

Experimental Thermal Characterization of Power Resistors Using a Low-Cost Measurement System

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Abstract :

This study presents a low-cost experimental procedure for characterizing the transient cooling behavior of three 10 Ω , 5 W power-resistor technologies: wirewound ceramic, cement, and aluminum-housed resistors. Each specimen was heated from a regulated 5V DC source until its surface temperature reached 80 °C. The supply was then disconnected and temperature was measured with an LM35 sensor interfaced to an Arduino Uno at 5 min intervals for 30 min, with an ambient temperature of 25°C. The experiment for each resistor was repeated 20 times with the participation of university students enrolled in a differential equations course, and representative central measurements were averaged for comparison with a first-order exponential cooling model. The resulting cooling constants were 0.13503, 0.21258, and 0.18326 min⁻¹ for the wirewound, cement, and aluminum-housed resistors, respectively. Model agreement was high, with R² values of 0.99414, 0.99366, and 0.99424 and RMSE values between 1.34 and 1.43 °C. The results show that a simple electronic experiment can provide a clear physical interpretation of first-order differential-equation models while revealing measurable differences among power-resistor constructions.

Keywords: modelling of dynamic systems, educational technology, thermal transient, power resistor, Newton's Cooling Law, teaching methodology.

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I. INTRODUCTION

Thermal transients are fundamental in electronics, as component temperature is influenced by power dissipation, thermal storage, geometry, packaging, and heat transfer to the environment. Contemporary electrothermal research frequently employs compact thermal networks and reduced-order models, which offer a practical compromise between physical interpretability and computational efficiency [1]-[4]. In engineering education, affordable sensor and microcontroller platforms enable the integration of analytical models with direct measurements, an approach that has demonstrated success in thermal, control, and laboratory instruction [5]-[9].

A particularly instructive scenario involves the cooling of a previously heated electronic component. When the component is modeled as a lumped thermal body and the ambient conditions are approximately constant, the temperature decay follows a first-order ordinary differential equation. This scenario establishes a direct connection among differential equations, electronics, heat transfer, instrumentation, and experimental data analysis.

This study aims to experimentally characterize and compare the cooling responses of three common power-resistor constructions using a straightforward LM35-Arduino Uno measurement system. The methodology is designed to be accessible for undergraduate differential equations laboratories and includes quantitative assessment of model accuracy using absolute error, relative error, mean absolute error (MAE), root mean square error (RMSE), and the coefficient of determination (R²).

II. THEORETICAL BACKGROUND

2.1 Thermal Behavior as a Dynamic System

Thermal processes represent a significant category of dynamic systems, as their state variables change continuously over time due to energy storage and exchange. In electronic components, temperature fluctuations are especially significant because electrical power dissipation is converted into heat, which is then transferred to the environment via conduction, convection, and radiation. Compact lumped-parameter thermal models are valuable for providing physically interpretable and computationally efficient representations of transient temperature behavior [1]-[4].

The thermal capacitance of a body is defined as indicated in Eq. (1), where m denotes mass and C_p denotes specific heat capacity. Thermal capacitance quantifies the component's capacity to store thermal energy. The equivalent thermal resistance, R_{th} , characterizes the opposition to heat transfer between the component and its environment. For a body at temperature $T(t)$ exchanging heat with an environment at a nearly constant temperature T_a , the first-order energy balance is given by Eq. (2). Therefore, Eq. (3) shows the rate of change of temperature respect to time. This equation demonstrates that a simple thermal process shares the same mathematical structure as a first-order electrical or control system.

$$C_{th} = mC_p \quad (1)$$

$$C_{th} \frac{dT}{dt} = - \left(\frac{T - T_a}{R_{th}} \right) \quad (2)$$

$$\frac{dT}{dt} = - \frac{1}{C_{th}R_{th}} (T - T_a) \quad (3)$$

2.2 Newton's Cooling Law

Newton's Cooling Law provides a classical framework for describing transient cooling. When certain conditions are met, the rate of temperature change of an object is approximately proportional to the difference between its instantaneous temperature and the ambient temperature [5], [6]. The process is governed by the first-order ordinary differential equation shown in Eq. (4), where $k < 0$ denotes the cooling constant.

$$\frac{dT}{dt} = k(T - T_a) \quad (4)$$

This model is especially applicable when the ambient temperature remains nearly constant and the object can be approximated as having a uniform temperature. In addition to its classical role in heat transfer, the model is valuable for instructional purposes because it directly links a physical phenomenon, an ordinary differential equation, an analytical solution, parameter estimation, and experimental validation [6], [10], [11].

2.3 Cooling Constant and Thermal Time Constant

A comparison between the thermal energy-balance model and the cooling equation yields Eq. (5). The corresponding thermal time constant is given by Eq. (6). A small time constant signifies a rapid approach to thermal equilibrium, while a large time constant indicates greater thermal persistence.

In power resistors, the transient response depends not only on electrical resistance and nominal power but also on factors such as construction, effective thermal mass, surface area, ceramic substrate, encapsulation, mounting conditions, and heat-transfer paths. As a result, devices with identical nominal electrical ratings may display different cooling constants and time constants [1]-[4].

$$k = - \frac{1}{R_{th}C_{th}} \quad (5)$$

$$\tau_{th} = |R_{th}C_{th}| = \left| \frac{1}{k} \right| \quad (6)$$

2.4 Electrical-Thermal Analogy

Lumped thermal modeling closely parallels the behavior of electrical circuits. In this analogy, temperature difference is analogous to voltage difference, heat-flow rate or dissipated power corresponds to electric current, thermal resistance is equivalent to electrical resistance, and thermal capacitance is analogous to electrical capacitance. Consequently, a first-order cooling process can be interpreted similarly to the discharge of an RC circuit.

This analogy is particularly valuable in electrical, electronic, and control engineering, as it enables students to integrate concepts that are frequently taught in isolation. More advanced thermal networks may include multiple thermal resistances and capacitances, resulting in several thermal time constants [2]-[4]. However, a single-state model remains suitable when the dominant thermal behavior is the primary focus.

2.5 Dynamic-System Modeling in Engineering Education

Differential equations serve as essential tools for representing dynamic systems in engineering. Electrical circuits, mechanical systems, thermal processes, fluid systems, chemical processes, and control systems are commonly modeled using differential equations. Despite this, students often acquire analytical solution techniques without developing a corresponding ability to interpret these equations as representations of physical processes.

Recent research in engineering-mathematics education highlights mathematical modeling as a critical link between abstract differential equations and real-world engineering phenomena [10]-[13]. Rezaei and Asghary found that a modeling-oriented approach enhances engineering undergraduates' problem-solving abilities and mathematical performance in differential equations [10]. Alnaser and Hoffmeier introduced scaffolded modeling laboratories throughout a differential equations course to support students in constructing and analyzing mathematical models [11]. Additional studies have emphasized contextual modeling and systems-thinking approaches to provide differential equations with greater physical relevance for engineering students [12], [13].

2.6 Educational Technology and Experimental Learning

Educational technologies enhance the connection between mathematical abstraction and physical interpretation. Interactive simulations, virtual laboratories, data-acquisition systems, sensors, microcontrollers, and engineering software enable students to observe multiple representations of the same dynamic phenomenon [14]-[18]. Interactive tools tailored for first- and second-order dynamic systems have been developed based on pedagogical principles from simulation, multimedia learning, and instructional design [14].

Arduino-based platforms are particularly advantageous due to their low-cost analog and digital data acquisition, simple programming, and compatibility with a wide range of sensors. Recent educational studies have demonstrated their effectiveness in calorimetry, temperature measurement, thermal processes, and control experiments [6], [15]-[18]. In the described activity, students observe the cooling of a physical resistor, collect temperature data using an LM35 sensor and Arduino Uno, derive the governing differential equation, calculate the theoretical response, and compare predictions with experimental results. This approach directly links the exponential solution to an observable physical process.

2.7 Active, Experiential, and Problem-Based Learning

The experiment may be analyzed through the frameworks of active, experiential, and problem-based learning methodologies. Rather than encountering a differential equation solely as a symbolic expression, students engage in generating the physical conditions underlying the model. The sequence from physical phenomenon to measurement, data collection, mathematical modeling, prediction, and experimental validation positions learners in an active role and replicates, in simplified form, the engineering research process.

Incorporating real measurements introduces considerations such as sensor accuracy, repeatability, experimental variability, parameter estimation, model error, and the limitations of idealized assumptions. These factors are essential for cultivating an engineering interpretation of mathematical models. Recent studies of engineering

students' meaning-making in ordinary differential equations further demonstrate the significance of linking formal mathematical results with interpretation and reasoning [19].

2.8 Relevance of the Proposed Experimental Approach

The proposed activity integrates mathematical modeling, physical experimentation, electronic instrumentation, and quantitative model validation. The Arduino Uno and LM35 sensor serve as the technological interface between the thermal process and mathematical analysis. The use of three resistor technologies demonstrates that identical differential-equation structures can describe systems with varying parameter values.

This activity extends beyond the basic verification of an exponential equation. Participants identify a real dynamic system, estimate a cooling coefficient, calculate a thermal time constant, compare various physical constructions, evaluate theoretical predictions against empirical measurements, and quantify model performance. This approach aligns with current recommendations for engineering mathematics activities that integrate differential equations with modeling, computation, experimentation, and authentic applications [10]-[20].

III. DEVELOPMENT

Three power resistors with the same nominal electrical characteristics (10Ω, 5W) were evaluated: a wirewound ceramic resistor, a cement power resistor, and an aluminum-housed power resistor (Figure 1). Each resistor was tested separately. A regulated DC supply was adjusted to 5V. Consequently, the electrical power dissipated during heating was as indicated in Eq. (7), corresponding to 50% of the nominal 5W rating, where P is the electrical power, V the power supply and R is the resistance.

$$P = \frac{V^2}{R} = \frac{5^2}{10} = 2.5W \quad (7)$$

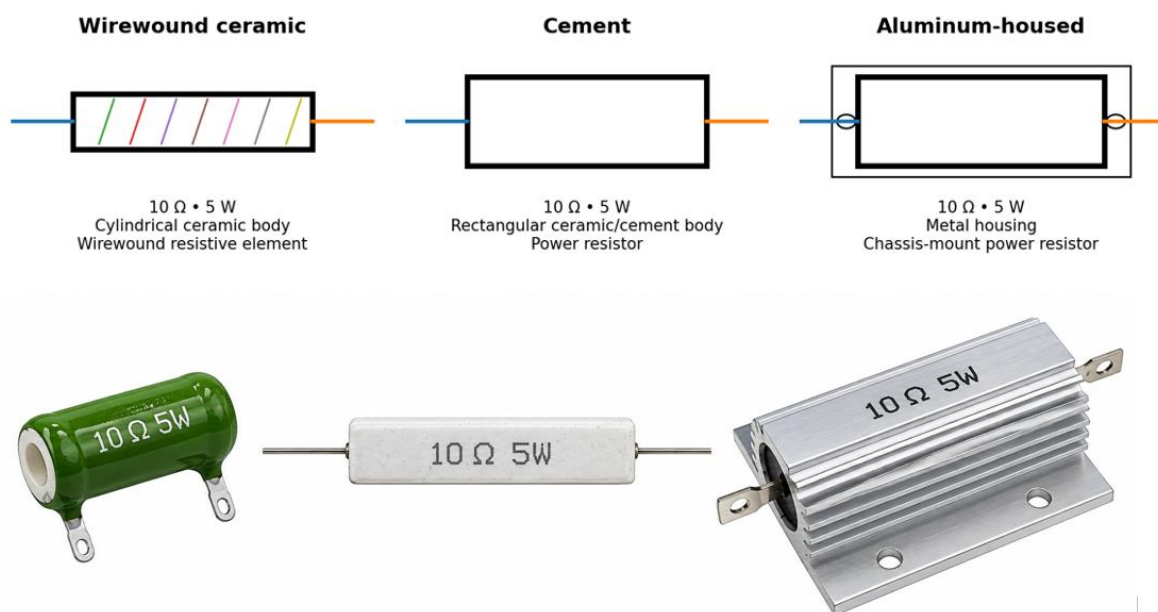


Figure 1. Schematic identification of the three 10Ω, 5W power-resistor technologies used in the study.

An LM35 analog temperature sensor was placed in thermal contact with the resistor under test. Its output was connected to an analog input of an Arduino Uno, which served as the acquisition interface, as shown in Figure 2. The resistor was energized until the measured surface temperature reached 80°C. At that instant, the electrical circuit was opened, establishing t=0 for the cooling stage. Temperature was then recorded at 5 min intervals for 30 min. Ambient temperature was approximately 25 °C throughout the tests.

The experiment for each resistor was performed 20 times with the support of university students enrolled in a differential equations course. The resulting measurements were reviewed to obtain representative central values

for the comparison reported here. The same initial temperature, ambient temperature, supply voltage, resistor value, and observation interval were maintained to make the three technologies comparable.

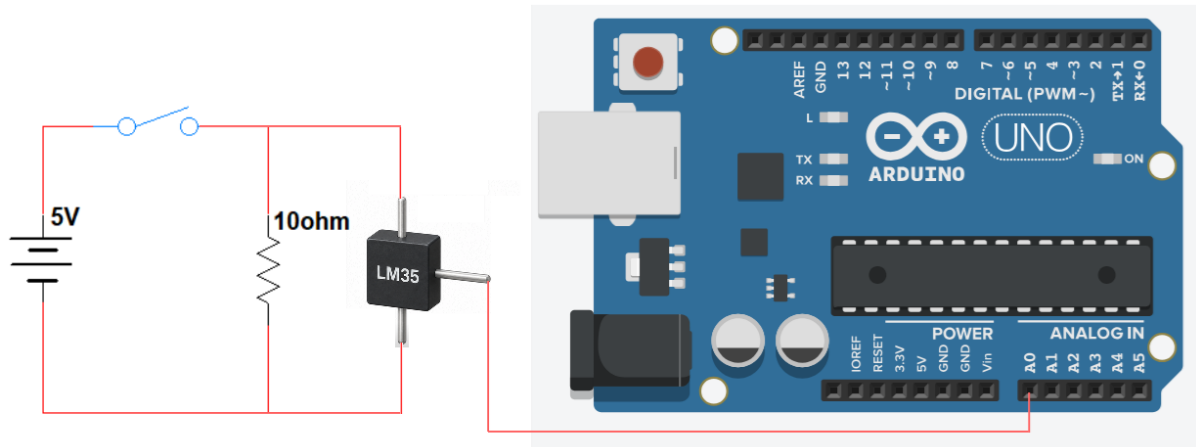


Figure 2. Experimental setup for measuring the temperature.

IV. RESULTS

Table 1 shows the real and theoretical values of temperature for each resistor, while Eq. (8) indicates the general solution of the differential equation that describes the cooling behavior derived from Eq. (4):

$$\frac{dT}{dt} = k(T - T_a)$$

$$\frac{dT}{T - T_a} = kdt$$

$$\int \frac{dT}{T - T_a} = \int kdt$$

$$\ln(c_1(T - T_a)) = kt$$

$$e^{\ln(c_1(T - T_a))} = e^{kt}$$

$$c_1(T - T_a) = e^{kt}$$

$$T - T_a = \frac{1}{c_1} e^{kt}$$

$$T = \frac{1}{c_1} e^{kt} + T_a$$

$$T(t) = Ce^{kt} + T_a, \text{ where } C = \frac{1}{c_1} \quad (8)$$

On the other hand, taking advantage of the initial temperature $T(0) = T_0$ and $T(5) = T_5$, the particular solution is obtained, as shown in Eq. (9)

$$T(0) = Ce^{k(0)} + T_a$$

$$T_0 = C + T_a$$

$$C = T_0 - T_a = 80 - 25 = 55$$

$$T(t) = 55e^{kt} + 25$$

$$T(5) = 55e^{k(5)} + 25$$

$$T_5 - 25 = 55e^{5k}$$

$$\frac{T_5 - 25}{55} = e^{5k}$$

$$\ln\left(\frac{T_5 - 25}{55}\right) = \ln(e^{5k})$$

$$\ln\left(\frac{T_5 - 25}{55}\right) = 5k$$

$$k = \frac{1}{5} \ln\left(\frac{T_5 - 25}{55}\right)$$

$$T(t) = 55e^{\left(\frac{1}{5} \ln\left(\frac{T_5 - 25}{55}\right)\right)t} + 25 \quad (9)$$

Substituting for each case, the particular equations for the temperature in the wirewound, cement, and aluminum-housed resistors are shown in Eqs (10)-(12). On the other hand, figures 3 - 6, represent the three experimental mean cooling curves, the wirewound, cement, and aluminum-housed resistor theoretical/experimental cooling curves, respectively.

Table 1. Theoretical and experimental mean temperatures (°C).

t(min)	Wirewound Theoretical	Wirewound Experimental	Cement Theoretical	Cement Experimental	Aluminum Theoretical	Aluminum Experimental
0	80.00	80.00	80.00	80.00	80.00	80.00
5	53.00	53.00	44.00	44.00	47.00	47.00
10	39.25	39.86	31.56	32.21	33.80	34.38
15	32.26	33.59	27.27	28.69	28.52	29.87
20	28.69	30.43	25.78	27.61	26.41	28.17
25	26.88	28.79	25.27	27.30	25.56	27.51
30	25.96	27.90	25.09	27.19	25.23	27.19

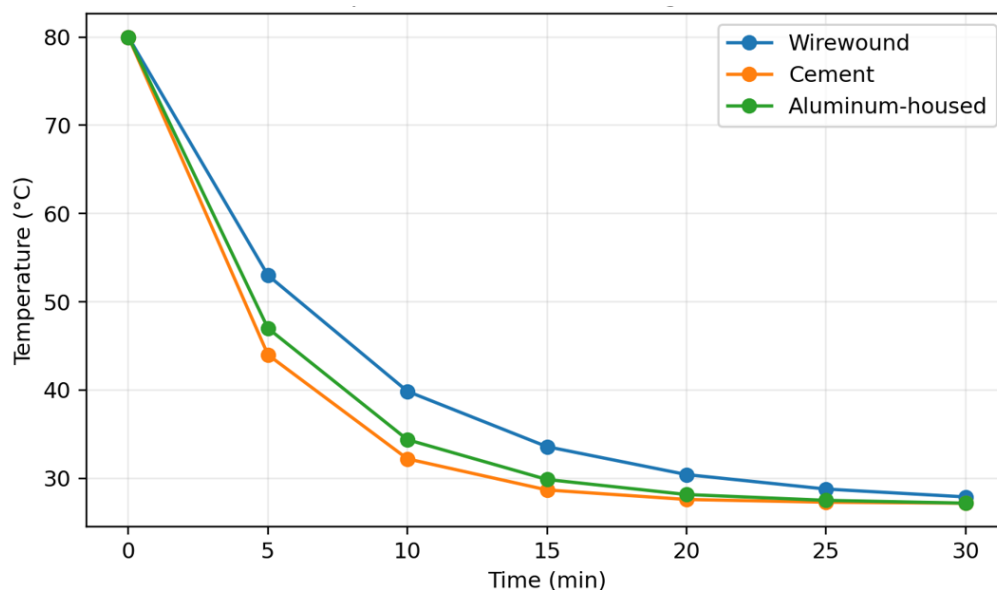


Figure 3. Experimental mean cooling curves for the three resistor technologies.

$$T_{R1}(t) = 55e^{-0.135025735011453t} + 25 \quad (10)$$

$$T_{R2}(t) = 55e^{-0.212578841213206t} + 25 \quad (11)$$

$$T_{R3}(t) = 55e^{-0.183258146374831t} + 25 \quad (12)$$

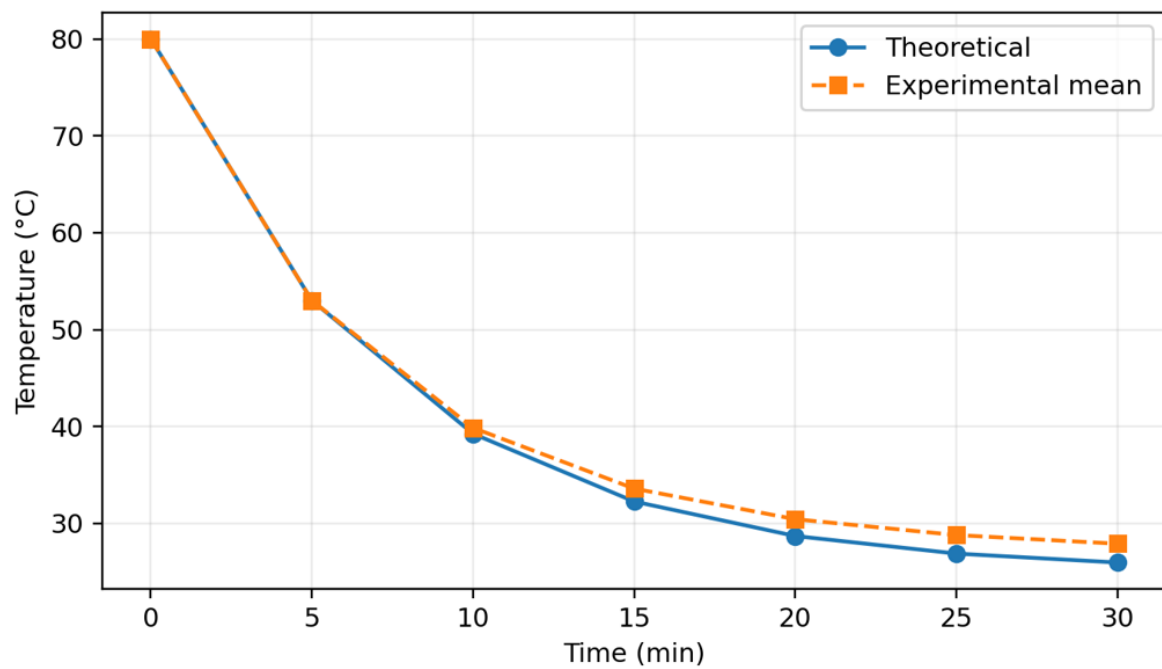


Fig. 4. Wirewound resistor: theoretical and experimental cooling.

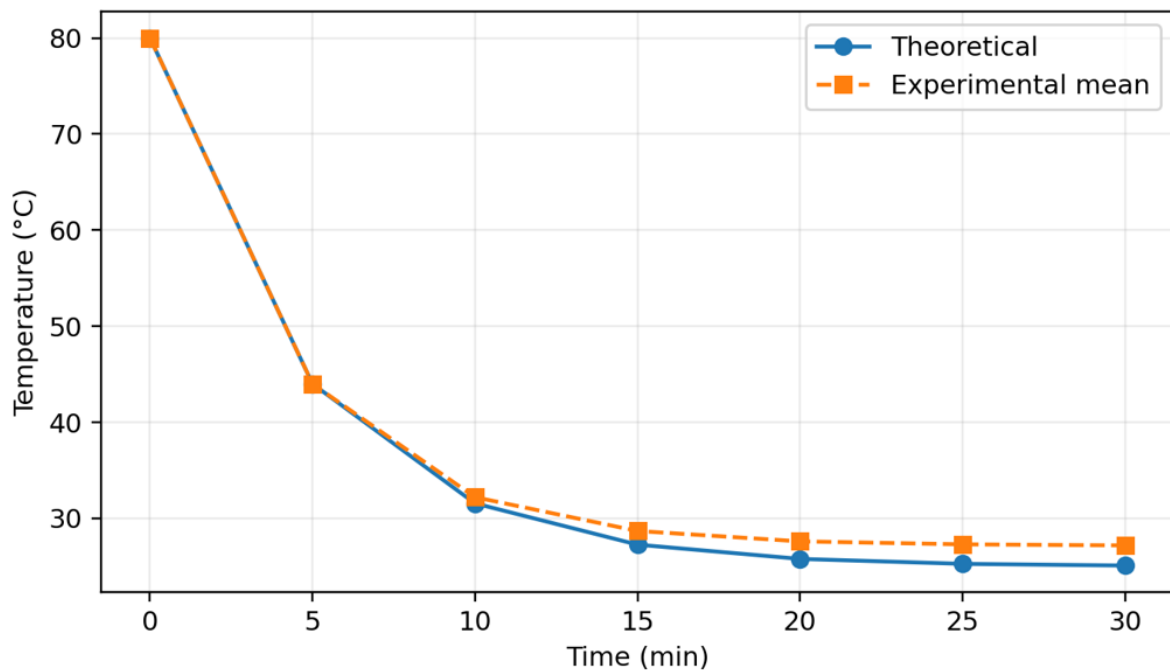


Fig. 5. Cement resistor: theoretical and experimental cooling.

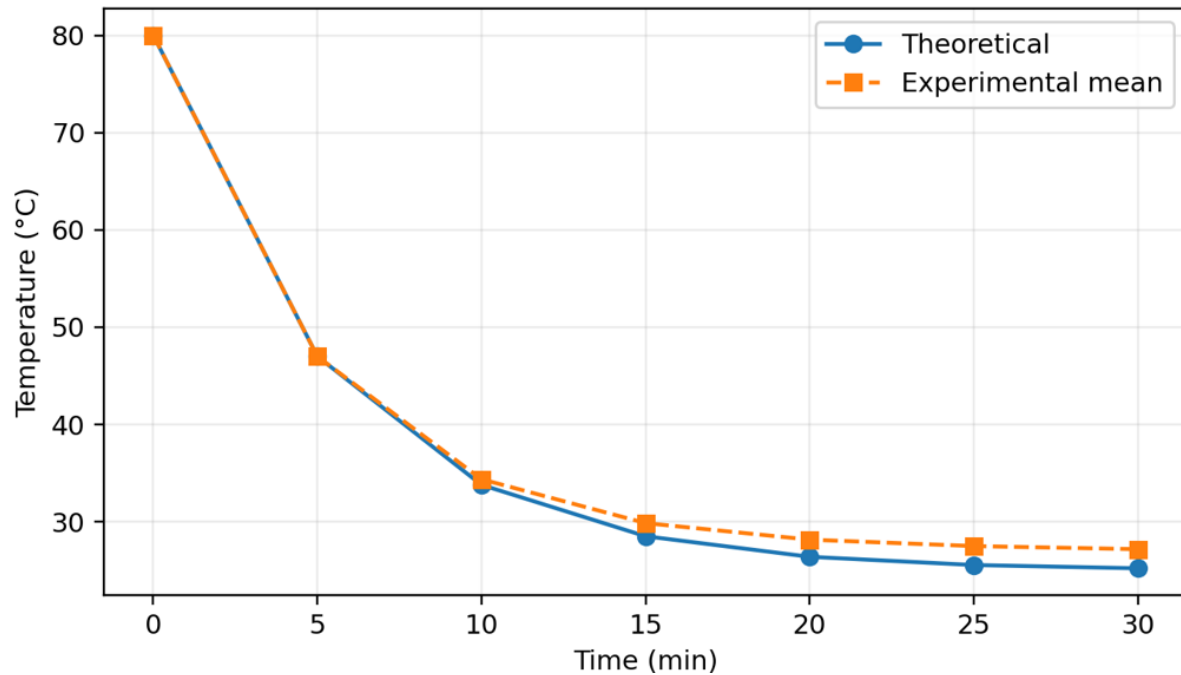


Fig. 6. Aluminum-housed resistor: theoretical and experimental cooling.

Tables 2 - 4 show the absolute and relative error for the wirewound, cement, and aluminum-housed resistor theoretical/experimental cooling curves, respectively, while Table 5 indicates the global model-performance indicators.

Table 2. Pointwise errors for the wirewound ceramic resistor.

Time (min)	Absolute error (°C)	Relative error (%)
0	0.00	0.00
5	0.00	0.00
10	0.61	1.52
15	1.33	3.97
20	1.74	5.70
25	1.91	6.63
30	1.94	6.96

Table 3. Pointwise errors for the cement resistor.

Time (min)	Absolute error (°C)	Relative error (%)
0	0.00	0.00
5	0.00	0.00
10	0.65	2.01
15	1.42	4.96
20	1.83	6.62
25	2.03	7.43
30	2.10	7.71

Table 4. Pointwise errors for the aluminum-housed resistor.

Time (min)	Absolute error (°C)	Relative error (%)
0	0.00	0.00
5	0.00	0.00
10	0.58	1.69
15	1.35	4.52
20	1.76	6.25
25	1.95	7.08
30	1.96	7.23

Table 5. Global model-performance indicators.

Resistor	k (min ⁻¹)	τ (min)	MAE (°C)	RMSE (°C)	R ²
Wirewound ceramic	0.13503	7.41	1.075	1.340	0.99414
Cement	0.21258	4.70	1.146	1.429	0.99367
Aluminum-housed	0.18326	5.46	1.086	1.358	0.99423

V. FINDINGS AND COMMENTS

The three resistor constructions demonstrated distinctly different transient responses, despite having identical nominal resistance and power ratings. The cement resistor exhibited the largest cooling constant (0.21258 min^{-1}) and the shortest time constant (4.70 min), followed by the aluminum-housed resistor (0.18326 min^{-1} ; 5.46 min). The wirewound ceramic resistor cooled at the slowest rate (0.13503 min^{-1} ; 7.41 min). These results align with the understanding that thermal behavior is influenced by construction, effective thermal mass, heat-transfer pathways, surface area, and packaging, rather than by electrical resistance alone.

The correspondence between the simple first-order model and experimental results was strong for all three specimens. The coefficient of determination (R^2) exceeded 0.993, and the root mean square error (RMSE) ranged from approximately 1.34 to 1.43 °C. The aluminum-housed resistor achieved the highest R^2 value (0.99424), although the differences among the three fits were minimal. During the later stages of the experiment, measured temperatures consistently exceeded theoretical predictions, indicating that a constant-parameter first-order model may slightly overestimate the cooling rate at lower temperature differentials.

Multiple physical and experimental factors may contribute to this deviation, including variations in natural convection as the temperature difference decreases, radiative heat transfer, the quality of thermal contact between the LM35 sensor and the resistor surface, sensor response dynamics, spatial temperature gradients within the resistor package, and minor fluctuations in ambient conditions. Contemporary electronic thermal modeling frequently employs multi-node or nonlinear thermal networks to achieve greater accuracy when necessary [1]-[4]. However, the current single-state model remains suitable for the intended low-complexity experiment and offers a robust quantitative description of the observed trend.

From an educational standpoint, this experiment connects the analytical solution of a first-order differential equation with a tangible electronic system and empirical data. Recent studies have highlighted the benefits of Arduino-based thermal laboratories, portable temperature-control experiments, and the integration of modeling with experimentation in engineering education [5]-[9]. This activity is notably straightforward, requiring only a DC power source, a power resistor, an LM35 temperature sensor, and an Arduino Uno.

VI. CONCLUSIONS

A straightforward and reproducible experimental platform was established to compare the transient cooling behavior of three 10 Ω, 5 W power-resistor technologies. Under identical initial and ambient conditions, the cement resistor exhibited the fastest cooling, the aluminum-housed resistor demonstrated intermediate performance, and the wirewound ceramic resistor cooled most slowly. The respective cooling constants were 0.21258, 0.18326, and 0.13503 min^{-1} .

The first-order exponential model accurately described the experimental data, yielding R^2 values above 0.993 and RMSE below 1.5 °C in all cases. The observed systematic late-stage deviation between theoretical and measured temperatures highlights a limitation of the constant-parameter model and suggests directions for future research, including multi-node thermal models, shorter sampling intervals, direct estimation from all experimental points, and controlled airflow conditions.

This experiment provides an accessible approach to integrating differential equations with electronics, thermal phenomena, sensing, and data analysis in undergraduate engineering education. Its minimal hardware complexity makes it well-suited for repeated student laboratory activities and for introductory investigations of dynamic systems.

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