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THERMAL MANAGEMENT CHALLENGES OF LI-ION BATTERY PACKS USING PARTIAL IMMERSION COOLING: ANALYZING PRESSURE DROP AND TEMPERATURE DISTRIBUTION

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1. ABSTRACT

A partial immersion cooling system is used for cooling a battery pack equipped with cylindrical Li-ion batteries considering various flow rates of the coolant. The partial immersion method is used to reduce the total weight of the battery pack and thus increase the power density. A tiny gap of 2 mm is considered between the cells to have a high cell density. Both pressure drop and temperature distribution are evaluated to find the optimum conditions of the cells. Different flow rates of the coolant as well as heat generation rates of the cells are evaluated to achieve the temperature target with the lowest pressure drop. The results show that during fast charging (15 kW), considering the coolant flow rate of 21.5 lpm, the average temperature of 33°C can be achieved in the battery pack while the hot spot temperature is 51°C. While for the heat generation rate of 3kW, the average temperature of 33.8°C can be achieved using 2.15 lpm flow rate.

2. INTRODUCTION

One key challenge faced by the electrification of vehicles reliant on lithium-ion batteries is their relatively poor energy and power density relative to liquid hydrocarbon fuels. To avoid over-sized batteries (and associated poor environmental impacts), it is critical to have a battery system that can be recharged quickly [1]. It can be tackled by having an ideal thermal management system which allows the battery to be recharged at power levels well beyond current fast chargers (e.g. >15kW) and hence very quickly. The heat generated during fast charging is difficult to be rejected due to resistive heating which reduces both the capacity and power capability of the batteries [2]. Different forms of Li-ion batteries have been used in electric vehicles including cylindrical, prismatic, and pouch cells, each with distinct advantages and thermal management needs [3]. Among these, cylindrical Li-ion batteries are particularly favoured in many EV applications due to their inherent ease of thermal management. Different approaches have been used such as boiling two phase flows, full immersion, partial immersion, etc. Jithin et al. [4] performed a numerical analysis on thermal management of a Li-ion battery pack with four cylindrical batteries using full immersion cooling with different dielectric fluids. They showed that recent developed engineered fluid has a higher performance compared with the conventional mineral oil and deionised water. Li et al. [5] investigated full immersion cooling effect with fluorinated liquid in single phase and two phase conditions experimentally.

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Partial immersion cooling can be introduced as a promising approach, particularly for cylindrical Li-ion batteries. By immersing only critical parts of the battery pack in a cooling fluid, this method seeks to balance effective thermal management with the goal of minimizing the system's weight. The purpose of this study is to evaluate the effectiveness of a lithium-ion (Li-ion) battery module composed of cylindrical cells, utilizing an innovative partial immersion cooling strategy. This method specifically targets cooling the first and last thirds of the batteries, particularly around the battery tabs. Various coolant flow rates and inlet temperatures are investigated to identify an optimal condition that reduces pressure drops while ensuring even temperature distribution throughout the module. The batteries are organized in a staggered configuration to minimize the size and weight of the module. The results of this research are anticipated to be integrated into a vehicle, showcasing the practical application and potential benefits of the innovative thermal management strategies developed through this study. This investigation addresses key thermal management issues and aims to advance the production of lighter, more efficient electric vehicles.

3. METHDOLOGY

For the electric vehicle (EV) thermal management, two distinct cooling loops are considered to manage the heat generated by the battery pack effectively. Within the first loop, known as the coolant loop, the heat generated by the battery pack is absorbed by a dielectric coolant. Following the initial heat absorption by the coolant, the second stage of heat transfer occurs in the battery pack evaporator. Here, the heat from the coolant is transferred to a refrigerant. In the refrigerant loop operated by a heat pump, the heat absorbed by the refrigerant is rejected to the ambient environment. This component of the system ensures that the heat removed from the battery pack is efficiently expelled outside the vehicle, maintaining a stable and cool environment for the batteries.

Fig. 1 shows the schematic of the whole system including the heat pump circuit and the battery pack loop. In the battery pack circuit, dielectric MIVOLT fluid is circulated to thermal management of the battery pack. R134a is circulated in the heat pump circuit to cool the dielectric fluid in the battery pack evaporator and also provide the cabin cooling load when required.

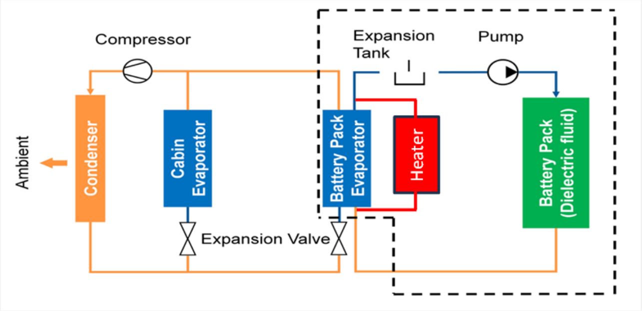

Fig. 1 Cooling cycle in the car including the battery pack and heat pump circuits.

Fig. 2 presents the schematic design for the battery module targeted in this simulation. The computational domain is displayed showing the fluid domain alongside the arrangement of the batteries, highlighting that the first third of one row and the last third of another row for cooling. It should be noted that the whole battery pack includes 16 modules and the total amount of heat generation rate mentioned in the study is for the whole pack. Inlet velocity is considered at the inlet while outflow condition was chosen for the outlet of the system. The study examines various charging rates, which correspond to different heat fluxes on the surface of the batteries. Thus, a constant heat flux boundary condition is applied to the batteries' surfaces, simplifying the model by not numerically simulating the batteries themselves.

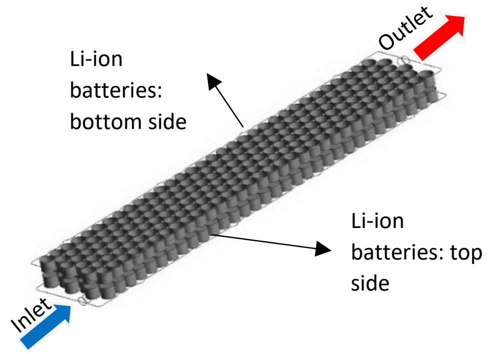

Fig. 2 Schematic of the a) individual module assembled in the battery pack and b) computational domain including the boundary conditions.

4. RESULTS

Different flow rates and inlet temperature of the coolant are studied for various charging rates. Fig. 3 shows the contour plots of the temperature distribution for the heat flux of 292 W/m2 on the surface of the batteries equal to the total heat generation rate of 3kW. As shown, by increasing the flow rate of the coolant, lower temperature can be achieved in the modules.

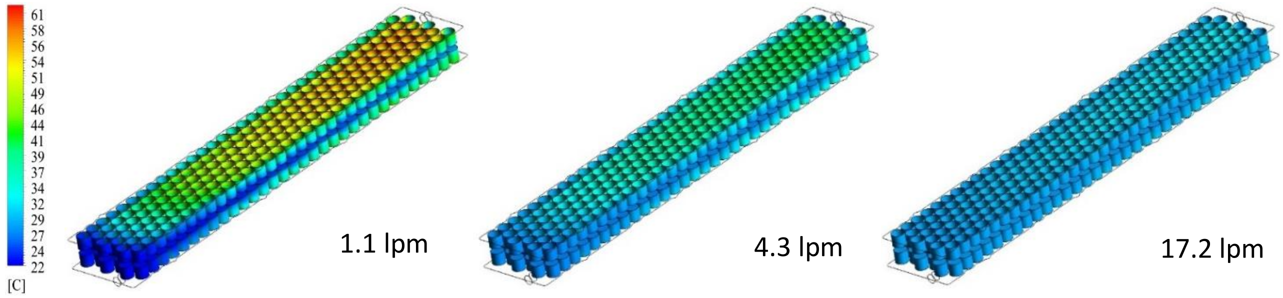

Fig. 3 Temperature contour plots for different for rate of the coolant for the heat flux of 292 W/m2.

Fig.4 display the temperature distribution for the heat flux of 1462 W/m^2 equal to the total heat generation rate of 15kW. As shown in Fig. 4 compared with Fig. 3, by increasing the charging rate and as a result generating more heat by the batteries, a higher flow rate is required to cool the batteries. As shown in Fig. 4, for the case of 5.4 lpm, the hot spot temperature is as high as 96°C which is not acceptable.

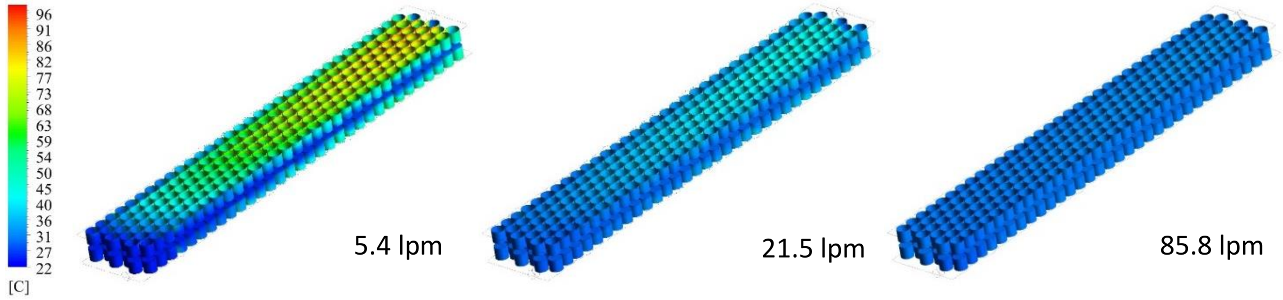

Fig. 4 Temperature contour plots for different for rate of the coolant for the heat flux of 1462 W/m2.

Table 1 summarizes the key features of the system for different cases for the heat generation rates of 3kW and 15kW. As expected, by increasing the flow rate, the maximum and average temperature of the batteries reduce; however, the pressure drop increases tremendously and thus considering a whole battery pack including higher number of modules (such as 16), it can be not possible to provide this pressure head across the pack considering the size of the pump and heat exchanger in the car.

Table 1 Key characteristics of the module for different heat generation rates and flow rates

	Flow rate (lpm)	Pressure drop (kPa)	Average Battery Temperature (℃)	Maximum Battery Temperature (℃)
3kW	1.07	0.05	36.4	61.6
	2.15	0.11	33.8	52.1
	4.29	0.32	31.6	44.3
	8.59	0.96	30.1	37.8
	17.17	3.12	29.2	33.6
15kW	5.4	0.45	43.2	98.0
	10.7	1.39	36.6	68.7
	21.5	4.62	33.1	51.0
	42.9	16.30	31.4	40.4
	85.8	60.04	30.68	34.6

5. CONCLUSIONS

In this study, partial immersion method was employed for thermal management of Li-ion battery module. Different charging rates as well as various flow rates of the cooling fluid were evaluated to tackle the challenge between the pressure drop in the module and temperature of batteries. The results show the capability of the method for the thermal management of the module. The results showed that for the fast charging considering 15kW heat generation for the battery pack including 16 modules, the average temperature of 33°C was achieved using the coolant with the flow rate of 21.5 lpm. While for the heat generation rate of 3kW, the average temperature of 33.8°C can be achieved using the flow rate of 2.15 lpm. The battery pack design developed from this study is slated for manufacturing and will be assembled into a car for real-world testing.

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