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Conference paper

Analysis of BTMS for Thermal Performance with Varying Casing Thickness

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ABSTRACT

Over the last few decades, renewable energy technologies have picked up pace with fears of exhausting non-renewable resources and environmental degradation. Batteries made with lithium-ion (Li-ion) are the foundation of electric vehicles (EVs) and are essential for high density energy storage. Lithium-ion (Li-ion) batteries are a key to energy storage with high energy density and are now the backbone of electric vehicles (EVs). Safe and efficient thermal regulation of lithium-ion battery assemblies is absolutely essential. Liquid cooling has been one of the promising Battery Thermal Management System (BTMS) solutions among many others. This work explores the thermal efficiency of lithium-ion battery arrays with various cylindrical casing thicknesses between 20 mm and 28 mm. A two-dimensional numerical model is established for 20 Li-ion 18650 cylindrical cells in staggered and in-line configurations. Simulations are conducted for 1C to 5C discharge rates under a constant coolant flow rate. Results are compared with a constant thickness case and exhibit good agreement within ±7% error. Results show improvement in temperature uniformity towards the cooling fluid flow route with varying casing thickness. The maximum temperature gradient between the first and last cell is decreased to 0.1 K at 1C and 1.8 K at 5C. In contrast, the new design increases the heat transfer by 10–15% compared to constant thickness casings.

1. INTRODUCTION

With the advent of electric vehicles (EVs), maintaining battery performance, safety, and reliability has emerged as a key engineering challenge. Lithium-ion batteries, although the most preferred option for EVs, are prone to thermal runaway and non-uniform temperature distribution, which may deteriorate battery health and reduce vehicle safety (Amer et al., 2024). To counter this, Battery Thermal Management Systems (BTMS) are used to control cell temperatures, increase heat dissipation, and avoid overheating under operating conditions (Rahmani et al., 2024).

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Among active BTMS techniques, liquid cooling has become well-known for its thermal homogeneity. Xia et al. proved liquid cooling was able to lower battery pack temperature by 10 °C and reduce differences in temperature between cells by 20 °C (Xia et al., 2019). Likewise, Tete et al. constructed a finite volume numerical model for a 5×5 pack of 18650 cells and demonstrated that their design kept battery temperatures under 28 °C at high discharge rates, with uniform coolant distribution and better thermal stability (Tete et al., 2022). Bree et al. investigated how various casing materials affected thermal behavior and found that aluminium casings improved thermal balance because they are light and have high thermal conductivity (Bree et al., 2023).

Geometric arrangement of battery packs and flow characteristics directly impact BTMS performance. Rao et al. experimentally studied cylindrical modules with adjustable contact surfaces and determined that augmentation of inlet velocity up to 0.05 m/s enhanced temperature homogeneity, lowering cell maximum temperatures and intra-pack temperature variations up to 28% in operating stages (Rao et al., 2017). New bionic channel structures like metal plates with spider-web patterns have also been computationally verified to increase cooling in high discharge rates, where the best thermal performance is achieved with optimal channel widths of 3 mm and angles of 120° (Wang et al., 2021). In addition, recent research highlights battery applications' all-temperature adaptability, which enhances thermal optimization techniques (Chen et al., 2023).

Although remarkable progress has been made in BTMS technologies, the role of casing thickness in thermal management has yet to be explored. Increasing casing thickness can enhance structural integrity but potentially raise thermal resistance, lowering heat dissipation efficiency. Thinner casings, on the other hand, can raise heat conductance but sacrifice insulation and mechanical stability (Bernardi et al., 1985). Resolving such a trade-off is essential in the optimization of BTMS designs for high-energy-density battery packs.

This research is intended to examine the impact of different casing thicknesses on BTMS thermal performance based on a two-dimensional numerical model in ANSYS Fluent. It seeks to find an optimum casing thickness that can provide a balance between thermal resistance and heat dissipation, reduce hot spots, and increase overall temperature homogeneity. The results are anticipated to inform the design of future-generation BTMS for EV use, enhancing battery safety, performance, and lifespan.

2. METHODOLOGY

A thermal management system with a pack of battery cells composed of twenty 18650 Lithium-Ion cells organized in both staggered and in-line configurations is the subject of this study. The effects of changing casing thickness on these cells' heat transfer performance at different rates of discharge—1C, 2C, 3C, 4C, and 5C —while keeping the coolant flow rate constant are examined using a two-dimensional numerical model. Twenty cells make up the liquid-cooled system, which is housed in an aluminium case with slots for each cell. ANSYS Fluent was used for simulations, and ANSYS Space Claim was used to construct the 2D model.

2.1 Justification for Two Dimensional Modeling

While the battery packs and coolant flows are naturally three-dimensional (3D) with complicated geometries and non-uniform heat generation, a two-dimensional (2D) model is used in this work for the assessment of the thermal impact of different casing thicknesses. This approximation takes advantage of the geometric homogeneity of cylindrical cells, for which radial and tangential heat transfer prevail. It also increases computational efficiency, allowing comprehensive parametric investigation over a wide range of discharge rates. Limitations are the exclusion of axial heat conduction and localized coolant flow complexities that can cause slight inaccuracies. However, the 2D method gives accurate thermal predictions with intended extension to 3D modelling for improved accuracy.

2.2 Schematic Configurations of Battery Pack and Casing Designs

The geometry model developed in space claim for inline and staggered cell arrangement is as shown in "Fig. (1)" This picture shows the schematic structures of lithium-ion battery packs with two casing thickness designs - constant thickness and variable thickness - under two cell arrangements - inline and staggered.

In the uniform thickness design, all cylindrical battery cases have the same thickness of walls in the direction of coolant flow. In contrast, in the variable thickness design, casing thickness is progressively greater downstream. This gradient is intended to offset increasing coolant temperatures close to the outlet, improving heat removal for cells experiencing hotter fluid.

The inline alignment puts cells in a straight grid in direct alignment with flow paths. In comparison, the staggered alignment shifts alternative rows of cells to ensure better mixing of the coolant and local turbulence, thus perhaps increasing convective heat transfer.

Labels in the staggered arrangement are used to identify three key elements: the battery casing, battery cells, and cooling fluid region, highlighting their interaction. This diagram is the basis for the numerical modelling and parametric examination performed in the research.

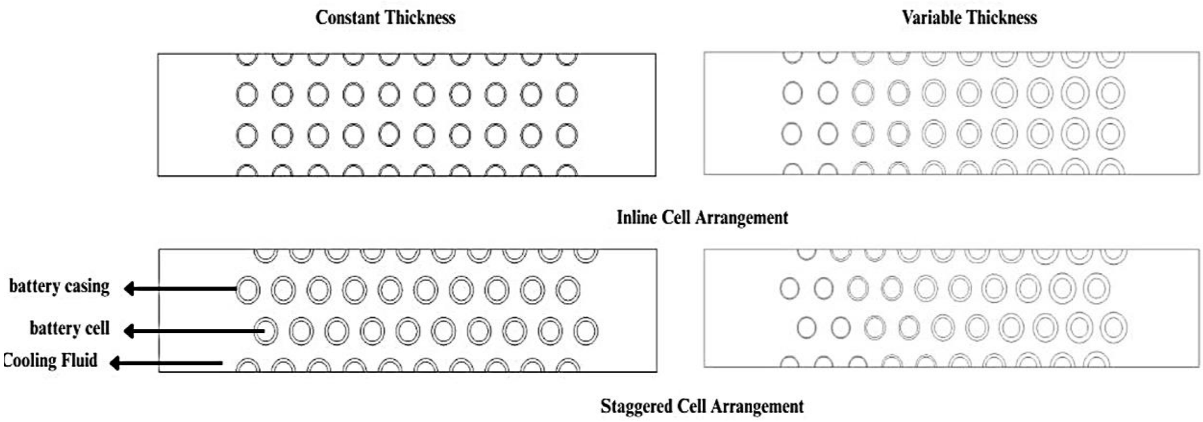


Fig 1. Battery pack configurations with constant vs. Variable casing thickness under inline and staggered cell arrangements

Through the coolant area of the battery package, the transmission of heat medium is regulated by the following mass, momentum, and energy conservation equations:

The continuity equation for mass conservation :

$$\Delta . V = 0 \tag{1}$$

Momentum Conservation equation :

$$\frac{\partial(\rho V)}{\partial t} + V.\nabla(\rho V) = -\nabla p + \mu \nabla^2 V \tag{2}$$

Energy Conservation equation:

$$\frac{\partial(\rho C_p T)}{\partial t} + V.\nabla(\rho C_p T) = \nabla(K\Delta T) = q \quad (3)$$

The present study makes use of the simplified Bernardi equation to determine the amount of heat produced. (Huang et al., 2017)

$$Q = \frac{1}{V}\left[I^2 R_i + IT\frac{dU_0}{dT}\right] \quad (4)$$

The entropic heat coefficient, dU0/dt, in "equation (4)", has a value of 0.01116. Equation (4) is employed to determine the rate of heat generation, and "Table 1" displays the values for the various discharge ratings ranging from 1C to 5C. (Tete et al., 2022)

Table 1. Heat generation at various discharge rates

Parameters	**Quantity**				
Discharge rate (C- rate)	1	2	3	4	5
Battery current (A)	3	6	9	12	15
Rate of generating heat Q (W/ m^3)	12907	47579	104017	182220	282189

The idea of continual heat emergence was used as a source term in this investigation. In a cell zone condition for a battery cell zone the source term is defined as a heat generation rate in W/m^3. The coolant is considered as a water liquid available in a fluent fluid database. For casing and battery cell aluminium and lithium-ion is taken as a material. The properties to be taken for a simulation are as shown in "Table 2" The property data for lithium – ion is taken from the battery manufacturer sheet.

Table 2. Thermophysical characteristics of Aluminum, Lithium-ion and Water

Property	**Unit**	**Water.**	**Lithium-ion**	**Aluminium**
Dynamic viscosity	kg/ms	0.000891	- - -	- - -
Thermal conductivity	W/mK	0.607	3	202.4
Specific heat	J/kgK	4180	880	871
Density	kg/m3	997	2775	2719

2.3 Boundary Conditions

In this particular scenario, the border and beginning conditions are shown in "Table 3." For the sake of the battery pack simulation, it was assumed that the water flow at the entry was consistent. To simplify the model and facilitate numerical simulation, the battery pack was allowed to open from both sides, with coolant entering through the inlet and exiting through the outlet.

Table 3. Boundary Conditions

Parameter	**Quantity**
Inlet velocity	0.01 m/s
Inlet Temperature	25^0C
Ambient temperature	25^0C
Top and bottom wall	Symmetry
Casing and Cell Wall	Coupled (Heat Transfer)

Five distinct heat generating values were chosen as source terms to match to discharge rates between 1C and 5C. Using the water as a thermal transfer medium, convective transfer of heat was investigated at the point of contact between the cooling fluid and the external surfaces of the cell casings.

2.4 Procedure for Solution

In this study, ANSYS Fluent, a computational fluid dynamics application suite, is used. The energy, momentum, and mass equations were solved employing the technique of finite volumes. The energy equation was resolved in order to analyze heat generation between aluminium casing and coolant (as coupled thermal conditions existing between cell wall and casing). The coolant flow is considered with uniform velocity of 0.01 m/s and temperature 25^0C. The realizable k-Ɛ model was incorporated to simulate turbulence modeling using a real, enhanced wall treatment for thermal effect. Pressure-based, second-order implicit scheme was employed for the solver, and transient analysis was carried out for 720 seconds. An upwind technique of the second order was used to solve the energy equation. The rate of generating heat was the source term for different discharging rates. The simulation proceeded initially with the homogeneous shell thickness of 3 mm for inline and staggered arrangement, to verify the temperature distribution with 3C as discharge rate. Then the study is conducted for variable casing thickness of 20 mm to 28 mm for multiple discharging rates ranging from 1C to 5C.

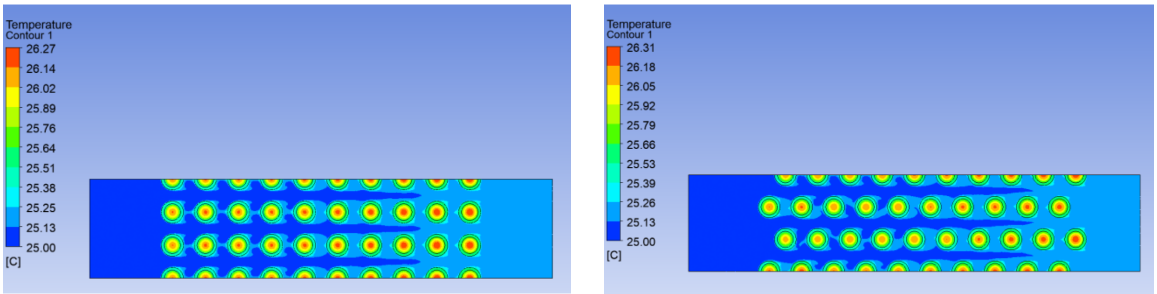
3. RESULTS AND DISCUSSION

The efficiency evaluation for a battery module with twenty rechargeable Lithium-Ion cells is glanced at in this section. This section discusses the noteworthy findings from this investigation.

3.1 Thermal Performance for Constant Casing Thickness

First analysis is performed for uniform casing thickness of 3 mm for inline and staggered cell patterns with 3C discharge rate. The temperature profile for both cases is as shown in "Fig. 2"

The "Fig. 2" signifies that at first the cell possesses a minimum temperature because it touched water having the temperature of 25^0C, but when water (coolant) is passing through, its temperature is rising as it absorbs heat from the hot cell. So the last cells are concerned about maximum temperature due to heat rejection to already warmed water. In inline cell arrangement maximum temperature with large concentration is achieved at the central part of the cell from the fifth transverse line, while in staggered cell arrangement maximum temperature comes at least three transverse lines. The maximum temperature concentration at the cell's centre has a smaller radius in the staggered arrangement. The staggered cell depicts the maximum temperature 26.31^0C which is somewhat higher than the inline cell configuration's maximum temperature but if we consider battery pack's average thermal value then staggered configuration depicts the slightly lower average temperature. In transient analysis it is clear that the mean temperature of the cell will increase for the first 100 seconds, and due to cooling by convection between casing and water it will decrease down and remain constant.



(a) (b)

Fig 2. The thermal distribution in the battery pack with (a) inline and (b) staggered cell arrangement with 3 mm constant casing thickness

3.2 Validation of Results for Constant Thickness

The analysis of the constant 3 mm thickness of the casing and 3C discharge rate is validated with a constant cell cylindrical casing thickness model developed by Tete et al. (Tete et al., 2022). The battery pack's average surface temperature is within 1 % variation with the results from Tete et al. The results for temperature distribution, battery pack's average thermal value and heat transfer is in a very good agreement with error less than ± 7%. Hence the numerical model developed in this case is validated as in "Fig. 3" So further analysis for the variable thickness is carried out and it is mentioned in the next section.

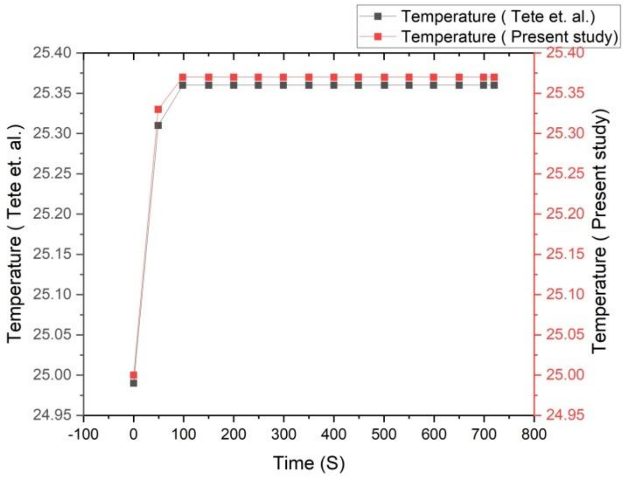


Fig 3. Validation of the Model

3.3 Thermal Performance by Varying Casing Thickness for Inline Cell Arrangement

Following this the analysis is carried out for the inline and staggered arrangement for different discharging rates of battery as 1C, 2C, 3C, 4C and 5C. As evident from "Fig. 4" battery pack's average thermal value increases as the rate of flow rises. The overall temperature climbed from 25.05^{0}C to 25.9^{0}C with the discharge rate changing from 1C to 5C. These battery stacks' current and voltage ratings determine the highest possible charging-discharging rates. With increase in discharge rate, heat generation throughout the batteries also tends to increase substantially, causing higher maximum temperature within the battery pack.

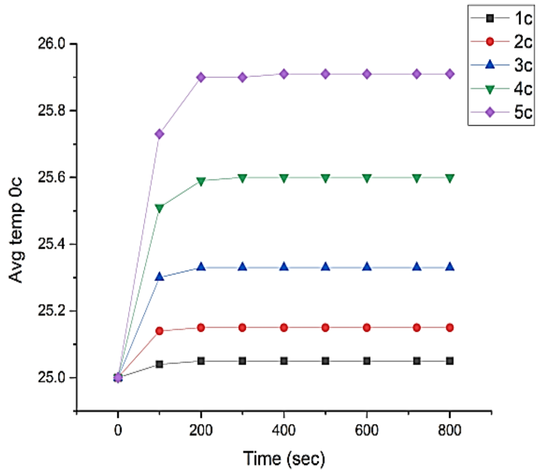


Fig 4. Average Battery Pack Temperature for Inline Cell Arrangement

The thermal behavior of the lithium-ion energy cell pack under multiple discharging rates and casing thickness configurations was studied to assess the efficiency of the proposed design. Results indicate a noticeable relationship between discharge rate and maximum cell temperature. The cells' highest surface temperature during the 1C discharge rate was 25.18 °C, while at 5C it was 28.93 °C. This rise in temperature is a result of increased internal generation of heat at high discharge rates, placing an additional thermal load on the cooling mechanism as shown in "Fig. 5"

The leading transverse line of cells has comparatively lower temperatures, as shown by the thermal gradient in space through the cell pack. This is because they are in direct contact with the entering coolant at its lowest temperature, allowing effective removal of heat from these upstream cells. But the second transverse trace indicates a distinct temperature rise, due to the coolants picking up heat as they flow through the first series of cells. This effect increases further downstream.

To counteract this, a stepwise increase in casing thickness was used in the design. Beginning with the third transverse line, the casing thickness is increased by 1 mm for every successive pair of lines and hence thickness increments of 1 mm, 2 mm, 3 mm, and 4 mm are applied respectively. The terminal transverse line, with maximum casing thickness, exhibits tempered cell temperatures in spite of the hot coolant near the outlet. The greater thermal dissipation from the cells into the coolant results from the thicker walls' larger active heat exchange area. In contrast, the constant casing thickness arrangement shows a cumulative thermal buildup after the first five transverse lines. In this case, the downstream cells have high temperatures owing to the combined effect of compromised heat transfer efficiency and the incremental increase in coolant temperature. High-temperature areas are mostly localized in the central parts of the cells, and peripheral regions are relatively cooler due to their location near the coolant flow. This finding indicates the insufficiency of constant casing thickness in providing an even thermal distribution.

In total, the findings show that the thickness casing design with varying thickness greatly improves thermal uniformity in the battery pack. Through intentionally increasing the casing thickness in the downstream section, the design compensates for the rise in temperature caused by the heated coolant, creating a more symmetric temperature profile.

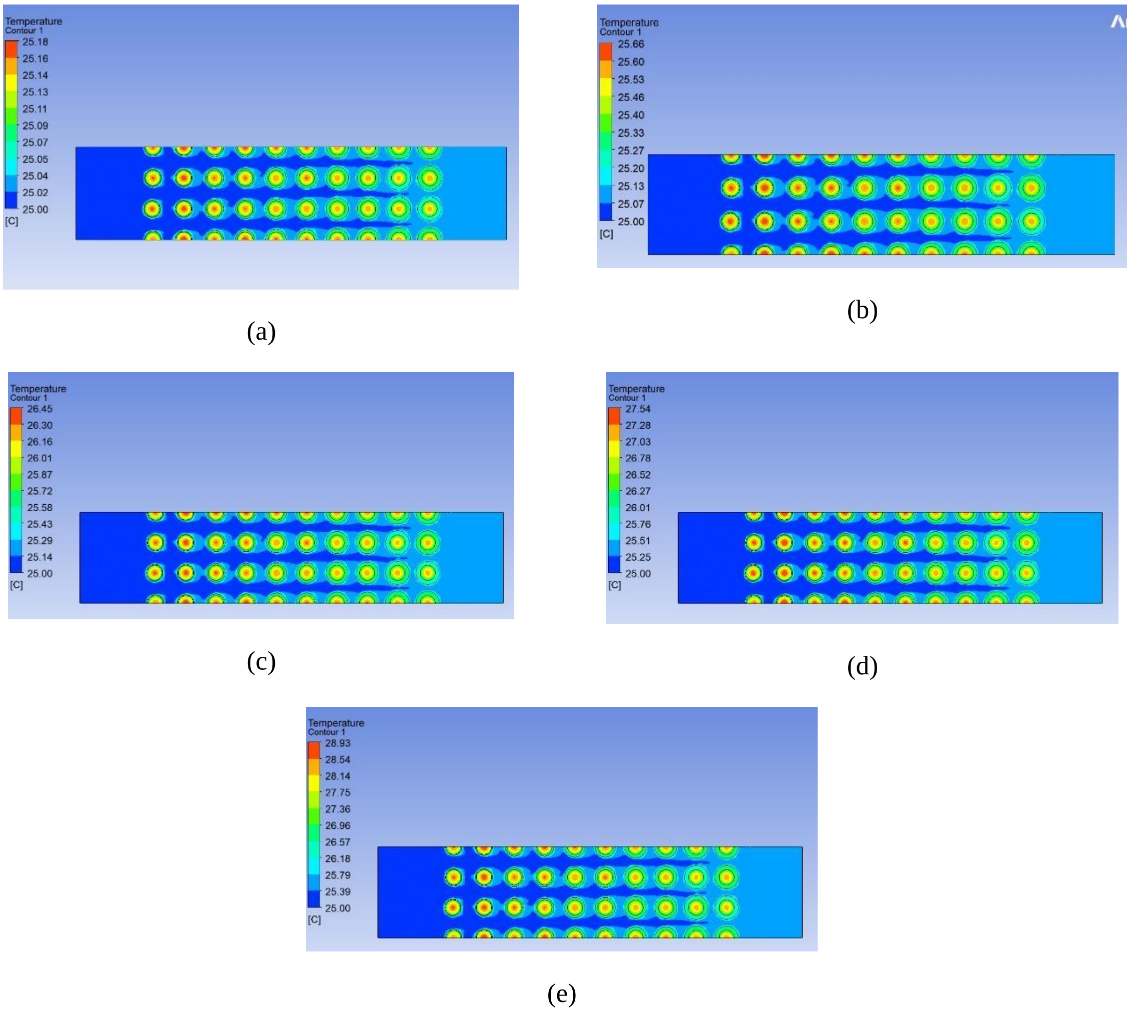


Fig 5. The thermal distribution in the battery module with inline cell arrangement and discharge rate (a) 1C (b) 2C (c) 3C (d) 4C (e) 5C

3.4 Thermal Performance by Varying Casing Thickness for Staggered Cell Arrangement

"Figure 6"shows the pattern of changes in the average battery pack temperature as rate of discharge rise for staggered designs. As expected, the direct proportionate increase in heat generation within the lithium-ion cells causes the average temperature of the battery unit to rise as it experiences higher discharge rates. The cooling system's efficiency under typical thermal loads is demonstrated by the average temperatures falling within their safe operating ranges as the discharge rates (1C and 2C) decrease. However, as the discharge rate increases to 3C, 4C, and 5C, the thermal load sharply increases, raising the average pack heating significantly.

This thermal performance improvement is due to the increased coolant flow distribution and local turbulence caused by the staggered configuration. More uniform and efficient heat extraction from the cells is made possible by the staggered arrangement, which improves coolant mixing and the effective coefficient of heat transfer at the cell-coolant interface.

This result highlights the significance of cell ordering in thermal management system design. Although both options have average pack temperatures within desired ranges, the staggered conformation has a thermal benefit, especially when there is a higher discharge rate with a greater risk of localized overheating. Such an insight is essential to optimize the design of battery packs used by electric vehicles that are driven under high-power conditions.

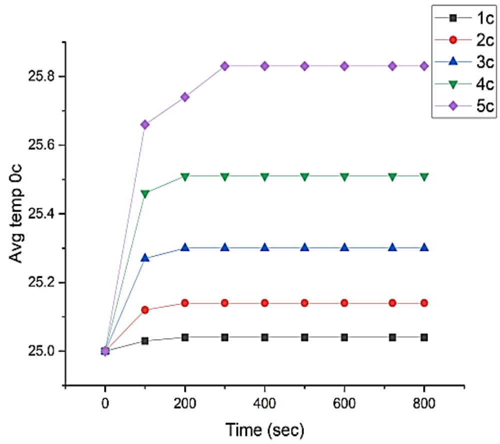


Fig 6. Average Battery Pack Temperature for Staggered Cell Arrangement

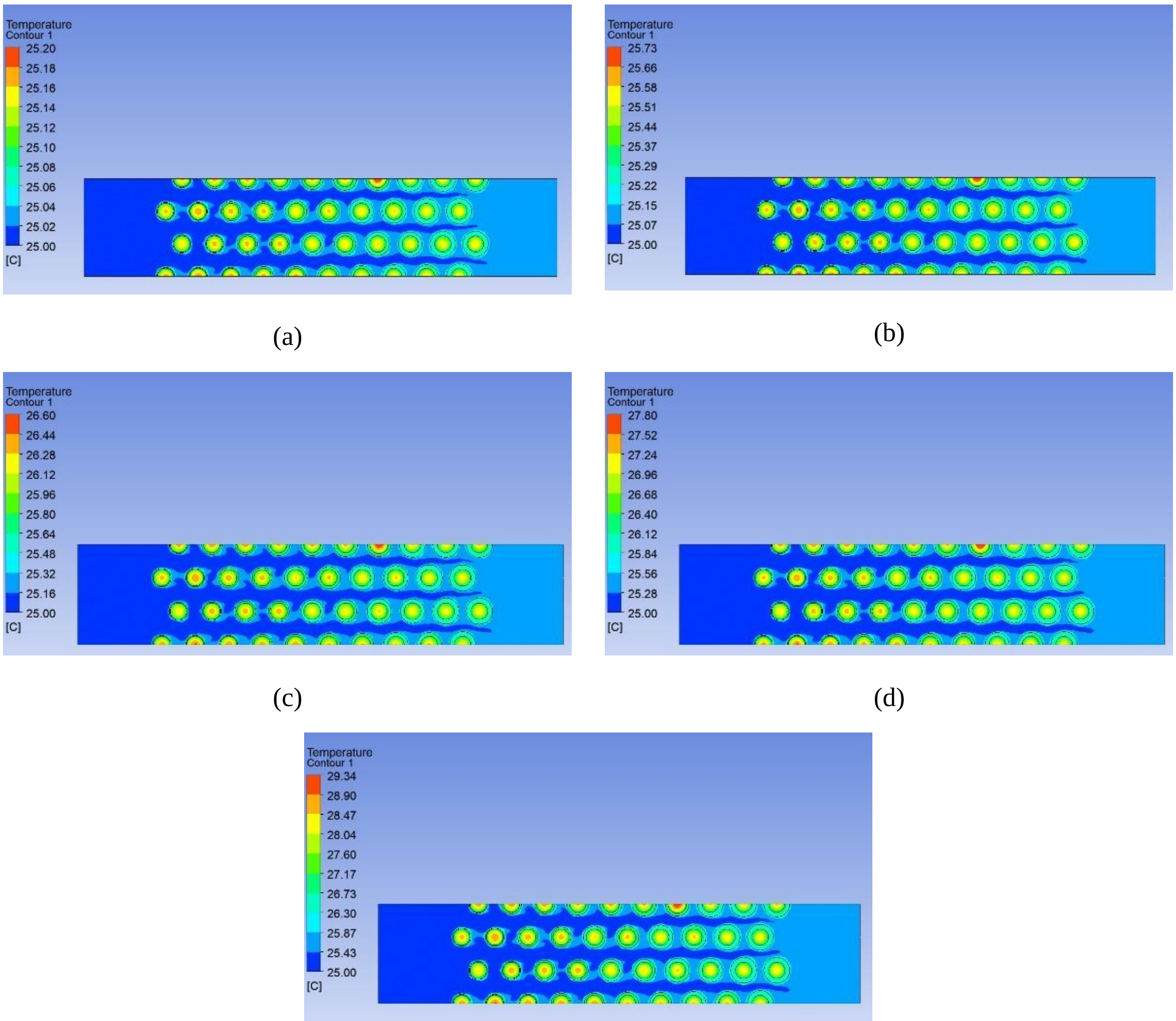
The battery pack's inline and staggered variations in temperature are not consistent. Cells at the coolant inlet, especially cells in the first transverse row, will be relatively cooler since they are directly exposed to the 25°C coolant. As coolant passes through the pack, it gets heated, thus causing a temperature increase in downstream cells. The temperatures increase, especially in the second transverse row and onward.

In inline design, the temperature increases progressively along the flow direction, with central and trailing cells reaching temperatures above the remainder due to accretion of heat transfer. Under constant casing wall thickness, central cells have peak temperatures, particularly with increased discharge rates. However, with an introduction of a ramped increase in casing thickness (from 1 mm to 4 mm) from the third transverse line onwards, the thermal conductivity to the coolant is reduced and thus marginally lower temperatures in the last cells despite total heat generation. This setup restricts the maximum temperature rise in rear cells, achieving a minor thermal control benefit.

Conversely, the concentration of heat is more focused with the staggered pattern. The contour plots reveal a smaller radius of maximum temperature concentration, which shows improved heat dissipation and lower thermal stress distribution across the pack as shown in "Fig. 7". Not many of the cells in the rear reach peak temperatures, which suggest that staggered geometry coupled with thicker casings is more effective in managing heat. The design affords increased coolant interaction and reduces thermal hotspots ; therefore, it is more appropriate for managing thermal loads at high rates of discharge.

The coolant's temperature differential when it enters and exits is still rather small (0.2°C to 0.7°C), indicating an effective cooling system with the ability to handle the heat load under both configurations. Still, the staggered configuration always performs better, with reduced peak temperatures and more uniform thermal distribution throughout the pack, particularly when discharge rates are higher.

Briefly, while both designs incorporate effective cooling and graded casing thickness, the staggered design benefits from superior thermal control in terms of localized overheating mitigation, battery protection, and consistent performance in varied discharge conditions.



(a) (b)

(c) (d)

(e)

Fig 7. Thermal distribution in the battery module with staggered cell arrangement and discharge rate (a) 1C (b) 2C (c) 3C (d) 4C (e) 5C

Table 4. Comparison of Results for different configurations

Configuration	Average Temperature ^{0}C	Max Temperature	Heat Flux
Inline Cell with Constant Thickness	25.39	26.27	314.48
Inline Cell with Varying Thickness	25.35	26.45	351.81
Staggered Cell with Constant Thickness	25.32	26.31	350.49
Staggered Cell with Varying Thickness	25.28	26.60	400.53

It can be seen from "Table 4" that both variation in casing thickness and cell arrangement have major impacts on the thermal performance of the battery pack. For the inline layout with uniform casing thickness, the pack average temperature is 25.39 °C, with the maximum temperature being 26.27 °C and heat flux 314.48 W/m². As the casing thickness is being changed in the same orientation, the mean temperature decreases slightly to 25.35 °C, while there is a slight increase in the maximum temperature to 26.45 °C. The heat flux increases tremendously to 351.81 W/m², reflecting improved heat transfer performance.

For the staggered orientation, the mean temperatures are all lower than their inline counterparts for both constant as well as varying thickness cases. With uniform thickness, the staggered pattern produces an average temperature of 25.32 °C and a maximum of 26.31 °C, along with a heat flux of 350.50 W/m². The staggered pattern with a non-uniform casing thickness exhibits the best overall thermal performance, with the minimum average temperature of 25.28 °C. A slightly increased maximum temperature of 26.60 °C is seen, which is likely attributed to downstream cell localized thermal effects. Notably, this arrangement achieves the maximum heat flux of 400.53 W/m², illustrating better heat removal across the pack. The heat transfer is increased by 11.87% in inline cell arrangement whereas for staggered cell arrangement it shows 14.25%.

These outcomes underscore that the variation in casing thickness enhances thermal efficiency through the increased heat transfer surface area, which assists with the sequential increase in coolant temperature along the downstream direction. Moreover, the staggered configuration aids in enhanced thermal uniformity through increased coolant mixing and minimized thermal gradients among neighboring cells. The combined action of staggered layout and different casing thicknesses leads to better uniformity of temperature distribution and increased heat flux, important for battery safety and longer operation life.

In general, the decreases in pack average temperature and significant increase in heat flux attest to the fact that these design modifications effectively enhance the battery's Thermal Management System's (BTMS) performance in harsh working environments.

4. CONCLUSION

On the 2D model of the pack of batteries with constant and variable thickness, a number of numerical simulations have been run. The analysis is done using discharge rates ranging from 1C, 2C, 3C, 4C, and 5C for the different thicknesses. The following are the study's noteworthy findings:

- It is discovered that the staggered arrangement reaches the maximum temperature, but only in specific places within a battery core cell, when the casing thickness is maintained at 3 mm and the discharge rate is set at 3C. The staggered cell arrangement's average temperature is marginally lower than the inline unit arrangement's.
- The greatest temperature increase in an inline cell arrangement is seen in the first cells, but as the cell gets closer to the last one, the temperature rise decreases due to the wider casing. The final adjacent cells have a minimal temperature differential as well.
- In an inline arrangement with 5C rating the highest and lowest temperature difference within the battery module is less than 5^0C and the average surface temperature is also below 27^0C for the same discharge rate.
- In a staggered arrangement of the cell with varying thickness of the casing gives the uniform temperature distribution across the two adjacent cells of the battery module and the average temperature of the battery pack for 5C rating is also remains below 26^0C, hence it is the best and optimum arrangement for the battery pack.
- The simulation results demonstrate that the staggered cell arrangement enhances heat transfer performance more effectively than the inline configuration. Specifically, the heat transfer improvement for the inline arrangement is 11.87%, while the staggered configuration achieves a higher enhancement of 14.25%.

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NOMENCLATURE

V	Velocity (m/s)	*Abbreviations*	
T	Temperature (^{0}C, K)	LIBs	lithium-ion batteries
Cp	Specific Heat (kJ/kgK)	EVs	electric vehicles
K	Thermal Conductivity W/mK)	HEVs	hybrid electric vehicles
Q	Heat Transfer (W)	BTMS	battery thermal management system
I	Current (A)	*Greek letters*	
P	Pressure (N/m^2)	ρ	density (kg/m^3)
$\dot{q}$	Heat Flux (W/m^2)	μ	dynamic viscosity (kg/ms)
R_i	Internal resistance (Ω)		

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