Emergent Scientist **4**, 2 (2020)

https://doi.org/10.1051/emsci/2020001

Emergent Scientist

Available online at:
www.emergent-scientist.edp-open.org

RESEARCH ARTICLE OPEN ACCESS

Bimetallic ammeter: a novel method of current measurement

Robert Frederik Uy*, Qiaozi Miao, and Chenghao Yuan

St. Joseph's Institution, 38 Malcolm Road, Singapore 308274, Singapore

Received: 22 February 2020 / Accepted: 3 June 2020

Abstract. An electric current flowing through a bimetallic coil heats it up, and due to thermal expansion, the coil either unwinds or winds depending on the direction of net heat transfer and the specific heat capacities of the metals used. This means that by relating a certain measure of its mechanical displacement with current, the bimetallic coil can be used as an ammeter. Thus, a mathematical model relating the current to the time taken by the bimetallic coil to unwind a fixed displacement was developed and verified through experiments, which show a good agreement between theoretical and experimental values.

Keywords: Bimetallic ammeter / current measurement / thermal expansion / heating effect of current / mechanical displacement

1 Introduction

Ammeters are instruments that measure electric current. Having advanced significantly since the advent of electricity, the human race has seen a myriad of current-measuring instruments. Many of these fall under the following categories: electromechanical ammeters, thermal ammeters, multimeters, oscilloscopes and virtual instruments [1]. Each of these apparatuses utilises certain observable effects of electric current, making the measurement of current possible.

In this modern era, electricity has indubitably become part and parcel of our daily lives, powering our lights, phones, laptops and even cars. With the ubiquity of electronic devices, we often observe that these gadgets and appliances tend to heat up or even overheat when used for a prolonged period. This is because when an electric current passes through metals, the delocalised electrons collide with the positive ions in the metal lattice, transferring energy to the conductor in the form of heat. Consequently, we observe the heating up of our digital devices.

Thermal expansion is a physical phenomenon happening around us all the time although it often goes unnoticed for most everyday objects. Albeit commonplace, it still is a vital aspect of the physical world as it has the potential to critically impact our lives – everything from the rise in sea levels to the structural integrity of infrastructure [2]. An object that interestingly exhibits thermal expansion is the bimetallic coil. It is known that when an object is heated up and experiences a rise in temperature, its increase in length is proportional to its coefficient of linear thermal expansion, which is a characteristic of the material that the object is made of. Therefore, since one metal expands faster than the other, a bimetallic coil made up of two different metals with different coefficients of linear thermal expansion will wind or unwind itself when heated up.

Current-measuring instruments based on thermal effects have already been invented and patented. Among these are the works of Miller [3], Goodwin [4,5] and Hall [6], which served as sources of inspiration for our work. Similarly, by using thermal expansion as the observable thermal effect of electric current, we have also developed a thermal ammeter. Since an electric current heats up the conductor it flows through, a bimetallic coil gets heated up when it is placed in series with an electric circuit, resulting in a mechanical displacement. Thus, a bimetallic ammeter was devised such that a particular current value corresponds to a specific time taken by the bimetallic coil to unwind from the starting point to the endpoint, both of which are fixed. A model, which is based on the conservation of thermal energy and relates the current and the time taken for the unwinding of the coil, was then formulated and experimentally verified, thus allowing the bimetallic ammeter to be used as an unusual yet interesting method of measuring current.

2 Methods

This study is composed of three stages: the conceptualisation and creation of the bimetallic ammeter, theoretical modelling and data collection.

* e-mail: robertfrederikduy@gmail.com

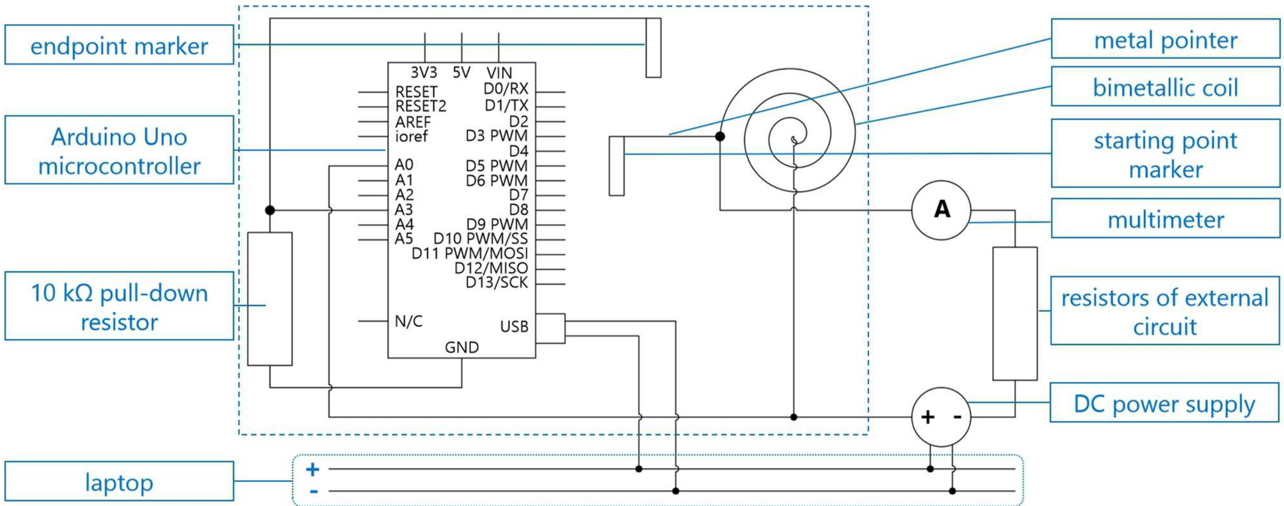

Fig. 1. A schematic diagram of the experimental setup. The part enclosed by the dashed box is the bimetallic ammeter. The conventional current flow is adopted for this diagram. The wires at the bottom show how the microcontroller and the external circuit are powered by the laptop.

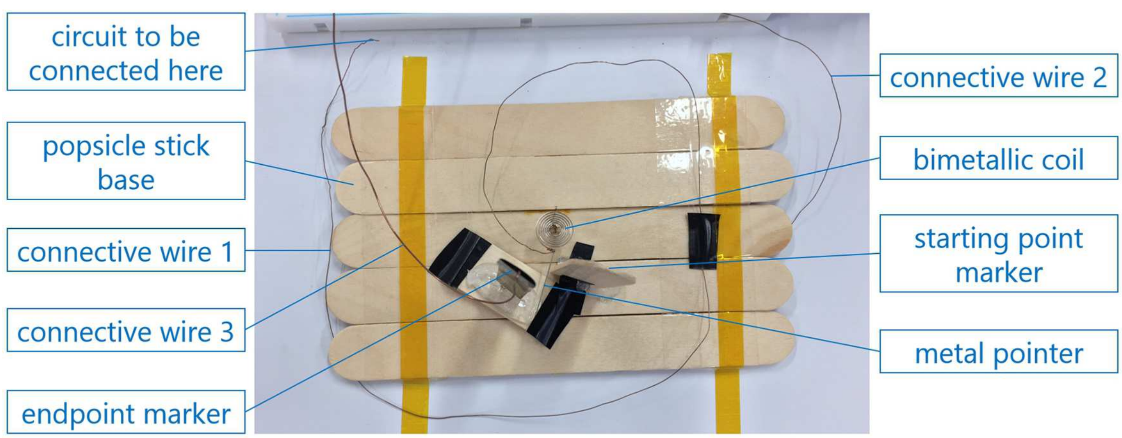

Fig. 2. A part of the top view of the bimetallic ammeter. It shows the various components on the popsicle stick base. To clarify, a part of connective wire 2 is located underneath the popsicle stick base and is connected to the fixed end of the coil. Note that the connective wires 2 and 3 are linked to parts in Figure 3.

2.1 The bimetallic ammeter

A schematic diagram of the bimetallic ammeter can be seen in Figure 1, and photographs of parts of the ammeter are shown in Figures 2 and 3.

In the experimental setup, the bimetallic coil, which is a Kitchen Hanging Fridge / Freezer Thermometer by Steve and Leif,[1] was removed from its original thermometer casing and was mounted on a popsicle stick base as shown in the picture in Figure 2. According to the manufacturers of the bimetallic coil, the two metals used are copper and zinc.

Connective copper wires were then attached to the two ends of the bimetallic coil by inserting the copper wires into holes at the two ends of the coil. The free end already had a hole as it is where the original thermometer's plastic pointer – which we removed and replaced with a metal pointer – was attached to, but the fixed end did not. Thus, a small hole was made by impaling it with the sharp end of a compass. The other ends of these connective wires were then put into certain holes of a breadboard, allowing for an easy connection to the circuit whose current is to be measured. The connective wire attached to the fixed end of the coil, which can be found at the centre of the coil, was also connected to an analog pin of the Arduino Uno microcontroller.

Moreover, another popsicle stick was used to mark and fix the starting point, which is the position of the metal pointer – connected to the free end of the coil – at room temperature. A metal strip was then placed to fix the endpoint, which is reached by the bimetallic coil after sufficient heating by the current. The starting point and endpoint were fixed in their respective positions such that the included angle between them with respect to the centre of the coil is 18°.

[1] Kitchen Hanging Fridge / Freezer Thermometer. https:// stevenleif .com/product/steve-leif-kitchen-hanging-fridge-freezer- thermometer/

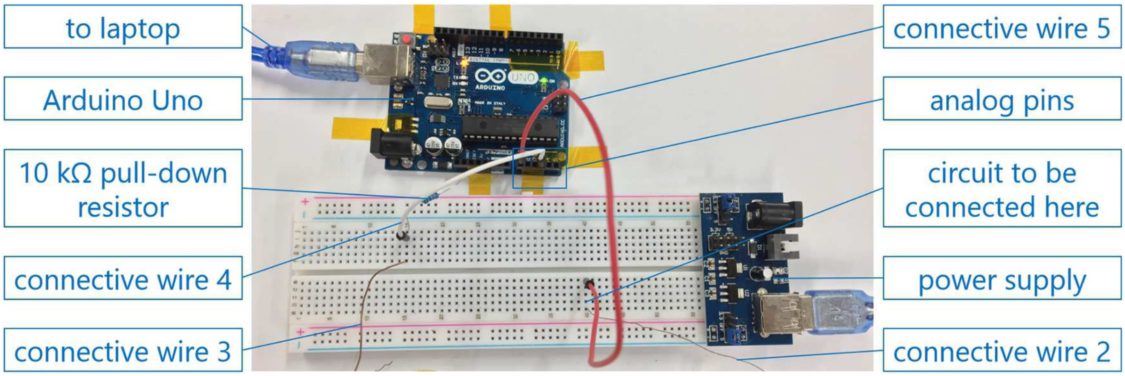

Fig. 3. A part of the top view of the bimetallic ammeter. It shows how components on the popsicle stick base are connected to relevant pins in the Arduino Uno microcontroller. Note that the connective wires 2 and 3 are linked to parts in Figure 2.

A copper wire was also attached to the metal strip using insulating electrical tape and was connected to another analog pin of the microcontroller, as well as to a 10-kiloohm pull-down resistor, which was, in turn, connected to the microcontroller's ground pin.

Referring to Figure 1, when the electric current from the external circuit enters the ammeter, it flows into the bimetallic coil. Simultaneously, the current is detected by the microcontroller, which then prompts the ammeter's Arduino program to record the time when the current started flowing through the ammeter. Note that the Arduino Uno microcontroller's ground is indirectly connected to the negative terminal of the external circuit's power supply as both the microcontroller and the power supply are connected to the laptop's ground through a USB connection.

The electric current continuously heats the bimetallic coil, causing it to unwind due to the different coefficients of linear thermal expansion of copper and zinc. Specifically, the average values of the coefficients of linear thermal expansion found in the existing literature [7–12] are $1.66 \times 10^{-5}/°C$ for copper and $3.00 \times 10^{-5}/°C$ for zinc. Since the inner metal – zinc – has a higher coefficient of linear thermal expansion than the outer metal – copper – the inner metal expands faster than the outer metal, resulting in the unwinding of the bimetallic coil.

Furthermore, a metal pointer was attached to one end of the bimetallic coil such that the pointer will move from the starting point to the endpoint as the coil is being heated up by the electric current. When the pointer then reaches the endpoint, the current will flow to the microcontroller's ground pin, passing through the pointer, the metal strip and the pull-down resistor. Consequently, the aforementioned microcontroller will trigger the Arduino program to record the time when it detected the current at the endpoint. The program will then subtract the first time value from the second time value to obtain the time taken by the bimetallic coil to unwind from the starting point to the endpoint. Once the time taken has been calculated, the ammeter is manually disconnected from the circuit to prevent further heating of the coil that would cause it to expand further, which would strain it as it is already at the fixed endpoint. Therefore, the pull-down resistor has a negligible influence on the current as current only flows through it momentarily, but it plays a crucial role in the circuit as it allows for the detection of current. Finally, a theoretical model is then used to calculate the current from the time measured by the microcontroller.

2.2 Mathematical model

As previously mentioned, a model relating the time taken by the bimetallic coil to unwind from the starting point to the endpoint and the current passing through the bimetallic ammeter was formulated. It involves three equations, which quantify the heat gained by the conductor, the heat dissipated to the surroundings, as well as the increase in temperature brought about by the net heat gain.

Firstly, the heat gained by the conductor is given by

$$Q_{\text{gain}} = I^2 R t, \tag{1}$$

where I is the current passing through the bimetallic ammeter, R is the resistance of the bimetallic ammeter, and t is the time taken by the bimetallic coil to unwind from the fixed starting point to the fixed endpoint.

Secondly, the heat dissipated to the surroundings is given by

$$Q_{\text{loss}} = -\int hA\Delta T(t)dt, \tag{2}$$

where h is the coefficient of overall heat transfer of the bimetallic coil, A is the surface area of the bimetallic coil, and $\Delta T(t)$ is the difference between the temperature of the bimetallic coil and the ambient temperature – which is also the initial temperature of the bimetallic coil – as a function of time.

Thirdly, the increase in temperature due to the net heat gain is given by

$$Q_{\text{net}} = mc\Delta T, \tag{3}$$

where m is the mass of the bimetallic coil, c is the specific heat capacity of the bimetallic coil, and ΔT is the overall change in temperature of the bimetallic coil.

By combining these three equations using the law of conservation of energy, we obtain the model relating I

and t:

$$mc\Delta T = I^2Rt - \int hA\Delta T(t)dt. \tag{4}$$

Due to difficulties in the measurement of the coefficient of overall heat transfer h and the surface area A of the bimetallic coil, Newton's law of cooling was applied to rewrite the expression for the heat loss to the surroundings. The aforementioned law states that the rate of cooling of an object is given by

$$\frac{dT}{dt} = -k\Delta T(t), \tag{5}$$

where k is the cooling constant.

The heat capacity of an object, by definition, is given by

$$C = mc = \frac{dQ}{dT}, \tag{6}$$

which can be rewritten as

$$\frac{dT}{dt} \times mc = \frac{dQ}{dt}. \tag{7}$$

By substituting equation (2) and equation (5) into equation (7), the relationship between h and k is obtained:

$$-k\Delta T(t) \times mc = -hA\Delta T(t), \tag{8}$$

which elegantly simplifies to

$$hA = mck. \tag{9}$$

Substituting equation (9) into equation (2), the heat loss to surroundings can be re-expressed as

$$Q_{\text{loss}} = -\int mck\Delta T(t)dt. \tag{10}$$

By solving equation (4) with its last term modified using equation (10), we obtain the time taken by the bimetallic coil to unwind from the starting point to the endpoint, which is given by

$$t = -\frac{1}{k}\ln\left(1 - \frac{mck\Delta T}{I^2R}\right). \tag{11}$$

2.3 Data collection

Figure 1 shows a schematic diagram of the experimental setup. Experiments were conducted in order to verify our model. These experiments include finding the values of the constants used in our model, as well as collecting data to verify the validity of the given model.

To obtain the values of the constants in equation (11), experiments were conducted, and existing literature values were used. Table 1 summarizes the values of the constants used in the model.

Firstly, the mass m of the bimetallic coil was measured to be 0.00023 kg using an electronic balance.

Secondly, the specific heat capacity $c = 388$ J/(kg·°C) was obtained by taking the mean of the specific heat capacities of copper and zinc found in the existing literature [12–14].

Table 1. Values of the constants used in the model.

Constant	Value
Mass (m)	0.00023 kg
Specific heat capacity c	388 J/(kg·°C)
Cooling constant k	0.0071 s^{-1}
Resistance R	0.8 Ω
Temperature change ΔT	18.23 °C

Thirdly, the cooling constant k was obtained through an experiment in which the bimetallic coil was heated up to 45 °C, and the time taken for it to cool down to 35 °C was measured using a stopwatch. The mean of three time values was then taken. Using Newton's law of cooling, which is shown in equation (5), the value of the cooling constant k can be obtained from the time taken t using the following equation:

$$k = \frac{\ln\left(\frac{T_i - T_a}{T_f - T_a}\right)}{t_{\text{cool}}}, \tag{12}$$

where T_a is the ambient temperature, T_i is the initial temperature, T_f is the final temperature, and t_{cool} is the time taken for the coil to cool from the initial temperature to the final temperature.

We were unable to measure the temperature of the bimetallic coil using our laboratory's thermometers as the alcohol-in-glass thermometer, the thermocouple and the infrared thermometer tend to measure the ambient temperature instead of the coil's temperature. Hence, our best choice was to record the temperature reading using the scale on the original thermometer casing, without the transparent plastic cover. Since most of the heat is lost to air in both the experimental setup and the bimetallic ammeter and both the original thermometer casing and the popsicle stick base are poor conductors of heat, the cooling constant k for both setups should be highly similar. Furthermore, we heated the coil using a blow dryer as using an electric current would result in inaccuracies in the data collected. If we were to use an electric current to heat the coil, the connective wire would exert a torque on the coil against its unwinding. This would then lead to a temperature reading that is lower than the actual value as the graduations on the original thermometer casing were not calibrated to take into account the torque exerted by the connective wire.

In our experiment, the ambient temperature T_a was 30 °C, the initial temperature T_i was 45 °C, the final temperature T_f was 35 °C, and the average time taken t_{cool} was 154 s. Hence, for our setup, the value of the cooling constant is $k = 0.0071$ s^{-1}.

Lastly, we measured the resistance of the bimetallic coil using a multimeter, which gave a reading of $R = 0.8$ Ω.

As shown in Figure 1, the devised bimetallic ammeter was connected in series to the circuit whose current is to be measured, as well as a multimeter. The circuit used was made up of resistors on a breadboard, which were in turn connected to a low voltage power supply. The multimeter

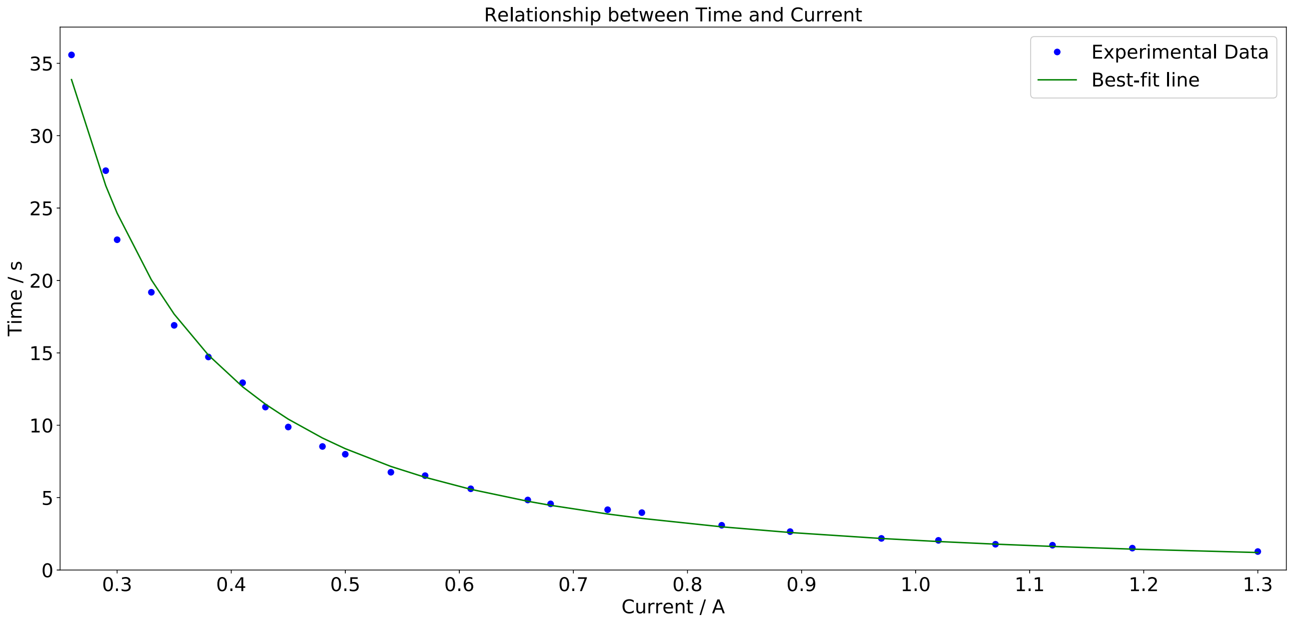

Fig. 4. Relationship between the current I and time taken to unwind t. The blue dots represent the experimental data values, whereas the green curve represents the best-fit curve with $\Delta T = 18.23\,^{\circ}\mathrm{C}$.

was used to obtain the experimental current value. To vary the current, the resistance of the resistors and the voltage supplied were varied. Moreover, for each current value, the time taken by the bimetallic coil to unwind was measured a few times, and the mean of the three most precise values was taken. This experiment allows us to correlate the average time taken with the current value.

3 Results

Figure 4 is a graph showing the relationship between the current and time. As expected, the time taken decreases as the current increases. This is because, for a higher current value, heat is gained by the bimetallic coil at a higher rate. Thus, the two metals, copper and zinc, increase in length at an increased rate, leading to a faster unwinding of the coil.

4 Discussion

Since we were unable to measure the temperature accurately and reliably, we used Python to find the best-fit curve for our data, which gave the value for the overall temperature change $\Delta T = 18.23\,^{\circ}\mathrm{C}$. Furthermore, the included angle between the starting point and the endpoint with respect to the centre of the coil is 18°, which supposedly corresponds to a 6 °C increase in temperature if read off the scale on the original thermometer casing. However, the overall temperature change ΔT is much higher than 6 °C because the connective wire attached to the coil's free end exerts a torque on the coil against its unwinding.

From the graph in Figure 4, it can be said that the theoretical model agrees well with the experimental data. In fact, an average error of only 4% was recorded, thus proving that the model being proposed is a good and reliable approximation.

4.1 Error analysis

Discrepancies between the theoretical model and the experimental data arose primarily due to the differing response times of the microcontroller. Aside from this, the uncertainties of the measurements due to the limited precision of the instruments used and slight differences in ambient temperature, which was assumed to be constant throughout the data collection phase of this study, also contributed to the deviations of the experimental data from the theoretical model.

4.2 Transmutation of output current value

It must be noted that the current measured by the bimetallic ammeter is the current flowing through it. Since the bimetallic ammeter has internal resistance, the ammeter causes the resistance of the entire setup to increase when it is connected in series with a particular circuit. By Ohm's law, this increase in resistance leads to a decrease in the current flowing through the setup, provided that the voltage supplied by the power supply remains constant. In this regard, we introduce a correction term to transmute the measured current value into the true current value of the circuit prior to its connection to the bimetallic ammeter. This correction term, which must be multiplied to the measured current value to obtain the desired current value, is given by

$$n = \frac{R_a + R_c}{R_c}, \tag{13}$$

where R_a is the internal resistance of the ammeter and R_c is the resistance of the circuit.

4.3 Limitations of the bimetallic ammeter

Another important aspect of the bimetallic ammeter that must be considered is its limitations.

Firstly, the range of current values that our bimetallic ammeter was able to measure accurately is 0.26 A to 1.30 A. This is because for electric currents less than 0.26 A, the microcontroller has a poor response in the detection of the current. Therefore, although the metal pointer is already in contact with the metal strip at the endpoint, the microcontroller does not detect the current immediately. This results in a longer time taken measured by the microcontroller, causing the measured current value to be lower than the actual value. Another reason is the fact that for even lower currents, the rate at which the coil gains heat is lower. Thus, the coil reaches steady state, in which the rate of heat absorption is equal to the rate of heat dissipation, before reaching the endpoint. Moreover, for current values higher than 1.30 A, the level of accuracy is lower since the slope of the current-time graph for higher currents is significantly smaller. This means that a small error in the measured time would result in a large deviation in the output current value, thus considerably decreasing the accuracy of the instrument.

Secondly, our bimetallic ammeter only works for specific ambient working conditions; that is, the ambient working conditions during the collection of data must be the same as during the time the ammeter is used for measuring current. For instance, our bimetallic ammeter only works well for ambient temperatures of about 30 °C and in the absence of wind as these are the major ambient conditions in which data was collected to obtain values for the constants of the model. The ambient temperature matters as a different surrounding temperature leads to a different rate of heat loss. Therefore, the time taken by the coil to unwind from the starting point to the endpoint also deviates from the expected value. Moreover, the presence of wind increases the rate of heat loss through convection, resulting in a lower rate of the unwinding of the coil. This would then lead to a higher time taken by the coil to unwind from the starting point to the endpoint and, consequently, a current value lower than the true value. Hence, if the ambient conditions were to change, the values of the constants must be re-calibrated so that accurate current measurements can be taken.

Thirdly, after each current measurement, the subsequent measurement can only be done after a waiting time that can be determined experimentally. To find out the waiting time, one must measure the time needed by the coil to return to its original position. Moreover, the coil must be placed somewhere with a lower ambient temperature to allow the bimetallic coil to cool to the original ambient temperature and not just approach it. Ensuring that the metal pointer reaches the starting point before making another measurement is essential as the increase in the length of the metals needed for the bimetallic coil to unwind to the endpoint must be consistent. An estimate for the order of magnitude of the waiting time is $1/k$, which is approximately 10^2 s for our setup.

Lastly, the voltage supplied by the external circuit's power supply is limited to a maximum of 5 volts so as not to damage the microcontroller.

4.4 Potential improvements

One potential improvement that can be probed in future studies would be finding the optimal positions of the fixed starting point and endpoint. This is something that has not been investigated in this study but could potentially widen the range of current values that can be accurately measured by the bimetallic ammeter.

In addition, the collection of data should be conducted in a place where the ambient temperature can easily be controlled. In our study, the data was collected in our school's laboratory, where the ambient temperature fluctuates throughout the day. Consequently, due to these slight differences in the ambient temperature, the rate of heat loss may have differed slightly at different times of the day. Therefore, to obtain more accurate and reliable data, the data should be collected in a room where the ambient temperature can be controlled.

5 Dead end

One dead-end we faced during the course of our study was finding out the current based on the angular displacement covered by the metal pointer as the bimetallic coil was being heated up by an electric current for a specific period – two seconds, for example. This is because we found it difficult to let the current flow to the ammeter for a very specific period accurately and repeatedly. This is mainly due to human reaction time which cannot be controlled easily during experimentation. Moreover, it is also difficult to pinpoint the exact location of the maximum displacement of the metal pointer, which is reached right before the ammeter is disconnected from the circuit, to accurately correlate the current value with the angular displacement of the pointer. However, future work could delve into finding solutions to circumvent the obstacles we faced.

Another dead-end we faced was using the original plastic thermometer casing. The casing, because it is made of plastic, tends to melt when the coil is heated up by the current for a prolonged period. Therefore, to address this problem, the bimetallic coil was mounted on the popsicle stick base.

We also faced a dead-end in trying to measure the temperature of the bimetallic coil. Having only access to an alcohol-in-glass thermometer, a thermocouple and an infrared thermometer, we were unable to measure the coil's temperature. This is because the alcohol-in-glass thermometer and thermocouple exerted a torque on the bimetallic coil, preventing it from unwinding, when these thermometers were placed at the coil's rim. Moreover, when placed on the fixed end of the coil to avoid the above scenario, the thermometer gave temperature readings with only a marginal increase from the ambient temperature.

This is because the surfaces of the alcohol-in-glass thermometer's bulb and the thermocouple's probe were mostly in contact with the surrounding air, not the bimetallic coil. Furthermore, due to the small surface area of the coil, the infrared thermometer tends to measure the temperature of the surfaces around the coil, instead of the bimetallic coil itself.

6 Conclusion

In this study, a novel bimetallic ammeter was devised, and alongside it, a model describing the relationship between the current and the time taken by the bimetallic coil to unwind was developed and experimentally verified. Being highly accurate, the measurements show an average error of only 4%, indicating a good agreement between the theoretical model and the experimental data. However, there is still room for improvement in the accuracy and design of the instrument. Such improvements could be delved into in future studies.

We would like to express our gratitude to St. Joseph's Institution for allowing us to use the school's laboratory and providing us with the apparatuses we needed. Moreover, we would also like to thank Ms Wong Kah Yan, Mrs Lydiawati Wong, Nguyen Khoi Nguyen, Nguyen Cao Duy and Do Thien Phuc for helping us in various ways throughout the course of our study.

References

1. H. Eren, Current Measurement, in: H. Peter, R. Thorn (Eds.), Handbook of Measuring System Design, edited by Sydenham, John Wiley & Sons, Chichester, England, 2005
2. D.R. Dounas-Frazer, P.R. Gandhi, G.Z. Iwata, Uncertainty analysis for a simple thermal expansion experiment, Am. J. Phys. **81**, 338–342 (2013)
3. J.H. Miller, Thermocouple ammeter. U.S. Patent 2,100,260, issued November 23, 1937
4. W.N. Goodwin, Jr., Thermal ammeter. U.S. Patent 1,456,951, issued May 29, 1923
5. W.N. Goodwin, Jr., Thermal ammeter. U.S. Patent 2,645,756, issued July 14, 1953
6. W.D. Hall, Thermal ammeter. U.S. Patent 2,211,773, issued August 20, 1940
7. Coefficients of Linear Thermal Expansion. Engineering ToolBox. 2003, https://www.engineeringtoolbox.com/linear-expansion-coefficients-d_95.html (accessed December 28, 2019)
8. H. De Keulenaer, Thermal expansion: Copper vs. aluminium. Leonardo Energy, 2019, Last modified November 5. https://help.leonardo-energy.org/hc/en-us/articles/202823322-Thermal-expansion-Copper-vs-aluminium?mobile_site=true (accessed December 28, 2019)
9. R. Scholl, W.B. Liby, Using a Michelson interferometer to measure coefficient of thermal expansion of copper, Phys. Teacher **47**, 306–308 (2009)
10. List of Thermal Expansion Coefficients (CTE) for Natural and Engineered Materials. MSE Supplies. https://www.msesupplies.com/pages/list-of-thermal-expansion-coefficients-cte-for-natural-and-engineered-materials (accessed December 28, 2019)
11. Linear Thermal Expansion Coefficient for Metals. AmesWeb. https://www.amesweb.info/Materials/Linear-Thermal-Expansion-Coefficient-Metals.aspx (accessed December 28, 2019)
12. R.A. Serway, W.J. Jewett, Physics for scientists and engineers with modern physics, Cengage Learning, Boston, 2018
13. Specific Heat of some Metals. Engineering ToolBox. 2003. https://www.engineeringtoolbox.com/specific-heat-metals-d_152.html (accessed December 28, 2019)
14. Specific Heat Capacity Table. Upper Canada District School Board. http://www2.ucdsb.on.ca/tiss/stretton/database/Specific_Heat_Capacity_Table.html (accessed December 28, 2019)

Cite this article as: Robert Frederik Uy, Qiaozi Miao, Chenghao Yuan, Bimetallic Ammeter: A Novel Method of Current Measurement, Emergent Scientist **4**, 2 (2020)