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Design and Construction of Newton's Law of Cooling Apparatus Featuring Digital Temperature Measurement and Data Logging Systems: A STEM Practical Aid

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ABSTRACT

This study presents the design and construction of a low-cost experimental apparatus for the demonstration and verification of Newton's law of cooling using locally sourced materials. The apparatus was fabricated from a 2.0 mm thick mild steel sheet and equipped with an Arduino Uno microcontroller and DS18B20 digital temperature sensors for automated temperature measurement and data logging. To evaluate its performance, the cooling process of 50 mL of water initially heated to 90 °C was monitored until thermal equilibrium with the ambient environment was approached. Both the water temperature and ambient temperature were recorded automatically throughout the experiment. Analysis of the experimental data revealed a linear relationship between the rate of cooling and the excess temperature of the water above its surroundings, consistent with Newton's law of cooling. The slope of the best-fit line was determined to be (0.0045 ± 1.87881) × 10^{-5} s^{-1}, with a coefficient of determination (R^2) of 0.99189. The high degree of linearity obtained demonstrates the reliability of the apparatus and confirms its suitability for verifying Newton's law of cooling within experimental uncertainty. Owing to its low cost, ease of construction, and automated data acquisition capability, the apparatus offers a practical alternative for teaching and laboratory demonstrations in educational institutions with limited resources.

Keywords— **Arduino Uno, cooling rate, DAQ, DS18b20, LCD, microcontroller, Laboratory**

I. INTRODUCTION

Newton's Law of Cooling states that the rate of change of temperature of a body is directly proportional to the difference between its temperature and that of the surrounding environment, provided that the temperature difference remains small [1]. Mathematically, the law can be written as:

$$\frac{dT}{dt} = -k(T - T_s) \qquad (1)$$

where T is the temperature of the body, T_s is the temperature of the surroundings, and t is time. k is the cooling rate. The solution of the equation above, which shows the dependence of temperature, T, on time, is:

$$T(t) = T_s + (T_0 - T_s)e^{-kt} \quad (2)$$

In this expression, T_0 is the initial temperature of the body and k is the cooling rate. The law has wide-ranging applications in science and engineering. In thermal system design, Newton's Law of Cooling is used in the design of heat sinks, cooling fans, and other cooling systems to ensure that systems operate within safe temperature limits. For instance, [2] discussed cooling mechanisms and heat-transfer principles that employ the law in electronics design. In the food industry, the law is also used to predict the cooling rates of food products during storage and refrigeration [3]. In the field of climate and environmental studies, the law is applied in studying heat exchange between the Earth's surface and the atmosphere and in the analysis of temperature changes in air masses and the cooling of the Earth's surface during the night. Similarly, it is often used to model the cooling of soil, lakes, ponds, and other natural systems after sunset [4]. Estimation of Time of Death (TOD) is based on the presumption that after death, the human body gradually cools toward the ambient temperature. This necessitates the use of Newton's law of cooling in Forensic examination [5], [7]. To estimate the time it takes a body to cool between two temperatures, or to determine the cooling rates of different objects, experiments are usually performed in laboratories. As a result of this, Newton's Law of cooling has become indispensable in manufacturing industries and in everyday engineering calculations. Despite its fundamental importance, the concept is often perceived by students as abstract when it is presented primarily through theoretical instruction without sufficient experimental illustration.

Newton's law of cooling apparatus is a laboratory setup for observing the cooling rate of a body. The apparatus consists of a copper calorimeter, thermometers, a heating source, a stop clock, and an insulating jacket. Water usually serves as the medium whose temperature change is being studied. In an experimental setup, the calorimeter is filled with hot water and allowed to cool naturally in a room of constant temperature. The temperature of the water is recorded at fixed time intervals, and a graph of temperature versus time is then plotted.

The integration of technology into physics education has received considerable attention in recent years, as digital tools, multimedia resources, and interactive simulations offers learners the opportunities to visualise abstract concepts and establish meaningful connections between theoretical principles and real-world phenomena. Such technology-enhanced instructional approaches have been shown to improve conceptual understanding and student engagement in science learning [8]. In this context, [9] reported the development of a Newton's law of cooling apparatus incorporating a microcontroller development board for automated temperature measurement and data acquisition. The system served as a cost-effective alternative to commercially available laboratory equipment, thereby increasing accessibility to experimental investigations. Similarly, [10] developed a microcontroller-based apparatus, thereby demonstrating the effectiveness of embedded systems in facilitating accurate and affordable physics experiments. These studies illustrate the growing application of microcontroller technologies in physics education and laboratory practice.

In many educational institutions, particularly those with underdeveloped laboratory facilities, the absence of simple, affordable, and reliable experimental apparatus further constrains the effective teaching of thermodynamic and calorimetric concepts. Furthermore, commercially available laboratory equipment is usually expensive or unsuitable for large student populations, thereby limiting opportunities for hands-on experimentation and active learning. These challenges underscore the need for the development of locally fabricated laboratory apparatus that is cost-effective, easy to operate, and capable of producing accurate and reproducible results. Consequent upon this, this study was carried out with the following objectives: (i) design and fabrication of a laboratory apparatus for studying Newton's law of cooling (ii) validation of the apparatus through an experiment, and (iii) demonstrate its suitability for use in laboratories.

II. MATERIALS AND METHODS

A. Design and construction of a double-walled enclosure

A 2.0 mm thick mild steel sheet was fabricated into two cylindrical containers with radii of 20.0 cm and 14.0 cm, and heights of 15.0 cm and 12.0 cm, respectively. The steel sheets were cut, rolled, and welded to form the cylindrical tanks. To enhance durability and provide protection against corrosion, the completed containers were coated with a protective paint layer. The smaller cylinder was concentrically suspended within the larger cylinder, maintaining a uniform clearance of 3.0 cm between the walls of both cylinders. The two containers were securely fastened in this configuration using bolts and nuts, thereby forming a double-walled enclosure. A circular cover with a radius of 10.0 cm was fabricated from medium-density fibreboard (MDF). Two holes of radius 6 mm were drilled in the cover: one at the centre and the other at a radial distance of 8.5 cm from the centre. These openings were provided to accommodate the temperature sensors used for data acquisition. Figure 1 illustrates the dimensions of the two cylindrical containers and their assembly into the double-walled enclosure.

B. Design and construction of a temperature measurement and data logging system

The temperature measurement and data logging unit consisted of one-wire temperature sensors, DS18B20, a 16x2 liquid crystal display (LCD) module, and an Arduino development board. The DS18B20 is a digital sensor with a programmable resolution of 9 – 12 bit. The resolution at power-up is 12 bit this corresponds to increment of 0.0625^0C from -10^0C to 85^0C. Additional information about the sensor can be obtained from [11] - [13]. The liquid crystal display module can display a total of 32 characters (16 characters in two lines) [14]. It is a dot matrix display. Arduino Uno features an Atmega 328 P microcontroller [15]. The components are connected as shown in Figure 2. The power, data, and ground terminals of the temperature sensors were connected to a common plug, and the plug was inserted into socket A, shown in the figure. The microcontroller was programmed to identify the temperature sensors in the circuit, index them, and display the results on the LCD during the initialization period. Additionally, the microcontroller was programmed to read the temperature sensors and log the temperature data every 10 seconds.

C. Experimentation

The experimental setup is shown in Figure 3. The space between the containers was filled with water at room temperature, and a wooden cork was placed in the inner container. A 50 ml beaker was filled with water and heated to a temperature of 90o C on a hot plate. The beaker was transferred into the apparatus and was placed on the wooden cork, and the unit was covered. The temperature sensors were inserted through the holes on the wooden cover into the water in the beaker and the water in the double-walled enclosure. The start button was pressed, and the system measured the temperature of the water in the beaker and the water in the double-walled enclosure every 10 s. the readings were logged into an excel spreadsheet, at the same time. The experiment was monitored for about 1 hour and 18 minutes, giving a total of 461 readings of both temperature sensors and time. The plot of temperature of the water in the beaker and the temperature of the surroundings versus time was obtained in real time during the experiment.

The excess temperature and the rate of cooling of the water were determined, and graphs of the parameters were plotted against time. The graph of the rate of cooling of water was also plotted against the excess temperature were plotted using the Origin Pro software, the software was also used to analyse the graph to obtain the cooling rate. The cooling rate was used in equation (2) to compute the temperature of the body at various values of time. The cooling curve of the body and the graph of the computed temperatures were compared

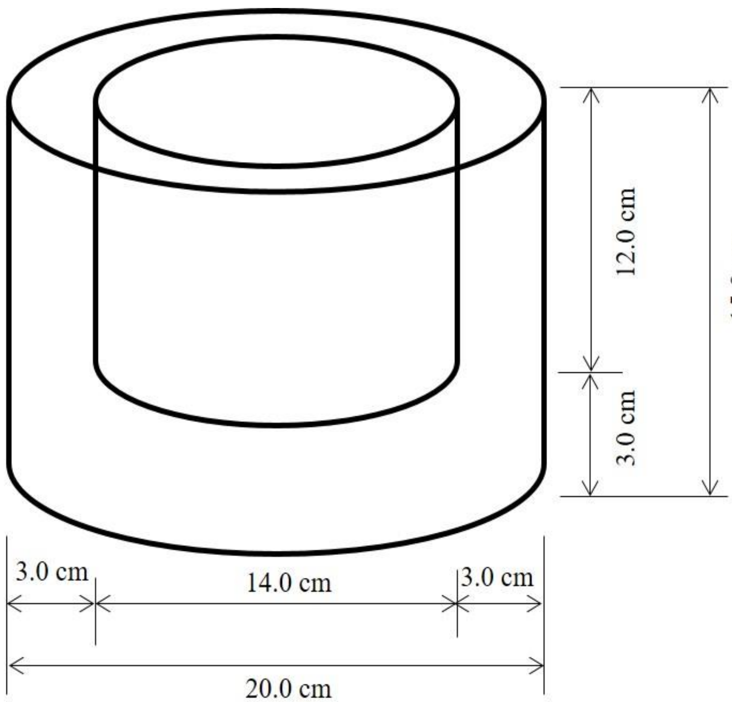

Figure 1: Dimensions and arrangement of mild steel containers to form a double-walled enclosure.

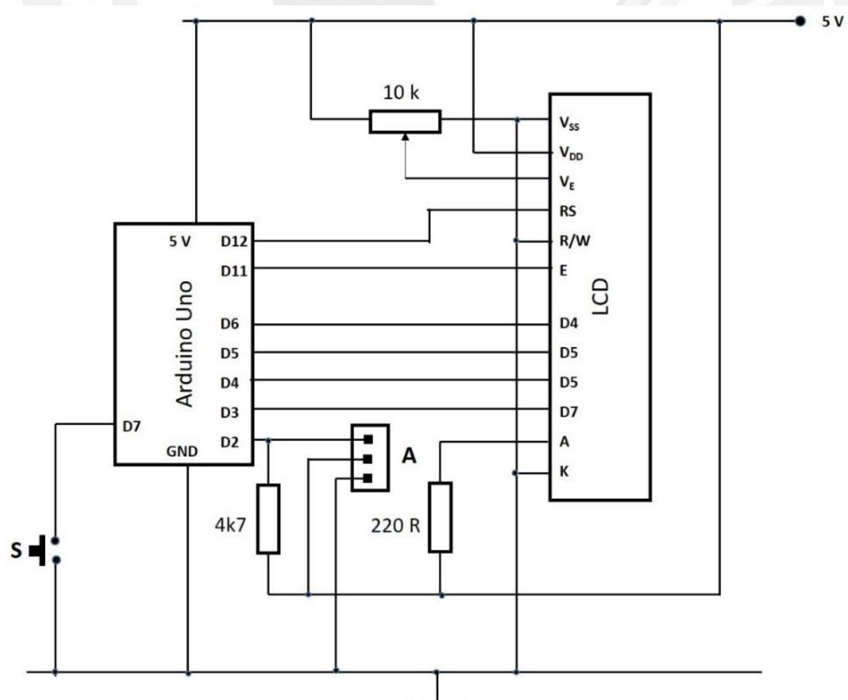

Figure 2: The circuit diagram of the temperature measurement and data logging system

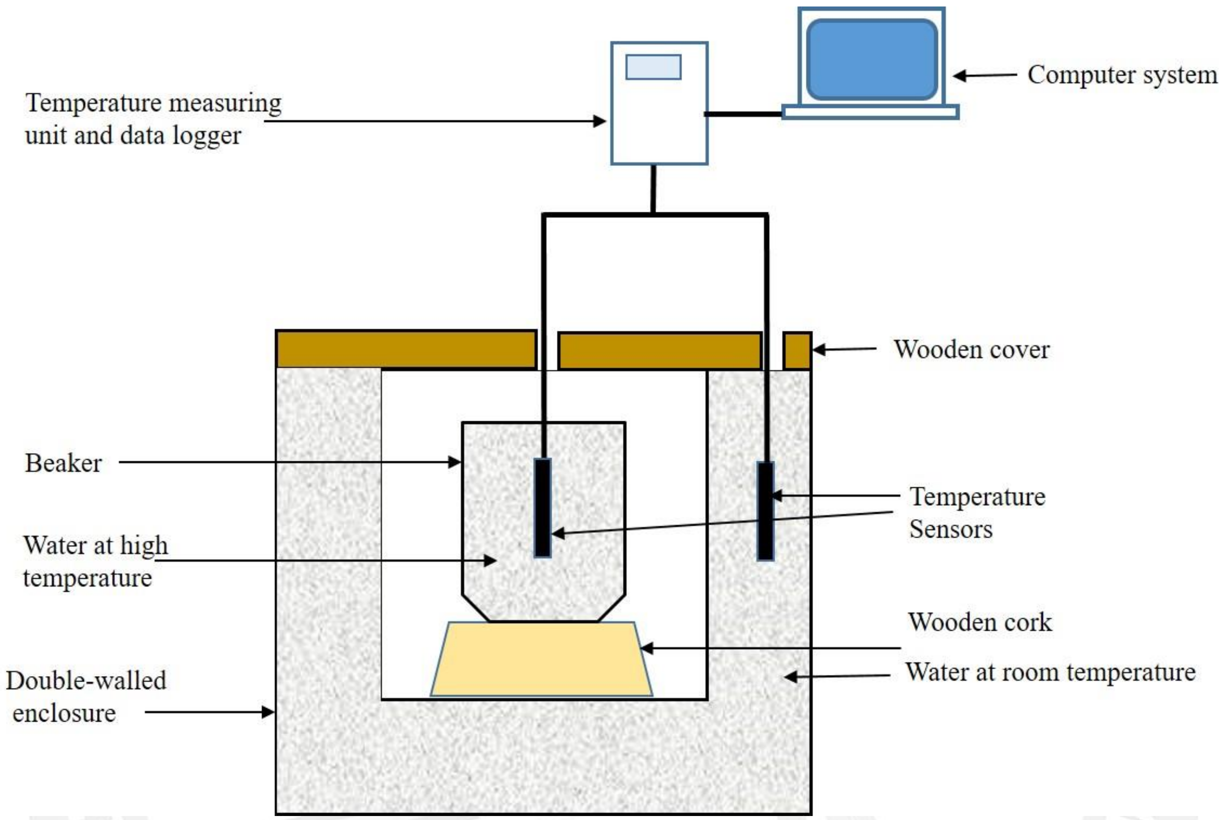

Figure 3: The experimental set-up for studying Newton's Law of cooling using the apparatus

III. RESULTS

Figure 4 shows the graphs of the temperature of water and the surroundings against time, as plotted in real-time during the experiment by Microsoft Excel. The graphs of excess temperature, i.e., the difference between the temperature of the water and the temperature of the surroundings, and the rate of cooling of the water, i. e. gradient of the cooling curve, in Figure 4 are shown in Figure 5. The graph of the rate of cooling versus excess temperature is shown in Figure 6. The cooling curve of the water and the computed temperature were compared in Figure 7.

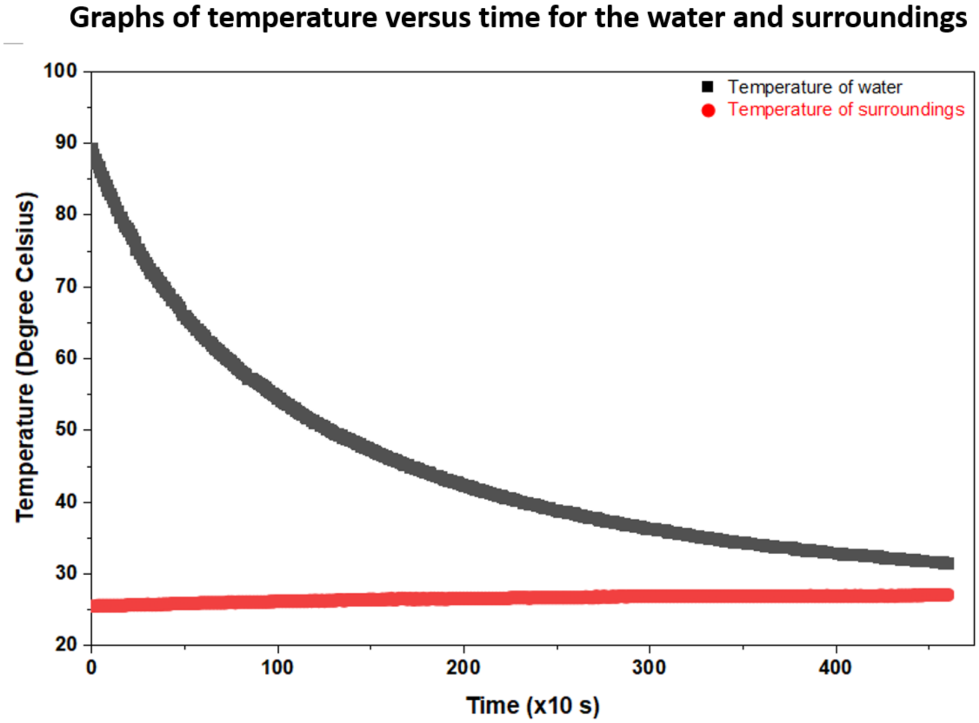

Figure 4: Graphs of temperatures of water and surroundings versus time

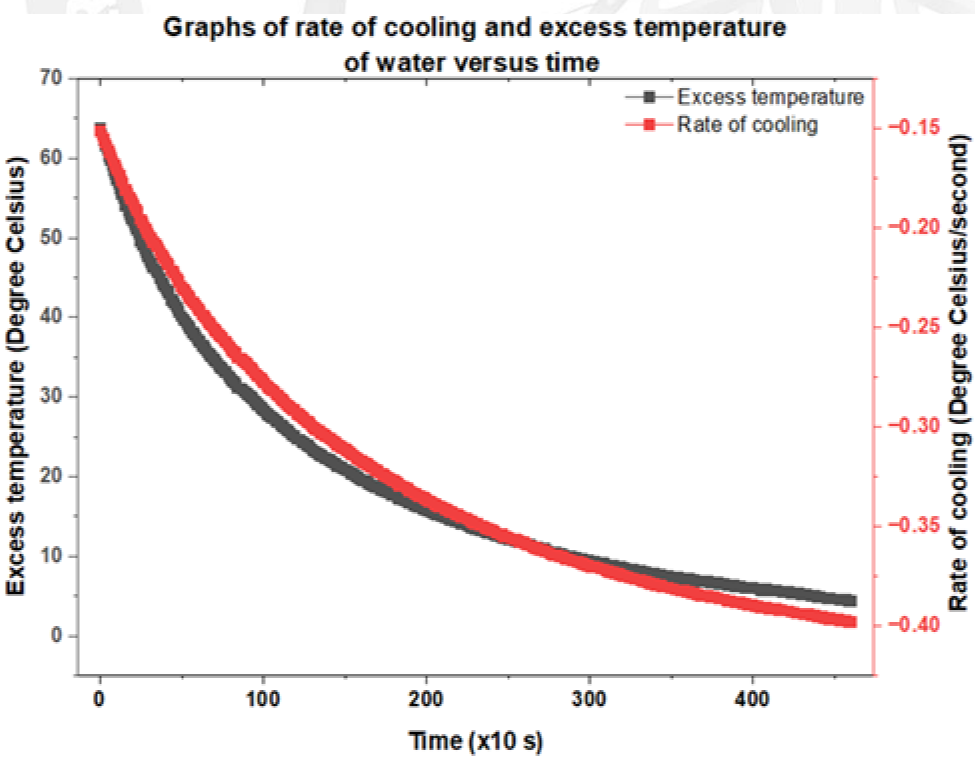

Figure 5: Graphs of excess temperature and the rate of cooling of the water versus time

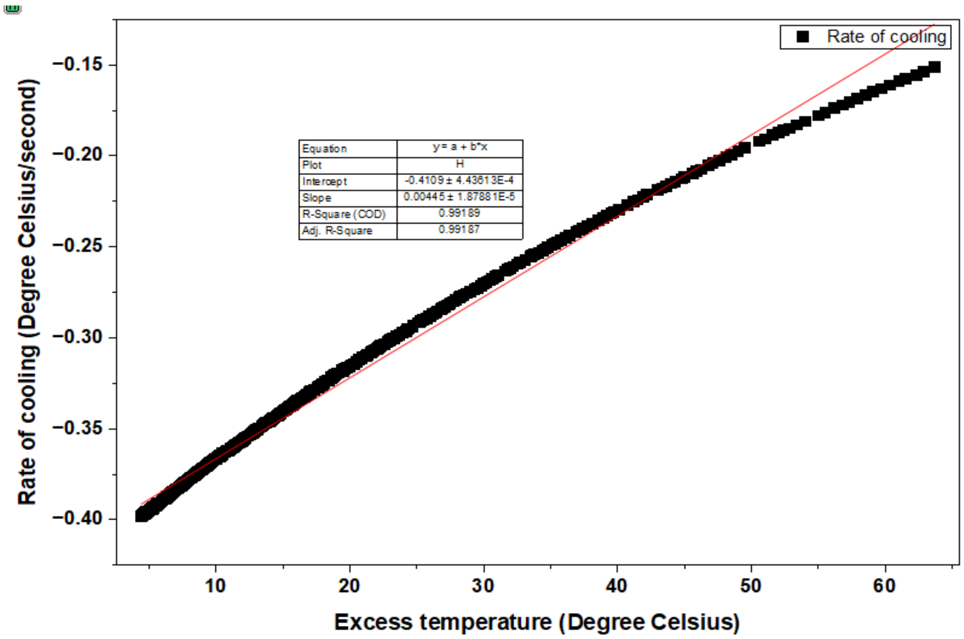

Figure 6: The graph of the rate of cooling versus excess temperature

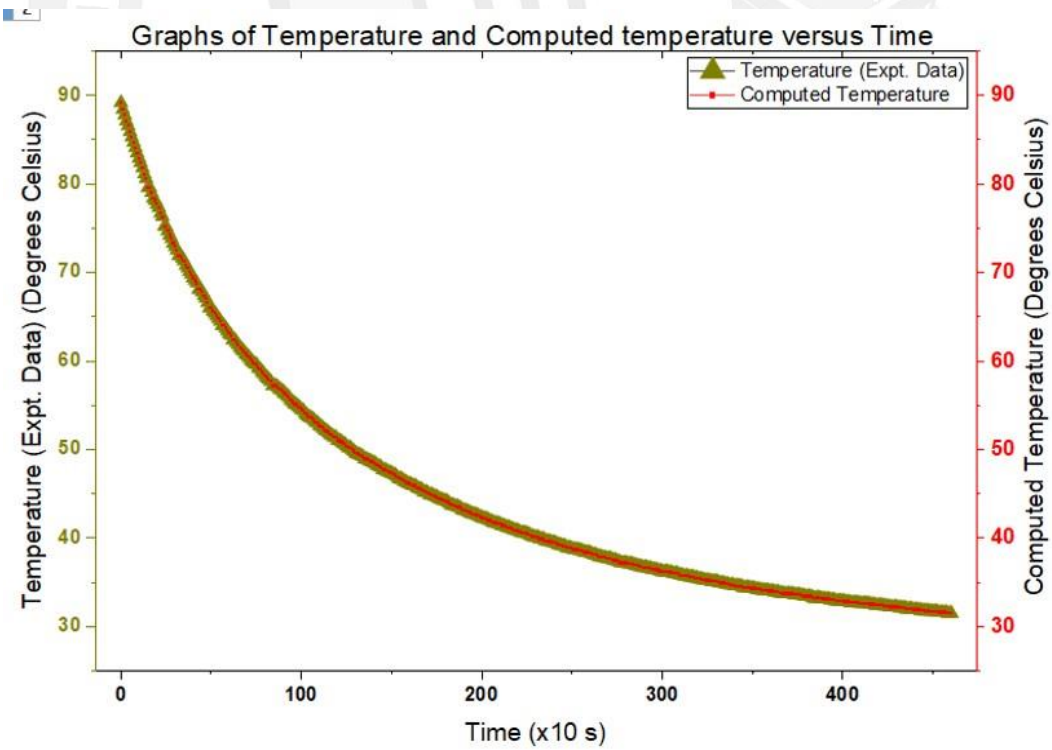

Figure 7: Graphs of water temperature and computed temperature versus time

IV. DISCUSSION

The cooling curve presented in Figure 4 exhibits an exponential decay pattern, which is consistent with the prediction of Newton's Law of Cooling as expressed in Equation (2). The temperature of the surroundings was initially approximately 25 ℃ and increased gradually to about 27 ℃ over the course of the experiment. This slight rise in ambient temperature may be attributed to heat transfer from the cooling water in the beaker to the water contained within the double-walled enclosure, resulting in a modest accumulation of thermal energy in the surroundings.

As shown in Figure 5, the excess temperature ($T-T_s$) and the rate of cooling exhibit similar trends throughout the cooling process, with both quantities decreasing as time progresses. This observation is in agreement with Newton's Law of Cooling, which states that the rate of heat loss from a body is directly proportional to its excess temperature above the surroundings. Furthermore, the plot of the rate of cooling against excess temperature, Figure 6, reveals an approximately linear relationship between these variables, providing experimental validation of the law within the temperature range investigated. The observed linearity indicates that the apparatus is capable of accurately demonstrating the fundamental relationship between cooling rate and temperature difference, thereby confirming its suitability for instructional and experimental applications. The Coefficient of Determination, R^2 was found to be 0.99189, and the slope of the line of best fit was $(0.0045 \pm 1.87881) \times 10^{-5}\ s^{-1}$.

As shown in Figure 7, the temperatures computed using Equation (2) (red curve) are in close agreement with the experimentally measured values (black curve) throughout the cooling process. The strong correspondence between the theoretical predictions and the experimental data indicates that the cooling constant obtained from the analysis of Figure 6 provides an accurate description of the cooling behaviour of the system. This agreement further confirms the validity of Newton's Law of Cooling for the experimental conditions investigated and demonstrates the reliability of the constructed apparatus for studying and illustrating the cooling process.

The slight increase in the temperature of the surroundings suggests that the volume of water contained in the double-walled enclosure was insufficient to absorb the heat released by the cooling body without experiencing a noticeable rise in temperature. This variation in the ambient temperature may have introduced minor deviations from the ideal conditions assumed in Newton's Law of Cooling, where the surrounding temperature is expected to remain constant. To minimize such errors, the enclosure could be redesigned with a larger capacity to accommodate a greater volume of water, thereby increasing its thermal inertia. Additional improvements may include the incorporation of a stirrer to promote uniform temperature distribution within the enclosure and the use of a liquid with a higher specific heat capacity than water to enhance heat absorption while limiting temperature fluctuations.

Furthermore, Newton's Law of Cooling is most accurately applicable when heat transfer occurs predominantly through convection. In the present experiment, additional heat-loss mechanisms such as thermal radiation and evaporation from the water surface may have contributed to the overall cooling process. These mechanisms are not explicitly accounted for in the simple form of Newton's Law of Cooling and could therefore introduce discrepancies between the observations. Nevertheless, their effects appear to be relatively small, as evidenced by the observed exponential cooling behaviour and the approximately linear relationship between the rate of cooling and the excess temperature.

V. CONCLUSION

A microcomputer-based system for investigating Newton’s law of cooling was successfully developed and tested. The system was used to measure, display, and record the temperature of 50 mL of water at regular time intervals during the cooling process. By automatically logging temperature data to a computer-based spreadsheet, the apparatus enabled real-time visualization of the cooling curve while simultaneously providing a permanent record of experimental data for subsequent analysis.

Analysis of the experimental results demonstrated that the system reliably captured the cooling behaviour of the water and generated data consistent with the predictions of Newton’s law of cooling. The close agreement between the theoretical model and the experimental observations confirms the accuracy and effectiveness of the developed apparatus. Furthermore, the automated data acquisition and storage capabilities of the system enhance the convenience, efficiency, and precision of experimental investigations. The developed apparatus therefore provides a simple, low-cost, and effective tool for the study and demonstration of Newton’s law of cooling in teaching and research laboratories

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