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Hydrothermal Performance of Liquid-Cooled Battery Thermal Management System with Multiple Inlets

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Abstract – Heat transfer and pumping power of water-cooled thermal management systems (TMSs) for lithium-ion batteries (LIBs) in electric vehicles (EVs) are investigated through a three-dimensional computational approach. TMSs are cylindrical shells that cover LIBs. Water flows through the shell and removes heat from LIBs. The focus of this study is to provide practical insights on the effects of number of inlets on the thermal performance and pumping power of TMSs. Two TMSs with one and four inlets at the top of the TMS's case are considered. Both TMSs include one outlet, which is located at the bottom of the case. The thermal performance of individual TMSs is evaluated by the maximum temperature of the battery cell and the temperature difference across the cell. The thermal performances are described based on the pumping power. Simulations are performed at different flow rates within a laminar regime. Results indicate that both TMSs provide safe operational temperatures for LIBs. However, compared to the one-inlet design, the four-inlet TMS archives the same thermal performance but at a lower pumping power. The lower pumping power is due to lower pressure drop in the four-inlet TMS resulting from flowing water with lower flow rate at individual inlets, and through a shorter path from individual inlets to the outlet, compared with the one-inlet TMS. Minimizing pumping power without any penalty in the thermal performance is significantly beneficial, especially when the TMS is used for a pack of LIBs in EVs.

***Keywords*:** Thermal management; Pumping power; Thermal performance; CFD; Lithium-ion battery.

1. Introduction

Thermal performances of Lithium-ion batteries (LIBs) in electric vehicles (EVs) strongly depend on the operating temperatures of batteries such that the temperature of a battery cell should be within 20-55 °C with less than 5 °C of the temperature difference across the cell [1, 2]. As a result, using effective thermal management systems (TMSs) is necessary to maintain the temperature of LIBs within the safe operational conditions. Liquid-cooled systems have been identified as effective TMSs for use in EVs due to their capabilities to remove large amount of heat [3]. However, in addition to enhance the heat transfer rate, an efficient active cooling system should operate with a minimized pumping power. Pumping power is a power required to drive the flow through the cooling system and is one of the main design parameters of an active cooling system [4]. Increasing the pumping power may hinder using the cooling system regardless of its capability to enhance the heat transfer rate [5]. Therefore, a simultaneous investigating the thermal performance and pumping power of a cooling system is essential to evaluate the overall performance of the cooling technology in any application, like EVs. In the present study, hydrothermal performances of TMSs with multiple inlets are investigated through a three-dimensional computational fluid dynamics (CFD) technique.

2. Problem Description

The schematics of two different TMS designs are illustrated in Fig. 1. Each TMS is a cylindrical shell such that water, as the coolant, flows through the annulus with a thickness of 1 mm (i.e., the inner and outer diameters of the annulus are 18 mm and 20 mm, respectively). For the simplicity, the case of TMS has zero thickness. The LIB cell has a diameter and height of 18 mm and 65 mm, respectively. The TMSs have a length of 50 mm. The LIB cell is located inside the empty space of the TMS. From both sides of the LIB cell, a height of 7.5 mm is outside the TMS's case and exposed to the air. The LIB cell has the specific heat, thermal conductivity, and density of 1027 $J.kg^{-1}.K^{-1}$, 25 $W.m^{-1}.K^{-1}$, and 4035 $kg.m^{-3}$, respectively [6]. One TMS has one inlet and another TMS has four inlets. For the one-inlet design, water enters and exits from the same side of the TMS. Both designs have one outlet. In both TMSs, inlets and outlets are located at the top and the bottom of the TMS's case, respectively. The diameter of inlet and outlet manifolds are 2 mm in both designs. Water at

22 °C enters the inlet(s) and exits the outlet. The simulations are performed at three volume flow rates of 0.05, 0.1, and 0.2 LPM (liter/min). The maximum Reynolds number based on the hydraulic diameter of the annulus is around 2100, which indicates a laminar flow for all flow rates in the simulations. By assumption of a laminar, steady, and incompressible flow, the constant properties for both the fluid and solid, and a constant heat generation inside the cell, the governing equations to simulate the flow and heat transfer are as follows:

Continuity: $$\nabla . \boldsymbol{u} = 0 \tag{1}$$

Momentum conservation: $$(\boldsymbol{u}.\nabla)\rho\boldsymbol{u} = -\nabla p + \mu\nabla^2\boldsymbol{u} \tag{2}$$

Energy conservation (fluid): $$\boldsymbol{u}.\nabla T_f = \frac{\lambda}{\rho c_p}\nabla^2 T_f \tag{3}$$

Energy conservation (solid): $$k\nabla^2 T_s + \dot{q} = 0 \tag{4}$$

where ρ, u, p, μ, λ, c_p, and T_f are the fluid density, velocity, pressure, viscosity, thermal conductivity, specific heat, and temperature, respectively. k and T_s are the thermal conductivity and temperature of solid, respectively. $\dot{q}$ is the volumetric heat generation in the battery cell. In this study, a constant value of $\dot{q} = 300\ \mathrm{KW.m^{-3}}$ is considered, which corresponds the critical condition at large discharge rates of LIBs [7]. The conjugate problem of heat conduction equation with convection in the fluid are solved, simultaneously, to calculate the temperature distribution on the interface of the solid and fluid. Through grid independence tests, a grid structure with 204,000 elements was selected, since by increasing the number of elements beyond 204,000, negligible changes in the magnitudes of heat transfer coefficients and friction coefficients were obtained. For the inlet boundary condition, water flow rate and temperature are set at the inlet. Zero axial gradients for all the variables are imposed for the outlet boundary conditions. The remaining surfaces are walls with a no-slip boundary condition. All surfaces of the TMS and LIB cell that are exposed to the air are adiabatic. Ansys Fluent was used to solve the governing equations.

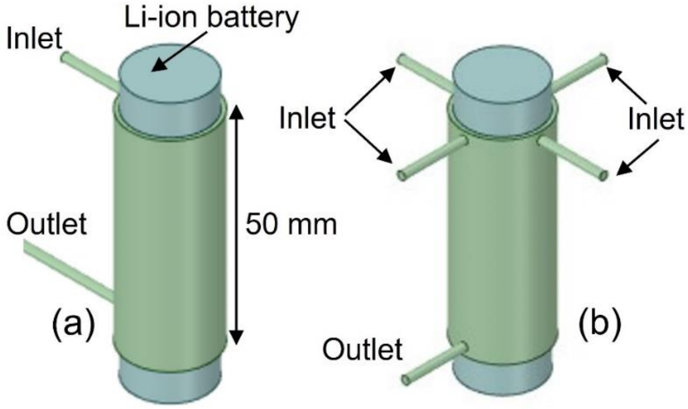

Fig. 1: Three-dimensional view of: (a) one-inlet TMS; (b) four-inlet TMS.

3. Results

In the present study, the thermal performances of TMSs are evaluated by the maximum temperature of the LIB cell and the temperature difference across the cell. To provide a better insight on the practical applications of the TMSs, their thermal performances are described based on the pumping power (P_p), which is calculated as follows [8]:

$$P_p = \dot{V} \times \Delta P \tag{5}$$

where $\dot{V}$ and ΔP are the total volume flow rate and the pressure drop across the TMS, respectively. Figs. 2 and 3 illustrate the maximum temperature of the battery cell and the temperature difference within the cell, respectively, at different pumping power. Both TMSs provide safe operational temperatures for LIBs. Increasing the flow rate results in an in an increased sensible heat and, in turn, reduction in the maximum cell temperature. At a given flow rate, which is equivalent to a given sensible heat, both TMSs result in almost the same maximum cell temperature and the temperature temperature variation within the cell. However, the four-inlet TMS archives the same thermal performance at a lower pumping power compared with the one-inlet TMS. Such difference in pumping power between two TMSs becomes larger at higher flow rates. Achieving the same thermal performance at a lower pumping power is mainly due to smaller pressure drops in the four-inlet TMS compared with the one-inlet design. Lower pressure drops are due to flowing the water with lower flow rates and through shorter paths from individual inlets to the outlet in the four-inlet TMS compared with the one-inlet design. Detailed flow field analysis is required to address the effects of multiple inlets on the pressure drop.

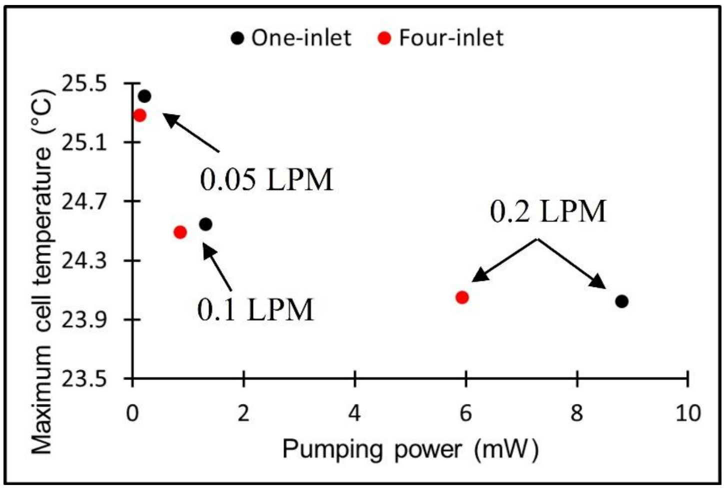

Fig. 2: Maximum battery cell temperature at different pumping power.

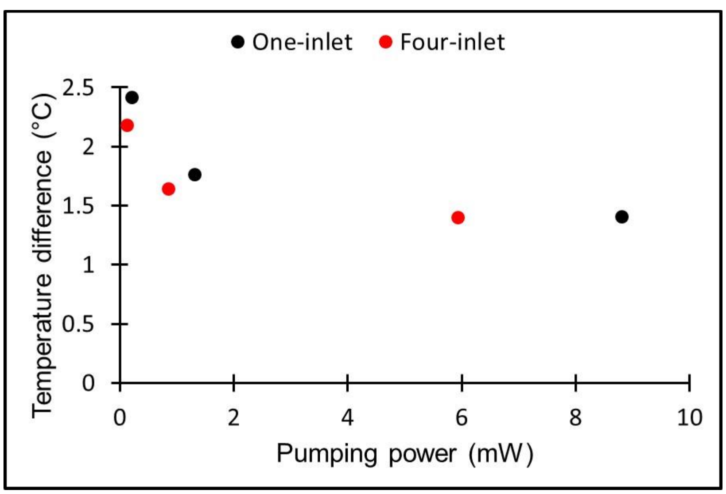

Fig. 3: Temperature difference across the battery cell at different pumping power.

The findings from Figs. 2 and 3 can be described in another way such that at a given pumping power, the four-inlet TMS removes larger amounts of heat from LIBs compared with the single-inlet TMS. As a result, the four-inlet TMS is beneficial for EVs with higher power. For the purpose of proof-of-concept, the TMSs in the present study were applied only to a single LIB cell and operated with low flow rates. However, in practical applications, an EV's TMS is used for cooling a pack of LIBs that is formed by integrating several battery modules in different configurations. As a result, reducing the pumping power without any penalty in the heat transfer, particularly in high operating flow rates, is substantially beneficial to save external power required to operate the TMS.

4. Conclusion

CFD analysis was performed to compare hydrothermal performances of LIB's TMSs with one and four inlets. Constant volumetric heat generation was considered for LIBs. To provide a better understanding on practical applications of TMSs, their thermal performances were described based on the pumping power. Although both TMSs provided safe operational temperatures for LIBs, the four-inlet design achieved the same thermal performance but at a lower pumping power compared to the one-inlet design. The lower pumping power is because of smaller pressure drops due to flowing water with smaller flow rates and through shorter paths from individual inlets to the outlet compared to the one-inlet design. Due to operation with a minimized pumping power, the four-inlet design is a promising TMS for use in EVs when cooling is required for the packs of LIB.

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