Paper ID: 432

Techno-economic Assessment of a Novel Transient Hot Wire Apparatus for Measuring the Thermal Conductivity of Liquids

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Abstract

The transient hot wire method is most widely used due to its simplicity and quickness to measure the thermal conductivity of fluids. Thin platinum wire is the most commonly used heating wire in conventional hot wire apparatus, which is expensive. An affordable and reliable transient hot wire apparatus is designed and constructed. Error of the apparatus is analysed by comparing with standard deionized water. Moreover, possible solutions to error have been demonstrated in this work. A copper wire of 171 mm length and 60μm diameter is used as heating wire, which is cost-effective and available. A manganin alloy wire having lower temperature coefficient of resistance immersed in water is used as the reference resistor in a Wheatstone bridge circuit. This ensures that the resistance of the known reference resistor remains stable despite the heat generated during the experiment. For precise data acquisition, an ADS1115 module integrated with an Arduino Nano providing 16-bit resolution is used as analogue to digital converter (ADC) which is widely available and reliable. The thermal conductivity of deionized water is measured across the temperature range of 30°C to 70°C. This device maintained precision with an average uncertainty of 1.29% with an average error of 0.72%, thereby affirming its applicability according to existing literatures for thermal conductivity measurement apparatus.

Keywords: Transient hot wire; Thermal conductivity; Cost analysis.

1. Introduction

Thermal conductivity is a significant characteristic of fluids (liquids and gases) for thermal applications. Numerous techniques exist to assess the thermal conductivity of fluids. The transient hot wire (THW) method is a commonly used technique to analyse the thermal conductivity of fluids along with certain soft solids. Due to its simplicity, high accuracy and relatively fast measurement time, it has emerged as a standard technique in the fields of material science, thermodynamics and fluid mechanics [1]. The THW method is extensively addressed in the literature [2–4]. The principle of this method is based on the transient heat transfer from a very thin, electrically heated wire to the surrounding material. A constant electric current from a reliable power supply unit passes through the hot-wire and the temperature of the hot-wire rises significantly. The wire is placed inside a fluid container(cell), and it is fully immersed in the sample fluid to measure the fluid's thermal conductivity. This wire is not only a heat source but also acts as a temperature sensor. The produced heat is dissipated from the wire to the surrounding fluid through the transient heat transfer method which elevates the rising of temperature too much. Conventional experimental setup mostly uses platinum or tantalum wire. Platinum is chemically stable and corrosion resistant and has greater stability over time, moreover, it has an optimum resistivity. In contrast, the high cost of platinum wire renders the thermal conductivity measuring equipment economically unviable. The key challenge lies in finding an affordable solution to measure thermal conductivity. Azarfar et al [5] demonstrated a conventional THW setup using copper as hot wire with relevant error correction. Copper is an abundantly available and economical material that can be used instead of platinum in thermal conductivity measurement. Conversely, copper has some drawbacks when using the THW method. Its resistivity is very low indicating that it requires more current flow to increase its surrounding temperature. Moreover, its mechanical strength is also low. It is essential to address these challenges while measuring thermal conductivity, and any potential errors should be minimised.

In this experimental setup, copper wire is selected though it has some limitations because it is more widely available and less expensive than platinum wire. Additionally, copper's excellent thermal conductivity ensures efficient heat transfer which makes it suitable for such experiments. This work primarily focuses on the techno-

economic construction of THW setup for measuring the thermal conductivity of liquid using inexpensive and widely available copper wire. Arduino Nano microcontroller with ADS1115 module is used as an analogue to digital converter (ADC) unit. Manganin alloy wire is used as the reference resistor which is immersed in water to ensure both its simplicity and reliability. Furthermore, error correction is done to get the measured value close to the standard value.

2. Methodology

The copper hot-wire serves as both a heating element and a temperature change sensor. It functions as a constant linear heat source. Temperature changes are detected by the resistance temperature detection method. When the copper wire is heated up its resistance changes according to its temperature coefficient of resistance (TCR) [6]. The copper hot wire is attached to a Whetstone bridge circuit. The temperature of the reference resistor also increases as current flows through the reference resistor which is connected directly with hot wire. This resistor must have significant thermal stability otherwise deviations will occur. In this setup, thin manganin wire is used which has a resistance of 0.88Ω. Moreover, this resistive manganin wire is immersed in water so that its temperature can't rise significantly though it has a very low TCR value.

The deviation in resistance of the copper hot wire is measured directly from the unbalanced Whetstone bridge voltage [7]. The ADC unit consists of Arduino Nano and ADS1115 ADC module is connected to the circuit according to the Fig. 1 to measure the voltage difference. ADS1115 module is a 16-bit AD converter. This module can measure the voltage difference very accurately between the two ends of the Whetstone Bridge circuit[8]. ADC unit sends voltage difference across the time data to the computer.

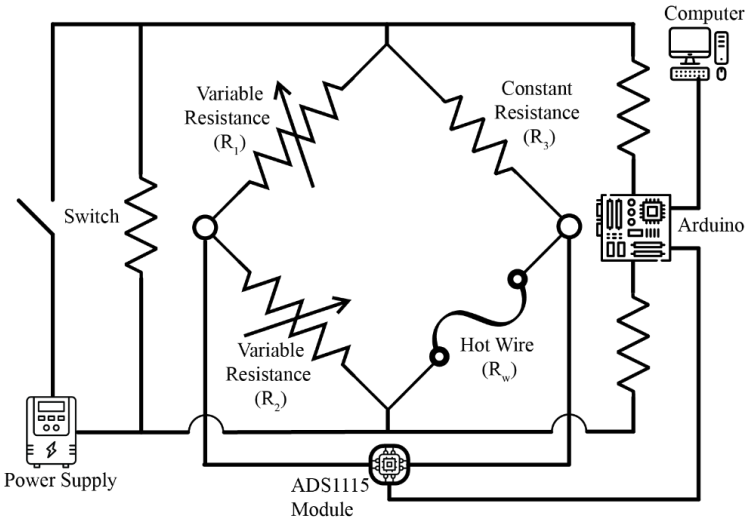


Fig. 1. Schematic Diagram of the THW

3. Mathematical Formulation

The hot-wire is assumed to generate heat uniformly along its length. In cylindrical coordinates, the transient heat conduction equation for a line heat source (the wire) immersed in an infinite medium can be expressed as[9]:

$$\frac{\delta^2 T}{\delta r^2} + \frac{1}{r}\frac{\delta T}{\delta r} = \frac{1}{\alpha}\frac{\delta T}{\delta t} \tag{1}$$

After applying proper boundary condition at r = a for an ideal line source in an infinite medium, the solution to the above equation for the temperature rise ΔT(t) at the wire surface over time is given by:

$$T(a,t) = \frac{q}{4\pi k}[\ \ln t + \ln\frac{4\alpha}{a^2 c}] \tag{2}$$

In Whetstone bridge circuit Kirchoff's voltage law is applicable. According to relation between temperature and resistance of the hot-wire along with the whole system, the voltage deviation can be found by:

$$V_g = \left[\frac{R_3}{(R_3+R_w)^2}\right](\beta R_w) v_s T \tag{3}$$

Substituting Eq. (1) into Eq. (2), we have

$$V_g = \left[\frac{R_3}{(R_3+R_w)^2}\right](\beta R_w)\ \frac{v_s q}{4\pi k}[\ln t + \ln\frac{4\alpha}{a^2 c}] \tag{4}$$

For

$$\left[\frac{R_3 R_w}{(R_3+R_w)^2}\right]\frac{v_s \beta q}{4\pi k} = A \tag{5}$$

and

$$A \ln\frac{4\alpha}{a^2 C} = B \tag{6}$$

Eq. (4) can be written as the simplest form of [10]

$$V_g = A \ln t + B \tag{7}$$

The Whetstone bridge voltage deviation, V_g can be obtained directly from the ADC unit attached to the circuit. Both thermal conductivity and thermal diffusivity can be calculated directly from slope, A and intersect, B of equation (7).

4. THW Apparatus

Fig. 2 shows the experimental set-up of THW apparatus. A copper wire having a length of 171mm and a diameter of 60μm is positioned in the center of an plastic (acrylic) frame in the liquid cell of the THW apparatus. A borosilicate glass tube with the length of 200mm, outside diameter of 25 mm and inner diameter of 23 mm is used as the liquid cell. A hollow polystyrene cylinder is used to support the cell and maintain a steady liquid temperature. The liquid cell with a copper wire is depicted schematically in Fig. 3. It is kept centrally by thick copper wires with a diameter of 2 mm and negligible resistance. Tin-lead alloy has been used to solder the hot wire and conduction wire joints.

One end of the copper hot wire is attached to the resistor R_2 and ADC unit. The other end of the wire is attached to the positive terminal of the DC power supply with a stabilizer and variable resistor. ADC unit consists of Arduino Nano connected with a computer and ADS1115 module. The negative terminal of the DC power supply with stabilizer resistor is connected with the variable resistor and constant reference resistor R_w according to Fig. 1.

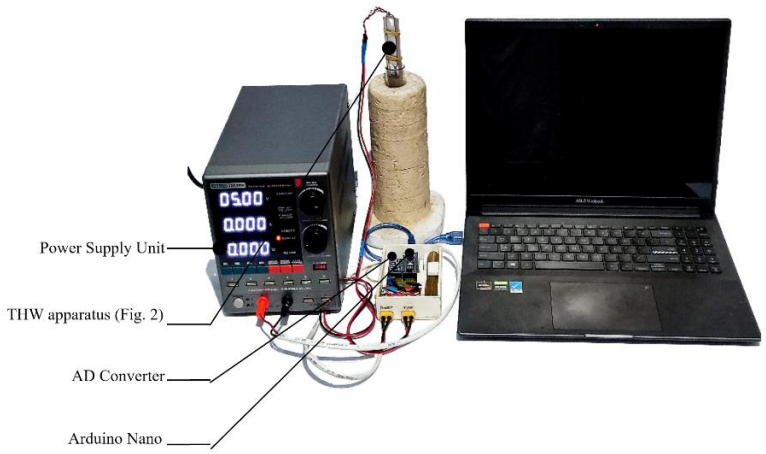


Fig. 2. Experimental set-up of THW

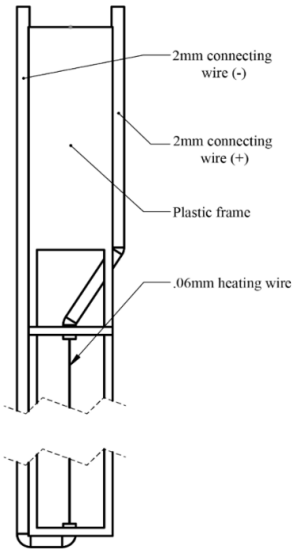


Fig. 3. THW apparatus

5. Possible Error Correction

Assael et al. [11] documented the necessary conditions for accurate measurements and minimizing error significantly for the transient hot-wire technique-based thermal conductivity of fluids measurement system. The possible error corrections are crucial because they address real-world deviations like finite wire length, boundary conditions, wire geometry, and convective effects. These corrections are necessary to ensure accurate, reliable, and meaningful measurements of thermal conductivity.

i. Convection: Though it is impossible to avoid convection in fluid, it can be negligible within a very short period of time. To avoid convective effects electrical pulse is not employed larger than 1 second.
ii. Finite wire diameter: In real-world scenario, wire diameter is not infinitesimal according to theory. Assael et al documented that in the case of a wire diameter of 20μm, truncation error due to finite wire diameter is less than 0.01% whereas a wire diameter of 100μm leads to an error of at least 3%. In this work, the diameter of 60μm wire is used which reduces error to less than 1%.
iii. Outer boundary correction: The cell wall is too close to the hot wire, this causes deviation from the ideal model. The distance between the cell wall along with the frame and wire must be more than 0.5 cm. In this setup, the cell wall is 1.1cm and the frame is 0.8cm away from the wire.
iv. Radiation effect: Radiation of heat deviates conductivity results from the ideal model for higher temperature difference. In this setup, the rising of wire temperature is limited to 3°C to eliminate the radiation effect.

v. End effect: As previously presented, the wire is not an infinitely long heat source, and it has two ends. Azarfar et al [5] introduced a soldering method to eliminate the end effect almost entirely. The configuration shown in Fig. 1 reduces the end effects by utilizing a long enough wire and low-resistance connectors. Tin-lead alloy has been used to solder the joints.

6. Data Acquisition

In this THW setup, a Wheatstone bridge is configured with the hot-copper wire (R_w) in one working arm and a constant reference resistance (R_3) made of manganin wire in the other arm. The Whetstone bridge circuit is balanced to zero V_g using a 1kΩ multiturn potentiometer, allowing precise adjustments. Initially, a very low voltage (0.1V) is applied to the circuit to achieve balance without significantly heating the wire. Once balanced, direct current from the power supply unit is applied to stimulate the wire and the resulting potential difference changes due to change in wire resistance is recorded over time.

An Arduino Nano microcontroller along with ADS1115 ADC is connected to a computer and monitors the potential difference across the bridge. Custom software processes the incoming data, recording the bridge voltage at approximately 45 data samples per second. The measurements are primarily taken between 0.1 and 1 second, a time frame chosen for optimal thermal conductivity calculations. Using this data, the deviation of the temperature of the hot- wire and the thermal conductivity of the sample liquid surrounding the wire is computed. Measurements have been taken at varying temperatures, ranging from 30°C to 70°C, in increments of 10°C. These data are used to study how the wire resistance and thermal conductivity of the fluid changed across the specified temperature range.

7. Calibration

Measurement of thermal conductivity requires accurate knowledge of the thermoelectrical properties of the components such as resistance of the hot wire and the reference resistor. Purity and uniformity of hot wire are also required for accurate measurement. Furthermore, there should be no resistance in the wiring of the whole circuit. All of these are not feasible in the practical experiment. In this circumstance, proper calibration of the setup is required to maintain its overall accuracy.

A correction factor has been determined from repeatedly acquired thermal conductivity data and implemented to the new data to get acceptable accuracy. As the acquired data from the setup by theoretical calculation are lower than the standard reference data, the correction factor is positive. Fig. 4 represents the correction factor for the temperatures ranging from 30°C to 70°C. Actual thermal conductivity can be determined by the equation:

$$\alpha_{actual} = \alpha_{setup} (1 + x_T) \quad (8)$$

Where α_{setup} is the thermal conductivity measured from device and x_T is the positive correction factor at the specific temperature

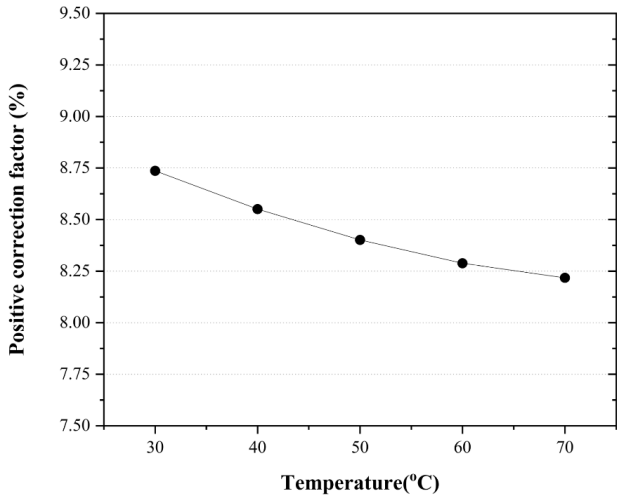


Fig. 4. Positive correction factor vs. Temperature

8. Result and Discussion

To determine the accuracy of the THW setup, the thermal conductivity of water is measured at a temperature range of 30°C to 70°C. The experiment is conducted at least five times for every specific temperature to determine repeatability. Fig. 5 shows the change of Wheatstone bridge voltage difference over the logarithmic time at 30°C. The standard deviation is represented by Fig. 6.

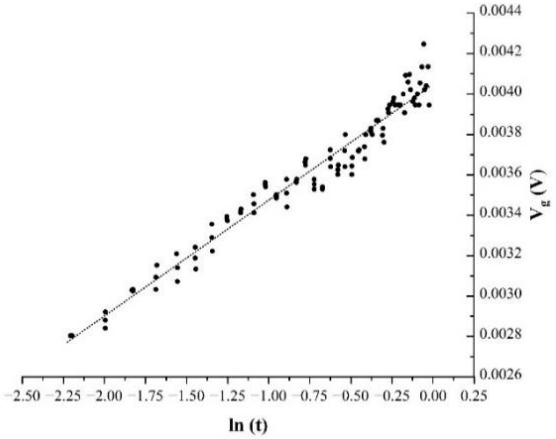


Fig. 5. Bridge Voltage vs. logarithmic time graph

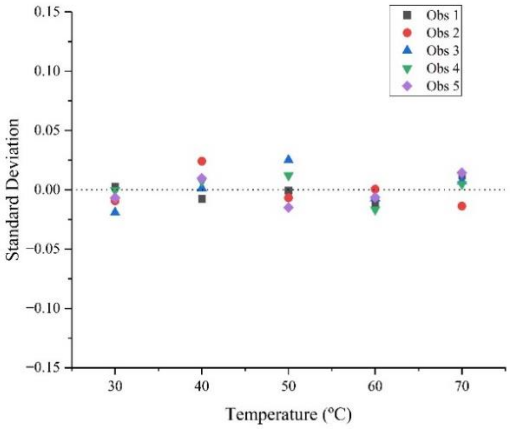


Fig. 6. Standard Deviation $[(k_{ref} - k_{exp})/k_{ref}]$

TABLE 1. Results of thermal conductivity of water

Observation (W/mK)	30°C	40°C	50°C	60°C	70°C
1	0.61660	0.63769	0.64808	0.64654	0.66666
2	0.62306	0.61655	0.63502	0.64152	0.65587
3	0.61880	0.63604	0.61987	0.63837	0.67211
4	0.62630	0.63146	0.64041	0.65701	0.66643
5	0.61096	0.64045	0.63129	0.64317	0.65273
Reference conductivity	0.61450	0.62856	0.64060	0.65091	0.65969
Standard deviation	0.00592	0.00946	0.01052	0.00717	0.00813
Relative uncertainty (%)	0.96	1.50	1.66	1.11	1.23
Error (%)	0.76	0.62	0.88	0.86	0.47

Percent errors have been calculated using the measured values and ideal or reference values of the thermal conductivity of water [12]. Table 1 shows the experimental results of the measurement of the thermal conductivity of water.

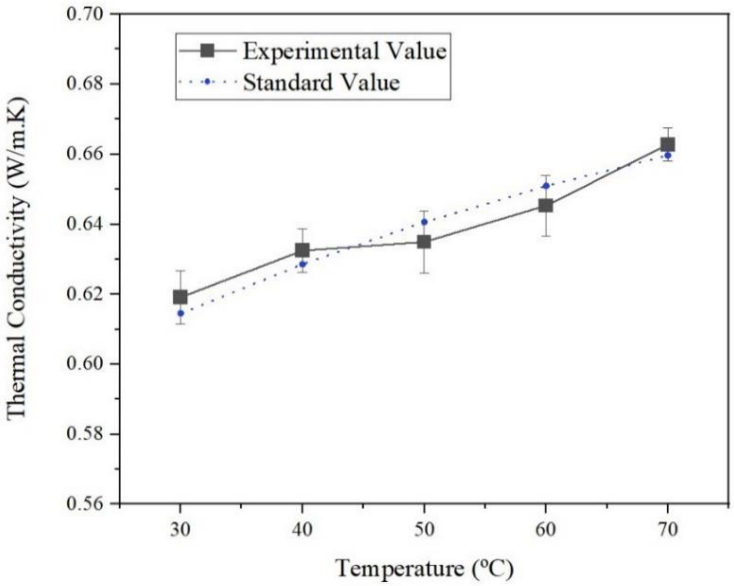


Fig. 7. Thermal Conductivity vs. Temperature graph of thermal conductivity measurement

The experiments provided results for deionized water are closely aligned with the reference values as detailed in Table 1. The total relative uncertainty is 1.29% and the error is 0.72% which indicates this device is recommendable.

9. Cost Analysis

Thermal conductivity measurement devices, particularly those based on the transient hot wire method, are essential in various industrial and research applications. However, existing devices are often expensive, limiting their accessibility. This section presents the economic analysis of our device, highlighting its cost-effectiveness compared to similar devices.

Table 2. Cost of the conducted copper hot-wire based THW apparatus

Component	Specification	Cost (USD)
Copper Hot Wire		4.00
Power Supply Unit	(Sugon 3005PM 30V/ 5A DC Power Supply)	80.00
AD Converter	(ADS1115)	4.25
Micro controller	(Arduino Nano)	3.80
Wiring and other Components		3.55
	Total	95.60

The price of the required platinum hot wire for conventional THW apparatus is approximately 40 USD which costs about 10 times the price of copper hot-wire.

Table 3. Comparison with existing devices [13, 14].

Device	Cost (USD)
SKZ1061C TPS Thermal Conductivity Tester	5655.00
KD2 Pro Thermal Properties Analyzer	10696.79
Conducted THW apparatus	95.60

As demonstrated in Table 3, the conducted THW apparatus, when subjected to a cost-benefit analysis, is found to be 98.31% more cost-effective than the least expensive research prototype. By using copper wire as hot wire instead of the typically expensive platinum wire, the cost of hot wire is reduced by nearly 90% without sacrificing significant performance. Additionally, the use of an Arduino Nano and streamlining data acquisition to work with standard computers further minimize costs while maintaining precision with only a 1.29% deviation.

10. Conclusion

This study presents a cost-effective transient hot wire apparatus for measuring the thermal conductivity of liquids using copper wire. By replacing platinum with copper and utilizing an Arduino Nano for data acquisition, the device achieves precision with a deviation of only 1.29% and an average error of 0.72%. Careful design considerations, such as error correction for outer boundary, finite wire diameter, and end effects contributed to reducing measurement errors. The apparatus offers a 98.31% cost reduction compared to existing platinum THW devices, making it highly accessible for industrial and research applications without sacrificing significant performance. This demonstrates the potential for affordable solutions in thermal conductivity measurement with minimized errors.

11. Acknowledgements

This research was financed by University Grants Commission, Bangladesh and Rajshahi University of Engineering & Technology as a Young Professional Research Grant (DRE/7/RUET/640 (53)/PRO/2023-24/33).

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