STM JOURNALS

Journal of
Polymer & Composites

ISSN: 2321-2810 (Online)
ISSN: 2321-8525 (Print)
Volume 11, Special Issue 8, 2023
DOI (Journal): 10.37591/JoPC

http://engineeringjournals.stmjournals.in/index.php/JoPC/index

Research JoPC

Liquid-Cooled Battery Thermal Management System: A Numerical Investigation of Effect of Coolant Path and Flow Rate Optimization

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Abstract

Battery thermal management system (BTMS) is crucial for ensuring the safety and performance of battery packs in electric vehicles. Liquid cooling is one of the most effective methods for BTMS, but the choice of coolant, fluid path and its flow rate can affect the heat transfer efficiency and the pressure drop. In this paper, a numerical simulation of a liquid-cooled BTMS using three designs with water as a coolant has been carried out. The Reynolds number of the fluid was kept as 800 and 2400 at the inlet of the cooling plate channel with heat flux boundary condition of 500 W/m^2 *on the top face. It was supposed that a battery pack is run for 1000 seconds and the heat generated by the battery is transferred to the coolant through convection. Finally, a comparison of the temperature distribution of coolant, temperature of the cooling plate was analyzed. As a result, it was found that increasing the Reynold's Number cooling plate temperature and the coolant temperature difference. The fluid path and the outlets also affect the rate of heat transfer along the cooling plate.*

Keywords: Thermal management, Liquid cooling, Design Optimization, Micro channel

INTRODUCTION

The automotive industry has been pushed to transition to sustainable vehicles including hybrid electric vehicles (HEVs), electric vehicles (EVs), fuel cell vehicles (FCVs) and plug-in hybrid electric vehicles (PHEVs) in order to address environmental challenges. The most advanced battery technology now used in the creation of EVs, HEVs, and PHEVs is lithium-ion batteries. Following is a summary of lithium-ion batteries' benefits: (1) high power density and specific energies [1], low self-discharge rates and high nominal voltage [2], no memory effect and long cycle life [3]. However, EVs need to carry a lot of battery cells in order to attain enough mileage equals to the normal fossil powered vehicles. As a result, it is crucial and significant to keep lithium-ion batteries for EVs working under safe environmental conditions. Lithium-ion batteries produce a lot of heat while discharging time [4, 5], which could cause the battery to overheat and result in some accidents or damages [6, 7]. When the temperature is below a certain level in cold weather, the battery's performance would also be harmed. A typical temperature range for lithium-ion batteries is between 20°C and 40°C [8–9], and a prolonged range is between -10°C and 50°C [10–11]. To control the battery temperature within a suitable range and ensure temperature uniformity while the dynamic system is functioning, thermal management solutions are consequently essential.

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Received Date: August 18, 2023
Accepted Date: September 11, 2023
Published Date: September 22, 2023

Citation: Daniel Samuel Parmar, Giphin George, Priyaranjan Sharma. Liquid-Cooled Battery Thermal Management System: A Numerical Investigation of Effect of Coolant Path and Flow Rate Optimization. Journal of Polymer & Composites. 2023; 11(Special Issue 8): S11–S18.

The performance and price of EVs are also impacted by the use of various thermal management systems in battery packs [12]. Numerous methods have been widely used and discussed, including phase change materials [13–14], forced convection with [15–17] liquids and air [18–19], heat pipes [20–21], and combinations of some of the mentioned technologies. The forced convection air cooling technology is limited by the air's poor thermal conductivity [22], which reduces the effectiveness of the cooling device. In comparison to air cooling, water cooling is more effective since it can absorb more heat and takes up less space Additionally, higher air velocity is needed to adequately cool lithium-ion batteries utilizing active cooling methods [23–24] due to the low thermal conductivity of air [25-26]. On the other hand, liquids have greater thermal conductivities, they provide better cooling than air does.

The Li-ion battery's heat is removed using a liquid cooling system with cold plates and a metal thin-wall structure with various liquid channels. This system can maintain a uniform temperature distribution by decreasing the operating temperature, a serpentine channel was created of a liquid cooling system that was optimized using CFD simulation and weighted average pressure drop as well as the mean and standard deviation of the cold plate temperature [27–28]. De-ionized water with 2% mass content sodium polyacrylate was employed as a cooling medium for simulation and experimental to study the material's capacity to disperse heat [29–30].

Several variables, including the liquid mass flow rate and ambient temperature (the temperature outside the battery shell), affect how well a liquid cooling system with cold plates performs. In this research, a three-dimensional model was created and a mini-channel cold plate battery thermal management system was designed. In-depth research was done on the relationship between the battery's temperature rise and distribution during the discharge process and the number of channels, flow direction, inlet mass flow rate, and ambient temperature.

METHODOLOGY

CFD Analysis

The investigation being made here consists of a battery pack. These battery packs are mounted on the cooling plate and it is assumed they have same dimensions. Heat from these battery pack is transferred to the cooling plate via plate and then to the coolant that is flowing inside the channel as shown in Figure 1. The top surface is assigned a boundary of heat flux of a single battery pack. The side walls and the bottom wall are kept insulated. The dimensions of the cooling plate are 1 mm × 160 mm × 200 mm.

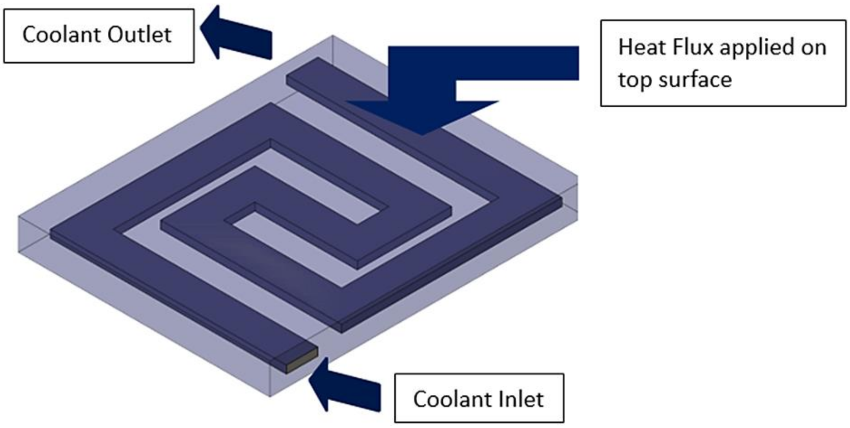

Figure 1. Schematic Diagram of the CFD Analysis.

The thickness of the micro-channel is kept to be 0.75 mm × 20 mm. Initially Configuration 1 (1) is used for the analysis. The meshing was carried out in Simscale platform. Three Configurations as shown in Figure 2. were analyzed where each has its own uniqueness. The first Configuration is the serpentine, Configuration 2 was created with more coolant area and Configuration 3 with one inlet and five outlets. The 2.4M cells and 779.8k nodes were used to create the mesh. Three Inflation layers with growth rate of 1.5 was used in the fluid region to increase the efficiency of the heat transfer.

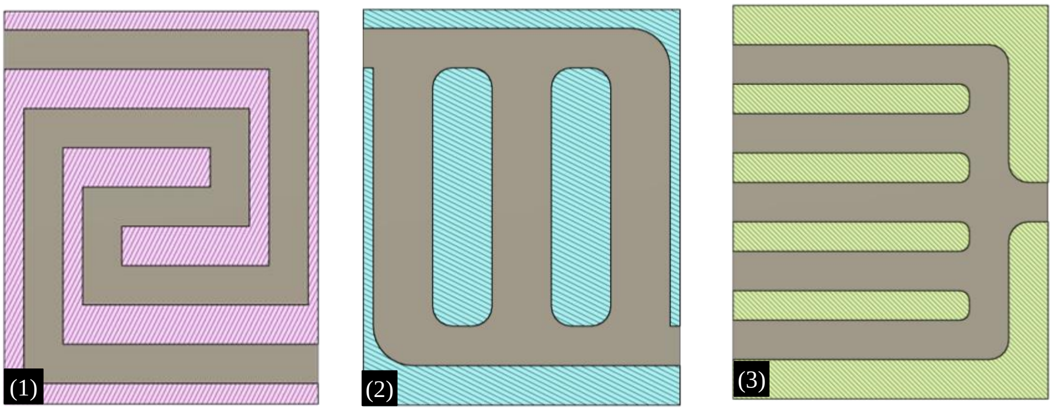

Figure 2. Section View of the Micro Channel of All Three Configurations.

The CFD simulation was carried in cloud platform, SIMSCALE. The geometry was imported in the platform and boundary conditions namely mass flow Inlet, pressure outlet, heat flux wall was assigned on the respective part of the geometry. The study consists of two mass flow rates which were defined in terms of Reynolds number as 800 and 2400. The initial temperature was kept as 300K. A uniform fixed heat flux of 500 W/m^2 was assigned on the top surface of the plate. The side walls and the bottom wall were kept to be insulated. The materials used for the analysis were water as coolant and Aluminum for the cooling plate. The properties of the materials of the place and the coolant along with the dimensions of the plate is discussed in the Table 1. The key factor used to analyze the performance of the Configuration was chosen to be area weighted average temperature (T_{avg}). The simulation was run for 1000 seconds in order to acquire the convergence of the residuals having the tolerance set to 1e-8.

Table 1. Cooling Plate Properties.

Coolant Fluid	**Water**
Coolant viscosity (kg m^{-1} s^{-1})	0.001003
Coolant conductivity (Wm^{-1} K^{-1})	0.6
Coolant specific heat (J kg-^{1} K^{-1})	4182
Coolant density (kg m^{-3})	998.2
Cooling Plate material	**Aluminium**
Plate conductivity (Wm^{-1} K^{-1})	202
Plate specific heat (J kg^{-1} K^{-1})	871
Plate density (kg m^{-3})	2719
Dimensions	
Plate thickness (mm)	1
Plate width (mm)	160
Plate height (mm)	200
Channel thickness (mm)	0.75
Initial channel width (mm)	20
Boundary Conditions	
Reynolds Number (Re)	800, 2400
Coolant inlet temperature (K)	300
Coolant outlet pressure (Pa)	0
Heat flux (Wm^{-2})	500

RESULTS AND DISCUSION

In the analysis we considered uniform heat flux on the top wall with various Reynolds number in the inlet. The maximum temperature obtained as shown in Figure 3 at the beginning for Configuration 1 was found to be 337K and 345K for Re 800 and Re 2400 respectively. Whereas at the end of the 1000 seconds the temperature obtained was 318K and 314K for the respective Reynolds number. If Configuration two is considered the maximum temperature is found to be 337K for Re 800 and 2400 but after cooling the minimum temperature is found to be 303K and 301K. The Configuration has the same maximum temperature but the minimum temperature obtained is 297K and 294K respectively.

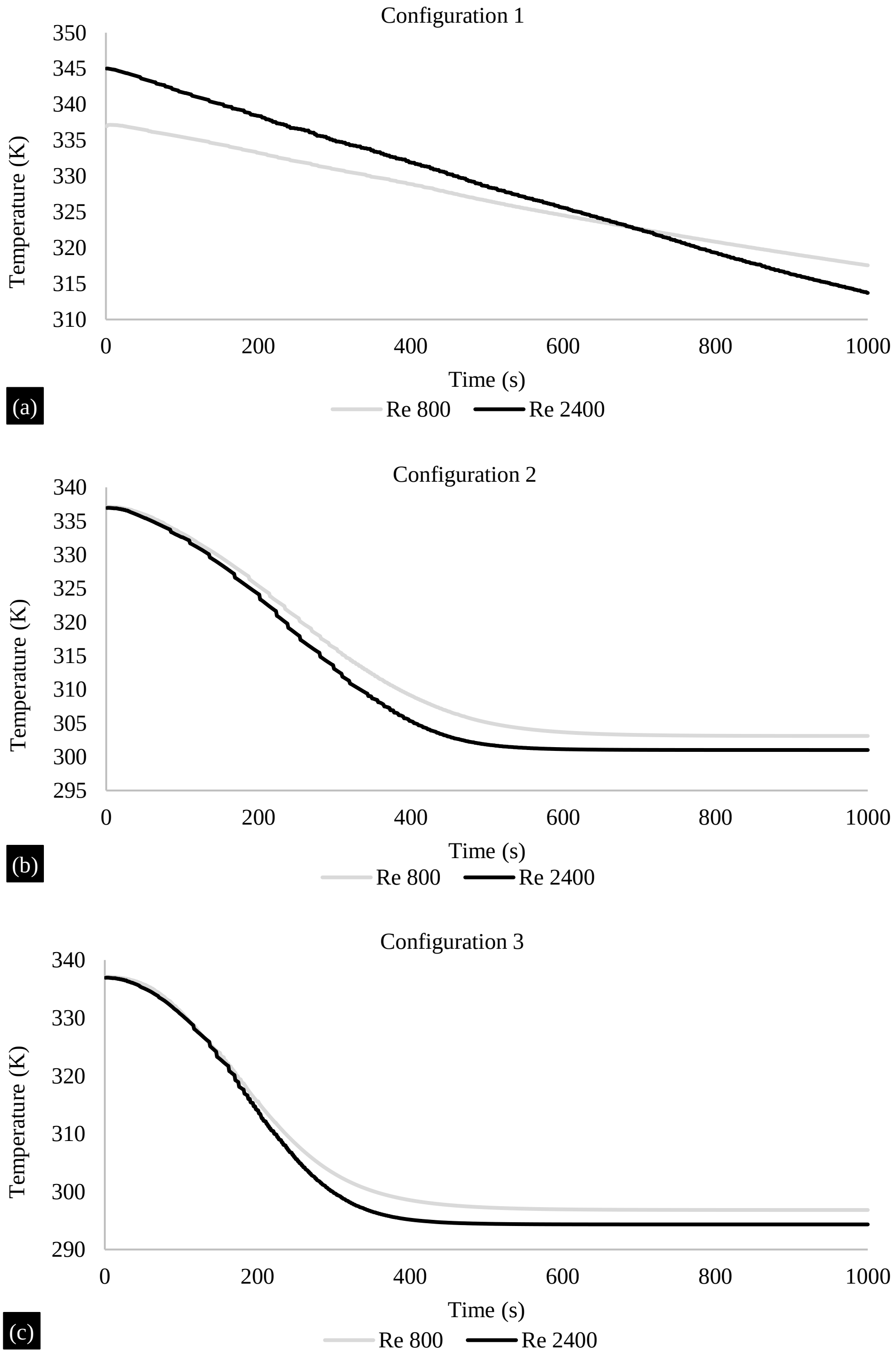

Figure 3. Temperature Plots of the Micro-channel Configurations.

The plots it is evident that temperature is uniform with constant heat transfer rate. The S-curve in the Configuration 2 and 3 signifies that the heat transfer rate is variable along the cooling plate this is because of the more area of the coolant channel in case of Configuration 2 and mor number of outlets in Configuration 3. Thus, we can say that Configuration 3 has the lowest cooling temperature and lowest uniform temperature. The Configuration 1 has the highest temperature and the highest uniform temperature difference. The Configuration 2 is a trade-off between the two Configurations 1 and 3. That offers optimum temperature and uniformity. The contour plots Figures 4, 5 and 6 comprising of the all the three Configurations and both Reynolds number show about the temperature distribution in the micro-channel. In all the Configurations it was observed that there is high temperature at the edge adjacent to the outlet of the channel, since this is possible as there is less time for heat transfer between the coolant and the plate. This was later compensated by increase of Reynolds number and as a result it was found that there is difference around 10K for Configuration 1, 5K for Configuration 2 and 6K for Configuration 3 in both the Re numbers. Thus, we can say that increasing the number oof the Re, surface area of the channel and the variation in coolant outlets can significantly change the behavior of the temperature distribution.

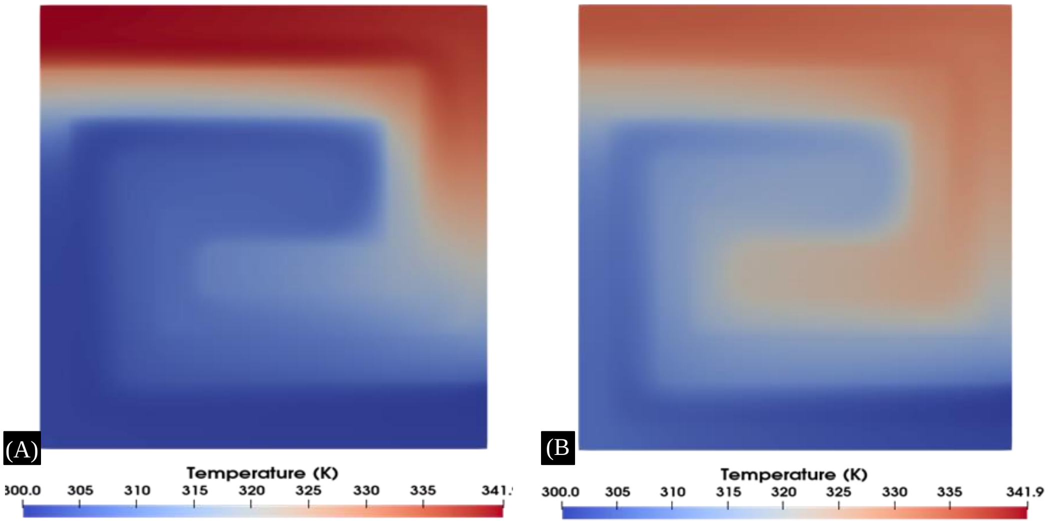

Figure 4. Temperature Contours of the Micro-channel Configuration 1, (A) Re 800 (B) 2400.

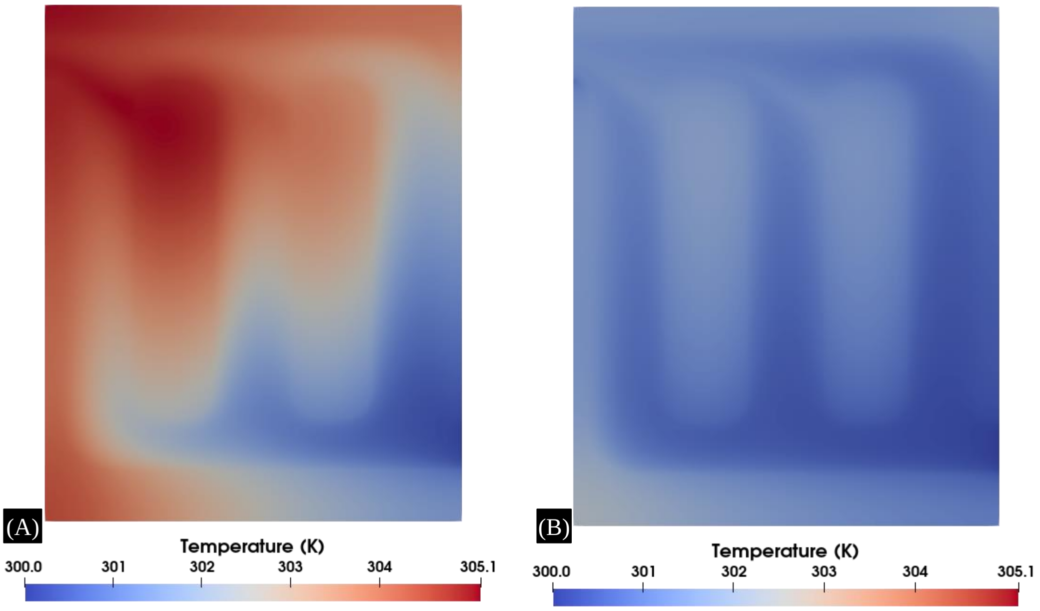

Figure 5. Temperature Contours of the Micro-channel Configuration 2, (A) Re 800 (B) 2400.

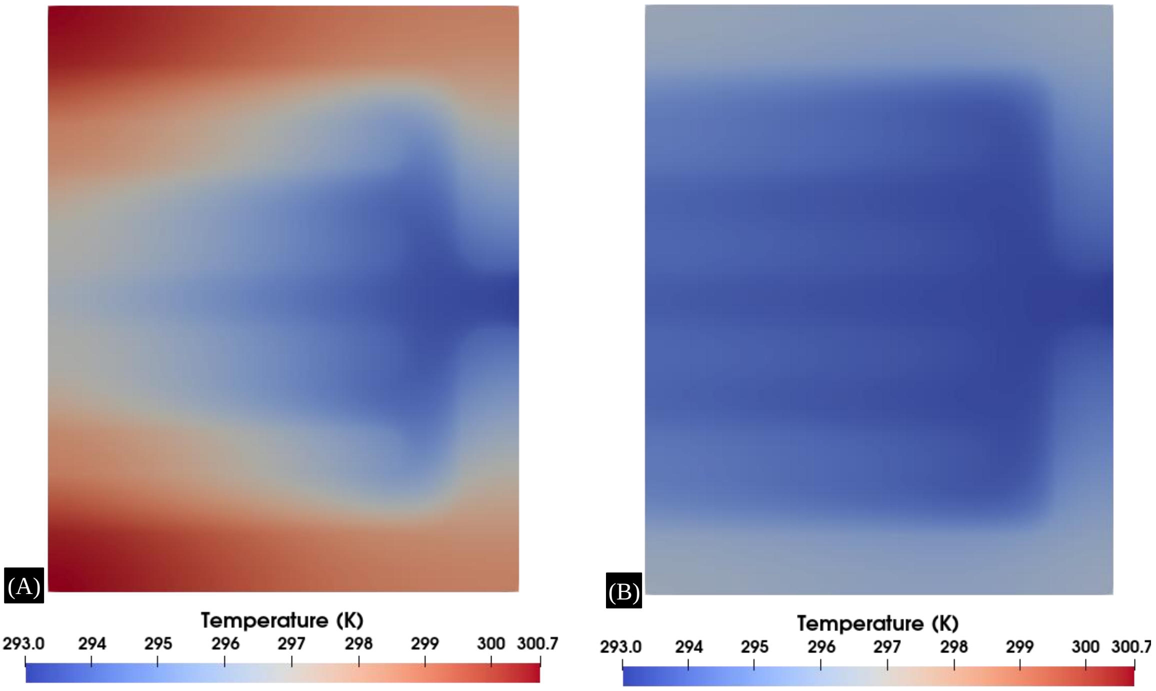

Figure 6. Temperature Contours of the Micro-channel Configuration 3, (A) Re 800 (B) 2400.

CONCLUSION

The results demonstrated that Configuration 1 had the highest heat accumulation and the lowest cooling efficiency, as evidenced by the highest maximum temperature and temperature difference. Conversely, Configuration 3 had the highest cooling efficiency, as indicated by the lowest cooling temperature and temperature variation. Configuration 2 was an intermediate solution, with moderate temperature and uniformity. The heat transfer rate was non-uniform along the cooling plate in Configuration 2 and Configuration 3, due to factors such as the coolant channel area and the number of outlets. These factors led to temperature differences of approximately 10K, 5K, and 6K for Configuration 1, Configuration 2, and Configuration 3, respectively, for both Reynolds numbers. These findings imply that the cooling efficiency is influenced by the number of coolant outlets, the channel area, and the Reynolds number. Future research in this context could aim to optimize these Configuration parameters to improve cooling efficiency under unsteady conditions. Other potential research directions include investigating alternative cooling methods or materials that can enhance temperature uniformity and lower maximum temperatures, as well as examining the effect of other parameters, such as channel geometry or different heat flux conditions, on micro-channel cooling systems.

Acknowledgments

We gratefully acknowledge Koneru Lakshmaiah Education Foundation, Vaddeswaram, for giving the infrastructure and necessary facilities to perform this work. We would also like to thank the lab staffs and technicians in fulfilling our lab needs and supplies.

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