Design and Geometry Optimization of Cooling Plate for Battery Module of EV

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Abstract: Temperature directly affects the safety, reliability and performance of several energy systems relevant for energy conversions. One such energy conversion device is a Li-ion cell. It's used as an energy storage and conversion in a wide variety of engineering applications. This research is particularly focused on studying thermal management of lithium-ion (Li-ion) battery modules in electric vehicles by using active, passive and hybrid active-passive methods. The thermal behavior prediction of batteries is performed by a novel electrochemical-thermal model. Different approaches such as single- and double-channel liquid cooling, pure passive by using phase change materials (PCM), and hybrid active-passive thermal management systems are investigated. Various cooling system configurations are examined to expand understanding of effect of each approach on the battery module thermal responses during a standard driving cycle. It is observed that the temperature distribution of Li-ion batteries is strongly influenced by the electrical and thermal operating conditions and simplified bulk models cannot precisely predict the thermal behaviour of these batteries.

Among the battery thermal management systems studied, the air assisted hybrid cooling system provides the best temperature distribution uniformity in the module while keeping the batteries temperature within the safe limits. Furthermore, this work attempted to recognize the most influential parameters on the temperature distribution in the battery module. It is seen that the thickness of cooling plates and PCM layers in active and hybrid systems has a significant effect on the thermal behavior of the batteries.

***Index Terms*–** **PCM batteries, Thermal Management, Hybrid cooling for EV, Li-io.**

1. Battery Thermal Management System

Recently battery thermal management system (BTMS) is used, and they are having various techniques to cool the battery and maintain the optimum temperature. High efficiency energy conversion is one of the most significant challenges intensive research activities are being conducted throughout the world for thermal management enhancement to meet industry needs.

There are two approaches to decrease the chance of thermal runaway and to boost thermal stability; one is affected by the electrode characteristics, such as electrode material [19], electrolyte [20], and separator [21]. The properties of battery thermal runaway processes vary with the battery material variation [22], and this is far away. Another solution is to apply a thermal system, called a battery thermal management system, to the batteries for a suitable operating environment. Thus, developing an effective BTMS for packs is the only way to avoid thermal runaway in batteries. BTMS has two main functions: To prolong battery life and improve electrical performance by keeping batteries within an optimal temperature range, having improved safety to prevent thermal runaway.

Moreover, two things are expected in BTMS: Battery temperature should be within the optimal range and to keep the non-uniform temperature within the required range between the cells. BTMS has to be combined with the battery pack. Furthermore, there are few things to consider before designing the battery pack's thermal management system; what is the proposed system's cost? What is the optimal temperature range? Which kind of heat transfer pattern is appropriate? Which method of cooling is suitable? Direct or Indirect? How much heat removes from the pack? The factor considered in the analysis includes ease of operation, capital cost, energy efficiency, reliability, and maintenance requirement.

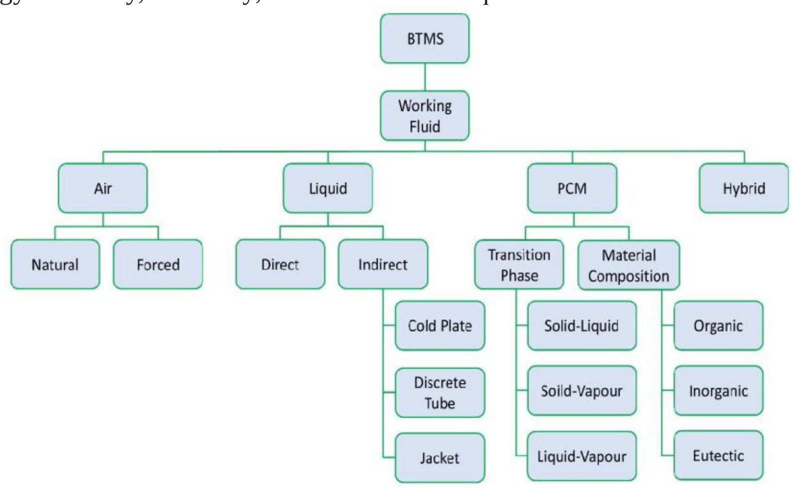


Fig 1 Available battery thermal management system according to the medium

2. Overview of Literature Review

One principal limitation of the performances of LiBs is their dependency on temperature. Thereby, the development of an efficient BTMS is crucial to keep the battery system in an optimal range. This paper reviews and classifies the existing and future BTMSs for electrified vehicles. On one hand, the traditional cooling systems are presented and discussed. Some conclusions from the conventional BTMSs are drawn as follows:

1. The air-cooling method proposes a simple structure, lightweight design and energy saving, but the cooling efficiency is low, and uniformity is generally not achieved. To improve the thermal performance, an enormous requirement that could sacrifice the simplicity and the battery pack energy density would be needed.

2. The liquid-cooling method has the highest cooling/heating efficiency and proposes a good uniformity but need additional components for the coolant circulation which adds complexity, weight, and energy consumption.

3. The refrigerant-based cooling has also a very high thermal efficiency but like the liquid-cooling, appears it requires additional thermal elements which can have a large power consumption.

4. The PCM provides an easy-to-integrate and low-cost solution, but in order to extract all the heat, since the thermal capacity is dependent on mass, PCM systems are usually heavy and volumetric.

5. The heat-pipe system has a very high thermal conductivity compared to other passive techniques, but the small contact area and bulkiness of the system due to evaporator and condenser sections make it difficult to integrate.

6. The thermoelectric module is a lightweight, compact, and noiseless structure, but it has a high-cost and low-energy efficiency.

3. CFD Simulation in GT-Suite

3D simulations depict the interaction of individual components with their environment, whereas 1D simulations depict the overall design of a system and the interactions of its components. As a result, a 1D simulation is ideal for improving the design of a complete system, whereas a 3D simulation is ideal for finding the optimal design features of specific components such as flow pattern around a blade or heat transfer with internal cooling air and exterior hot gas. A 3D simulation may also be used to confirm the results of a 1D simulation, such as pump cavitation prediction on an NPSH map (Zhang, 2020).

To cater to the requirements of this thesis, a software called GT-Suite, developed by Gamma Technologies, was used for 1D CFD simulation. It is a commonly used tool among most major vehicle manufacturers. This section explains the fluid flow in pipes through an internal network calculated by GT-Suite.

3.1 Equations Governing GT-Suite

In GT-Suite, the solutions for the conservation equations of continuity, energy, and momentum, also known as the Navier-Stokes equations, are calculated in one dimension (1D), yielding results that are averaged around the direction of flow (Gamma Technologies, 2020). These equations are:

Conservation of Continuity:

$$\frac{dm}{dt} = \sum_{boundaries} \dot{m}$$

Conservation of Energy (Explicit Solver in GT-Suite):

$$\frac{d(me)}{dt} = -\rho \frac{dV}{dt} + \sum_{boundaries} (\dot{m}H) - hA_s(T_{fluid} - T_{wall})$$

Conservation of Enthalpy (Implicit Solver in GT-Suite):

$$\frac{d(pHV)}{dt} = V \frac{dV}{dt} + \sum_{boundaries} (\dot{m}H) - hA_s(T_{fluid} - T_{wall})$$

Conservation of Momentum:

$$\frac{d\dot{m}}{dt} = \frac{dpA + \sum_{boundaries} (mH) - 4C_f \frac{pu|u|}{2} \frac{dxA}{D} - K_p \left(\frac{1}{2} pu|u|\right) A}{dx}$$

3.2 Discretization in GT-Suite

To accurately model the system, the system is discretized into several volumes called computational cells where each flow split is represented by one volume and every pipe is divided into single or more volumes. This type of discretization is known as a "staggered grid" and a schematic shown in Figure 2. In this approach, the scalar variables like pressure, temperature, density, enthalpy, internal energy are approximated to be uniform over each volume. The vector variables such as rate of mass flow, velocity, etc., are calculated for each cell boundary. The larger discretization results in less accurate results, but the computational time is significantly faster. Smaller discretization results in higher accuracy but requires a much longer computational time which increases exponentially as the discretization is made finer.

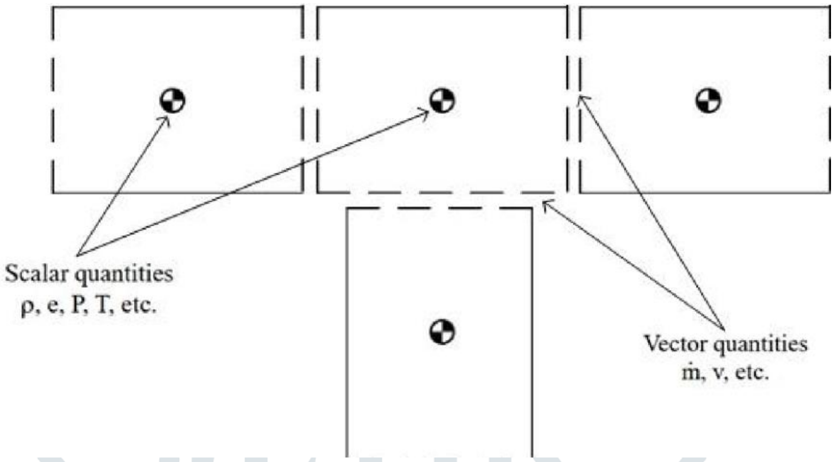


Fig. 2 Discretization in GT-Suite

3.3 Flow Connections

Physical components in GT-Suite are linked together by connections. These connections are considered as a plane in which the momentum equation is solved to calculate the mass transfer and the velocity. Different connections available are Orifice, Valve, Throttle, Pressure loss and Annular loss (Gamma Technologies, 2020).

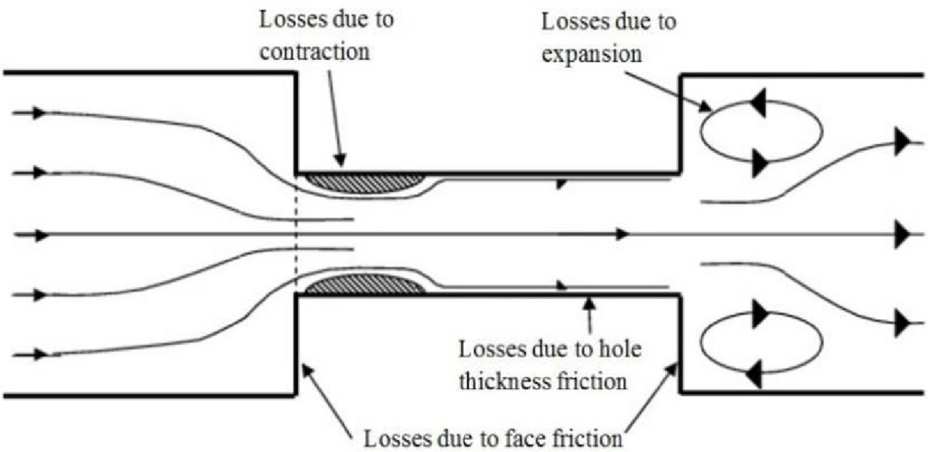


Fig. 3 Various reasons for pressure losses in an orifice

3.4 Pressure Loss Connection

It is easier to apply a known pressure loss as a function of mass or volumetric flow rate in certain situations. For such instances, a pressure loss relation has been added to GT-Suite. This relation can be used to enforce a known pressure loss in complex components such as heat exchangers, where calculating/solving for the pressure loss is not preferred. This relation, unlike the others, does not solve the momentum equation, and the solution is merely forced. In addition to this, a time constant parameter is also provided to avoid mass flow rate fluctuations and to keep the solution steady (Gamma Technologies, 2020).

3.5 Flow Splits

When a finite volume has multiple openings, the interactions cannot be accurately captured by conventional one-dimensional treatment. In order to overcome this limitation and calculate the conservation of momentum, flow splits are used. To calculate the momentum solution, the flow split geometry is determined for each boundary by its expansion diameter (the diameter in which the flow can spread after entering the flowsplit), characteristic length (the distance between the boundary plane and the opposite side of the flowsplit) and by considering the angles between the flows through the volume (Gamma Technologies, 2020). The flow split solution is similar to the pipe solution such that the scalar quantities of the pipe are calculated at the volume's centre. The momentum equation, on the other hand, is calculated for each volume opening individually (Gamma Technologies, 2020).

4. Methodology

4.1 Case Definition

A battery cooling plate is critical parts of battery because it's maintained battery temperature. To test effectiveness of cooling plate with different design quickly tested with the help of 1D simulation without any experimental test. So, the main objective was to study the flow pattern in the cooling plate tubes, in every case, the test was run four times at four different flow rates to observe how the flow affects the filling and the creation of coolant traps in the circuit. A simplified version of a cooling system can be seen in Figure 4 and Figure 5 presents the flowrate for every case and test run.

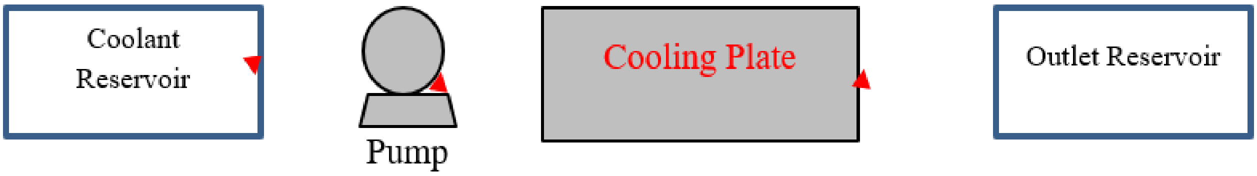
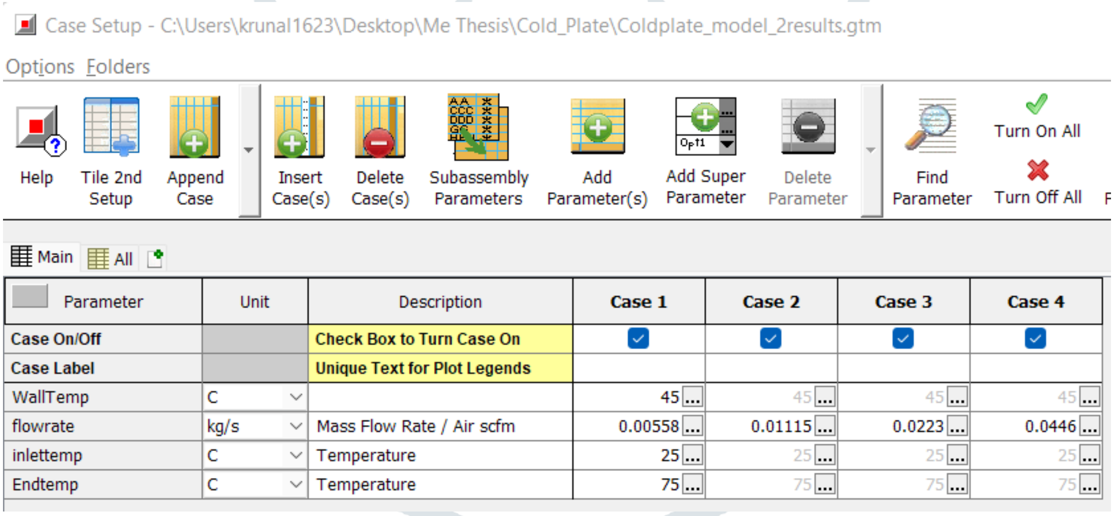


Fig. 4 Simplified cooling system



Parameter	Unit	Description	Case 1	Case 2	Case 3	Case 4
Case On/Off		Check Box to Turn Case On	☑	☑	☑	☑
Case Label		Unique Text for Plot Legends				
WallTemp	C		45	45	45	45
flowrate	kg/s	Mass Flow Rate / Air scfm	0.00558	0.01115	0.0223	0.0446
inlettemp	C	Temperature	25	25	25	25
Endtemp	C	Temperature	75	75	75	75

Fig. 5 Flowrate readings

4.2 Coolant Mixture

To cool down the battery and other hot components the coolant is circulated around the coolant system by the pump. The battery is cooled by coolant passing by in channels insider the cooling plate. Coolant mixture also absorbs the heat at the cooling plate and other components that require cooling and then it releases the heat at the mixing tank or in close system in radiator part. Figure 6 shows ethylene glycol 50-50 material properties.

The coolant usually consists of the water mixed with ethylene glycol with some additions. This is done to reduce freezing point temperature and improve corrosion resistance. It also raises the boiling point temperature that is important for the hot day conditions when the higher temperature difference between air and coolant is desirable as it improves the heat transfer performance of the cooling plate.

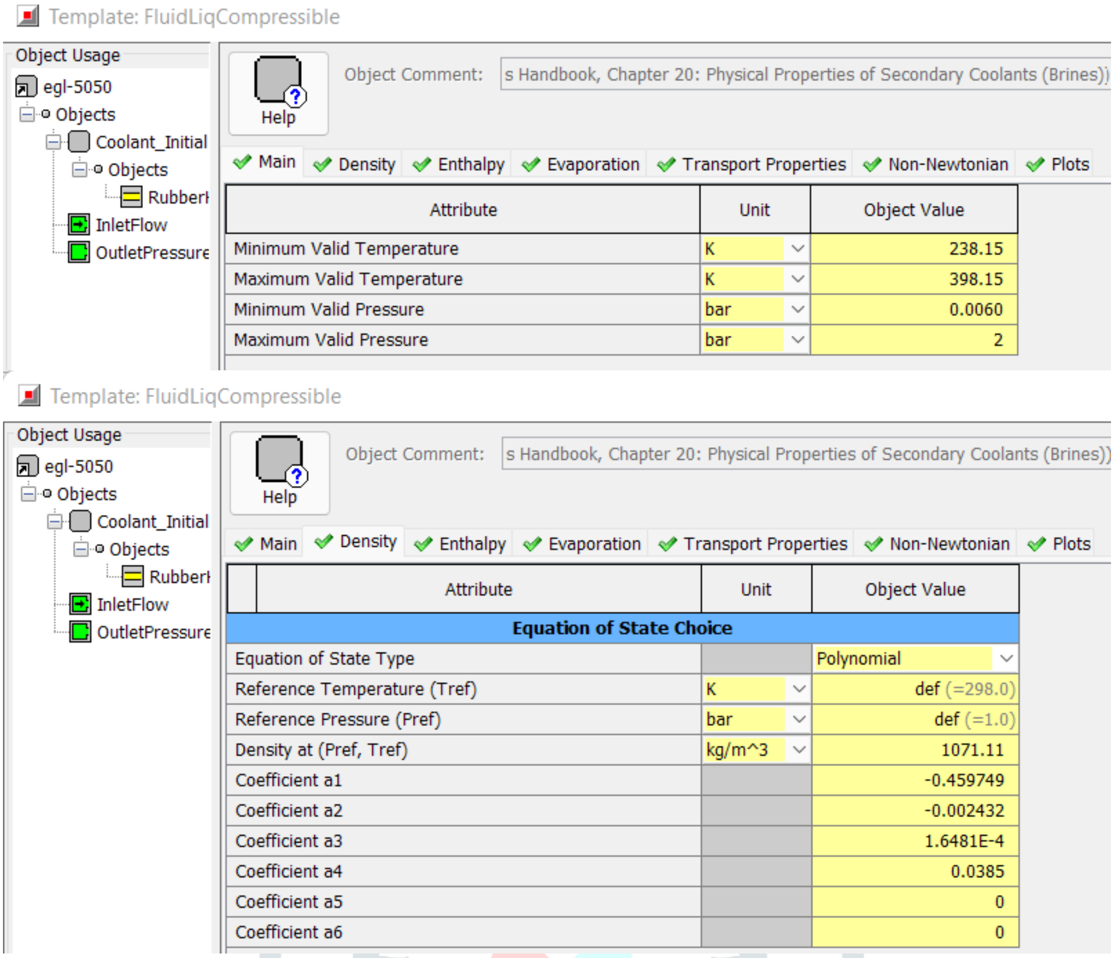
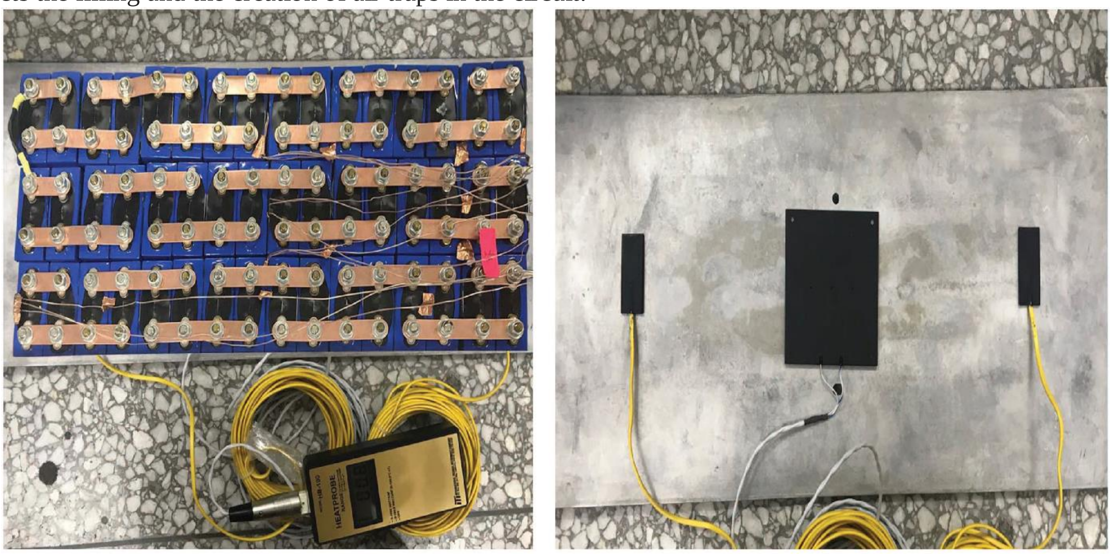


Fig. 6 Ethylene glycol 50-50

4.3 Experimental Setup

Figure 7 show the experimental test setup. In every case, the test was run four times at four different flow rates to observe how the flow affects the filling and the creation of air traps in the circuit.



(a) (b)

Fig. 7 Cooling Plate Test setup

4.4 CAD Modeling

In the test rig, all cases included the battery cooling plates, the inlet tank and outlet tank. These components were common to all the cases. The size of the cooling plate is designed to be 620 × 340 × 4.5 mm (excluding the height of the pipe at the inlet and outlet). The method of cooling the bottom was chosen for this simulation, which is convenient for setting, saving space, and easy repair. The structure of the cooling plate is shown in Figure 4.5. The area of the internal fluid is determined by the structure of the battery and the fabrication of the cooling plate. The total size of the cell is 600 × 310 × 2.5 mm. Different cooling plate was modelled, shown in Figure 8-10 below.

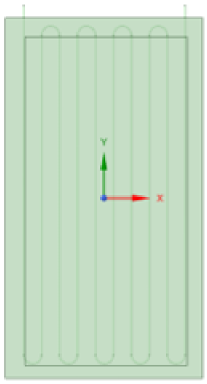


Fig. 8 Model-1

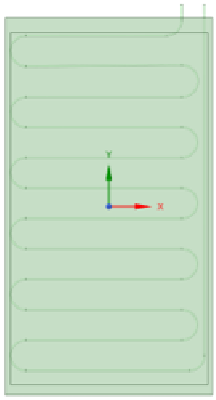


Fig. 9 Model-2

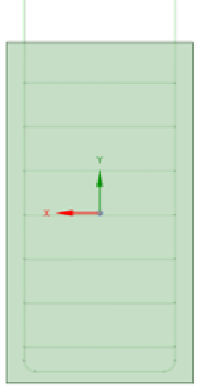


Fig. 10 Model-3

5. Result and Discussion

5.1 Filling Times

The time taken to fill the circuit at the Scania Test Rig has been documented in Table 1.

Table 1Timetaken to fill the circuit at the Scania Test Rig

Model	Test Run	Flow [Kg/Sec]	Max. Pressure [bar]	Max. Temperature [°C]	Simulation Time [s]
1	1	0.00558	2.52	40.1	10
	2	0.01115	3.25	35	6.7
	3	0.0223	6.47	44.9	2.7
	4	0.0446	17	44.8	1.8
2	1	0.00558	2.48	37.9	8.9
	2	0.01115	3.19	33.1	5.3
	3	0.0223	5.83	44.5	2.3
	4	0.0446	14.5	44.2	1.4
3	1	0.00558	2.09	41.9	10
	2	0.01115	2.25	41.8	10
	3	0.0223	2.89	41.6	10
	4	0.0446	5.54	38.7	8.3

From above table it has been shown that first plate model having highest pressure 17 bar at 0.0446 kg/s flow on the other hand, second plate design having 14.5 bar maximum pressure at same mass flow. However, this flow takes less time to flow 1.8 sec and 1.4 sec respectively which is not carry high heat due to convection due to that temperature of battery surface and cooling plate increasing as well as which undoubtedly greatly increases the power consumption, and it is unreasonable to adopt the cooling plate. The % change in pressure drop and temperature with respect to flow rate shown in below Figure 11-16 for both models.

Model-1

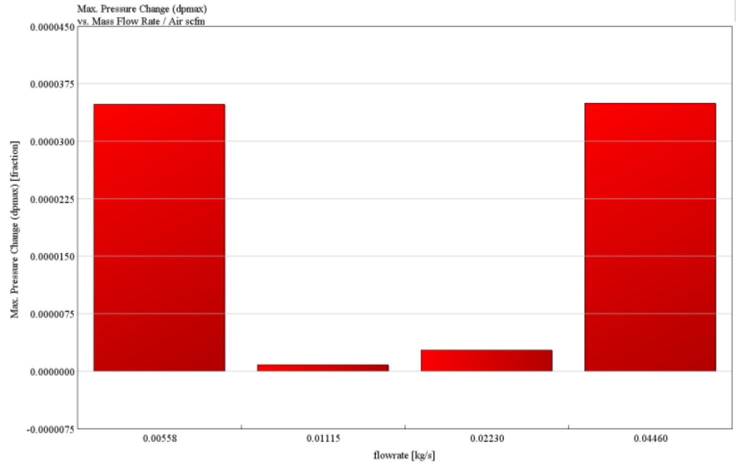


Fig. 11 Mass flow rate vs Max Pressure Change

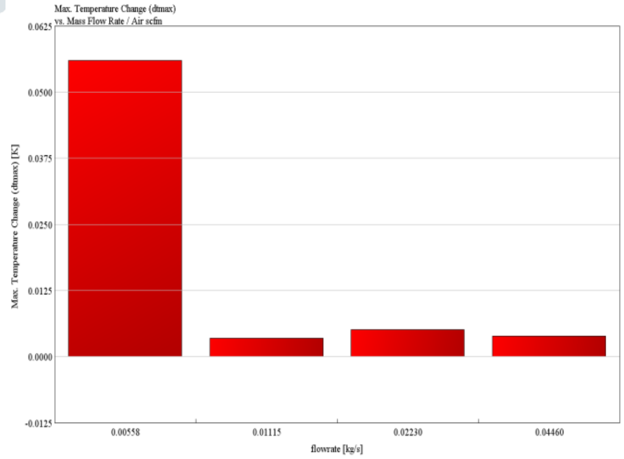


Fig. 12 Mass flow rate vs Max Temperature Change

Model-2

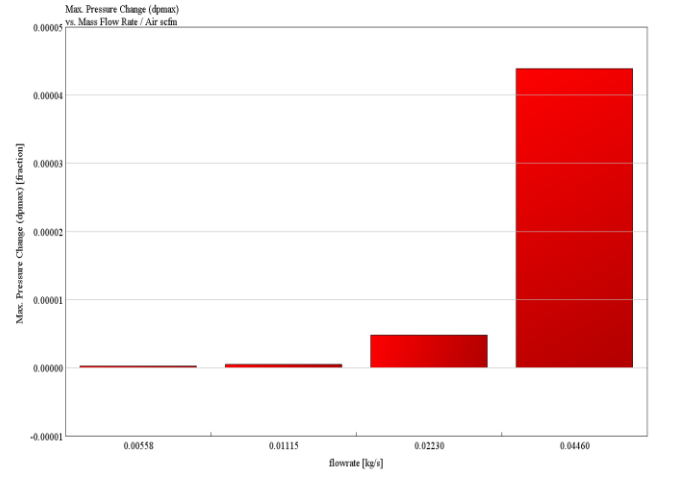


Fig. 13 Mass flow rate vs Max Pressure Change

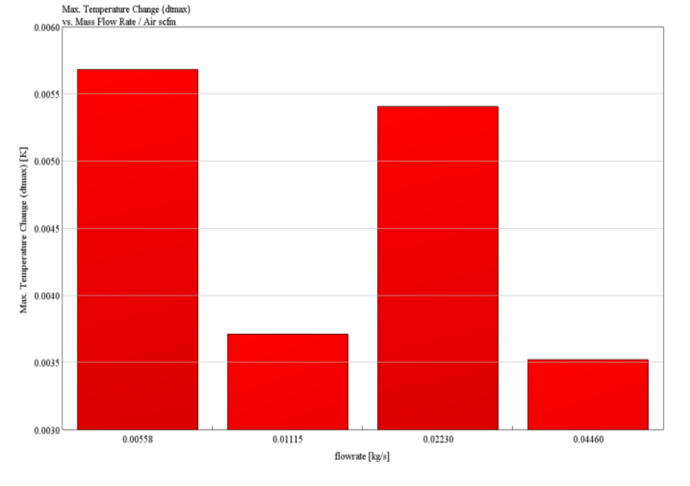


Fig. 14 Mass flow rate vs Max Temperature Change

Model-3

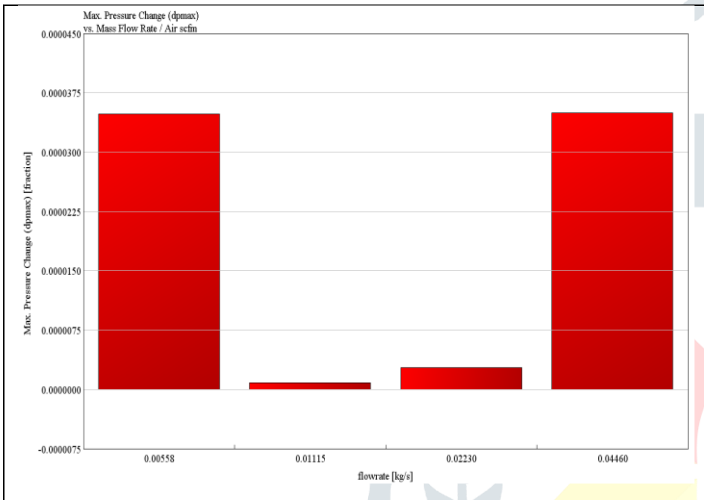


Fig. 15 Mass flow rate vs Max Pressure Change

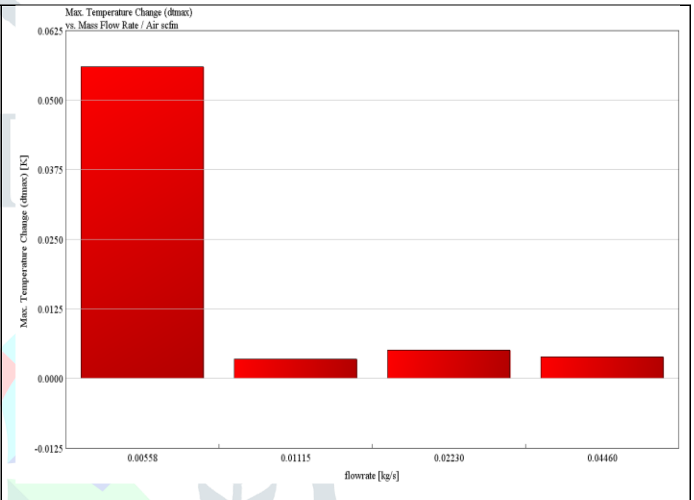


Fig. 16 Mass flow rate vs Max Temperature Change

5.2 Effect of Different Structure

The coolant flowed from the left side of these cooling plates and out of the right side. The inlet and outlet were both set in the top of the cooling plates, which are convenient for manufacturing. As shown in Figure 17-19, the pressure loss (ΔP), the maximum temperature of cooling.

The plate (Tmax), and standard deviation of the temperature (Tσ) change with the discharge of battery under the mass flowrate of 0.0223 kg/s.

Model-1

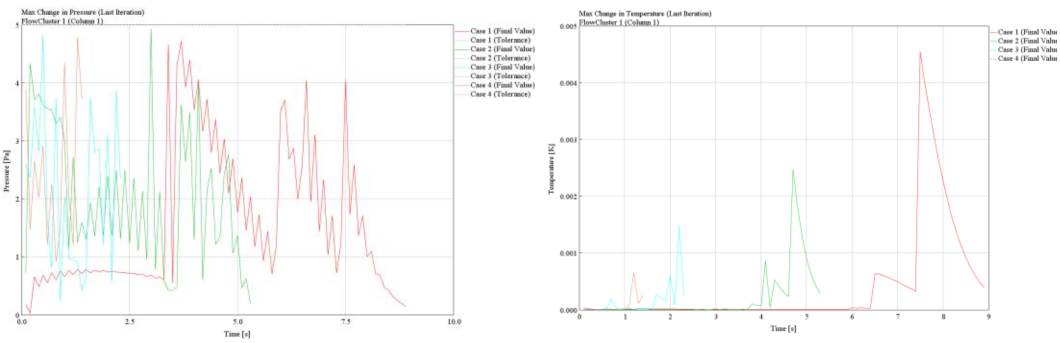


Fig. 17 (Color) Effect of different structures: (a) pressure loss; (b) maximum temperature

Model-2

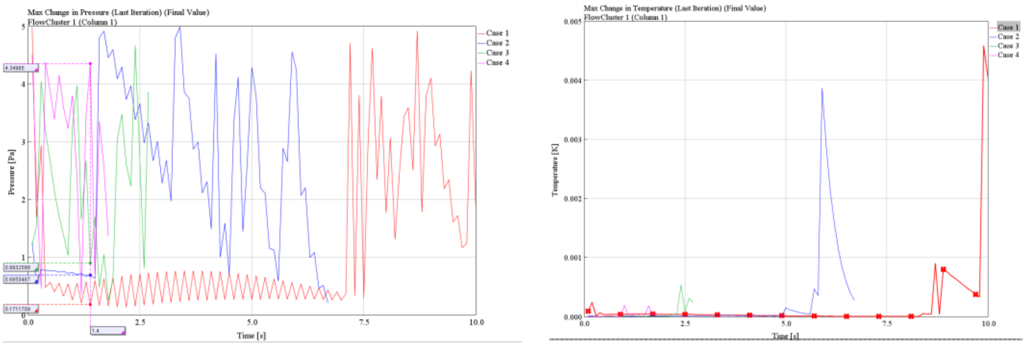


Fig. 18 (Color) Effect of different structures: (a) pressure loss; (b) maximum temperature

Model-3

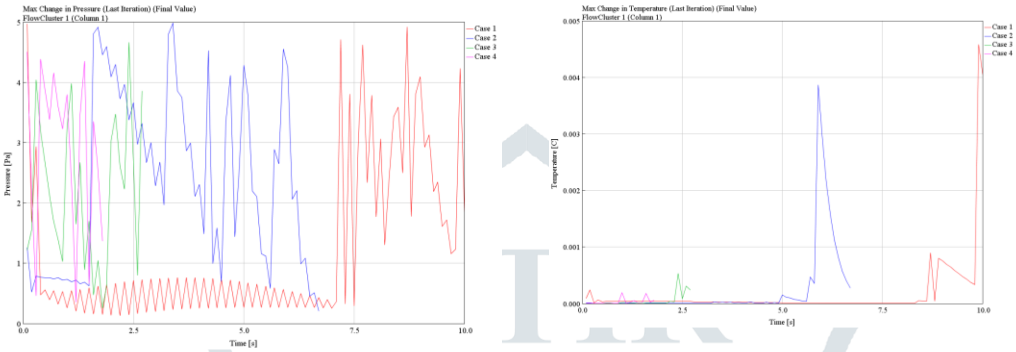


Fig. 19 (Color) Effect of different structures: (a) pressure loss; (b) maximum temperature

3. Conclusion

The work done during this paper can be used as an example of what is possible in GT-Suite and how can filling simulations be carried out with GT-Suite. While this study provides a good initial point for validation, further study is necessary to test additional parts of the circuit with a different setup to obtain more accurate results, as suggested. This will ensure repeatability in the technique and build upon the previously done work to provide quick solutions to the otherwise cumbersome task of building a new circuit.

By comparing and analyzing three liquid-cooled plates, it was found that the cooling plate with the curve structure has the lowest pressure loss at different flow rates, and the cooling plate resistances of the U-shaped structure and ladder-shaped structure were the largest. The heat exchange capacities of several cooling plates were basically the same, but the temperature uniformity of the U-shaped structure was the worst, and the cooling capacity of the cooling plate was greatly affected by the flow rate. The maximum temperature of these types of cooling plate always exists at a certain mass flow rate, which can hardly be eliminated. To ensure the temperature difference of the cooling plate inlet and outlet ($\leqslant$10 K), it is necessary that the mass flow rate of the cooling plate is no less than 0.0223 kg/s. Increasing the mass flow rate is an effective way to cool batteries in a short time.

This paper only simulated the heating of one of the batteries, using the average heat flux, and did not change the battery heating with time under different working conditions. Future work will start from these two aspects and be more closely related to the real situation of EVs.

References

[1] https://www.bp.com/en/global/corporate/energy-economics/statistical-review-of-world-energy.html.

[2] Jiayuan Lin, Xinhua Liu, Shen Li, Cheng Zhang, Shichun Yang, “A review on recent progress, challenges and perspective of battery thermal management system” International Journal of Heat and Mass Transfer 167 (2021).

[3] Bibin Chidambaranathan, M. Vijayaram, V. Suriya, R. Sai Ganesh, S. Soundarraj, “A review on thermal issues in Li-ion battery and recent advancements in battery thermal management system”, Materials Today: Proceedings, Science Direct, May- 2020.

[4] Smart, M.C.; Ratnakumar, B.V.; Whitcanack, L.D.; Chin, K.B.; Surampudi, S.; Croft, H.; Tice, D.; Staniewicz, R. Improved Low-Temperature Performance of Lithium-Ion Cells with Quaternary Carbonate-Based Electrolytes. J. Power Sources 2003, 119–121, 349–358, doi:10.1016/S0378-7753(03)00154-X.

[5] Guo, L.S.; Wang, Z.R.; Wang, J.H.; Luo, Q.K.; Liu, J.J. Effects of the Environmental Temperature and Heat Dissipation Condition on the Thermal
Runaway of Lithium-Ion Batteries during the Charge-Discharge Process. J. Lossb Prev. Process Ind. 2017, 49, 953–960, doi: 10.1016/j.jlp.2017.05.029

[6] Wright, R.B.; Christophersen, J.P.; Motloch, C.G.; Belt, J.R.; Ho, C.D.; Battaglia, V.S.; Barnes, J.A.; Duong, T.Q.; Sutula, R.A. Power Fade and Capacity Fade Resulting from Cycle-Life Testing of Advanced Technology Development Program Lithium-Ion Batteries. J. Power Sources 2003, 119–121, 865–869, doi:10.1016/S0378-7753(03)00190-3.

[7] Yuksel, T.; Litster, S.; Viswanathan, V.; Michalek, J.J. Plug-in Hybrid Electric Vehicle LiFePO4 Battery Life Implications of Thermal Management, Driving Conditions, and Regional Climate. J. Power Sources 2017, 338, 49–64, doi: 10.1016/j.jpowsour.2016.10.104.

[8] Selman, J.R.; Al Hallaj, S.; Uchida, I.; Hirano, Y. Cooperative Research on Safety Fundamentals of Lithium Batteries. J. Power Sources 2001, 97–98, 726–732, doi:10.1016/S0378-7753(01)00732-7.

[9] Thomas, E.V.; Case, H.L.; Doughty, D.H.; Jungst, R.G.; Nagasubramanian, G.; Roth, E.P. Accelerated Power Degradation of Li-Ion Cells. J. Power Sources 2003, 124, 254–260, doi:10.1016/S0378-7753(03)00729-8.

[10] Lundgren, H.; Svens, P.; Ekström, H.; Tengstedt, C.; Lindström, J.; Behm, M.; Lindbergh, G. Thermal Management of Large-Format Prismatic Lithium-Ion Battery in PHEV Application. J. Electrochem. Soc. 2016, 163, A309–A317, doi: 10.1149/2.09411602jes.

[11] Vazquez-Arenas, J.; Gimenez, L.E.; Fowler, M.; Han, T.; Chen, S. A Rapid Estimation and Sensitivity Analysis of Parameters Describing the Behavior of Commercial Li-Ion Batteries Including Thermal Analysis. Energy Convers. Manag. 2014, 87, 472–482, doi: 10.1016/j.enconman.2014.06.076.

[12] Qiao, S.; Hu, M.; Fu, C.; Qin, D.; Zhou, A.; Wang, P.; Lin, F. Experimental Study on Storage and Maintenance Method of Ni-MH Battery Modules for Hybrid Electric Vehicles. Appl. Sci. 2019, 9, 1742, doi:10.3390/app9091742.

[13] Wang, Q.; Ping, P.; Zhao, X.; Chu, G.; Sun, J.; Chen, C. Thermal Runaway Caused Fire and Explosion of Lithium Ion Battery. J. Power Sources 2012, 208, 210–224, doi: 10.1016/j.jpowsour.2012.02.038.

[14] Basu, S.; Hariharan, K.S.; Kolake, S.M.; Song, T.; Sohn, D.K.; Yeo, T. Coupled Electrochemical Thermal Modelling of a Novel Li-Ion Battery Pack Thermal Management System. Appl. Energy 2016, 181, 1–13, doi: 10.1016/j.apenergy.2016.08.049.

[15] Pesaran, A.A.; Keyser, M. Thermal Characteristics of Selected EV and HEV Batteries. In Proceedings of the Sixteenth Annual Battery Conference on Applications and Advances. Proceedings of the Conference (Cat. No.01TH8533); IEEE: Long Beach, CA, USA, 2001; pp. 219–225.

[16] Feng, X.; Xu, C.; He, X.; Wang, L.; Zhang, G.; Ouyang, M. Mechanisms for the Evolution of Cell Variations within a LiNixCoyMnzO2/Graphite Lithium-Ion Battery Pack Caused by Temperature Non-Uniformity. J. Clean. Prod. 2018, 205, 447–462, doi: 10.1016/j.jclepro.2018.09.003.

[17] He, F.; Ma, L. Thermal Management in Hybrid Power Systems Using Cylindrical and Prismatic Battery Cells. Heat Transf. Eng. 2016, 37, 581–590, doi:10.1080/01457632.2015.1060776.

[18] Bayraktar, I. Computational Simulation Methods for Vehicle Thermal Management. Appl. Therm. Eng. 2012, 36, 325–329, doi: 10.1016/j.applthermaleng.2011.10.040.

[19] Peng, P.; Jiang, F. Thermal Safety of Lithium-Ion Batteries with Various Cathode Materials: A Numerical Study. Int. J. Heat Mass Transf. 2016, 103, 1008–1016, doi: 10.1016/j.ijheatmasstransfer.2016.07.088.

[20] Gnanaraj, J.S.; Zinigrad, E.; Asraf, L.; Gottlieb, H.E.; Sprecher, M.; Aurbach, D.; Schmidt, M. The Use of Accelerating Rate Calorimetry (ARC) for the Study of the Thermal Reactions of Li-Ion Battery Electrolyte Solutions. J. Power Sources 2003, 119–121, 794–798, doi: 10.1016/S0378-7753(03)00255-6.

[21] Roth, E.P.; Doughty, D.H.; Pile, D.L. Effects of Separator Breakdown on Abuse Response of 18650 Li-Ion Cells. J. Power Sources 2007, 174, 579–583, doi: 10.1016/j.jpowsour.2007.06.163.

[22] Jhu, C.-Y.; Wang, Y.-W.; Wen, C.-Y.; Shu, C.-M. Thermal Runaway Potential of $LiCoO_2$ and Li (Ni1/3Co1/3Mn1/3) O_2 Batteries Determined with Adiabatic Calorimetry Methodology. Appl. Energy 2012, 100, 127–131, doi: 10.1016/j.apenergy.2012.05.064.

[23] Ling, Z.; Wang, F.; Fang, X.; Gao, X.; Zhang, Z. A Hybrid Thermal Management System for Lithium-Ion Batteries Combining Phase Change Materials with Forced-Air Cooling. Appl. Energy 2015, 148, 403–409, doi: 10.1016/j.apenergy.2015.03.080.

[24] Chen, D.; Jiang, J.; Kim, G.-H.; Yang, C.; Pesaran, A. Comparison of Different Cooling Methods for Lithium-Ion Battery Cells. Appl. Therm. Eng. 2016, 94, 846–854, doi: 10.1016/j.applthermaleng.2015.10.015.

[25] Jin, L.W.; Lee, P.S.; Kong, X.X.; Fan, Y.; Chou, S.K. Ultra-Thin Mini channel LCP for EV Battery Thermal Management. Appl. Energy 2014, 113, 1786–1794, doi: 10.1016/j.apenergy.2013.07.013.

[26] Chacko, S and Charmer, S Lithium-Ion Pack Thermal Modeling and Evaluation of Indirect Liquid Cooling for Electric Vehicle Battery Thermal Management. Woodhead Publ. 2011, 13--21.

[27] Zhao, C.; Sousa, A.C.M.; Jiang, F. Minimization of Thermal Non-Uniformity in Lithium-Ion Battery Pack Cooled by Channeled Liquid Flow. Int. J. Heat Mass Transf. 2019, 129, 660–670, doi: 10.1016/j.ijheatmasstransfer.2018.10.017.

[28] Zhao, J.; Rao, Z.; Li, Y. Thermal Performance of Mini-Channel Liquid Cooled Cylinder Based Battery Thermal Management for Cylindrical Lithium-Ion Power Battery. Energy Convers. Manag. 2015, 103, 157–165, doi: 10.1016/j.enconman.2015.06.056.

[29] Pesaran, Ahmad A Battery Thermal Management in EV and HEVs: Issues and Solutions. Indep. BATTERY Manuf. Assoc. INC 2001, 43, 34–39.