instrumentation consists of a programmable current source that applies, for a short time ($(t_2 - t_1) \approx$ a few seconds), a step wise current on the heating source and a high precision voltmeter that sequential measures the signals from the sensor for very short time intervals, on the order of tens of milliseconds.

The computer controls the measurement sequences, acquires data, and a special designed software converts the voltage registered data into temperature data according to sensor calibration data, and then in thermal conductivity data according to expression (4).

3.1. The testing cell

A testing cell was assembled to meet the requirements resulted from the above presented model and to avoid the most possible sources of errors. The cell, as presented in figure 4, has two main components: a quasi-adiabatic recipient made of Teflon, and the heating/sensing device made of Platinum wire. The platinum sensor is a very convenient solution because the temperature dependence of platinum resistance is well known, linear, and time stable over the temperature range of interest in our experiments. For measurements, the cell is immersed in the tested sample which is kept in a thermal isolated recipient, preferable made in Teflon.

For hot wire heating source, as well as for temperature sensor, a 35 μm diameter platinum wire was used. A configuration of two wire segments of 3.8 mm ($R_1 = 4.2 \Omega$ at 24°C) and respectively 7.6 mm length ($R_2 = 8.4 \Omega$ at 24°C) was chosen to avoid the end effect, as resulted from the theoretical model analysis. At 0°C , the two resistors are $R_{10} = 3.85 \Omega$ and respectively $R_{20} = 2R_{10} = 8.4 \Omega$. The sensor calibration was made by following standard procedures [5, 6] by using the well known temperature dependence of the platinum resistance in the 0 to 100°C temperature range [5, 6]:

$$R(T) = R_0 (1 + R_T \cdot \Delta T) \quad (5)$$

where R_0 is the sensor resistance at 0°C , ΔT is the measured increase of the temperature, and $R_T = 3.850 \times 10^{-3} [^\circ\text{C}^{-1}]$ is the average change in sensor resistance, referred to its nominal value at 0°C . It must be noticed that the platinum sensor actually can work in the temperature range from -200°C to 850°C . A third-order polynomial, respectively a second-order polynomial must be used in the range -200°C to 0°C and respectively 0°C to 850°C instead of equation (5). Because our experiments are made at room temperature, the relation (5) is acceptably accurate for our purposes, and the temperature increase can be simply expressed as:

$$\Delta T = \frac{R(T) - R_0}{R_T}. \quad (6)$$

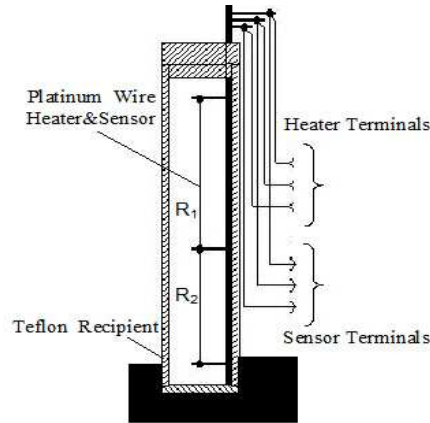


Fig. 4. The testing cell configuration.

3.2. The experimental set-up for measurement of the thermal conductivity of liquids

An experimental set-up was build to implement the Transient Hot Wire method for laboratory use. The block diagram in Fig. 5 presents the main units of the measurement system which is computer controlled. The Control and Measurement Unit commands the very stable Current Source to suddenly apply a step-wise current pulse on the heating wire immersed into the fluid in Testing Cell. The pulse duration is determined to satisfy the time window conditions in relations (3), and is of the order of seconds. In all that time, the Measurement Unit detects and stores the temperature rise for very small time intervals (tens of milliseconds). Acquired Data are transmitted to Computer through the serial RS232. They are either stored in text files or are processed by the Instrument Control Tool Box in MATLAB. They can also be imported and processed in EXCEL data files.

The measurement and processing data routines convert temperature read data in thermal conductivity data, and/or displays them in graphical forms. Statistical analysis can also be accomplished. A complete measurement process, including the graphical representation and statistical processing of data, may take up to a few minutes.

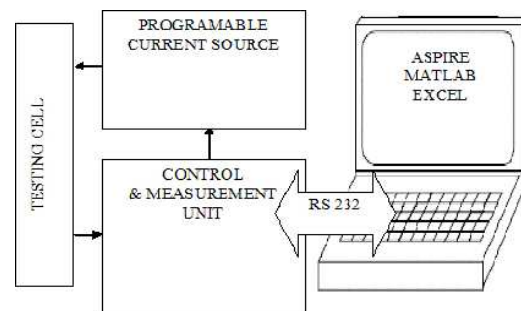


Fig. 5. Block diagram of the experimental set-up for measurement of the thermal conductivity.

To implement the Hot Wire Method for research laboratory needs, we have chosen a solution that integrates the Control, as well as Measurement and Data Acquisition functions, in a single system. The QuickStart Development System from Analog Devices offers a reliable hardware and software configuration very suitable for the mentioned demands. It consists of a suite of low cost comprehensive WINDOWS compatible software development tools (ASPIRE) with supporting hardware.

The core hardware component is the MicroConverter ADuC845 which integrates high resolution Σ/Δ ADCs with, up to 10 channel input multiplexing, a fast 8 bit MCU, and program/data Flash/EE memory on a single chip [7]. There are two (primary and auxiliary) 24 bit Σ/Δ ADCs with internal buffering. The ADCs incorporate flexible multiplexing input, a temperature sensor, and a PGA (on primary ADC only) allowing direct measurement of low-level signals. They also include on-chip digital filtering and programmable output data rates that are intended for measuring wide

dynamic range, low frequency signals, such as those in temperature measurement applications.

The devices operate from a 32 kHz crystal with an on-chip PLL generating a high frequency clock of 12.58 MHz. The microcontroller core is an optimized single-cycle 8052MCU offering up to 12.58 MIPs performance. The available nonvolatile Flash/EE program memory options are 62 Kbytes, 32 Kbytes, and 8 Kbytes. 4 Kbytes of non-volatile Flash/EE data memory and 2304 bytes of data RAM are also provided on-chip. The program memory can be configured as data memory to give up to 60 Kbytes of NV data memory in data logging applications. On-chip firmware supports in-circuit serial download via the UART serial interface ports. The serial port is a full duplex, meaning that it can transmit and receive simultaneously. The physical interface to the serial data network is via Pins RxD (P3.0) and TxD (P3.1).

QuickStart Development System allows to rapidly evaluate MicroConverter performance and functionality, and to perform prototype development. The system provides software tools, development board, integrated serial download/debug cable, and power supply. It fully supports assembly level code development via a serial port debug path. The Windows application ASPIRE integrates all tools necessary to edit, assemble, simulate and debug code and allows the user to compile, edit, and debug Assembly source code via the serial port.

3.3. Configuring the microconverter for thermal conductivity measurements

The MicroConverter ADuC845 offers a very convenient, rapid, low cost, and accurate solution to implement the Hot Wire Technique for measurement of the thermal conductivity in liquids. Using the QuickStart Development System, the hardware test configuration and the test program were designed in accordance with theoretical model of the Transient Hot Wire Technique. The interfaces with computer and the heater/sensor device are illustrated in figure 6. To avoid the end effect in the sensor wire, a simple solution was adopted, by using a differential connection of terminals that read the sensor signal. There is a bidirectional communication between PC and ADuC845, through the serial RS232.

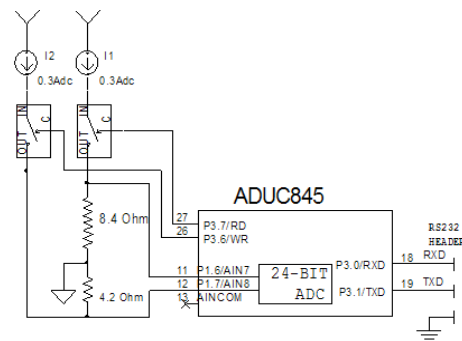


Fig. 6. MicroConverter interfaces with the heater/sensor cell and the computer.

For each test run, the MicroConverter software controls the measurement process, and the Instrument Control Tool Box in MATLAB achieves data storage, statistical and graphical processing, and displaying.

The diagrams in Figs. 7 and 8 present the program sequences performed during a test run in the Aspire and respectively MATLAB environments.

For a specific measurement application, the system is programmed to achieve the designed actions in certain predefined test conditions. In our case, the initial settled parameters of a particular test are the heating current, the test run duration, and the rate of reading the temperature rise. During each test run, the system achieves the following actions:

- connects the heating current source and starts the measurement;
- acquires data during the test run and sends them to the computer;
- stops the test and disconnects the current source at the end of the programmed time.

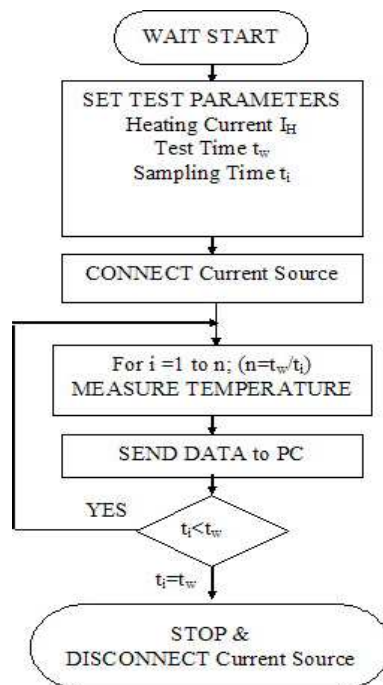


Fig. 7. Diagram of instructions executed by the Aspire software during a measurement sequence.

The test begins when a start signal is sent to the ADuC845 by manually actuating the switch C in figure 6. At that moment, the current source is connected to the heating wire and current flows through the heater for a predefined time interval settled by the program (t_w in diagram). In the same time, the current through the sensor is measured in a sampling mode and the read values at each sampling time moment (t_i in diagram) are sent to computer and stored in data files.

At the end of the measurement time, the source is automatically disconnected, and the measured data, their graphical representation, and statistical analysis can be extracted and/or displayed. A new test can be executed when the switch C is again actuated.

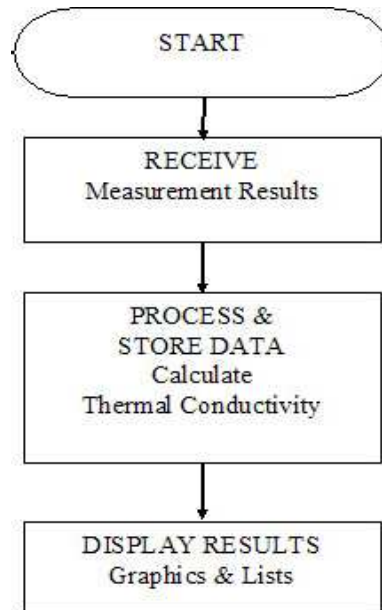


Fig. 8.Diagram of instructions in MATLAB during a measurement sequence.

The measurement time interval, t_w , is set in accordance with conditions in relation (3), so that the measurement time window is of optimum duration to provide that the end effect in the sensor is compensated, the heat dissipated by the wire is confined to the measured sample, and the thermal convection in fluid is avoided. On the other hand, the sampling period, t_i , is chosen to have sufficient short and sufficient many test points in order to obtain comprehensive information and accurate and reliable plots, satisfactory approximating the continuous function in equation (4).

Data are firstly acquired and stored in text files, in a hexadecimal format, in the Aspire environment, and then they are transferred in text files in the MATLAB, being subsequently processed by means of the Instrument Control Tool Box. In the MATLAB environment, data are converted in temperature units and in thermal conductivity units, on the basis of relations (6), and respectively (4), they are plotted on graphs with either a linear, or a logarithmic scale of time, and also, they are statistical processed. When plotting data, the initial registered values for the first three sequences are eliminated, because they are strongly affected by the heat capacity effect of the sensor wire.

Data can be also stored, processed, statistical analyzed, and graphical represented in EXCEL files.

4. Results and discussion

A picture of the described experimental set-up is presented in Fig. 9.

The system was used to characterize a new class of nanofluids produced by suspending different nanoparticles in ordinary cooling liquids, like deionized water and ethylene glycol. Actually, the ratios of the thermal conductivity of the new fluids to that of the base original fluids have been determined.

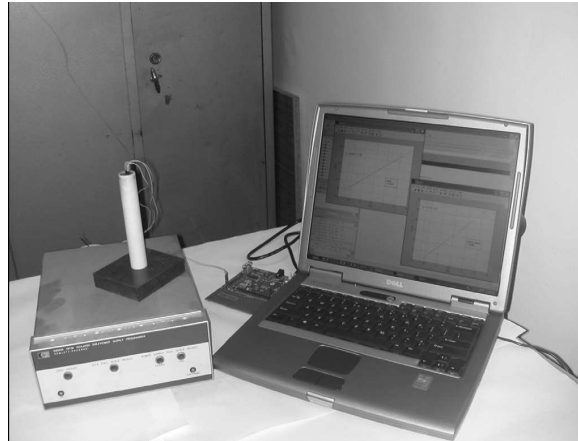


Fig. 9. The experimental set-up for measurement of the thermal conductivity.

Taking into account the range of values expected for thermal conductivities of the considered class of liquids, and making the appropriate corrections, the measurements were made in the following working conditions:

- the heating current was set at 300 mA. Depending on the nature of the tested sample, this level of current can produce a temperature rise up to 14 K, which is estimated as an upper limit designated to protect the heating cell against overheating damages. At higher temperatures, an overload protection is activated and the test cell is disconnected from the source. In liquids investigated in our experiments, the total temperature rise during a test run varied from approximately 1.5 K up to approximately 6 K;

- the duration of a test was set to 2 seconds. The run time is actually the time window t_w in the diagram in Fig. 7. Considering restrictions assumed for the test time, as they were expressed in relation (3), and taking into account the constructive features of the testing cell, we found that a lower limit of the order of hundred of ms, and an upper limit of the order of tens of seconds cover very well our experimental conditions. We had to investigate liquids with thermal conductivities ranging from $0.256 \text{ Wm}^{-1}\text{K}^{-1}$ (pure ethylene glycol) to $0.6 \text{ Wm}^{-1}\text{K}^{-1}$ (deionized water). Thus, a test time of 2 s was considered to be a sufficiently good approach to ensure the elimination of the thermal convection effect;

- the sampling time was set to 40 ms, resulting 50 readings of the temperature during a test run. This way, sufficient data were obtained to have comprehensive

information on transient thermal process, resulting an accurate estimation of the thermal conductivity.

Data were stored in data files created by the Aspire software, and they were exported into MATLAB, to be interactively or later processed, and to calculate the thermal conductivity.

Figure 10 presents the diagram of the temperature rise read each 40 ms time intervals, during the application for 2 seconds of a heating current step.

It must emphasize that in our experiments, the temperature rise registrations for the first 200 ms of the test were strongly affected by the non-vanishing heat capacity of the wire, and consequently, great disturbances have been seen in graphics at small times. This initial time period when the errors arising from the self heating effect in the platinum wire disturb the accuracy of the measurement depends on experimental conditions regarding heater and sensor material characteristics. In graphical representation, this effect is reflected as a deviation from the ideal form in Fig. 1 and is reflected as a delay in temperature rise.

To avoid this disturbance to affect the measurement results, these initial noisy values are not taken into account when thermal conductivity is calculated. The heating step pulse duration, of 2 seconds chosen in our experiments, may also vary as a function of the material under test.

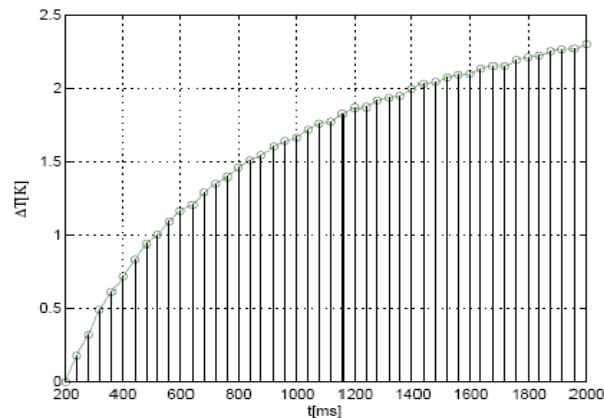


Fig. 10. Graphical representation in MATLAB of the temperature rise detected each 40 ms time intervals during a test period of 2 seconds.

Figure 11 illustrates the resulted plot on a logarithmic scale of time, as they were obtained in graphical files in MATLAB. The slope of the curve having the equation shown on graphics represents the thermal conductivity, and the x axis intercept represents the thermal diffusivity.

Multiple run test results for different materials can be represented on the same graphics, as it is illustrated in Fig. 12. This facility is very useful in experiments that require comparing thermal conductivities of different liquids, to evaluate their thermal transfer performances.

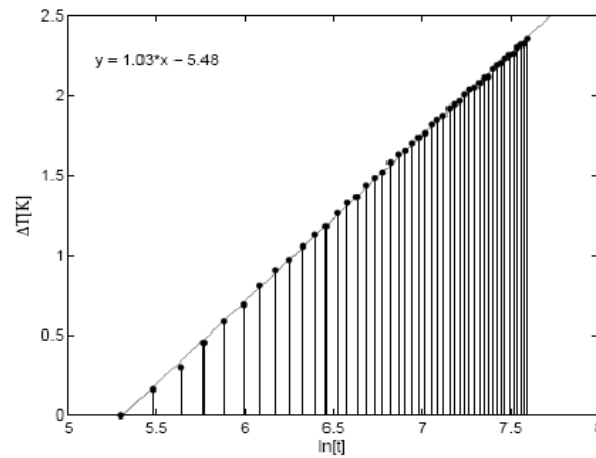


Fig. 11. Graphical representation in MATLAB of the output data, together with the numerical values for the thermal conductivity (the slope) and thermal diffusivity (the x axis intercept).

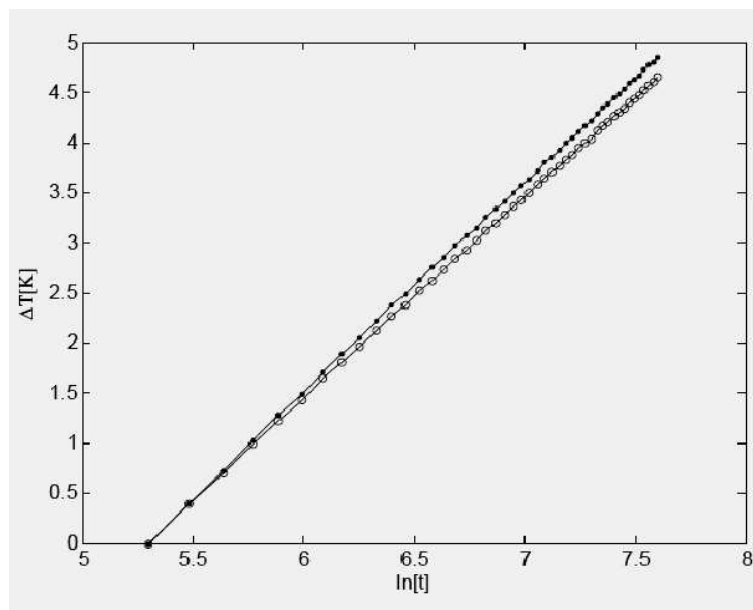


Fig. 12. MATLAB graphical representation of two different measured samples.

As it was mentioned earlier, the Instrument Control Tool Box in MATLAB can also accomplish and display statistical analysis of data. A print screen picture of the graphical window display containing the curve equation with the slope value expressing the measured thermal conductivity, and having inserted a small window which contains the results of the statistical analysis, is presented in Fig. 13.

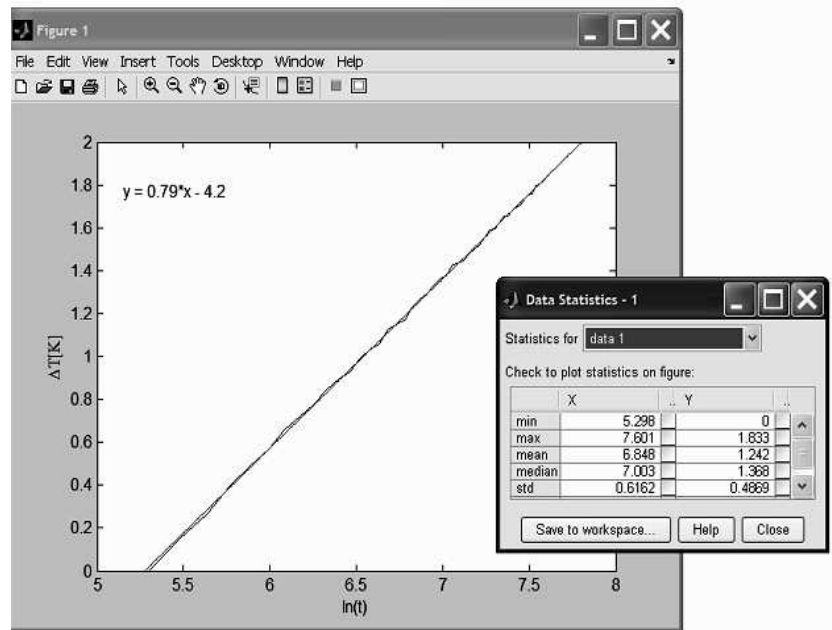


Fig. 13. The MATLAB graphical representation and the statistical data obtained after a test run.

To correctly evaluate the value of the thermal conductivity of a specified material, calibration of the system is needed. Because standard reference materials with certified values for thermal conductivity are not widely available and are very expensive, and because the main aim of our experiments was to study the enhancement in thermal conductivity of some basic cooling fluids (like deionized water or ethylene glycol) when different nanoparticles were introduced in suspension, it was more convenient to express the thermal conductivity of the studied fluids in a normalized form. Consequently, we have measured and stored the thermal conductivities of the pure base fluids, and the subsequent measured values of thermal conductivities of the experimentally prepared nanofluids were reported to the corresponding normalizing stored values. Figure 14 exemplifies such data extraction illustrating a Microsoft EXCEL chart representing the normalized thermal conductivity of the ethylene glycol based nanofluid as a function of the volume fraction of dispersed nanoparticles.

In this way, the use of some expensive standard samples was avoided, and the calibration of the system was made in terms of the normalized values for thermal conductivities with respect to different pure liquids. This method had an additional advantage in the case of our experiments, because the presumable measurement uncertainties and errors compensate to each other, when the normalized values are considered as working data.

It must be noticed that a special attention must be done to the environmental test conditions. This fact requires the system calibration with respect to pure liquids every time at the beginning of a new set of measurements.

Better measurement sensitivity and stability was exhibited by materials having lower thermal conductivity (ethylene glycol) than that with higher thermal conductivity (deionized water). This is because higher temperature rise of the heater is produced in a lower thermal conductive medium.

The system could be used for measurements on gaseous sample too, providing that appropriate test cells should be constructed, and software should be adapted to the appropriate test conditions.

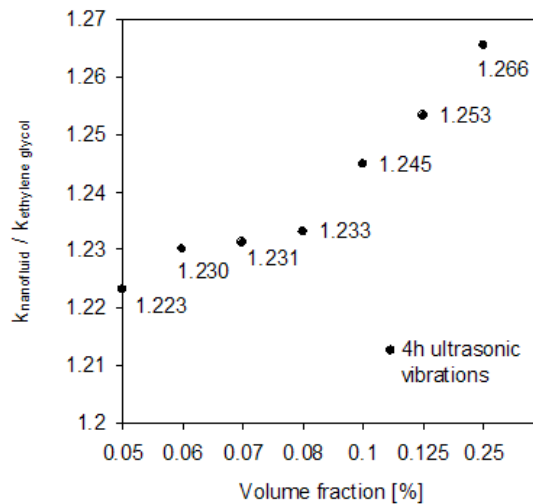


Fig. 14. Microsoft EXCEL chart representing the normalized thermal conductivity.

4. Conclusions

The Transient Hot Wire Technique for measurement of the thermal conductivity in liquids was implemented in an in-house made computer controlled experimental set-up. The main advantage of this technique is that the thermodynamic state of the material under test is not changed during the measuring process due to the small heat disturbance and thermal properties can thus be assigned to the equilibrium temperature attained prior to the disturbance. The essential criterion for accurate measurements is a non-disturbed temperature field, the form of which is generated by the corresponding heat source. The ideal heat source has a negligible thickness, should be constructed from a material with convenient heat capacity to avoid the self heating effect, and should provide ideal thermal contact. The ideal model gives an optimal measuring time and a maximum time window in which the evaluation procedure can be applied over the temperature response. The time window corresponds to the optimum overall sensitivity where the correlation between all the sensitivity coefficients is minimal. Due to the relatively short experimental times and large amounts

of parametric data involved, use of this method requires a suitable automated data acquisition and analysis system.

The system described in this work was used to evaluate the thermal performance of a new class of cooling fluids prepared by suspending some composite nanoparticles in deionized water or in ethylene glycol. The heater & sensor test cell, the thermal isolated recipient, and also the measurement & data acquisition and processing chains were designed and implemented in such a way that the major error sources to be eliminated and to provide proper corrections in certain circumstances, when the errors could not be avoided.

The measurement and control processes are accomplished and integrated by using the Quick Start Development System from Analog Devices which is based on the MicroConverter ADuC845. The acquired data are transmitted to the computer by means of the RS 232 serial, and subsequently, they are processed through the Instrument Control Tool Box in MATLAB. Data can be also imported, processed and represented graphical form in Microsoft Excel.

The QuickStart Development System from Analog Devices offers a very convenient, rapid, low cost, highly sensitive and accurate solution for implementation of the Hot Wire Technique for research laboratory needs. The Development System acquires measured data with high speed and accuracy certified by the use of the processor ADUC845 with the embedded Δ/Σ analog digital converter of 24 bits. The high resolution of the converter ensures a good precision of measurements. The flexible and easy to use software controls the test conditions and manipulates the read data. Easy modification and enhancement of test parameters are possible, by simply modifying the circuitry biasing and appropriate software programming.

Performing a test run with the described system, takes only 2 s. The interactively or afterwards data processing, including graphical displaying and/or statistical analysis, can take up to a few minutes.

Comparative data from multiple material samples can be extracted and processed for research laboratory needs.

Straightforward interfacing the Quick Start to the heater/sensor testing cell offered the possibility to adopt a simple and reliable solution to avoid the end effect in the sensor wire, by using a differential connection of terminals that read the sensor.

The interfaces with the Instrument Control Tool Box in MATLAB and Microsoft Excel provide a very useful tool for storage, processing, and displaying data either in graphical or numerical forms.

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