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Comparative Electro-Thermal Mathematical Modeling of Transient Temperature Distribution in Pouch and Cylindrical Li-Ion Battery Cells

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Abstract

The increasing rate of internal heat accumulation during high-power discharge represents a major challenge in the design of Battery Thermal Management Systems (BTMS) for electric vehicles. Battery cell geometry plays a significant role in determining heat propagation pathways and heat dissipation characteristics. This study aims to conduct a comparative evaluation of the transient temperature distribution between cylindrical and pouch Lithium-ion battery cells using a one-dimensional (1D) electro-thermal mathematical model. The model was developed based on the principles of energy conservation and the Bernardi heat generation equation and was numerically solved using the Finite Difference Method (FDM) with an Explicit Euler scheme implemented in Python. Simulations were performed under various discharge rates (1C, 3C, and 5C). The results indicate that cylindrical cells are highly susceptible to the core thermal trapping phenomenon, reaching a maximum core temperature of 52.64°C at a 5C discharge rate, whereas the maximum core temperature of pouch cells was limited to 50.61°C under the same operating condition. Furthermore, the larger surface-area-to-volume ratio of pouch cells resulted in lower and more uniform surface temperature profiles. The developed 1D model was successfully validated against published three-dimensional finite element simulation data, yielding prediction errors ranging from 0.09% to 1.12%. Overall, the findings indicate that the proposed comparative 1D model provides reliable temperature predictions while requiring relatively low computational effort, making it a practical option for preliminary thermal analysis and battery pack design in electric vehicle applications.

Keywords: Lithium-Ion Battery, Thermal Management, Pouch Cell, Cylindrical Cell, Finite Difference Method

1. Introduction

The rapid growth of the electric vehicle (EV) market has intensified the need for energy storage systems that can deliver both high performance and reliable operational safety (Martyushev et al., 2023). Among the available technologies, lithium-ion (Li-ion) batteries have become the preferred choice because of their high energy density and long service life

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(Ahmed & Maraz, 2023). Despite these advantages, excessive heat generation remains a major concern, especially during fast charging and high C-rate discharge operations. If the generated heat is not effectively dissipated, elevated temperatures may accelerate capacity degradation, reduce battery lifespan, and, under severe operating conditions, trigger thermal runaway (Sabeel et al., 2025).

The thermal performance of a battery pack is strongly influenced by the geometric configuration of its constituent cells, as cell geometry determines the available heat transfer pathways and the effectiveness of heat dissipation. Among the various cell configurations, cylindrical cells (e.g., the 21700 format) and pouch cells are the two designs most widely adopted in current electric vehicle applications. Owing to their distinct structural characteristics, these cell types exhibit different surface-area-to-volume ratios and thermal conduction paths, leading to different temperature distribution and cooling behavior. Understanding these thermal characteristics is therefore essential for developing and optimizing Battery Thermal Management Systems (BTMS) capable of maintaining safe and efficient battery operation (Saber et al., 2025).

Previous studies have extensively investigated the feasibility and performance of lithium-ion battery technologies from different perspectives. Hummes et al. (2023), for instance, compared several battery configurations, including cylindrical, prismatic, pouch, blade, and structural designs, to evaluate their suitability for both economy- and performance-oriented electric vehicles. Their evaluation combined an extensive review of the existing literature with the Multi-Attribute Utility Theory (MAUT) to rank each battery technology according to eleven performance criteria. To further validate the assessment, the authors incorporated a case study based on the commercial Tesla Model Y. The results showed that blade batteries performed the best overall in both vehicle categories, receiving the highest ratings across practically all evaluation parameters. Furthermore, cylindrical batteries had consistently great performance and were judged to be better suited for high-performance cars, but pouch batteries demonstrated significant potential for applications motivated solely by cost considerations. Prismatic batteries, on the other hand, were regarded as the least competitive of the technologies tested. Finally, the case study analysis revealed that emerging battery technologies, such as the Licerion pouch battery (Sion), the 4680 cylindrical batteries (Panasonic), and the blade battery (BYD), have the potential to significantly improve driving range, capacity-to-volume ratio, and cost efficiency when compared to current battery technologies.

Another work (Wang et al., 2017) attempted to describe and forecast the thermal behavior and temperature distribution of cylindrical lithium-ion batteries in order to solve the problem of temperature non-uniformity within battery packs. The study used a Finite Element Method (FEM) technique with ANSYS software, and the simulated results were validated through experimental testing. The results showed that the numerical simulations had a good level of agreement with experimental observations. The difference between simulated and measured temperatures was about 10%, with a maximum error of 11.56%, over a range of ambient temperature conditions and discharge rates.

A more recent contribution was reported by Sabale et al. (2026), who investigated the mechanical performance and structural integrity of lithium-ion (Li-ion) battery cells, modules,

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and battery packs with cylindrical, prismatic, and pouch configurations for electric vehicle (EV) applications. Their research integrated high-resolution numerical modeling with experimental validation to characterize stress distribution, strain evolution, and potential failure mechanisms. Model predictions were verified through a series of controlled experiments, including compression, drop, vibration, and impact tests. The close agreement between numerical and experimental results demonstrated that the proposed computational framework can effectively support safety-oriented battery design, cell configuration optimization, and the development of more structurally robust battery systems for future electric vehicles.

Beyond simulation accuracy, computational efficiency has become an increasingly critical requirement for battery thermal models, particularly as the field moves toward real-time and embedded applications. High-fidelity FEM and CFD simulations, while accurate, are generally too computationally intensive to be embedded directly into a Battery Management System (BMS) or used for rapid design iteration. To address this limitation, reduced-order modeling (ROM) approaches—including proper orthogonal decomposition, lumped-parameter formulations, and simplified electro-thermal models derived from higher-fidelity physics—have been developed to preserve acceptable predictive accuracy while substantially lowering computational cost, enabling real-time or near-real-time implementation (Li et al., 2020; Coman et al., 2021). This computational efficiency is also a prerequisite for the emerging concept of the Battery Digital Twin (BDT), a continuously updated virtual representation of a physical battery used to support real-time state monitoring, predictive diagnostics, and thermal management decisions (Naseri et al., 2023). Because digital-twin frameworks require thermal sub-models that can be solved repeatedly and rapidly alongside other physical domains, computationally efficient, low-order thermal models such as the one developed in this study represent directly relevant building blocks for such real-time and digital-twin-oriented applications.

Although numerous studies have investigated the characteristics of Lithium-ion batteries through numerical and experimental approaches, most have focused on a specific battery geometry or have employed high-dimensional simulation methods, such as the Finite Element Method (FEM), which require substantial computational resources and relatively long computation times. Furthermore, studies specifically comparing the transient temperature distributions of cylindrical and pouch Lithium-ion battery cells using a one-dimensional (1D) electro-thermal approach derived from first principles remain limited. In particular, the potential of such simplified electro-thermal formulations to serve as a foundational reduced-order component for real-time applications, including digital-twin-based battery thermal management, has not been explicitly addressed in the context of geometry-comparative studies. Yet computationally efficient and simplified models are highly desirable as preliminary predictive tools for the design and development of Battery Thermal Management Systems (BTMS). Therefore, this study aims to develop and validate a one-dimensional electro-thermal model based on the principles of energy conservation and the Bernardi heat generation equation to compare the transient temperature distributions of cylindrical and pouch Lithium-ion battery cells under various discharge rates. In addition to evaluating the influence of cell geometry on battery thermal characteristics, this study also seeks to assess the capability

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of the proposed model as a computationally efficient alternative to three-dimensional FEM-based thermal simulations while maintaining a high level of predictive accuracy.

Taken together, the contributions of this study can be summarized as threefold. First, from a theoretical standpoint, the model provides a physically grounded, first-principles justification—based on Biot number analysis and the inherent symmetry of the assumed heat generation and boundary conditions—for reducing the three-dimensional heat conduction problem in both pouch and cylindrical Li-ion cells to a one-dimensional formulation without a significant loss of predictive accuracy, offering a generalizable criterion for evaluating when such dimensional reduction is appropriate for other cell geometries. Second, from an engineering standpoint, the comparative analysis quantifies the geometry-dependent core thermal entrapment phenomenon within a unified modeling framework and translates these findings into concrete design guidance for BTMS development, indicating that cylindrical cell packs benefit from core-focused cooling strategies, whereas pouch cell packs are more amenable to surface-based cooling. Third, from a computational standpoint, the proposed 1D-FDM model is shown to achieve prediction errors of only 0.09–1.12% relative to a full three-dimensional FEM benchmark while requiring more than 99.5% fewer spatial degrees of freedom and completing all simulated discharge scenarios in under 150 seconds on a standard laptop computer, confirming its suitability as a lightweight, reduced-order building block for rapid, iterative BTMS design and for real-time, digital-twin-based battery thermal management applications

2. Methods

2.1. Geometry Design

2.1.1. Pouch Geometry

Pouch batteries feature a flat, rectangular form factor enclosed within a flexible polymer–aluminum laminate packaging (Thomas III et al., 2013). Their thin and wide geometric configuration provides a high surface-area-to-volume ratio, enabling efficient heat dissipation and promoting lower and more uniform temperature distributions throughout the cell (Kim et al., 2012). Because of these qualities, pouch cells provide considerable improvements in thermal management performance and space utilization inside electric vehicle battery packs. However, they are prone to swelling produced by the buildup of internally generated gases during electrochemical reactions, necessitating additional mechanical protection to withstand external impact and structural loads.

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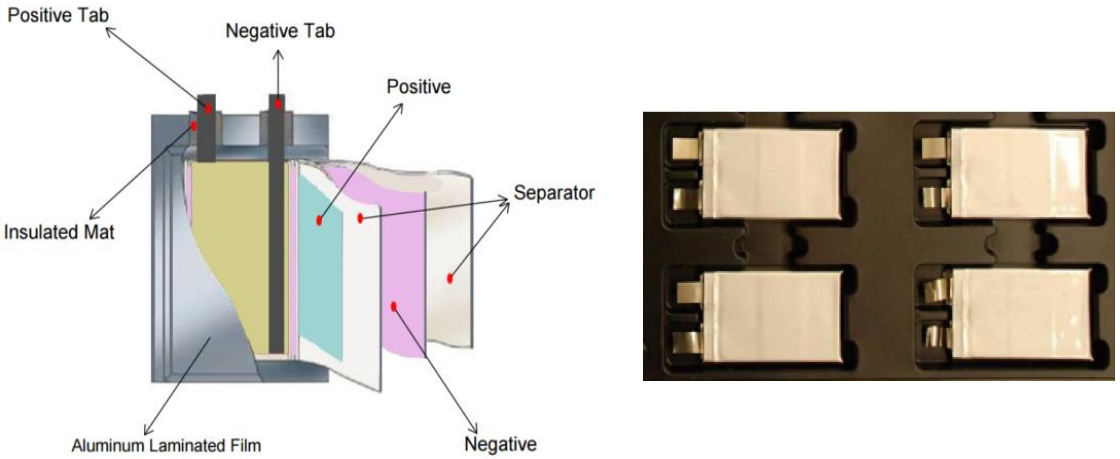
Figure 1. Pouch Geometry (Yoo et al., 2019) and (Sahraei et al., 2011)



2.1.2. Cylindrical Geometry

Cylindrical batteries are designed in the form of rigid cylindrical cells enclosed within robust metallic casings, as commonly found in standard formats such as the 18650 and 21700 cell types (Baazouzi et al., 2023). For an equivalent cell volume, this cylindrical geometry provides a considerably lower heat dissipation surface-area-to-volume ratio compared with pouch cells. Consequently, heat generated at the cell core must travel through a longer radial conduction path before being released to the surrounding environment. This limitation increases the susceptibility of cylindrical batteries to the core thermal trapping phenomenon, where heat accumulates in the central region of the cell. Despite this thermal disadvantage, cylindrical cells are widely recognized for their excellent mechanical strength, cost-effective manufacturing processes, and well-established cycle-life durability (Mekdour et al., 2025).

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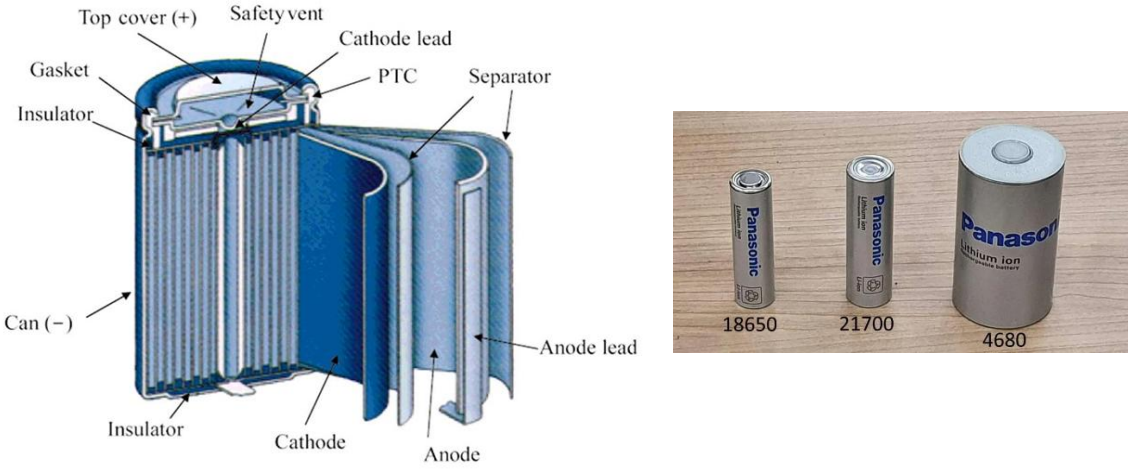
Figure 2. Cylindrical Geometry (Bankole et al., 2013) and (BatteryDesign.net, 2026)



2.2. Research Design and Model AssumPtions

This study employs a parametric mathematical modeling approach to reduce computational complexity while preserving the fundamental physics of heat transfer. Several assumptions were adopted in model development, and the parameters used in this study are summarized in Table 1:

1. The materials within the battery cell, including the cathode, anode, and separator, are assumed to be represented as a homogeneous lumped medium with uniform average thermophysical properties.
2. The internal heat generation rate ($\dot{q}$) is assumed to be uniformly distributed throughout the entire battery volume.
3. The convective heat transfer coefficient (h) at the external battery surface is assumed to remain constant throughout the simulation.
4. Heat transfer within the cylindrical cell is represented using a one-dimensional radial conduction model, whereas heat transfer within the pouch cell is represented using a one-dimensional through-thickness Cartesian conduction model

Table 1. Physical Properties and Simulation Parameters

Properties	Pouch	Cylinder
$\rho\ (kg/m^3)$	2258.79	
$C_p\ (J/kg°C)$	1225.36	
$k\ (W/m°C)$	0.973	
$h\ (W/m^2°C)$	10	
T_∞ (°C)	298.15	
$R_{in}\ (ohm)$	0.002	
$V_{cell}\ (m^3)$	0.00017252625	
$Capacity\ (Ah)$	20	
$Dimensions\ (m)$	L = 0.00708	R = 0.02

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2.3. Internal Heat Generation Model

Heat generation within a Lithium-ion battery primarily originates from two sources, Joule heating caused by internal resistance and entropic heat generated during electrochemical reactions. The volumetric heat generation rate, $\dot{q}\ (W/m^3)$, can be determined using the Bernardi equation (Bernardi et al., 1984):

$$\dot{q} = \frac{1}{V_{cell}}\left[I^2 R_{int} - IT\frac{dU_{ocv}}{dT}\right]$$

2.4. Governing Equations

The transient temperature distribution is derived from the energy conservation equation combined with Fourier's law of heat conduction. The thermal diffusivity of the material is represented by (Mattia et al., 2025) $\alpha = \frac{k}{\rho.C_p}$.

2.4.1. Pouch Cell Thermal Model

Due to the large surface area relative to its thickness, heat transfer in pouch cells is predominantly governed by one-dimensional conduction through the thickness direction. Therefore, the thermal analysis is conducted along the x-axis, extending from the center plane of the cell ($x = 0$) to the outer cell surface ($x = L$). The governing transient heat conduction equation is given by (Hua et al., 2017a) and (Bergman & Lavine, 2017):

$$\frac{\partial T}{\partial t} = \alpha\left(\frac{\partial^2 T}{\partial x^2}\right) + \frac{\dot{q}}{\rho.C_p}$$

2.4.2. Cylindrical Cell Thermal Model

In cylindrical cells, the primary heat transfer pathway is governed by radial conduction from the cell core ($r = 0$) toward the outer surface ($r = R$). where the largest thermal resistance is encountered. The corresponding transient heat conduction equation is given by (Zhou et al., 2007) and (Wang & Mai, 2004):

$$\frac{\partial T}{\partial t} = \alpha\left(\frac{\partial^2 T}{\partial r^2} + \frac{1}{r}\frac{\partial T}{\partial r}\right) + \frac{\dot{q}}{\rho.C_p}$$

2.5. Initial Conditions

At the initial condition ($t = 0$), the temperature of the entire battery domain is assumed to be uniform and equal to the ambient temperature (T_{inf}):
The following boundary conditions are imposed on both battery geometries:

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$$T(r,0) = T(x,0) = T_{inf}$$

1. Thermal Symmetry Boundary Condition (Cell Center): Owing to the symmetry of the temperature distribution, the net heat flux at the cell center is assumed to be zero (Patankar, 1980) and (Hua et al., 2017b).
   Pouch ($x = 0$): $\frac{\partial T}{\partial x}|_{x=0} = 0$
   Cylinder ($r = 0$): $\frac{\partial T}{\partial r}|_{r=0} = 0$

2. Convective Boundary Condition (Outer Surface): Heat conducted from the battery interior to the outer surface is transferred to the surrounding environment through convective heat exchange.
   Pouch ($x = L$): $-k.\frac{\partial T}{\partial x}|_{x=L} = h(T_{surface} - T_{inf})$
   Cylinder ($r = R$): $-k.\frac{\partial T}{\partial r}|_{r=R} = h\left(T_{surface} - T_{inf}\right)$

2.6. Numerical Discretization

The governing partial differential equations were solved numerically using the Finite Difference Method (FDM) with a Forward Time Central Space (FTCS) scheme (LeVeque, 2005). The spatial domain was discretized into finite nodes with grid spacing of Δr for the cylindrical cell and Δx for the pouch cell, while the transient response was evaluated using discrete time steps Δt. The temporal derivative was approximated using the Forward Difference (Explicit Euler) scheme, where the temperature at the next time step was calculated from the previous time step (Kreyszig et al., 2011). For the spatial discretization, the second-order derivative was approximated using the Central Difference scheme, which was formulated from the Taylor series expansion (Varberg et al., 2007). This discretization converts the governing heat transfer equation into an explicit algebraic formulation that can be solved iteratively until the desired simulation time or steady-state condition is reached (Holman, 2010).

2.6.1. Pouch Cell Model Discretization

$$T_i^{n+1} = T_i^n + \Delta t\left[\alpha\frac{T_{i+1}^n - 2T_i^n + T_{i-1}^n}{\Delta x^2} + \frac{\dot{q}}{\rho.C_p}\right]$$

2.6.2. Cylindrical Cell Model Discretization

$$T_i^{n+1} = T_i^n + \Delta t\left[\alpha\left(\frac{T_{i+1}^n - 2T_i^n + T_{i-1}^n}{\Delta r^2} + \frac{1}{r_i}\frac{T_{i+1}^n - T_{i-1}^n}{2\Delta r}\right) + \frac{\dot{q}}{\rho.C_p}\right]$$

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Where i denotes the spatial index and n represents the temporal index. the numerical algorithm was implemented in Python, utilizing the NumPy library for iterative matrix computations. Battery physical parameters obtained from the literature were incorporated into the computational model, and simulations were performed until either steady-state condition were reached or the discharge process was completed. Numerical stability was maintained by ensuring that the Fourier number (Pupeikis et al., 2010), $F_o = \frac{\alpha \Delta T}{\Delta x^2}$ remained below 0.5 throughout the simulation.

2.7. Validation Model

The developed one-dimensional (1D) electro-thermal model was validated by comparing the numerical simulation results with published three-dimensional (3D) finite element method (FEM) simulation data from the literature. The validation process was performed under identical operating conditions, including discharge rates of 1C, 3C, and 5C, for both cylindrical and pouch Lithium-ion battery cell geometries.

The validation parameters included the maximum core temperature and the average surface temperature obtained from the developed FDM-based model and the reference FEM model. The comparison was conducted to evaluate the capability of the proposed model in reproducing the transient thermal behavior of different battery geometries. The relative error between the numerical model and reference data was calculated using Equation (Chapra & Canale, 2015):

$$Error\ (\%) = \left| \frac{T_{model} - T_{ref}}{T_{ref}} \right| \times 100\%$$

Where T_{model} represents the temperature predicted by the developed 1D electro-thermal model, and T_{ref} represents the temperature obtained from the FEM simulation data. Model validation was first conducted to evaluate the accuracy and reliability of the proposed simplified approach, providing confidence before applying it to the comparative thermal analysis of cylindrical and pouch battery cells.

3. Result and Discussion

Figure 3 illustrates the transient temperature evolution at the core of both pouch and cylindrical battery cells under discharge rates of 1C, 3C, and 5C. A consistent increase in temperature rise is observed as the discharge rate becomes higher, producing noticeably steeper temperature profiles. Higher C-rates also shorten the discharge duration, with the total simulation time decreasing to approximately 720 s at 5C. This behavior can be attributed to

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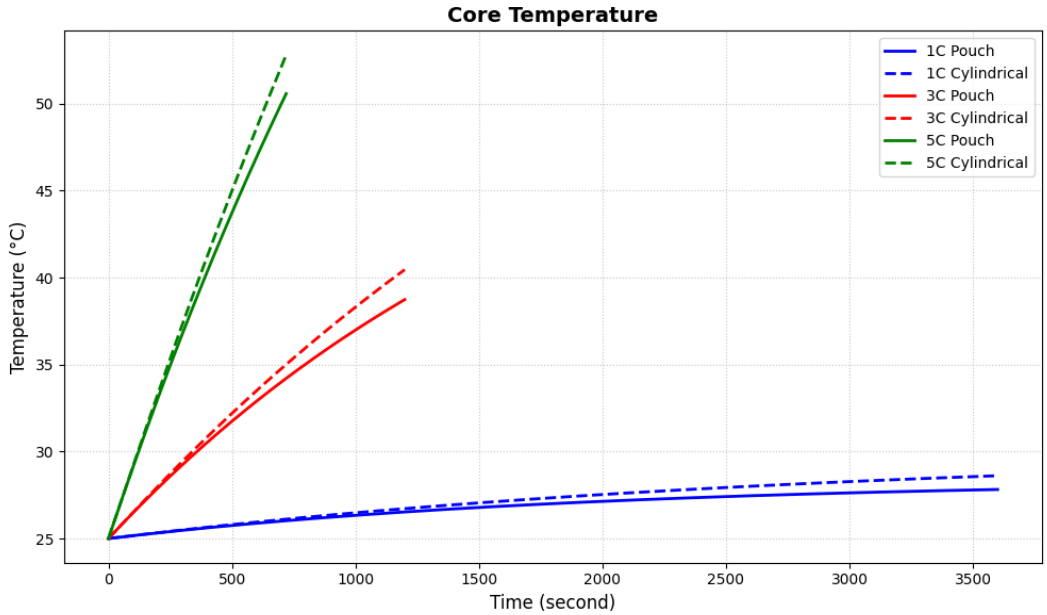
the larger discharge current, which accelerates battery depletion while simultaneously increasing Joule heat generation in proportion to the square of the current.

The steeper temperature increase observed at higher discharge rates is primarily attributed to Joule heating, which dominates the internal heat generation process. According to the Bernardi heat generation model, the irreversible heat generation term is proportional to the square of the electric current (I^2R). Consequently, increasing the C-rate leads to a substantial rise in discharge current, causing the rate of internal heat generation to increase nonlinearly. This effect is reflected in the simulation results, where the battery temperature under the 5C discharge condition rises considerably faster than under the 1C condition.

A clear difference in thermal behavior can be observed between the two battery geometries. Across all discharge rates, the cylindrical cells (dashed lines) consistently reach higher core temperatures than the pouch cells (solid lines). The largest temperature difference appears under the 5C discharge condition, where the cylindrical cell exceeds 52°C, whereas the pouch cell remains close to 50°C. This contrast mainly arises from the different heat transfer paths associated with each cell geometry. In cylindrical cells, heat generated at the core must travel radially through the cell before reaching the outer surface, where it is finally released to the surrounding environment by convection. The relatively long conduction path increases thermal resistance, promoting heat accumulation near the center of the cell, a behavior commonly referred to as core thermal entrapment. By comparison, the much thinner profile of pouch cells shortens the conduction distance, allowing heat to reach the external surface more rapidly. Consequently, heat is distributed more uniformly throughout the cell, resulting in a lower peak core temperature than that observed in cylindrical cells.

Figure 3. Core Temperature



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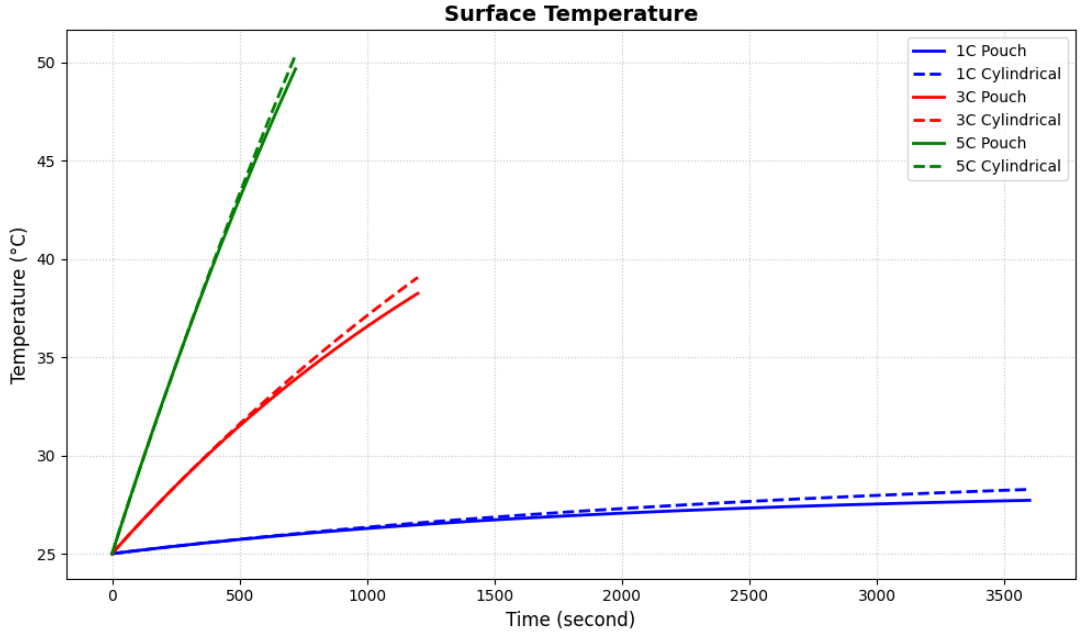
The second graph illustrates the transient surface temperature profiles of both battery cell geometries. Similar to the temperature behavior at the cell core, the surface temperature increases progressively with discharge time and increasing discharge rate. However, the surface temperature remains consistently lower than the corresponding core temperature at any given time. This phenomenon is expected from a heat transfer perspective, as the outer battery surface continuously dissipates thermal energy to the surrounding environment through convective heat transfer, while the ambient air temperature is maintained at 25°C.

The comparative analysis presented in the second graph once again highlights the superior thermal performance of pouch cells, as the surface temperature of cylindrical cells remains consistently higher despite both cell geometries having equivalent volumes and internal heat generation rates. Pouch cells are able to maintain lower and more stable surface temperatures due to their significantly larger surface-area-to-volume ratio. Their thin and wide geometry provides an inherent thermal advantage by functioning similarly to a natural heat sink, thereby increasing the effective area available for convective heat dissipation. Consequently, heat can be released to the surrounding environment more efficiently than in cylindrical cells, whose heat dissipation is limited by the comparatively smaller external surface area of the cylindrical casing.

Figure 4. Surface Temperature



To assess the predictive capability of the developed electro-thermal model, a validation study was performed by comparing the Python-based Finite Difference Method (FDM) simulation results with reference Finite Element Method (FEM) simulation data available in literature by (Pao-La-Or & Somphong, 2020). The validation was carried out under discharge rates of 1C, 3C, and 5C using the maximum core temperature and average surface temperature

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as the key comparison metrics for both pouch and cylindrical battery cells. The corresponding temperature comparison results are summarized in Table 2.

Table 2. Comparison of Numerical and Literature Result

Temperature Result	1C		3C		5C	
	Literature	Numeric Model	Literature	Numeric Model	Literature	Numeric Model
Max Temp. of core (pouch)	26.52	27.9	35.69	38.35	48.45	50.61
Max Temp. of core (cylinder)	28.31	29.72	39.8	40.44	52.92	52.64
Avg. surface Temp (pouch)	26.48	27.81	35.05	38.27	46.12	49.69
Avg. surface Temp (cylinder)	28.05	28.34	38.66	39.04	49.89	50.17

As shown in Table 3, the constructed numerical model has excellent agreement with the reference data for all discharge circumstances investigated. To offer a quantitative assessment of model accuracy, the relative error was computed for each temperature parameter. The error values obtained are summarized in Table 3.

Table 3. Relative Error between the Numerical Model and Literature Data

Error Value	1C	3C	5C
Max Temp. of core (pouch)	0.46%	0.86%	0.67%
Max Temp. of core (cylinder)	0.47%	0.20%	0.09%
Avg. surface Temp (pouch)	0.44%	1.04%	1.12%
Avg. surface Temp (cylinder)	0.10%	0.12%	0.09%

The validation results, presented in Table 3, reveal that all percentage errors fall within the range of 0.09%-1.12%. The largest inaccuracy was reported for the pouch-cell surface temperature under the 5C discharge condition, reaching 1.12%, while the cylindrical cell's core and surface temperatures had a minimum error of 0.09% at the same discharge rate. The consistently low error values demonstrate that the created one-dimensional electro-thermal

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model accurately reproduces the temperature behavior indicated by the three-dimensional reference model.

The high accuracy of the simplified 1D model can be explained by two complementary factors. First, because internal heat generation is uniform and the convective boundary condition is applied uniformly over the entire outer surface, the resulting temperature field is inherently axisymmetric: no meaningful gradient develops in the angular or axial direction (cylinder) or the in-plane directions (pouch). The dimensional reduction therefore discards no genuine physical information, only directions along which no significant gradient exists. Second, the relatively low Biot number of both geometries ($Bi = h.L/k \approx 0.073$ for the pouch cell and $Bi = h.R/k \approx 0.206$ for the cylindrical cell, based on Table 1) indicates that convective resistance at the surface is comparable to or exceeds internal conduction resistance. The overall temperature evolution is therefore governed primarily by the global energy balance between volumetric heat generation and surface heat rejection, both of which are preserved exactly in the 1D formulation. This explains why the resulting errors remain consistently low (0.09–1.12%) across all discharge rates, and why the comparatively higher Biot number of the cylindrical cell also explains, from first principles, the larger core-to-surface gradient—the core thermal entrapment phenomenon—observed in this st

The modest variances between the numerical simulation findings and the reference data are most likely due to changes in the modeling methodologies used. The created model employs a one-dimensional Finite Difference Method (1D-FDM), whereas the reference model is based on a three-dimensional Finite Element Method (3D-FEM), which may capture local temperature distributions more precisely. Nonetheless, all computed error levels are considerably within the widely accepted engineering tolerance threshold of 5%, showing that the created numerical model has been validated and is appropriate for comparative thermal evaluations of cylindrical and pouch battery cell designs. Furthermore, the validation process was carried out utilizing simulation data published in the literature and has yet to be confirmed against direct experimental measurements. Future research should focus on incorporating more realistic operating conditions, including non-uniform heat generation, and experimental validation, to further enhance the model's capability to predict battery thermal behavior under practical operating conditions.

Table 4. Computational Efficiency of the 1D-FDM Simulation

C-rate	Time Steps	Computational Time
1C	720,000	96.68 s
3C	240,000	32.53 s
5C	144,000	19.53 s
Total C-rate	1,104,000	148.74 s

The computational efficiency of the proposed model can be quantified directly, as shown in Table 4. The reference three-dimensional FEM model (Pao-La-Or & Somphong, 2020) discretized the pouch and cylindrical cells using 11,621 nodes/53,204 tetrahedral elements and 10,565 nodes/55,461 tetrahedral elements, respectively. By contrast, the present

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1D-FDM formulation discretizes each geometry using only 50 spatial nodes—a reduction of over 99.5% in spatial degrees of freedom—reducing the computation at each time step to a small set of explicit scalar updates rather than the assembly and solution of a large coupled matrix system. On a standard laptop computer (Intel Core i7-10750H CPU @ 2.60 GHz), the complete transient simulation required 96.68 s, 32.53 s, and 19.53 s of wall-clock time for the 1C (720,000 time steps), 3C (240,000 time steps), and 5C (144,000 time steps) discharge cases, respectively, totalling approximately 148.74 s (≈2.5 minutes) for all three discharge rates and both cell geometries combined. This confirms that the proposed 1D model achieves prediction errors below 1.2% while requiring only a small fraction of the numerical complexity of a full 3D FEM simulation, supporting its suitability for rapid, iterative BTMS design studies.

It should also be noted that the homogeneous, lumped-medium assumption—while adequate for predicting bulk core and surface temperatures—cannot resolve localized thermal features visible in a full 3D model. The original FEM reference study (Pao-La-Or & Somphong, 2020) reported that the most severely heated region during discharge is located at the positive current-collector tab rather than at the geometric cell core, due to the lower electrical conductivity of the aluminum tab relative to the copper negative tab. Because the present model treats the cell as a single homogeneous medium with uniformly distributed heat generation, it cannot capture this tab-level hot-spot, nor other localized effects such as anisotropic in-plane versus through-thickness conductivity or edge effects at the pouch cell perimeter. These simplifications are acceptable for comparing bulk, geometry-dependent thermal behavior, but should be regarded as a boundary of the model's applicability.

From a design perspective, these findings carry direct implications for BTMS development. Because cylindrical cells exhibit a longer radial conduction path and higher internal thermal resistance, cooling strategies for cylindrical packs should prioritize reducing the effective conduction distance from the cell core—for example, internal cooling pins or tab-cooling architectures that also address the localized tab heating noted above. In contrast, the larger surface-area-to-volume ratio of pouch cells makes them intrinsically more amenable to surface-based cooling, such as cold plates applied directly to the cell faces. Because the developed 1D model requires only a fraction of the computational cost of a full 3D FEM simulation, it is well suited for early-stage, iterative BTMS design tasks—such as screening candidate cell geometries or setting preliminary C-rate limits—before committing to more expensive high-fidelity simulations for final design verification.

4. Conclusion

The numerical simulations and comparative analyses performed in this study demonstrate that battery cell geometry plays a decisive role in determining transient temperature distributions. Across all discharge rates investigated (1C, 3C, and 5C), pouch cells consistently exhibited better thermal performance than cylindrical cells by maintaining lower core and surface temperatures throughout the discharge process. This thermal advantage is mainly attributed to the shorter heat conduction path of pouch cells, which promotes more efficient heat dissipation. By contrast, the longer radial conduction path in cylindrical cells

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increases thermal resistance, leading to greater heat accumulation and consequently higher peak temperatures.

This study also developed a one-dimensional electro-thermal model based on the principles of energy conservation and the Bernardi heat generation equation using the Finite Difference Method (FDM). Comparison with three-dimensional reference data reported in the literature showed good agreement, with relative prediction errors ranging from 0.09% to 1.12%. These error values are significantly lower than the engineering tolerance limits commonly used in thermal modeling studies, indicating that the proposed one-dimensional approach achieves high levels of accuracy while requiring significantly less computational complexity than three-dimensional models.

As a result, the suggested model has the potential to serve as an effective preliminary predictive tool for monitoring and evaluating the thermal behavior of lithium-ion batteries. Furthermore, it provides a significant platform for future research focusing on the design and optimization of Battery Thermal Management Systems (BTMS) for electric vehicles. Future studies should extend the proposed model by incorporating experimental validation, battery aging effects, fast-charging scenarios, and thermal runaway prediction capabilities to further enhance its applicability for real-world BTMS design.

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References

Ahmed, M. D., & Maraz, K. M. (2023). Revolutionizing energy storage: Overcoming challenges and unleashing the potential of next generation Lithium-ion battery technology. *Materials Engineering Research, 5*(1), 265–278. https://doi.org/10.25082/mer.2023.01.003

Baazouzi, S., Feistel, N., Wanner, J., Landwehr, I., Fill, A., & Birke, K. P. (2023). Design, properties, and manufacturing of cylindrical Li-Ion battery cells—A generic overview. *Batteries, 9*(6), 309. https://doi.org/10.3390/batteries9060309

Bankole, O. E., Gong, C., & Lei, L. (2013). Battery recycling technologies: Recycling waste lithium ion batteries with the impact on the environment in-view. *Journal of Environment and Ecology, 3*(1), 14–16. https://doi.org/10.5296/jee.v3i1.3257

BatteryDesign.net. (2026). Cylindrical cells. https://www.batterydesign.net/battery-cell/formats/cylindrical-cells/

Bergman, T. L., & Lavine, A. S. (2017). *Fundamentals of heat and mass transfer* (8th ed.). John Wiley & Sons.

Bernardi, D., Pawlikowski, E., & Newman, J. (1984). A general energy balance for battery systems. *Journal of the Electrochemical Society*. https://escholarship.org/uc/item/9fx5f0h8

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Chapra, S. C., & Canale, R. P. (2015). *Numerical methods for engineers* (7th ed.). McGraw-Hill Education.
Coman, P. T., Darcy, E. C., Strangways, B., & White, R. E. (2021). A reduced-order lumped model for Li-ion battery packs during operation. *Journal of The Electrochemical Society, 168*(10), 100525. https://doi.org/10.1149/1945-7111/ac2dcb
Hua, Y. C., Zhao, T., & Guo, Z. Y. (2017a). Optimization of the one-dimensional transient heat conduction problems using extended entransy analyses. *International Journal of Heat and Mass Transfer, 116*, 166–172. https://doi.org/10.1016/j.ijheatmasstransfer.2017.08.101
Hua, Y. C., Zhao, T., & Guo, Z. Y. (2017b). Transient thermal conduction optimization for solid sensible heat thermal energy storage modules by the Monte Carlo method. *Energy, 133*, 338–347. https://doi.org/10.1016/j.energy.2017.05.073
Holman, J. P. (2010). *Heat transfer*. McGraw-Hill.
Hummes, D. N., Hunt, J., Hervé, B. B., Schneider, P. S., & Montanari, P. M. (2023). A comparative study of different battery geometries used in electric vehicles. *Latin American Journal of Energy Research, 10*(2), 94–114. https://doi.org/10.21712/lajer.2023.v10.n2.p94-114
Kim, Y., Ho, T., Thelliez, M., Tan, E., & AVL Powertrain Engineering. (2012). *3D thermal analysis of Li-ion battery cells with various geometries and cooling conditions using Abaqus*. Conference proceeding.
Kreyszig, E., Kreyszig, H., & Norminton, E. J. (2011). *Systems of units: Some important conversion factors*.
LeVeque, R. J. (2005). *Finite difference methods for differential equations*.
Li, A., Ponchant, M., Sturm, J., & Jossen, A. (2020). Reduced-order electro-thermal battery model ready for software-in-the-loop and hardware-in-the-loop BMS evaluation for an electric vehicle. *World Electric Vehicle Journal, 11*(4), 75. https://doi.org/10.3390/wevj11040075
Martyushev, N. V., Malozyomov, B. V., Sorokova, S. N., Efremenkov, E. A., & Qi, M. (2023). Mathematical modeling of the state of the battery of cargo electric vehicles. *Mathematics, 11*(3), 536. https://doi.org/10.3390/math11030536
Mattia, L., Beiranvand, H., Zamboni, W., & Liserre, M. (2025). Lithium-ion battery thermal modelling and characterisation: A comprehensive review. *Journal of Energy Storage*. https://doi.org/10.1016/j.est.2025.117114
Mekdour, K., Madikere Raghunatha Reddy, A. K., Guimaraes Selva, T. M., & Zaghib, K. (2025). Comparative analysis of cell design: Form factor and electrode architectures in advanced Lithium-Ion batteries. *Batteries*. https://doi.org/10.3390/batteries11120450
Naseri, F., Gil, S., Barbu, C., Cetkin, E., Yarimca, G., Jensen, A. C., Larsen, P. G., & Gomes, C. (2023). Digital twin of electric vehicle battery systems: Comprehensive review of the use cases, requirements, and platforms. *Renewable and Sustainable Energy Reviews, 179*, 113280. https://doi.org/10.1016/j.rser.2023.113280
Pao-La-Or, P., & Somphong, N. (2020). Comparison and analysis of temperature distribution in pouch and cylindrical Li-ion battery by finite element thermal model. *International Journal of Smart Grid and Clean Energy*, 915–923. https://doi.org/10.12720/sgce.9.5.915-923
Patankar, S. V. (1980). *Numerical heat transfer and fluid flow*. Hemisphere Publishing Corporation.

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Pupeikis, D., Stankevičius, V., & Burlingis, A. (2010). The effect of the Fourier number on calculation of an unsteady heat transfer of building walls. *Journal of Civil Engineering and Management, 16*(2), 298–305. https://doi.org/10.3846/jcem.2010.34

Sabale, S. K., Watvisave, D., Nanwatkar, R., & Gaike, V. V. (2026). Numerical modeling and experimental validation of mechanical performances of Li-Ion battery cells/modules/packs with various form-factor design for EV applications. *International Journal of Engineering Trends and Technology, 74*(1), 193–216. https://doi.org/10.14445/22315381/ijett-v74i1p115

Sabeel, K., Al-Greer, M., & Bashir, I. (2025). Advancements in vibration testing: Effects on thermal performance and degradation of modern batteries. *Batteries*. https://doi.org/10.3390/batteries11020082

Saber, N., Richter, C. P., & Unnthorsson, R. (2025). Review of thermal management techniques for prismatic Li-Ion batteries. *Energies, 18*(3), 492. https://doi.org/10.3390/en18030492

Sahraei, E., Hill, R., & Wierzbicki, T. (2011). Calibration and finite element simulation of pouch lithium-ion batteries for mechanical integrity. *Journal of Power Sources, 201*, 307–321. https://doi.org/10.1016/j.jpowsour.2011.10.094

Thomas III, J., Qidwai, S., Pogue III, W., & Pham, G. (2013). Multifunctional structure-battery composites for marine systems. *Journal of Composite Materials*. https://doi.org/10.1177/0021998312460262

Varberg, D., Purcell, E. J., & Rigdon, S. E. (2007). *Calculus* (9th ed.). Pearson Prentice Hall.

Wang, B. L., & Mai, Y. W. (2004). Transient one-dimensional heat conduction problems solved by finite element. *International Journal of Mechanical Sciences, 47*(2), 303–317. https://doi.org/10.1016/j.ijmecsci.2004.11.001

Wang, Z., Ma, J., & Zhang, L. (2017). Finite element thermal model and simulation for a cylindrical Li-Ion battery. *IEEE Access, 5*, 15372–15379. https://doi.org/10.1109/ACCESS.2017.2723436

Yoo, S., Hong, C., Chong, K. T., & Seul, N. (2019). Analysis of pouch performance to ensure impact safety of Lithium-Ion battery. *Energies, 12*(15), 2865. https://doi.org/10.3390/en12152865

Zhou, J. H., Yu, A. B., & Horio, M. (2007). Finite element modeling of the transient heat conduction between colliding particles. *Chemical Engineering Journal, 139*(3), 510–516. https://doi.org/10.1016/j.cej.2007.08.024

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