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DESIGN AND SIMULATION OF THERMAL MANAGEMENT SYSTEM FOR LITHIUM-İON BATTERIES OF HYBRID AND ELECTRIC VEHICLES

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ABSTRACT

Lithium-ion batteries have become indispensable in low-power devices like mobile phones and laptops. Their emerging prominence in high-power sectors, particularly automotive, prompts renewed attention. While they offer unparalleled energy benefits, addressing safety and thermal management is paramount. This research centers on contrasting cooling strategies for battery packs in electric and hybrid vehicles. We critically evaluate standalone cooling systems, advocating for combined cooling systems to efficiently reduce both the peak temperature and temperature discrepancies within the pack. A realistic discharge cycle, emulating actual driving conditions, is employed. The study encompasses the design, simulation, and analysis of three specific cooling mechanisms tailored for Li-ion batteries in vehicular applications. Emphasis is laid on the impact of air and PCM cooling configurations on heat extraction during rigorous driving cycles. Heat dispersion is gauged by tracking temperature variations over time at diverse points. To ensure a holistic understanding, individual cooling mechanisms are explored both theoretically and empirically. The findings underscore the enhanced heat distribution capabilities of integrated thermal management systems, particularly when paired with phase change materials, vital for expansive battery packs under intense power requirements.

Keywords: Lithium-ion batteries, Thermal management, Electric vehicles

INTRODUCTION

The advancement and proliferation of internal combustion engines, along with the subsequent growth of the automotive industry, have played pivotal roles in shaping modern societies. By 2018, global statistics indicated that out of approximately 1,500 million passenger cars on the road, electric and hybrid electric vehicles made up a mere one percent. As environmental concerns such as escalating air pollution, the threat of global warming, and the complex geopolitical dynamics of the oil and gas industries become more pronounced, there is an urgent need to pivot towards cleaner energy alternatives. The automotive industry's inclination towards electric and hybrid electric vehicles is driven by both the imminent depletion of fossil fuels and the tightening of environmental regulations.

Among the critical components of these vehicles, batteries, particularly lithium-ion batteries, have emerged as prominent energy storage systems, rivalling fuel cells. Their appeal largely stems from their high energy density and impressive lifespan. However, these batteries come with their own set of challenges. They are notably susceptible to safety hazards, primarily tied to thermal management. Ensuring optimal performance of the battery and, by extension, the entire powertrain hinges on proficient heat management. Elevated temperatures within individual battery cells can lead to compromised performance, diminished capacity, reduced lifespan, and in extreme cases, even explosions [1], [2].

MATERIALS AND METHODS

The fundamental laws governing heat transfer in this model are the first law of thermodynamics or conservation of energy and Fourier's law of heat conduction, described as

$$\rho C_p \frac{\partial T}{\partial t} + \rho C_p \mathbf{u} \cdot \nabla T + \nabla \cdot \mathbf{q} = Q \qquad (1)$$
$$\mathbf{q} = -k \nabla T$$

In the equation above, Q represents generated heat in heat sources.

For air flow around batteries, Navier-Stokes equations are considered in the form of continuity (conservation of mass):

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0 \qquad (2)$$

and the conservation of momentum equations including gravity described as:

$$\rho \frac{\partial \mathbf{u}}{\partial t} + \rho \mathbf{u} \cdot \nabla \mathbf{u} = -\nabla p + \nabla \cdot [-p\mathbf{I} + \mathbf{K}] + \mathbf{F} + \rho \mathbf{g} \tag{3}$$

where:

$$\mathbf{q} = -k\nabla T \tag{4}$$

Q represents generated heat in heat sources [1].

For air flow around batteries, Navier-Stokes equations are considered in the form of continuity (conservation of mass):

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0 \tag{5}$$

and the conservation of momentum equations including gravity described as:

$$\rho \frac{\partial \mathbf{u}}{\partial t} + \rho \mathbf{u} \cdot \nabla \mathbf{u} = -\nabla p + \nabla \cdot [-p\mathbf{I} + \mathbf{K}] + \mathbf{F} + \rho \mathbf{g} \tag{6}$$

where:

$$\mathbf{K} = \mu(\nabla \mathbf{u} + (\nabla \mathbf{u})^T) - \frac{2}{3}\mu(\nabla \cdot \mathbf{u}) \tag{7}$$

and conservation of energy, formulated in terms of temperature:

$$\rho C_p \left(\frac{\partial T}{\partial t} + (\mathbf{u} \cdot \nabla) T\right) = -(\nabla \cdot \mathbf{q}) + \tau : \mathbf{S} - \frac{T}{\rho} \frac{\partial \rho}{\partial T}\bigg|_p \left(\frac{\partial p}{\partial t} + (\mathbf{u} \cdot \nabla) p\right) + Q$$
$$\mathbf{S} = \frac{1}{2}\left(\nabla \mathbf{u} + (\nabla \mathbf{u}^T)\right) \tag{8}$$

All equations above are solved for heat source (solid) and free air (fluid) domains. Boundaries used in this model are briefed in table below [2].

Table 8: Boundary conditions used in the model without cooling system.

Boundary Type	Heat Transfer	Fluid Flow
Symmetry	$-\mathbf{n} \cdot \mathbf{q} = 0$	$\mathbf{n} \cdot \mathbf{u} = 0$
Open Boundary	$T = T_0$, if $\mathbf{n} \cdot \mathbf{u} < 0$	$[-p\mathbf{I} + \mathbf{K}]\mathbf{n} = -(f_0 + p_{\text{hydro}})\mathbf{n}$
	$-\mathbf{n} \cdot \mathbf{q} = 0$, if $\mathbf{n} \cdot \mathbf{u} \geq 0$	$p_{\text{hydro}} = \rho_{\text{ref}} \mathbf{g} \cdot (\mathbf{r} - \mathbf{r}_{\text{ref}})$
Temperature	$T = T_0$	-
Wall	-	$\mathbf{u} = \mathbf{0}$

RESULTS AND DISCUSSION

This research explored the temperature variations of a battery pack, devoid of a cooling system, during the Harsh Cycle. This cycle involves a vehicle reaching and maintaining its maximum speed until the battery's state of charge reaches 20%, all within an ambient temperature of 35°C.We are investigating four different case studies to reach their temperature distribution:

Case I: Temperature Distribution of The Model Without Cooling System: In this case, the system is studied without applying any cooling system. Fluid and solid domains constituting the model are the air around batteries and batteries themselves as heat sources. Figure 1 also presents temperature distribution at the end of cycle. It was found that the battery in center of the pack (one in the front-left corner of the model) experiences the maximum temperature. Temperature distribution in batteries (model without cooling system)

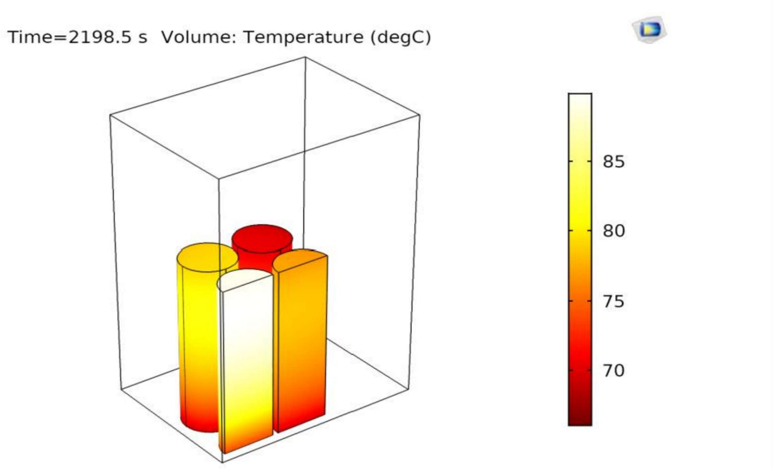

Figure 44: Temperature distribution in batteries (model without cooling system)

Case II: Temperature Distribution of The Model With Fan Cooling System: In this model, air is blown to the pack with constant velocity of 0:5 m/temperature Distribution of The Model With Fan Cooling System: figure 2 shows temperature difference between the coolest and hottest spots on surface of the battery in this model is considerable and has a maximum of 24:0◦C and obviously, between batteries at top of first row and bottom of last row.

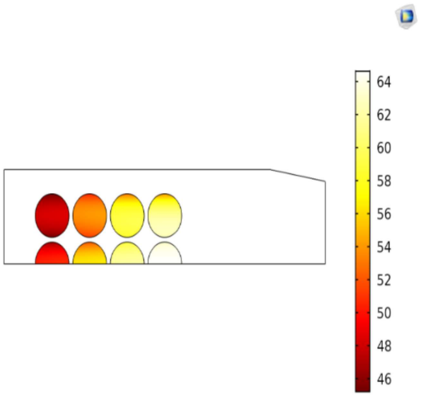

Figure 45 : Temperature distribution in batteries at t=2071s

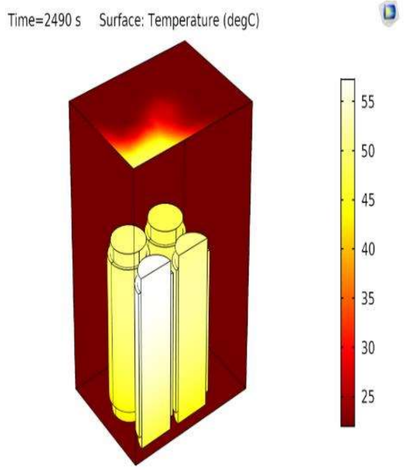

Figure 3:Temperature distribution in Batteries with PCM

Case III: Temperature Distribution of The Model with PCM Cooling System: As shown in Figure 3, PCM of inner side starts to melt at t = 400s and where surface maximum temperature is 44◦C. N-decosane is not a proper choice for cooling method depending solely on latent heat.

Case IV: Temperature Distribution of The Model with and PCM Cooling System: In this section, the thermal management system design is finalized by combining PCM and fan cooling system. Figure 4 presents temperature distribution at t = 2165s. It can be found from simulation that maximum temperature of 54:86◦C happens at t =2167s, which shows 39.45%, 13.88% and 19.44% decrease compared to the model without cooling, the one with fan and system with PCM, respectively.

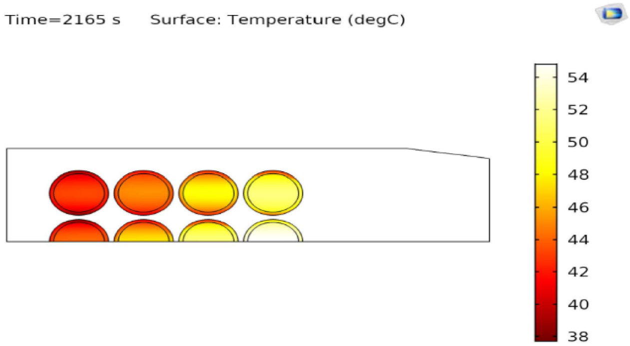

Figure 4: Temperature distribution in batteries with PCM and fan

Table 9: Comparison of maximum temperature gradient in cases based on the COMSOL simulation

Case	Maximum temperature	Effect TMS	Temperature gradient	Effect TMS
No TMS	90.6 ◦C	-	19◦C	-
Forced Air	63.7◦C	Improved 29.69 %	24◦C	Weakened 17.24%
PCM	68.10◦C	Improved 24.83%	12◦C	Improved 36.84%
PCM and forced air	54.86◦C	Improved 39.45%	14.82◦*C*	Improved 22%

CONCLUSIONS

In assessing the thermal dynamics of a 12-battery pack with 3350 mAh capacity, it was identified that the pack exceeded safe thermal limits. While the PCM cooling system promoted even heat dispersion, its efficacy in minimizing peak temperatures was limited. The forced-air method excelled in rapid heat removal but accentuated temperature disparities and demanded more space. An integrated approach, combining both techniques as seen in case IV, emerged as the most balanced solution. However, the study had limitations, such as model simplifications, assumptions in heat generation and transfer, and variations in PCM materials used, which should be recognized when interpreting the results. Future endeavors should address these nuances for more precise outcomes.

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