Transient numerical investigation on cold plate based water cooling system for battery module with large lithium-ion pouch cells

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Abstract. This investigation presented a transient numerical study on cooling performance of cold plate based water cooling system for battery module with large lithium-ion pouch cells. The study was conducted at heat generation rates of large pouch cells with 0.07 W/cm^3, 0.05 W/cm^3 and 0.03 W/cm^3. The operating temperature of cooling water were considered as 15 ℃, 25 ℃ and 35 ℃. The operating mass flow rates of water were considered as 0.05 kg/s, 0.10 kg/s and 0.15 kg/s. k-ε turbulence model in ANSYS CFX was used to simulate the flow in the water channel. The average battery temperature, maximum battery temperature and temperature difference between maximum and minimum were considered as critical parameters for analysing the cooling performance of battery thermal management system (BTMS) with large sized lithium-ion pouch cells. The study reported that for 0.03 W/cm^3, the present cooling model was sufficient and for battery modules with higher heat generation rates need optimized strategy to provide efficient cooling.

1. Introduction

The accelerated use of fossil fuel has resulted in the environmental degradation issue with large CO_2 emissions. The automobile and aviation industry are investigating methods to move towards the sustainable energy. The electric vehicle (EV) market is looking competitive with the advancements in battery-operated electric vehicles (BEVs), hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs) and fuel cell vehicles (FCVs). Lithium-ion battery is preferred as energy source in modern EVs due to its high specific energy [1,2], high power density [1,2], high nominal voltage and low self-discharge rate [3] and long-life cycles [4]. To elevate the performance of battery, the operating temperatures should be maintained between 20 ℃ to 40 ℃ [5]. Battery operating temperature exceeding above the specified temperature could cause decreased performance and, in some cases, thermal runaway leading to thermal explosion. A well designed and efficient thermal management system could provide optimum operating environment. Therefore, battery thermal management system is required to provide better performance and secure the safety [6]. The operating temperature of the battery is critical factor as it affects the thermal and electrochemical behaviour of a battery leading to performance degradation and reduction in cycle life [7]. Considerable amount of

research is being conducted on BTMS with different cooling methods such as air cooling [8], water cooling [9], phase change composite based cooling [10], heat pipe cooling [11], mineral oil cooling [12,13] andintegrated system for cooling as well as heating [14, 15]. Although the air cooling method is simple in construction and operation, low thermal conductivity of air and requirement of high air velocity, makes it less desirable. The water cooling method is more efficient due to higher specific heat and thermal conductivity as compared to air. However, the water cooling brings more complexity due to safety issue with more cost. Phase change material (PCM) based cooling system provides passive type of cooling system and latent heat of fusion of PCM could be used to remove the heat generated. Kim et al. modelled discharge behaviour of Lithium-ion battery with varying environmental temperature and the material properties provided will be used in the present simulation [16].

The literature study shows that air-cooling has limitations and enhanced water cooling system could be solution to the thermal management issue in modern lithium-ion pouch cells. In the present investigation, the transient analysis is conducted to understand the temperature distribution of lithium-ion pouch cells in battery module. The average temperature, maximum temperature and temperature difference were considered as critical parameters for analysing effectiveness of water channel based battery module cooling system.
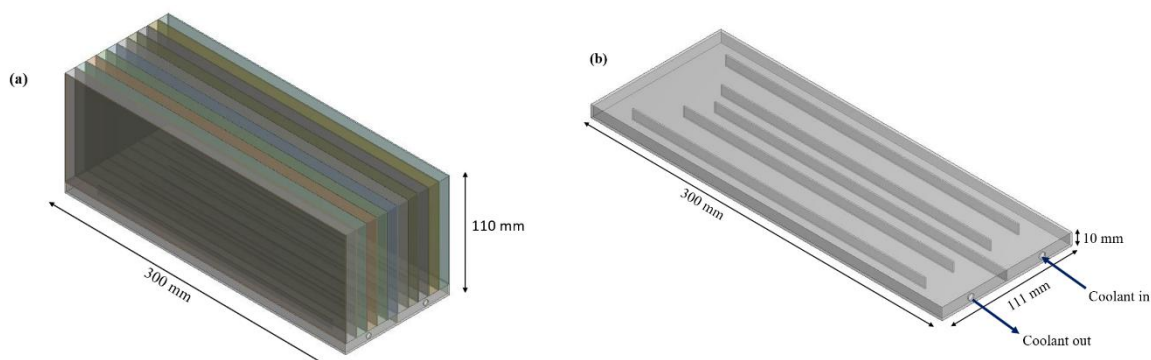
2. Numerical method
Commercial computational fluid dynamics (CFD) software ANSYS CFX 18.0 was used to study the heat transfer characteristics of the BTMS. The details of the geometry, meshing and boundary conditions are provided in this section.

2.1. Geometry
The dimensions of commercially available 20Ah lithium-ion pouch cell was chosen. A schematic of the BTMS under consideration with a single battery module was shown in figure 1. The system consisted of 10 lithium-ion pouch cells, 11 cold plates situated on the either sides of the battery, cooling channel with five long fins and water as a coolant. The dimensions of the model were listed in table 1.

Table 1. Geometric size parameters of the battery thermal management system (BTMS).

Parameter	Specification
Overall Size of the system (mm)	$300 \times 111 \times 110$
Size of single prismatic lithium-ion battery (mm)	$300 \times 100 \times 10$
Size of the cold plate (mm)	$300 \times 110 \times 1$
Size of cooling channel (mm)	$300 \times 111 \times 10$
Number of fins in cooling channel	5

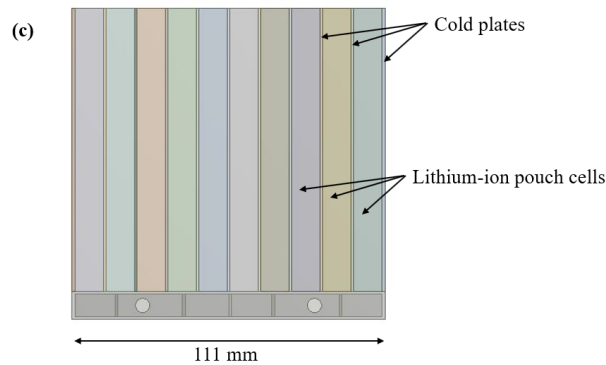**(c)**

Cold plates

Lithium-ion pouch cells

111 mm

Figure 1. In Geometry (a) Battery thermal management system with single battery module (b) Cooling channel design (c) BTMS (front view).

2.2. Meshing and material

The mesh generation was carried out using ANSYS meshing. Total of 1,032,382 nodes and 1,276,271 elements were generated after meshing. The mesh was refined based on the proximity and curvature sizing. The fine layer was provided to capture the fluid flow and heat transfer near the solid-liquid interface. Moreover, the grid independence study was conducted to verify the accuracy of the results of the simulated model. Outlet water temperature, outlet pressure and average battery temperature were considered for grid independency. The grid independency was found within 1.0% with the 1,276,271 elements and the same model was selected to carry out simulations. Figure 2 shows the meshing of the numerical model
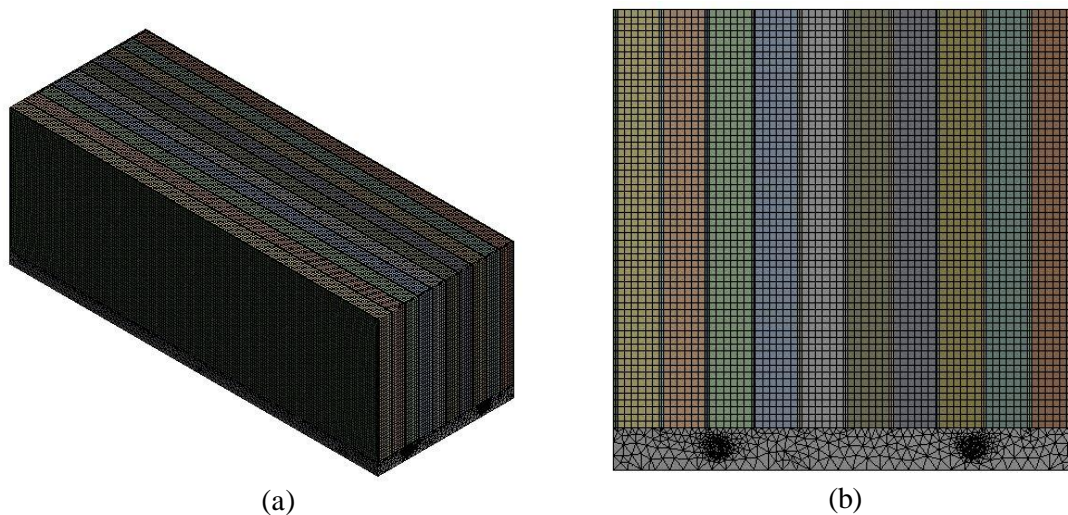

(a)   (b)

Figure 2. Meshing (a) full view (b) front view

The thermal and physical properties of the materials used in the analysis are taken from Kim et al. [16] and are provided in the table 2. The general properties were employed for aluminium channel and water.

Table 2. Thermal and physical properties of the lithium-ion battery[16].

Parameter	Specification

Density (kg/m^3)	2092.0
Specific heat at constant pressure (J/kg-K)	678.0
Thermal conductivity (W/m-K)	18.2

2.3. Boundary conditions

This section provides details for boundary conditions and assumptions. The lithium-ion battery generates considerable amount of heat during charging and discharging due to electrochemical reaction occurring at electrodes as well as ohmic loss. This heat needs to be dissipated for smooth operation of the battery. In the present study, the constant heat generation rates of 0.07 W/cm^3, 0.05 W/cm^3 and 0.03W/cm^3 were considered as volumetric heat generation rate by the large lithium-ion batteries. The water mass flow rates were varied from 0.05 kg/s to 0.15 kg/s. The inlet temperature of water was varied from 15 ℃ to 35 ℃, considering the nominal coolant temperatures. All external walls assumed to be adiabatic for simplicity of the study.

3. Results and discussion

The results presented the transient analysis of BTMS with single battery module with variations of different parameters. The results were recorded for every 10 seconds from the initial time till the thermal steady state was observed. The dual cold plate method was adopted for efficient cooling of lithium-ion battery cells.In dual cold plate method, thin aluminium plates are attached to both sides of the battery to efficiently remove the dissipated heat. The heat generation rate, water mass flow rate and water inlet temperature were considered as variable input parameters. The average, maximum and difference between maximum and minimum battery temperature were considered as critical performance parameters. For better efficiency and long-life cycle two important parameters needs to be considered: (1) uniformity of the temperature in the single battery as well as in the battery module and battery pack; (2) maximum temperature in the single battery as well as in the battery module and battery pack.Many electric vehicle manufacturers recommend maintaining the temperature difference between maximum and minimum in the single battery within 2~3 ℃ and in the whole battery pack within 5~6 ℃. This recommendation is provided for safety as well as efficient performance. Therefore, in this study maximum temperature and temperature difference are considered as critical parameters.

Figure 3 shows the variation of average temperature of all lithium-ion pouch cells in module with respect to variation of heat generation rate, water mass flow rate and water inlet temperature. The heat generation rate due chemical reaction and internal resistance for lithium-ion pouch cell of 0.03 W/cm^3, 0.05 W/cm^3 and 0.07 W/cm^{3}were considered.The water mass flow rates of 0.05 kg/s, 0.10 kg/s and 0.15 kg/s were considered. The inlet water temperature was varied as 15 ℃, 25 ℃ and 35 ℃. Figure 3a, figure 3b and figure 3c shows the variation of average temperature of all lithium-ion pouch cells in the module with water inlet temperature of 15 ℃, 25 ℃ and 35 ℃, respectively.As expected, maximum average temperature was observed for heat generation rate of 0.07 W/cm^3 and water mass flow rate of 0.05 kg/s. Minimum average temperature was observed for heat generation rate of 0.03 W/cm^3 and water mass flow rate of 0.15 kg/s.The average temperature of lithium-ion pouch cells decreased continuously for inlet water temperature 15 ℃ as elapsed time increased and reached steady state after around 800 seconds.The average temperature of lithium-ion pouch cells increased continuously for inlet water temperature of 25 ℃ and 35 ℃ as elapsed time increased and reached steady state after around 800 seconds.The maintenance of average temperature of lithium-ion pouch cells in the operating temperature range is necessary for long life cycle and better performance of the battery.
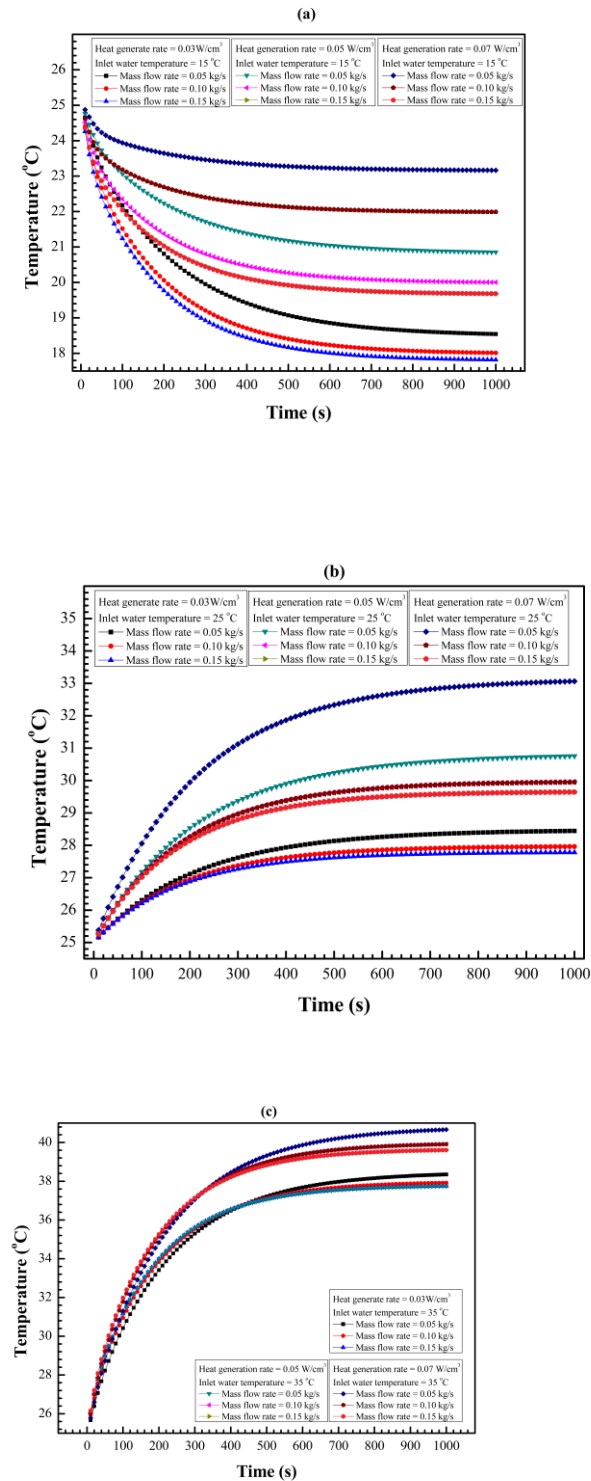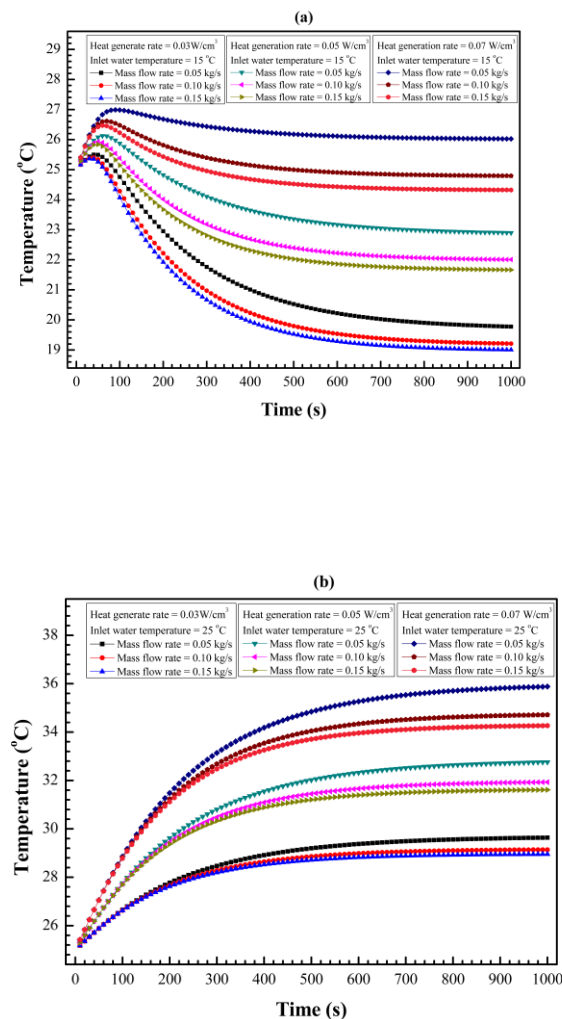
Figure 3. Average temperature of Li-ion batteries with various heat generation rates, water inlet mass flow rates and water inlet

temperatures.

Figure 4 shows the variation of maximum temperature of all lithium-ion pouch cells in module with respect to variation of heat generation rate, water mass flow rate and water inlet temperature. Figure 4a, figure 4b and figure 4c shows the variation of maximum temperature of all lithium-ion pouch cells in the module with water inlet temperature of 15 ℃, 25 ℃ and 35 ℃, respectively. As expected, highest maximum temperature was observed for heat generation rate of 0.07 W/cm^3 and water mass flow rate of 0.05 kg/s. Lowestmaximum temperature was observed for heat generation rate of 0.03 W/cm^3 and water mass flow rate of 0.15 kg/s. The maximum temperature of lithium-ion pouch cells increased initially and then decreased continuously for inlet water temperature 15 ℃ as elapsed time increased and reached steady state after around 800 seconds.The maximum temperature of lithium-ion pouch cells increased continuously for inlet water temperature of 25 ℃ and 35 ℃ as elapsed time increased and reached steady state after around 900 seconds. The maximum temperature of lithium-ion pouch cells increased sharply after 200 seconds for inlet water temperature 35 ℃.
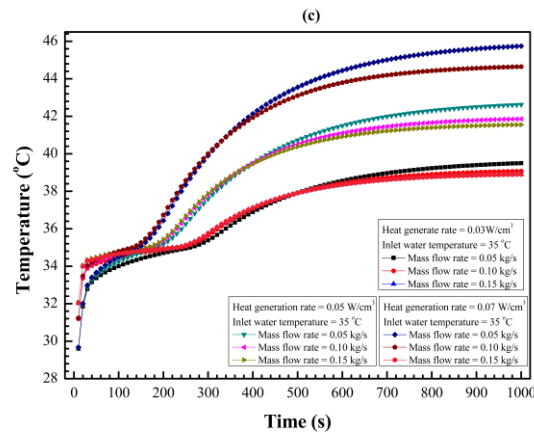
Figure 4. Maximum temperature of Li-ion batteries with various heat generate rate, water inlet mass flow rate and water inlet temperature.

Figure 5 shows the variation of temperature difference between maximum and minimum of all lithium-ion pouch cells in module with respect to variation of heat generation rate, water mass flow rate and water inlet temperature. Figure 5a, figure 5b and figure 5c shows the variation of temperature difference between maximum and minimum of all lithium-ion pouch cells in the module with water inlet temperature of 15 °C, 25 °C and 35 °C, respectively. As expected, highest temperature difference was observed for heat generation rate of 0.07 W/cm^3 and water mass flow rate of 0.05 kg/s. Lowest temperature difference was observed for heat generation rate of 0.03 W/cm^3 and water mass flow rate of 0.15 kg/s. The temperature difference of lithium-ion pouch cells increased initially and then decreased continuously for inlet water temperature of 15 °C as elapsed time increased and reached steady state after around 800 seconds. The temperature difference of lithium-ion pouch cells increased continuously for inlet water temperature of 25 °C as elapsed time increased and reached steady state after around 900 seconds. The temperature difference of lithium-ion pouch cells increased initially, then decreased and again increased continuously for inlet water temperature of 35 °C as elapsed time increased and reached steady state after around 900 seconds. The maintenance of temperature difference of lithium-ion pouch cells in the battery module in the operating temperature range is very important for long life cycle and better performance of the battery. Maintaining the battery temperature difference within 5 °C for uniformity is important for safe operation of the battery module. As shown in figure 5, the maximum temperature difference of 5 °C was maintained for heat generation rate of 0.03 W/cm^3 case only. For higher heat generation rates of 0.05 W/cm^3 and 0.07 W/cm^3, two strategies could be adopted for efficient cooling. Firstly, a cooling channel could be optimized for better cooling with modified design for uniform distribution of heat removal. Secondly, the mass flow rates of water could be increased to enhance the heat removal rate.
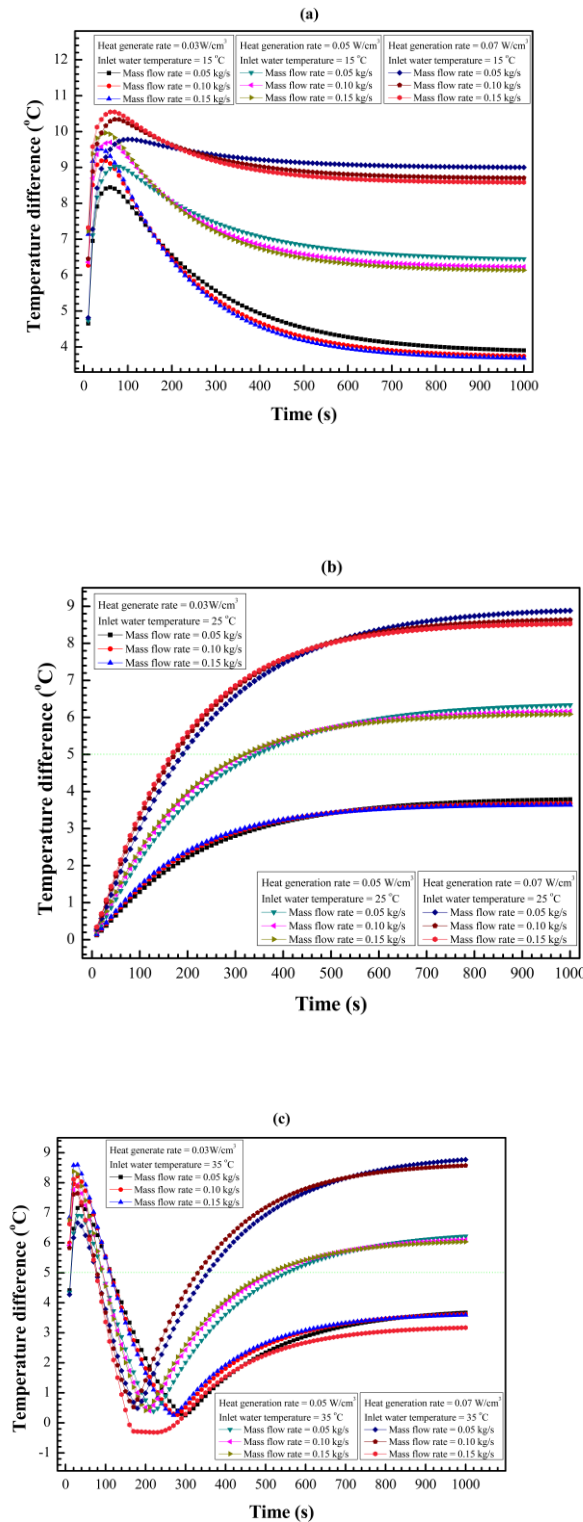
Figure 5. Temperature difference between maximum and minimum of Li-ion batteries with various heat generate rate, water inlet mass flow rate and water inlet

temperature.

Figure 6 shows the variation of temperature distribution of lithium-ion pouch cells in module with heat generation rate of 0.03 W/cm^3, water mass flow rate of 0.05 kg/s and water inlet temperature of 35 ℃. As coolant flows in the cooling channel, heat dissipated by lithium-ion pouch cells was continuously removed. The figure 6 indicates that, the heat was accumulated at the top surface leading to increase in the surface temperature of top section of the battery module. The dual channel cooling system could be proposed in case of battery module with large lithium-ion batteries generating high amount of heat which needs to be dissipated.
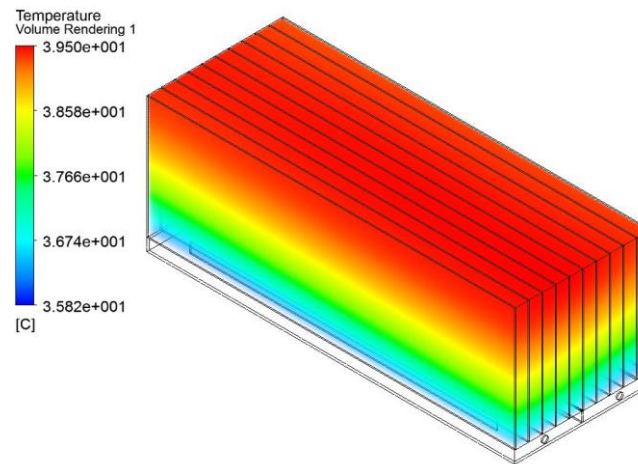

Figure 6. Temperature difference of Li-ion batteries with various heat generate rate, water inlet mass flow rate and water inlet temperature.

4. Conclusions
The present numerical study reported the transient simulation analysis for cold plate based water cooling system for battery module with large lithium-ion pouch cells. Various parameters were varied and temperature distribution in the battery module was reported. The heat generation rate of 0.03 W/cm^3, 0.05 W/cm^3 and 0.07 W/cm^3 were considered based on large size lithium-ion pouch cell. The water was selected as coolant with mass flow rates of 0.05 kg/s, 0.10 kg/s and 0.15 kg/s. The inlet water temperature was varied as 15 ℃, 25 ℃ and 35 ℃ considering mild to extreme hot weather condition. The average battery temperature, maximum battery temperature and temperature difference between maximum and minimum were considered as critical parameters for analysing the cooling performance of BTMS with large sized lithium-ion pouch cells. The study points out that for 0.03 W/cm^3, the present model is sufficient and for battery modules with higher heat generation rates need optimized strategy to provide efficient cooling.

5. References

[1]   Ling Z, Wang F, Fang X, Gao X and Zhang Z, A hybrid thermal management system for lithium ion batteries combining phase change materials with forced-air cooling, 2015 *Appl. Energy* **148** 403-409
[2]   Ge H, Huang J, Zhang J and Li Z, Temperature-adaptive alternating current preheating of lithium-ion batteries with lithium deposition prevention, 2016 *J. Electrochem. Soc.* **163**(2) A290-A299

[3]   Ritchie A and Howard W, Recent developments and likely advances in lithium-ion batteries, 2006*J. Power Sources***162**(2) 809-812

[4]   Ye Y, Saw LH, Shi Y and Tay AOA, Numerical analyses on optimizing a heat pipe thermal management system for lithium-ion batteries during fast charging, 2015*Appl. Therm. Eng.***86**281-291

[5]   Teng H, Ma Y, Yeow K and Thelliez M, An Analysis of a Lithium-ion Battery System with Indirect Air Cooling and Warm-Up, 2011 *SAE Int. J. Passeng. Cars – Mech. Syst.* **4(3)**1343-1357

[6]   Feng X, Fang M, He X, Ouyang M, Lu L, Wang H and Zhang M, Thermal runaway features of large format prismatic lithium ion battery using extended volume accelerating rate calorimetry, 2014*J. Power Sources***255** 294-301

[7]   Panchal S, Dincer I, Agelin-Chaab M, Fowler M andFraser R, Uneven temperature and voltage distributions due to rapid discharge rates and different boundary conditions for series-connected LiFePO4 batteries, 2017*Int. Commun. Heat Mass Transf.***81** 210-217

[8]   Chen K, Song M, Wei W and Wang S, Structure optimization of parallel air-cooled battery thermal management system with U-type flow for cooling efficiency improvement, 2018*Energy***145** 603-613

[9]   Li K, Yan J, Chen H and Wang Q, Water cooling based strategy for lithium ion battery pack dynamic cycling for thermal management system, 2018*Appl. Therm. Eng.***132** 575-585

[10]   Ianniciello L, Biwolé PH andAchard P, Electric vehicles batteries thermal management systems employing phase change materials, 2018*J. Power Sources***378** 383-403

[11]   Liang J, Gan Y and Li Y, Investigation on the thermal performance of a battery thermal management system using heat pipe under different ambient temperatures, 2018 *Energy Conv. Manag.* **155** 1-9

[12]   Seo JH, Patil MS, Kim DW, Bang YM and Lee MY,Numerical study on the cooling performances of various cooling methods for laminated type battery, 2017 *Proceedings of the Asian conference on Thermal Sciences* (Jeju island, Korea) ACTS-P00363

[13]   Patil MS, Seo JH, Bang YM, Kim DW, Ekanayake G, Singh G, Kim HM, Choi YH and Lee MY, A novel design for lithium-ion battery cooling using mineral oil, 2016 *Advanced Science and Technology Letters***141** (GST 2016) 164-164

[14]   Seo JH, Patil MS, Cho CP and Lee MY,Heat transfer characteristics of the integrated heating system for cabin and battery of an electric vehicle under cold weather conditions, 2018 *Int. J. Heat Mass Transf.***117** 80-94

[15]   Patil MS, Cho CP and Lee MY, Numerical study on thermal performances of 2.0 kW burner for the cabin heater of an electric passenger vehicle, 2018*Appl. Therm. Eng.***138** 819-831

[16]   Kim US, Yi J, Shin CB, Han T and Park S, Modeling the Dependence of the Discharge Behavior of a Lithium-Ion Battery on the Environmental Temperature, 2011 *J. Electrochem. Soc.***158** (5) A677-A618