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Enhancing Electric Vehicle Battery Thermal Management using Phase Change Materials: A CFD Analysis for Improved Heat Dissipation

Divya D Shetty[1], Mohammad Zuber[1], Chethan K N[1], Laxmikant G Keni[1], Irfan Anjum Badruddin Magami[2], Chandrakant R Kini[1,*]

[1] Department of Aeronautical and Automobile Engineering, Manipal Institute of Technology, Manipal Academy of Higher Education, Manipal, Karnataka, India
[2] Department of Mechanical Engineering, King Khalid University,Abha Saudi Arabia

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ABSTRACT

The adverse environmental issues and climate change has compelled world to shift to renewable energy systems. Conventional IC engines are the major contributor for air pollution which is the main cause for the global warming. Therefore, EVs (Electric Vehicle) are the future of the automotive industry. The important issues faced by EVS are battery heat generation. Hence in order to remove heat efficiently from the EV battery CFD analysis of a passive thermal management system using PCM for Li-ion batteries is studied for three different discharge rates. Compared to bare cell, the cell with passive BTMS reduces the maximum temperature rise by 2%, 2.1% and 1% at discharge rates of 1.5 C, 1.0 C and 0.5 C respectively thus implying that the BTMS adopted is effective in removing heat from the surface of the cell.

1. Introduction

The conventional automobile incorporated with internal combustion engine on its complete combustion releases harmful gases like CO_2, NOx and PM, among which CO_2 is a major contributor for global warming [1]. It is assessed that by 2100 the concentration o will increase up to 570 PPM [2]. This will further increase sea level by 38 cm and global temperature rise by 1.9 °C. Because of this increase in global temperature, the world started implementing the use of renewable sources of energy [3]. Alternative energy concepts like hybrid vehicle, plugged-in hybrid vehicle and electric vehicle (EVs). EVs are considered as zero-emission vehicle and so a best option to address environmental issues like global warming. Due to the rapid rise in pollution and many other environmental issues globally, the emission norms are stringent because of which many countries have started employing EVs [4]. The important challenge in implementing EVs are battery supporting a good driving range, fast charging battery and a better performance. To attain these parameters, suitable battery technology needs to be known for extensive application [3].

* *Corresponding author.*
E-mail address: chandra.kini@manipal.edu (Chandrakant R Kini)

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Due to their qualities including a high energy density, a long operating life, and a range of suitable operating temperatures, lithium-ion batteries are a well-known option for EV applications [5]. When compared to other batteries, Li-ion batteries have a high potential to be recyclable and a low self-discharge rate. However, it is crucial to eliminate heat produced while Li-ion cell charging and discharging to provide effective operating conditions for long life [6]. Lithium-ion batteries become unstable when running at unusual temperature ranges. Between 40 ºC and 15 ºC is the Li-ion cell's effective operating range. Additionally, a battery pack's individual cells' temperature differences should be no more than 5 ºC. The ideal balance between battery life and performance will be preserved as a result [7]. Li-ion batteries also have the drawback of increasing resistance with age, which increases heat generation and results in a thermal runaway. Its temperature should be kept between 60 ºC and 80 ºC [2] to prevent thermal runaway and early deterioration of battery capacity. It is necessary to conduct in-depth research on Li-ion batteries and fully comprehend a number of crucial parameters, including battery cycle life and full discharge cycle, which will then help design an effective Battery Thermal Management System (BTMS) for further enhancing its performance characteristics [6].

Li-ion batteries used in EVs use a variety of thermal management methods, including air-cooled, liquid-cooled, heat pipe-containing phase change materials, and hybrid cooling systems [8]. Because air has a limited thermal conductivity, air-based BTMS have a significant power consumption disadvantage. Additionally, the temperature distribution within the battery pack is not consistent, which further reduces battery performance [9]. Liquid-based cooling technique has better cooling capacity than air-cooled BTMS. The majority of liquid cooling systems utilize cooling passages between the battery cells, while occasionally the cooling medium is directly submerged into the battery cell itself. It has been discovered that a number of liquid cooling system designs, including cooling plates with mini-channel structures and serpentine cooling channels, are extremely effective and compact in design [10]. Heat transfer fluids used in BTMS frequently include water, ethylene glycol, mineral oil, refrigerants, Nano fluids [11] and dielectric fluids [12]. The cooling channel's type, dimensions, geometry, and coolant flow path all play a significant role in how well the cold plate functions [13]. The effect of L shape cooling channel on convection heat transfer is also crucial [14]. In the meantime, the cooling systems based on phase change materials are determined by the physical properties of the material that can be used for BTM in electric vehicles [15].

A PCM-based cooling system has the disadvantage of having low thermal conductivity, which causes it to react slowly to large thermal loads. Poor mechanical properties, leakage, and a slow rate of heat transmission between the PCM and its surroundings are among of PCM's other drawbacks. Although researchers are striving to improve PCM's thermal conductivity by adding metal particles or metal foams, extra cooling is still necessary in addition to PCM for the battery to operate at its best [16]. Heat pipes can effectively transfer heat from the battery, but they require additional cooling systems, just like PCM technology requires. Heat pipes are a possible technique for BTMS use, although more study is needed [17].

By utilizing chemical linkages to absorb and release heat, PCM material transforms its phase. At room temperature, the PCM utilized for the BTMS will be solid. When PCM's surroundings warm up, it absorbs the extra heat until it reaches its melting point [18]. The PCM becomes liquid at higher temperatures before returning to its original solid state when the temperature drops to normal. With simple maintenance requirements, low operating costs, good heat dissipation, and distribution capacity, integrating PCM as a passive battery thermal management system is an effective choice. A preferred type and thickness of PCM are required [19] to choose the best PCM for battery thermal control.

Capric acid PCM was utilized for battery temperature management by Verma *et al.,* [20]. In this study, PCM (capric acid) is utilized to lower the battery's total temperature and keep it constant. In light of this, it is discovered that PCM (capric acid) has the ability to absorb high temperatures, preventing any localized heat generation that would result in battery degradation and safety concerns. For battery thermal management, Al Hallaj and Selman [21] looked into the cooling capacity of a hexacosane paraffin combination. The proposed PCM's melting temperature was adequate for use with BTMS. The outcome implies that PCM undergoes a phase transition from solid to liquid while soaking up heat from the cylindrical Li-ion batteries' surface.

Paraffin (PA) is a typical PCM for BTMS applications, but it has inherited weaknesses such low thermal conductivity and leakage that need to be changed [22]. A composite PCM material with increased heat conductivity was created by Goli *et al.,* [23] by mixing graphene filler with paraffin. By later adding 1 weight percent of graphene filler, compared to standard PA, the thermal conductivity of PA was increased by 60 times. A copper mesh was incorporated by Wu *et al.,* [24] into a PA/expanded graphite composite PCM, which serves as a skeleton to safeguard the composite PCM material for BTMS application. Since expanded graphite is a porous substance, it may absorb liquid PA and prevent leaking. The BTMS system's overall heat conductivity and strength could be improved by using copper mesh as the framework for the modules. As a result, it has been found that the composite PCM with copper mesh has increased both the rate and homogeneity of heat transfer.

Azad *et al.,* [25] The influence of a temperature increase on the melting of PCM was calculated and physically investigated. The process of natural convection in melted PCM was also closely monitored. The experimental set-up consists of a cylindrical enclosure with a 5-inch diameter and a 2-inch thickness and a central steel tube with an outer diameter of 0.25 inches that is transporting heat transfer fluid. In experiments, the heat transfer fluid was maintained at constant temperatures of 40 ºC,50 ºC, and 60 ºC. As a result, it is found that the amount of stored energy increases linearly after 6 hours of heating at a low wall temperature. The literature review makes it clear that the choice of PCM and its optimal thickness around the cell are important factors affecting the heat transmission characteristics. Because the kind, thickness, and thermal conductivity of PCM are frequently constrained by the weight of the BTMS and the battery pack design, BTMS optimization is crucial and absolutely necessary [26].

Therefore, it is crucial to create a computational model, examine the functionality of a single cell, and gather data on heat generation and the highest temperature rise in order to develop an effective PCM-cooled BTMS [22]. Creating a thermal model of a cylindrical Li-ion battery is the main goal of the current work in order to calculate the thermal parameters, such as temperature distribution and maximum temperature at various discharge rates. PCM is also put to the cell's surface to improve cooling performance and achieve consistent temperature distribution. The temperature change on the battery and heat transfer on the cell's surface are investigated. The suggested technique offers an efficient passive cooling solution employing PCM and will assist in keeping the operating temperature of Li-ion batteries for electric car applications within the optimized range. The electrical and thermal field characteristics of the are estimated based on the dual potential MSMD with NTGK sub-module as stated in the reference [27].

2. Methodology

2.1 Governing Equation

Based on the dual potential MSMD with NTGK sub module, the electrical and thermal field characteristics of the is calculated as follows [27]:

$$\frac{\partial\left(\rho C_p T\right)}{\partial t} - \nabla \cdot \left(k_c \Delta T\right) = \left|\nabla \phi_{pos}\right|^2 + \sigma_{neg}\left|\nabla \phi_{neg}\right|^2 + q_{E_{ch}} \tag{1}$$

$$\left.\begin{aligned} \nabla \cdot \left(\sigma_{pos} \nabla \phi_{pos}\right) &= j \\ \nabla \cdot \left(\sigma_{neg} \nabla \phi_{neg}\right) &= -j \end{aligned}\right\} \tag{2}$$

Where ϕ is electric potential, σ is electric conductivity and suffixes pos, neg represents positive and negative electrode.

Volumetric current transfer is given by,

$$j = \frac{C_N}{C_{ref} Vol} Y\left[U - \left(\phi_{pos} - \phi_{neg}\right)\right] \tag{3}$$

Where Vol volume of active zone is, C_{ref} is the battery capacity used to get U and Y parameter functions. Deep of discharge (DoD) is calculated as follows,

$$DoD = \frac{Vol}{3600 Q_{nominal}} \int_0^t j dt \tag{4}$$

Depending on Deep of discharge, the U and Y parameter functions are evaluated as follows,

$$\left.\begin{aligned} U &= \left\{\sum_{n=0}^{5} a_n \left(DoD\right)^n\right\} - C_2\left(T - T_{ref}\right) \\ Y &= \left\{\sum_{n=0}^{5} b_n \left(DoD\right)^n\right\} \exp\left(-C_1\left\{\frac{1}{T} - (1) T_{ref}\right\}\right) \end{aligned}\right\} \tag{5}$$

Where C_1 and C_2 are constants for a particular battery and T_{ref} is the reference temperature.

The Electro-Chemical reaction heat is given by,

$$q_{E_{ch}} = j_{E_{ch}}\left[U - \left(\varphi_+ - \varphi_-\right) - T\frac{dU}{dT}\right] \tag{6}$$

Where the first term in Eq. (6) represents heat due to over potential and second term represents entropy-based heat generation.

The Li-ion cell specifications, material properties for NTGK model, U and Y coefficients and cooling system material properties are listed in Tables 7, 8 and 9 respectively.

2.2 Geometry and Meshing

A solid cylinder of 650 mm in length and 26 mm in diameter serves as the cell in the current study. The anode, cathode, and middle component, which is referred to as a jelly roll, are the three primary parts of the cell used in the NTGK formulation. In fact, the cell will be coated in an outer shell material, but because the model needs to be as simple as possible, the thermal resistance of the outside shell is disregarded, and it is thus not represented in the model. Using Ansys design modeler, a geometrical model of the cooling system for a single cell battery is created. The coolant channel and coolant container are developed as the solid and fluid, respectively. The container is composed of aluminium and contains PCM that is 1 mm thick. Figure 1 provides the cooling system's dimensions. The Li-ion cell and PCM are in close proximity to one another. The PCM surrounding the cell absorbs the heat produced when discharging it at various flow rates.

In order to solve the NTGK single-cell model without cooling at a constant discharge current of 6 Amperes, mesh independence experiments have been performed. When taking into account maximum temperature rise as the parameter of interest, 1.15 mm is shown to be the ideal mesh size. As a result, a single cell with PCM cooling uses a mesh with 258964 elements. Table 1 contains NTGK model metrics for each example. In Figure 2, we can see the mesh model. Table 1 provides a description of the mesh's quality.

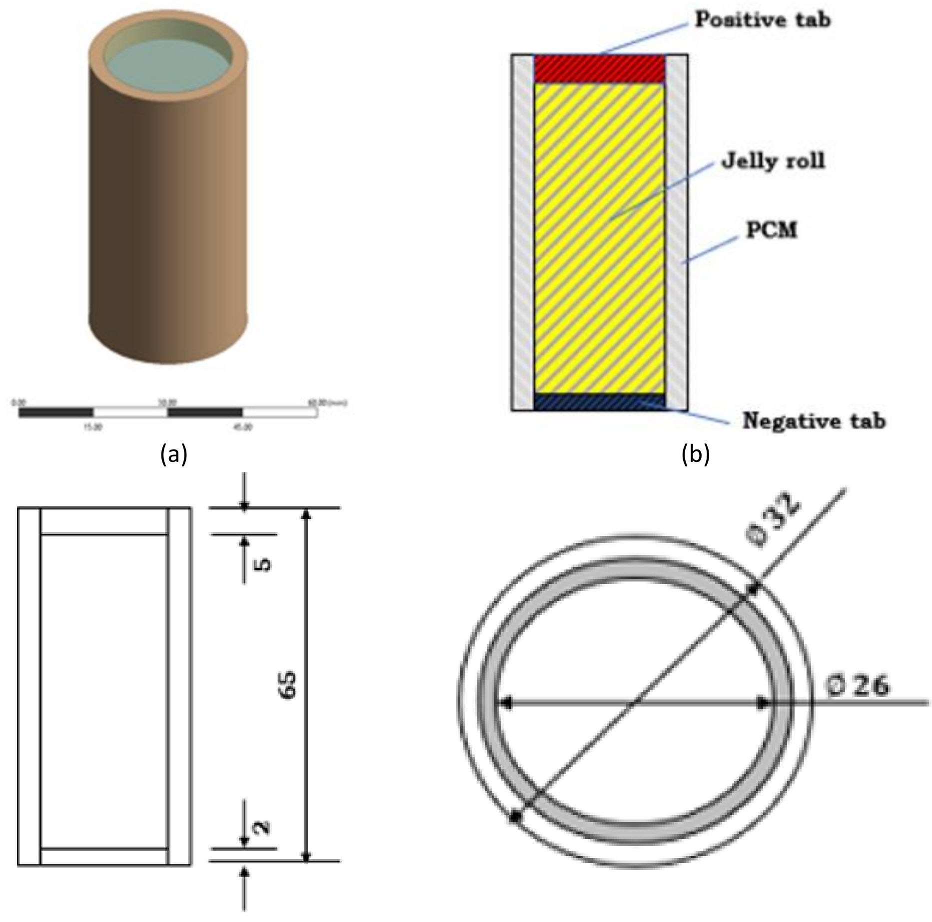


Fig. 1. Single Li-ion cell with cooling system (a) Model of the cell with PCM cooling (b) Schematic of cooling system depicting various components (c) Front view (d) Top view

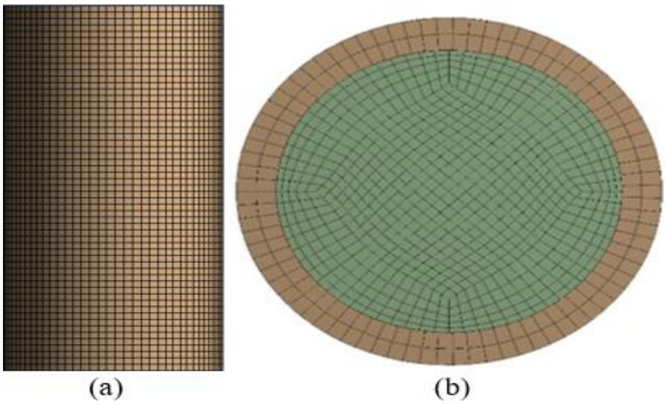


Fig. 2. Single cell meshed model with PCM cooling (a) Front view (b) Top view

Table 1
Mesh quality of cell with cooling system

Parameter	Maximum	Minimum	Average
Element quality	0.998	0.635	0.914
Aspect ratio	2.877	1.051	1.468
Skewness	0.467	3.823e-03	7.975e-02
Orthogonal quality	0.999	0.815	0.989

2.3 Battery Specification

In this instance, several discharge rates are analyzed by battery cell simulation, and each discharge rate's simulation time is distinct. The dual potential MSMD model and electrochemical NTGK models are utilized for the battery simulation. NTGK parameters are taken into account from a reference work, battery specifications are presented in Table 2, and boundary conditions are shown in Table 5. As shown in Table 5, boundary conditions are used for the single-cell battery's cell wall, positive tab wall, and negative tab wall. Different discharge current rates result in different boundary conditions. The pressure-linked equations (SIMPLE) methodology is used to construct the transient time model while taking into account a battery cell drained at a constant current. In all situations, simulation time steps of 30 seconds were used. Table 2 provides a description of the MSMD battery specification. Tables 3 and Table 4 respectively display the material characteristics for the cooling channel and cooling medium.

Table 2
$LiCoO_2$ 26650 lithium ion cell specification[28]

Properties	Value
Diameter	26 mm
Height	65 mm
Mass	0.088 kg
Cathode material	LiCoO2
Anode material	Graphite
Nominal capacity	4 Ah
Nominal voltage	3.7 V
Cut off voltage	2.75 V
Charge limit voltage	4.2 V
Maximum charge current	1C
Maximum discharge current	2C
Emissivity	0.8

Table 3
Material property of cooling system [25]

Property	Cooling channel (Aluminium)
Density (kg/m3)	2719
Specific heat (J/kg-K)	871
Thermal conductivity (W/m-K)	202.4

Table 4
The Properties of n-octadecane (90% pure) [25]

Property	PCM
Density	814 (kg/m^3)
Specific heat	2150 (j/kg-k)
Thermal Conductivity	0.358 (w/m-k)
Viscosity	0.0085 (Pa.s)
Pure solvent melting heat	189000 (j/kg)
Melting temperature	300 (k)

2.4 Boundary Conditions

In Boundary conditions for varying discharge current rates are applied to the cell wall, positive tab wall, and negative tab wall of a Li-ion cell battery. Three distinct discharge rates are used in the simulation for a single-cell battery with PCM. The starting cell temperature, duct conveying PCM, and PCM initial temperature are all maintained at the values listed in Table 5 for BTMS.

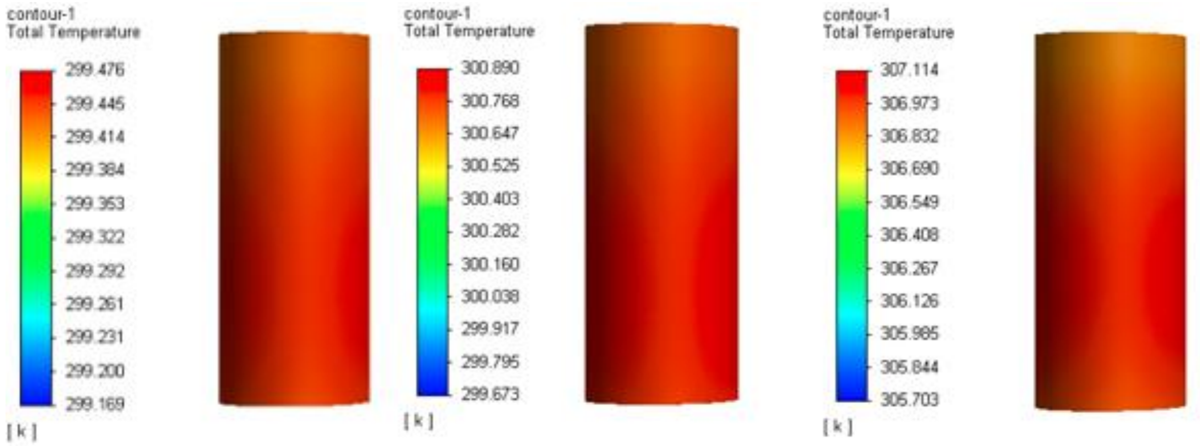
Table 5
BTMS boundary conditions [28]

Current (A)	2	4	6
Ambient temperature (K)	297	297	296
Cooling channel temperature (K)	297	297	296
Coolant/solid interface			
Cell initial temperature (K)	297	297	296

3. Results and Discussion
3.1 Single Cell with BTMS

The LiCoO2 26650 lithium-ion battery's C-rate was examined using the Ansys Workbench for three distinct discharge modules of 0.5C, 1.0C, and 1.5C. The Bare cell's maximum temperature was determined to be 313.95 K for 1.5C discharge rate, 307.95 K for 1.0C discharge rate, and 302.45 K 0.5C discharge rate without cooling. As time passes and an electrochemical reaction occurs inside the battery cell, the temperature of the cell rises as a result of the increased internal heat produced. Due to the large current drawn over a brief period of time, figure 4 illustrates the maximum temperature rise for a 1.5C discharge rate with cooling as 307.114 K.

Figure 3 shows the temperature contour of a single cell with PCM cooling for three different discharge rates 0.5 C, 1.0 C, and 1.5 C. The maximum temperature for discharge rates 0.5 C, 1.0 C, and 1.5 C are 299.47 K, 300.89 K, and 307.14 K respectively as illustrated in Figure 4. From the temperature contours, it can be observed that the overall cell temperature is closely uniform. The temperature difference between the top and bottom parts is considerably less.



(a) (b) (c)

Fig. 3. Temperature contour of a Single Li-ion cell with a cooling system at a discharge rate of (a) 0.5 C (b) 1 C and (c) 1.5 C respectively

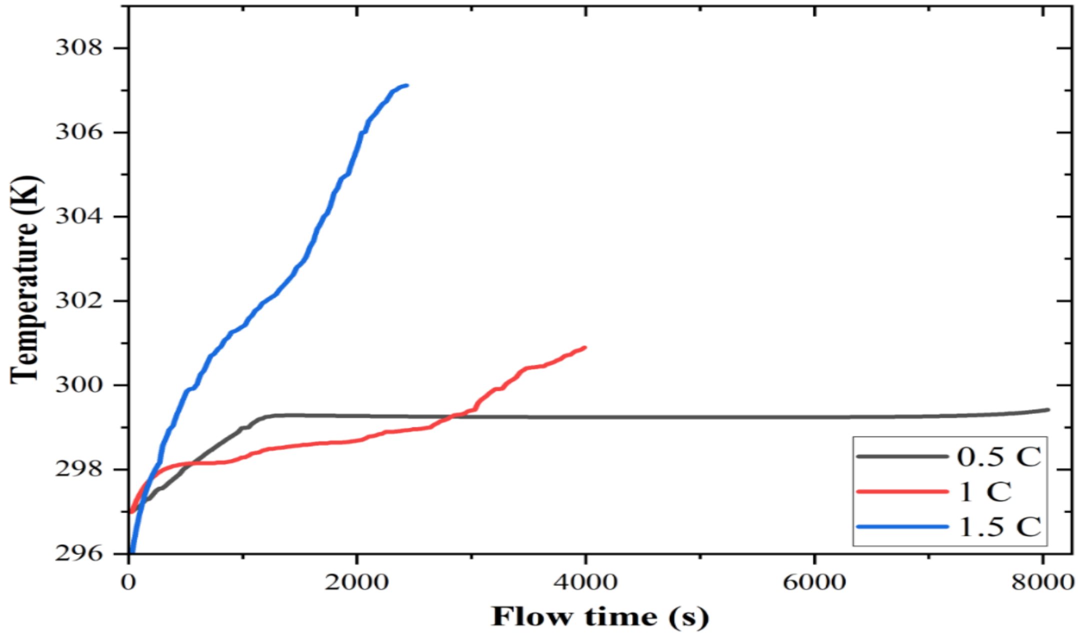


Fig. 4. Comparison between temperature curve of single cell battery at a discharge rate of 0.5C, 1.0C & 1.5C

3.2 Comparison of Performance of Single Cell with Cooling (BTMS) and without Cooling

For discharge rates of 1.5 C, 1.0 C, and 0.5 C, respectively, Figures 5, 6, and 7 show the variation in cell temperature over time with and without cooling. These graphs indicate that there is a substantial temperature fluctuation when a single-cell battery is integrated with a thermal management system made out of PCM. Directly applying PCM to the li-ion cell's surface helps to lower the battery's temperature, which prolongs battery life. A mechanism like this aids in preventing battery thermal runaway as well. In each of these situations, the battery begins at a base temperature of between 296 and 298 K. The maximum temperature that the cell would reach without cooling is determined by the battery's programmed discharge rates. The temperature of the cell before complete discharge rises with increasing discharge rates.

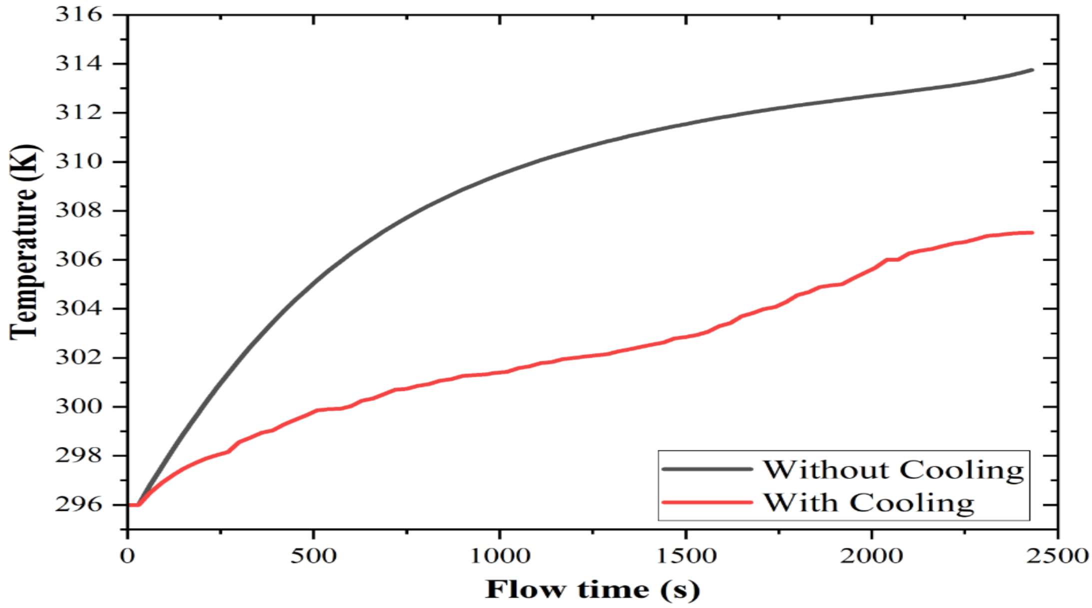


Fig. 5. Comparison of Li-ion cell temperature with cooling and without cooling at 1.5 C discharge rate

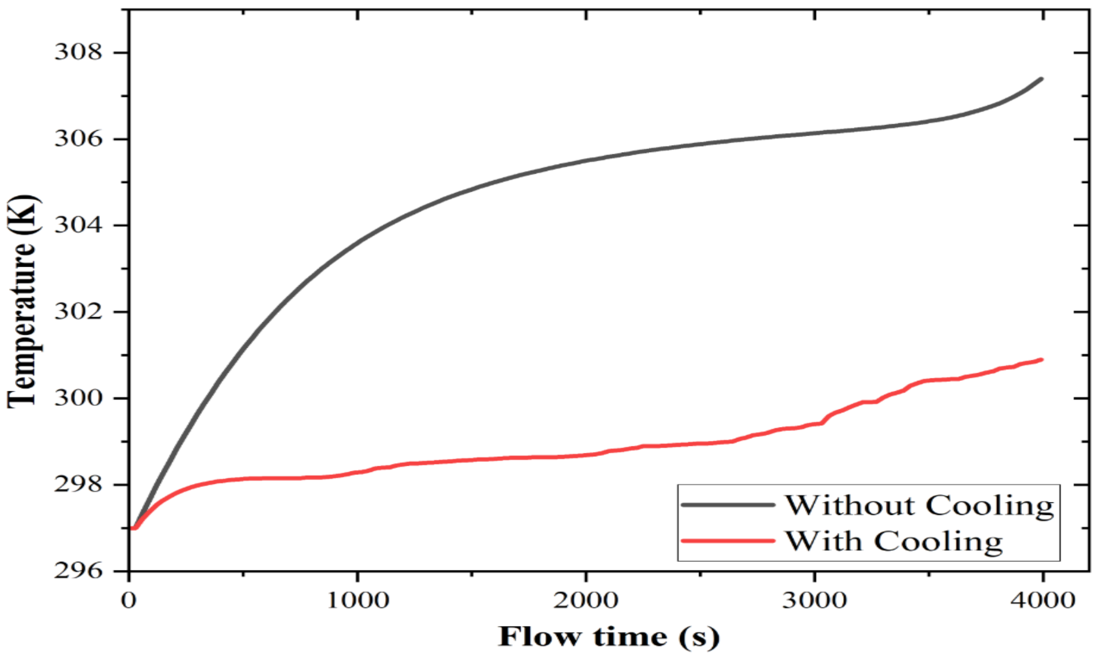


Fig. 6. Comparison of Li-ion cell temperature with cooling and without cooling at 1 C discharge rate

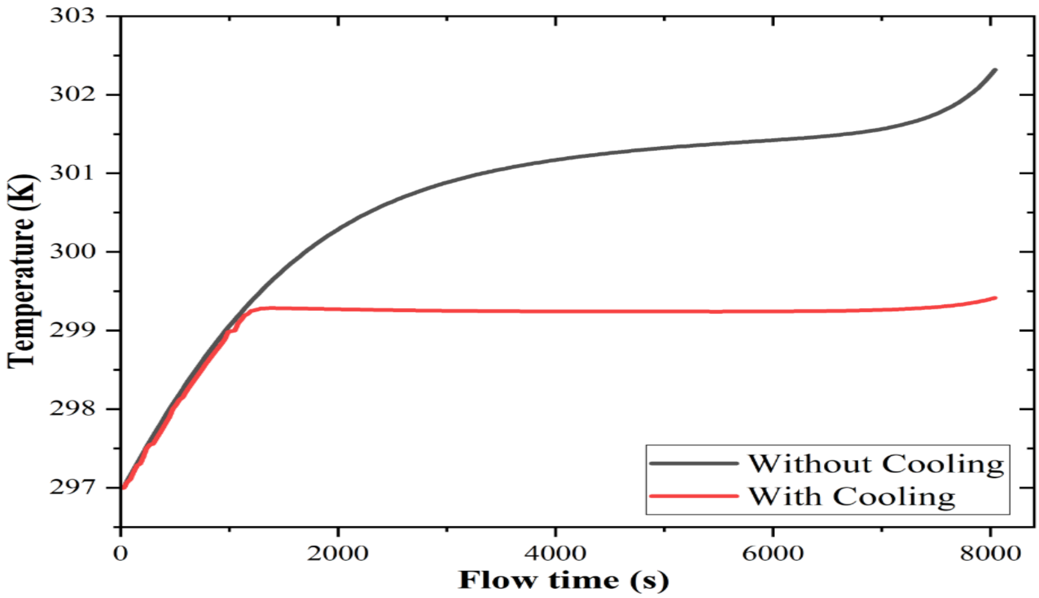


Fig. 7. Comparison of Li-ion cell temperature with cooling and without cooling at 0.5 C discharge rate

The maximum temperature of the cell with a discharge rate of 1.5 C is 314 K without cooling, and it would be closer to 307 K if BTMS were used. The maximum temperature rise in a cell is also found to be 307.37 K and 302.31 K for discharge rates of 1.0 C and 0.5 C, respectively, and 300.89 K and 307.144 K for cooling, as illustrated in Figure 3. As demonstrated in Figures 5, 6, and 7, adding a thermal management system will reduce the maximum temperature rise by 2%, 2.1%, and 1%, respectively, for discharge rates of 1.5 C, 1.0 C, and 0.5 C. Table 6 summarizes the maximum temperature increase in a single cell with and without cooling.

Table 6
Outcome of CFD analysis of single cell Li-ion battery with and without BTMS

Discharge rate (C)	Initial cell temperature (K)	Maximum temperature rise without cooling (K)	Maximum temperature rise with cooling (K)	Percentage Reduction in maximum temperature
0.5	297	302.31	299.476	1%
1.0	297	307.37	300.890	2.1%
1.5	296	313.73	307.144	2%

3.3 Limitations of Present Work

In the present work, the study is limited to single-cell cooling. The same study can be applied to battery packs. As the PCM selected was used for heat transfer and energy storage application compatibility parameters of PCM with the cell material can be studied in the future. Different methods can be used to improve the thermal conductivity of PCM. Further these results can be validated with experimental studies.

4. Conclusions

CFD analysis of a single 26650 LiCoCO2 cell for use in electric vehicle applications has been done in the current work. To simulate, we employ the dual potential NTGK model. When a single cell is discharged at varied rates of 2A (0.5 C), 4A (1.0 C), and 6A (1.5 C), the variation of the cell temperature and voltage over time is examined. A cell's maximum temperature rise has also been controlled using PCM as a coolant on the surface. Simulated maximum temperature increases in the cell with cooling have been done at different constant current discharge rates. The simulation study's findings are summed up as follows: The maximum temperature rise in a single cell with Battery Thermal Management System (BTMS) is observed to be 307.15 K, 300.89 K, and 299.476 K at discharge rates of 1.5 C, 1.0 C, and 0.5 C, respectively. At discharge rates of 1.5 C, 1.0 C, and 0.5 C correspondingly, the cell with BTMS reduces the maximum temperature rise by 2%, 2.1%, and 1% relative to the bare cell, indicating the effectiveness of the BTMS used in the current investigation. When three cells are arranged in series, the temperature rise is greater than when they are arranged in parallel.

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