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Mathematical analysis of threshold temperature attainment in polypropylene during oven heating at 500°C

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Abstract: Polypropylene (PP) heating is governed by heat-transfer conditions, whereas its subsequent thermal degradation depends on temperature, holding time, and the surrounding atmosphere. Before incorporating degradation kinetics, it is essential to determine whether a prescribed temperature threshold can be attained under a given heating condition. This study presents an analytical investigation of threshold-temperature attainability in PP using a Newtonian heating model derived from the lumped thermal capacitance approach. The first-order ordinary differential equation is solved analytically to examine the temperature response, equilibrium, asymptotic stability, monotonicity, finite-time threshold reachability, and parameter sensitivity. An idealized oven source temperature of 500° C is considered, while the initial material temperature and effective heating-rate constant are treated as model parameters. The analysis establishes that for $K > 0$ and $T_0 < T_a$, a prescribed threshold temperature T_c is attainable in finite time if and only if $T_0 < T_c < T_a$. The corresponding threshold attainment time is derived explicitly. The sensitivityu analysis shows that increasing the initial temperature or effective heating-rate constant reduces the attainment time, whereas increasing the threshold temperature extends it. Furthermore, the normalized sensitivity of the attainment time to the heating-rate constant is exactly -1, inidicating an inverse proportional relationship. The main contribution is a systematic mathematical characterization of threshold-temperature attainability and its parameter dependence, extending the interpretation of the conventional Newtonian heating model without introducing a new heat-transfer law or degradation-kinetics model. Since no experimental data are used, the findings are limited to the idealized mathematical framework and do not represent experimentally validated heating times or predictions of PP degradation.

Keywords: polypropylene; thermal attainability; ordinary differential equations; threshold temperature; Newtonian heating

1. Introduction

PP is a thermoplastic polymer widely used in industrial applications. Heating changes is physical state and, under suitable conditions, may initiate thermal or thermo-oxidative degradation. The degradation response depends on temperature, exposure time, heating rate, and the surrounding atmosphere. Recent thermogravimetric and kinetic studies have examined the pyrolysis behaviour of PP under different heating programmes and oxygen concentration (Dubdub, 2023; Fu et al., 2023; Ohkawa et al., 2025; Sidhu et al., 2023). Other studies have investigated long-term thermo-oxidative ageing, stabilizer consumption, and changes in the thermal and mechanical properties of PP during service and reprocessing (Cai et al., 2026; Gijsman & Fiorio, 2023; Hoebel et al., 2026; Knoben et al., 2025;

Nasser & Al-Mosawi, 2026; Zeng et al., 2024). These findings show that thermal exposure and chemical degradation are related but distinct phenomena.

Recent investigation of PP and polyolefin pyrolysis have addressed intrinsic reaction kinetics, primary and secondary decomposition pathways, product distributions, and the effects of reactor temperature, feed mass, residence time, and heating rate (Hassibi et al., 2023; Jiang et al., 2022; Kumar et al., 2024, 2026; Pan et al., 2023; Papuga et al., 2024; Perez & Toraman, 2024; Wu et al., 2024). Other work has focused on the thermal ageing and degradation of PP during repeated processing, including changes in crystallinity, thermal stability, and mechanical performance (Akhras et al., 2024; Bouregba et al., 2024; Douiri et al., 2024; Yu et al., 2024; Zhang et al., 2024). Studies of catalytic and co-pyrolysis systems have further shown that catalyst type and feedstock composition can be influence decomposition behaviour and product characteristics (Das, 2024; Lorbach et al., 2024; Otaru & Albin Zaid, 2025). Collectively, these studies primarily investigate degradation mechanisms, reaction kinetic, ageing, and pyrolysis outcomes. In the contras, the present study addresses a complementary aspect of PP thermal processing, namely the mathematical attainability of a prescribed material temperature under constant-source heating conditions. These distinctions important because the thermal response of a material determines whether a specified temperature threshold can be reached before degradation kinetics or other temperature-dependent processes are considered. Accordingly, this study examines the conditions under which a specified threshold temperature is reachable in finite time and whether the material temperature asymptotically approaches the constant source temperature.

The Newtonian heating model based on the lumped-capacitance approach is commonly used to represent transient thermal responses when internal temperature gradients are sufficiently small. Recent studies have examined its use and limitations in transient heat-transfer modelling, including the role of the Biot number, thermal resistance and capacitance, and the estimation of effective thermal time constants (Fan et al., 2024; McMasters et al., 2023; Tian et al., 2024; Wei et al., 2023). The present study does not propose a new heat-transfer equation or reproduce a new physical mechanism. Instead, it develops a systematic mathematical characterization of threshold-temperature attainment using a first-order Newtonian heating model. Specifically, this study establishes the necessary and sufficient condition for a threshold temperature to be reached in finite time, derives an explicit expression for the threshold attainment time, and examines its sensitivity to the initial temperature, threshold temperature, and effective heating-rate constant. This analysis complements recent lumped and coupled thermal modelling approach (Lorbach et al., 2024) by making the finite-time attainability condition and its parameter dependence explicit. For a constant source temperature of 500°C, the analysis establishes that a threshold temperature below 500°C can be reached in finite time only when the initial temperature is below that threshold. A threshold equal to the source temperature is approached asymptotically, while a threshold above the source temperature is unreachable. The results provide a practical mathematical basis for estimating the time required to reach a specified temperature and assessing whether a target temperature is compatible with a given oven setpoint. However, the actual time required for PP degradation cannot be determined without experimental information on the effective heating parameter and an appropriate material-specific degradation threshold. Thus, the proposed analysis provides a preliminary mathematical framework for subsequent experimental investigations of PP thermal processing and degradation.

This study is analytical and does not use experimental data, curve fitting, or kinetic parameter estimation. Its contribution lies in mathematically characterizing thermal attainability. Chemically relevant threshold temperatures must be determined using thermogravimetric or calorimetric data, or appropriate material indicators.

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2. Material and methods

2.1 Research type and approach

This study presents an analytical investigation of a Newtonian heating model for PP. The research procedure consists of formulating the energy-balance equation, deriving its analytical solution, examining its equilibrium and stability properties, establishing the conditions for finite – time threshold-temperature attainment, and evaluating the sensitivity of attainment time to model parameters. The overall procedure is summarized in Figure 1, which presents the sequence from problem identification and literature review through model assumptions and parameter specification, energy-balance formulation, analytical solution, dynamic-property analysis, threshold-attainment analysis, numerical illustration, sensitivity analysis, and conclusion. The source temperature is fixed 500°C as a mathematical heating scenario. To demonstrate the numerical implications of the model, an illustrative parameter set is considered an initial material temperature of $T_0 = 25$°C, a threshold temperature of $T_c = 450$°C and an effective heating-rate constant of $K = 0.02\ s^{-1}$. These values are adopted solely for mathematical illustration and are not obtained from experimental measurements or calibrated oven characteristics. The threshold attainment time is calculated using the analytical expression derived from model. Furthermore, sensitivity analysis is conducted by considering variations in the initial temperature, threshold temperature, and heating-rate constant. Specifically, the illustrative parameter ranges are $T_0 = 20 - 30$°C, $T_c = 400 - 450$°C, and $K = 0.01 - 0.03\ s^{-1}$. Since no experimental measurements are available, the numerical results are interupted as model-based ilulustration rather than predictions of actual heating behavior of a specific oven system.

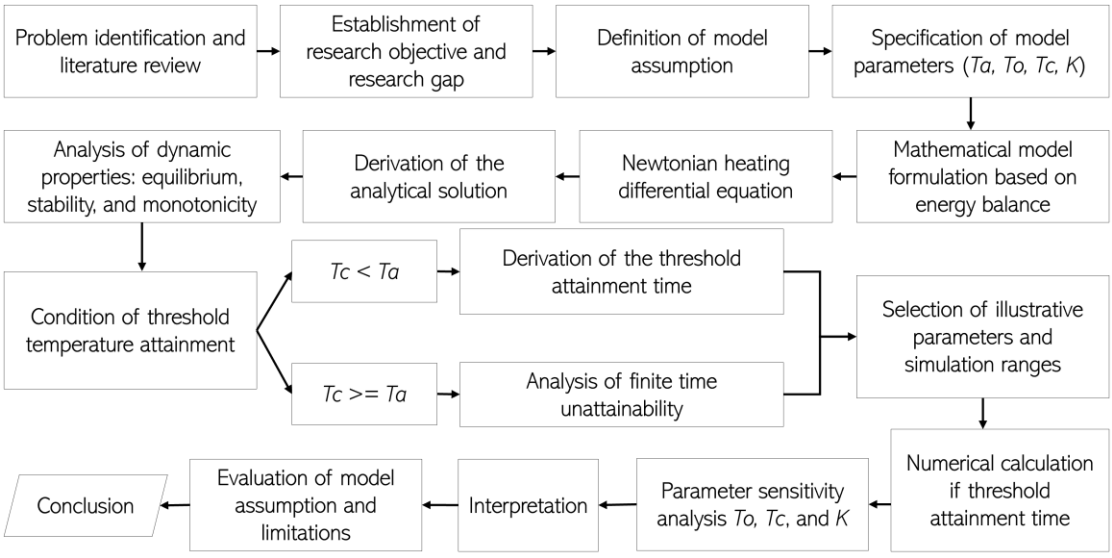


Figure 1. Research methodology flowchart

2.2 Model formulation

Using a lumped thermal capacitance approach, with $T(t)$ defined as the average material temperature, T_a as the heat source temperature, h as the effective heat transfer coefficient, A_s as the heat transfer area, ρ as the density, V as the volume, and c_p as the specific heat capacity, the energy balance is expressed as equation 1.

$$\rho V c_p \frac{dT}{dt} = hA_s(T_a - T) \tag{1}$$

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Using the initial condition $T(0) = T_0$ and the definition of $K = \frac{h\,A_s}{\rho\,c_p}$, equation (1) simplifies to equation (2).

$$\frac{dT}{dt} = K(T_a - T) \tag{2}$$

The parameter K has units of inverse time, and the oven settings alone cannot determine its value. Determining K requires information about heat transfer and sample geometry or temperature-versus-time data.

2.3 Assumptions and limitations

The model assumes a constant source temperature and constant effective heat-transfer parameters. The lumped-capacitance approximation is based on the assumption that internal temperature gradients within the PP sample are negligible compared with the temperature difference between the surface of material and its surroundings. A commonly used criterion for evaluating this assumption is the Biot number, defined as $B_i = hL_c/k_{PP}$, where h_{ef} is the effective heat-transfer coefficient, $L_c = V/A_s$ is the characteristic length, and k_{PP} is the thermal conductivity of PP. The lumped-capacitance approximation is generally considered appropriate when $B_i < 0.1$. However, the present study does not specify a particular sample geometry or experimentally measured thermal properties, therefore the B_i cannot be quantitatively evaluated, and the validity of this approximation for a specific PP specimen remains to be experimentally verified. Recent analytical and experimental heat-transfer studies also discuss the applicability of lumped-capacitance approximations and the influence of Biot number on transient temperature fields (McMasters et al., 2023; Tian et al., 2024; Wei et al., 2023).

The effective heat-transfer coefficient (h) represents the combined effects of convection and thermal radiation from oven environment. In particular, radiation may become significant at an oven temperature of 500°C. Its contribution can be represented through a linearized radiation heat-transfer coefficient, which depends on the surface and surrounding temperatures and the surface emissivity. Accordingly, h should not be interpreted as convection, only coefficient. Internal heat conduction within the PP is represented indirectly through the lumped-capacitance assumption rather than being explicitly resolved in the model. Furthermore, the thermal properties of PP, including thermal conductivity, specific heat capacity, and density, may vary with temperature. At elevated temperatures, phase changes and thermal degradation may also alter the material's thermal response. These effects are not explicitly incorporated into the present model, which describes sensible heating using constant effective parameters. In particular, the oven temperature of 500°C represent an imposed source-unchanged while approaching this temperature. Consequently, the model provides an idealized mathematical analysis of temperature attainability, and its quantitative application to actual PP heating and degradation requires temperature-dependent material properties, specimen geometry, and experimental validation.

2.4 Definition of threshold temperature reachability

The model analysis begins by solving Equation (2) to obtain an explicit solution describing how the material temperature changes over time. We then analyse monotonicity and temperature bounds to show how the material temperature evolves from its initial value toward the threshold temperature and/or the source temperature specified in the scenario.

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For the subsequent analysis, the model parameters are assumed to satisfy positive of K, and $T_0 < T_a$, where K is the effective heating-rate constant, T_0 is the initial temperature. Under these conditions, the material temperature increases monotonically from T_0 toward T_a. accordinglt, the threshold temperature is considered under three regimes that $T_0 < T_c < T_a$, $T_c = T_a$, and $T_c > T_a$.

Definition 1. Let $T_c > T_0$ be a prescribe threshold temperature. The threshold T_c is said to be reachable in finite time if there exists a time t_c with $0 < t_c < \infty$ such that $T(t_c) = T_c$. Otherwise, the threshold is said to be unreachable in finite time. Under the assumptions $K > 0$, and $T_0 < T_a$, the reachability of T_c is determined by its relation to the source temperature T_a.

Proposition 1. Consider the Newtonian heating model in equation (2) with the initial condition $T(0) = T_0 < T_a$. For a prescribe threshold temperature $T_c > T_0$, the following conditions hold:

1. If $T_0 < T_c < T_a$, the threshold is reachable in finite time;
2. If $T_c = T_a$, the threshold is approached asymtotically as $t \to \infty$, but is never attained in finite time;
3. If $T_c > T_a$, a threshold is unreachable because the material temperature remains below the source temperature for all finite $t > 0$.

Therefore, under the stated assumption, the threshold T_c is reachable in finite time if and only if $T_0 < T_c < T_a$.

3. Results and discussion

3.1 Analytical solution

Equation (2) has the analytical solution $T(t) = T_a - (T_a - T_0)e^{-Kt}$. For the oven scenario with $T_a = 500\,°C$, Equation (2) reduces to the expression given in Equation (3).

$$T(t) = 500 - (500 - T_0)e^{-Kt} \tag{3}$$

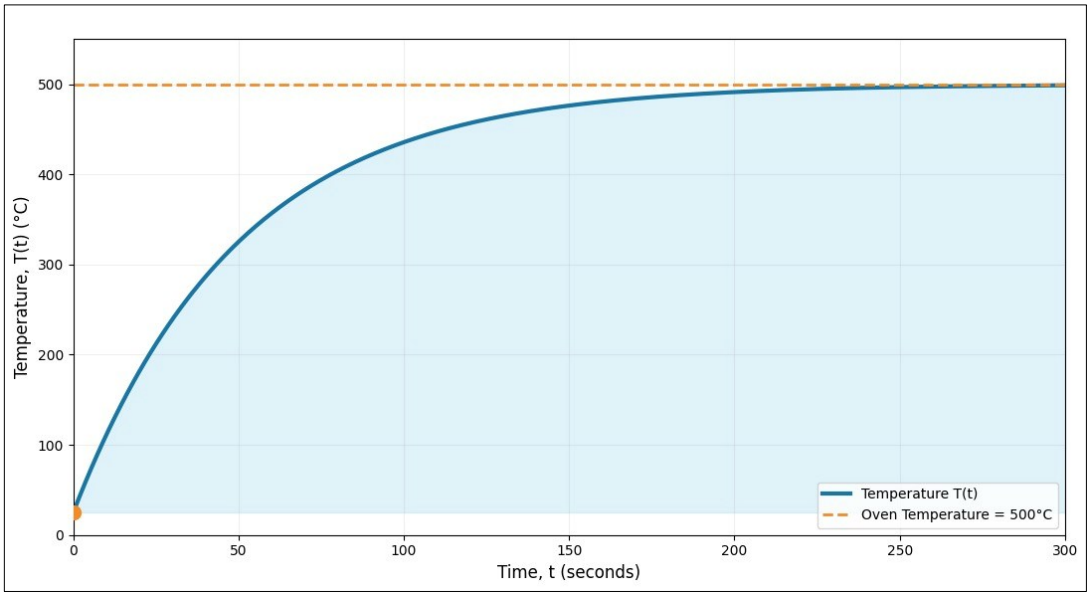


Figure 2. Analytical solution with $T_a = 500^o$ C

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As shown in Figure 2, for the illustrative value $T_0 = 25^{\circ}$, then $T(t) = 500 - 475\, e^{-Kt}$. The material temperature increases from the initial temperature toward the oven temperature of 500°C, approaching the source temperature asymptotically. The time required to reach temperature $T(t)$ is given by Equation (4).

$$t(T) = \frac{1}{K} \ln\left(\frac{500 - 25}{500 - T(t)}\right) \tag{4}$$

which also depends on the value of K.

3.2 Equilibrium, stability, and monotonicity

Next, the equilibrium of the system is obtained by setting differential equation (2) equal to 0, meaning that there is no change in temperature over time. This yields an equilibrium temperature T^* equal to T_a. To examine stability the stability of this equilibrium, define the deviation from equilibrium as $\sigma(t) = T(t) - T^*$, as given in Equation (5).

$$\sigma(t) = T(t) - T_a \tag{5}$$

Since $T^* = T_a$, Equation (2) can be written as $\frac{d\sigma}{dt} = -K\sigma(t)$, with the solution is $\sigma(t) = \sigma(0)e^{-Kt}$ which tends to zero as time approaches infinity for $K > 0$. Thus, the equilibrium temperature $T^* = T_a$ is asymptotically stable. This stability result means that the source temperature is approached asymptotically, it does not mean that the equilibrium is attained in finite time.

Using the given scenario, with a threshold temperature of T_c for the PP material and an initial material temperature of T_0, to determine the time required to reach the prescribed threshold, substitute $T(t) = T_c$ into Equation (3) and solve for t. This gives the threshold-attainment time in Equation (6).

$$t_c = \frac{1}{K} \ln\left(\frac{500 - T_0}{500 - T_c}\right) \tag{6}$$

provide that $K > 0$, and $T_0 < T_c < 500^{\circ}$C. Under these conditions, t_c is positive and finite. For the illustrative case of $K = 0.02\ s^{-1}$, and $T_c = 450^{\circ}$C, in Figure 2 we can see that the threshold attainment time is $t(T_c) = 112.56\ s$.

The value of K for an actual PP specimen can not be determined withour heat-transfer properties, specimen geometry, or measured temperature-time data. To illustrate the effect of K, the sensitivity analysis uses $K = 0.01, 0.02,$ and $0.03\ s^{-1}$ while holding T_0 =25°C, T_c =450°C, and $T_a = 500^{\circ}$C fixed. The corresponding threshold-attainment times (t_c) are 225.13 , 112.56 , and $75.04\ s$, respectively. These values are hypothetical simulation assumptions, not measured oven characteristics. The calculated t_c represents the time required to reach the prescribed threshold temperature, not the time required to reach thermal equilibrium.

For $T_0 < T_c < T_a$ and $K > 0$, the attainment time is $t_c = \left(\frac{1}{K}\right) \ln\left(\frac{T_a - T_0}{T_a - T_c}\right)$. Its partial derivatives with respect to the model parameters are $\frac{\partial t_c}{\partial T_0} = -\frac{1}{K(500 - T_0)} < 0$, and $\frac{\partial t_c}{\partial T_c} = \frac{1}{K(500 - T_c)} > 0$. Thus for fixed values of the other parameter, increasing the initial temperature or the heating-rate constant

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reduces the time required to reach the threshold, whereas increasing the threshold temperature increases that time. The normalized sensitivity coefficient is $\frac{K}{t_c}\frac{\partial t_c}{\partial K} = -1$. This indicates that a 1% increase in K produces an approximately 1% decrease in the threshold attainment time, for fixed T_0, T_c, and T_a. These results quantify the dependence of threshold-attainment time on the initial temperature, target temperature, and effective heating-rate constant.

Although the Newtonian heating model and its analytical solution are well established in classical heat-transfer theory (Cengel & Ghajar, 2020; Incropera et al., 2017; Lienhard IV & Lienhard V, 2019), their conventional application primarily describes the transient temperature response of a material toward thermal equilibrium. Previous studies on PP have mainly focused on degradation kinetics, pyrolisis mechanism, and the effect of heating conditions on degradation products, atmosphere, and analytical methods on degradation behavior and products(Bockhorn et al., 1999; Chan & Balke, 1997; Dubdub, 2023; Fu et al., 2023; Gao et al., 2003; Sidhu et al., 2023). In contrast, the present study adresses the mathematical characterization of threshold temperature attainability as complementary aspect of PP thermal processing. Its contribution does not lie in introducing of a new heat-transfer model, but in systematically establishing the condition for finite-time threshold attainment and analyzing their implications for the time required to reach a prescribe temperature. Specifically, the analysis establishes that finite-time threshold attainment occurs if anf only if $T_0 < T_c < T_a$, derives an explicit expression for the threshold attainment time, and quantifies its sensitivity to the initial temperature, threshold temperature, and effective heating-rate constant. Furthermore, the normalized sensitivity of the attainment time to the heating-rate constant is exactly -1, indicating that an invers proportional relationship between the heating-rate constant and the attainment time. These results provide a mathematical framework for determining whether a prescribed temperature is theoretically attainable and how the heating parameter influence its attainment time, without requiring a degradation-kinetics model. The framework is illustrated using an oven source temperature of 500°C, while its quantitative application to actual PP heating requires experimental parameter estimation and validation.

Accordingly, the threshold temperature in this study should be interpreted as a prescribe target temperature rather than the actual onset temperature of PP degradation. Identifying the onset of degradation requires independent evidence from thermogravimetric analysis, calorimetry, or other appropriate material characterization methods. Furthermore, when applied to an oven at $500°C$, actual heating behavior in an oven may be influenced by sample dimensions and arrangement, airflow, thermal radiation, contact conditions, and temperature dependent material properties. At elevated temperatures, PP may generate degradation products. Therefore, any experimental work must be inventigated by using appropriately designed equipment and safety controls.

This study has several limitations that should be addressed in future research. The proposed model is analytical and has not been yet experimentally validated. Future work should include measuring the temperature response of PP samples in a controlled oven setup to estimate the effective heating-rate constant (K), and validate the model predictions. Furthermore, thermogravimetric analysis (TGA) and differential scanning calorimetry (DSC) could be employed to characterize the thermal behavior of PP and experimentally identify relevant degradation threshold. Further model development may consider variable oven temperature, temperature-dependent thermal properties, internal temperature gradients through Biot number analysis, and degradation kinetics under different atmospheric conditions. These extensions would provide a foundation for developing a more comprehensive model of PP heating and thermal degradation.

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4. Conclusion

For the mathematical heating scenario with a constant source temperature of $T_a = 500^o$ C, the analytical solution shows that the material temperature increases monotonically from its initial temperature T_0 toward the source temperature T_a, which acts as an asymptotically stable equilibrium. For $K > 0$ and $T_0 < T_a$, the prescribed threshold temperature T_c is reachable in finite time if and only if $T_0 < T_c < T_a$. Under this condition, the threshold attainment time is given by $t_c = \left(\frac{1}{K}\right) \ln \left(\frac{T_a - T_0}{T_a - T_c}\right)$. If $T_c = T_a$, the material temperature approaches the threshold asymptotically but does not reach it in finite time. If $T_c > T_a$, the threshold is unreachable because the material temperature remains below the source temperature. The sensitivity abalysis further demonstrates that increasing the initial material temperature reduces the threshold attainment time, whereas increasing the threshold temperature increases it. Similarly, increasing the effective heating-rate constant (K) reduces the attainment time, with its normalized sensitivity being exactly (-1). These findings provide a mathematical characterization of threshold-temperature attainability and the influence of heating parameters under the assumed constant-source conditions.

Author's declaration

Author contribution

Novrianti contributes to developing the mathematical model of Newtonian heating used in this study and formulating the differential equation to analyse the attainability of thermal states in PP. **Noverina Alfiany** provides guidance and input on the mathematical formulation and reviews and refines the analytical results presented in the manuscript. **Afifah Rizka** contributes by analysing the solutions obtained, including the system's stability. **Corry Handayani** contributes by analysing PP chemistry, its physical changes and polymer chain scission, and the role of temperature in these processes.

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Data availability

This study uses no experimental data, survey data, or secondary datasets. It is analytical and focuses on developing and mathematically analyzing a heating model to examine a material's thermal state.

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Conflict of interest

The authors declare that they have no financial or non-financial competing interests that could have influenced the work reported in this manuscript.

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Ethical clearance

Not applicable

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