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Temperature evaluation of pouch lithium-ion battery module at different arrangement and thermal conditions

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Abstract: Thermal transport, which occurs in a single cell due to charging and discharging, will affect the cell's electrical performance. The heat generated needs to be appropriately managed via external cooling to ensure optimum electrical and electrochemical performance and whilst minimizing any cell degradation. Therefore, modelling of thermal behavior of the batteries is essential, which will essentially serve as a tool for evaluating cell performance and safety. Additionally, this can be used as a guideline, particularly in the design stage of battery module/pack design. This paper presents a thermal analysis of a lithium-ion battery module with different cell arrangements under various inlet velocities. The average outlet temperature of each module and average battery surface temperature are simulated at different cell gaps. Increasing the air velocity of the inlet cooling air will increase the magnitude of turbulence in the cell casing domain. At low airspeed, tighter cell gaps promote better cooling; however, when the airspeed increases, larger spacing between cells gives pronounce cooling effect. This is manifested by a higher outlet air temperature up to 3 degrees Celsius between arrangement of 5-mm to 10-mm. Moreover, higher cell gaps cause the cell temperature to be relatively uniform at higher air speed.

Keywords: Lithium-ion battery; Heat Transfer; CFD

1. Introduction

Due to the high consumption of energy worldwide, especially petroleum resources and high harmful emissions to the environment, the transportation industry has received much concern. Therefore, automobile manufacturers have conducted so much research to produce green power and clean vehicles over the past decades. Electric vehicles (EVs), hybrid vehicles (EVs) and fuel cell electric vehicles (FCEVs) are more energy-efficient and cleaner than the common internal combustion engine vehicle [2]. Cost, reliability, safety, cycle life, and charging duration are the main challenges to increasing EVs popularity in the market. Lithium-ion batteries have gained popularity for applications in the energy storage system of EVs mainly due its high energy density [1]. Cost plays a vital role in the adoption of electric vehicles for both manufacturers and users. Therefore, improving the battery's power performance and cycle life is essential as it determines the cost.

Extensive use of batteries is the key to a broader energy storage capability to reduce carbon footprint, particularly for the automotive sector. Additionally, acceptance of renewable energy requires a reliable energy storage system and this requires batteries, which can be monitored [13]. To fully transform to an electric powertrain, the source of energy to charge batteries must be clean and sustainable [14]. Different cell chemistries will react differently which can be evaluated using cyclic voltammetry in which its cell capacity can be accurately measured [21-22]. Therefore, to extensively investigate the cell behavior, the cyclic voltammetry should be carried out with thermal effect. In relation to thermal impact on cell, a potentiometric measurement is essential particularly to probe impact of entropy at various state of charge [23)].

Nevertheless, the deployment of batteries on a larger scale will induce thermal issues. The batteries are typically discharge or used under constant power condition. This highlights that the characterization of battery should be made in this condition [24)]. A single battery needs to be analyzed under a constant power before it can be architecture to a pack level [25)].

Numbers of batteries required in a pack level will be determined from the analysis. High numbers of cells will cause complexity with respect to temperature variation. A temperature gradient will be established across the battery pack. Temperature non-uniformity causes localized performance variation. Impact of thermal on battery performance is significant in which operating cell at a high temperature will cause the cell to be operated more efficiently but prolonged use at high temperature will increase the rate of degradation [7-9)]. Most studies were conducted to investigate battery thermal management improvement to increase the reliability of batteries in electric vehicle and hybrid electric vehicle as temperature management is the most serious issue which affects battery performance and lifespan as well [1)]. Direction of heat is also important which could eventually affect the rate of degradation of battery. Regulating battery temperature from its surface versus tab will result in significant difference in degradation rate [16)].

Mainly, all the studies discussed the ideal cooling method for battery thermal management system (BTMS) for different lithium-ion cell formats. This is primarily due to the high-temperature sensitivity of the batteries, as small temperature changes will affect its performance. Air cooling, liquid cooling, PCMs, and cell arrangement are among methods used to achieve the researcher's goal to improve thermal management system [3)] and [4)].

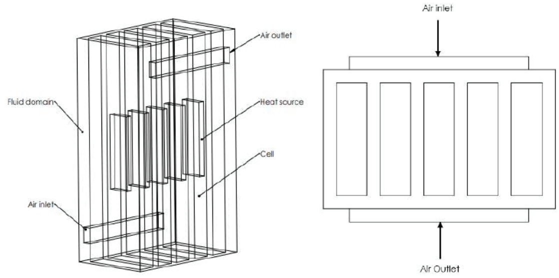
However, before any attempt is made on thermal management system, the rudimentary principle of energy balance at the cell internal needs be well comprehended [17)]. This can be model by solving the partial differential equation of the ion and charge transfer to predict the cell electrochemical performance, which then will be coupled to thermal model to further evaluate its thermal behavior [19)].

There are some studies carried out on battery cell arrangement to improve BTMS. Complexity typically increases with regards to thermal management especially for pack level. Uneven heat generation would be the main issue which requires a close attention [18)]. In 2013, Fan. L et. al [5)] investigated the cooling effectiveness of the battery model on even and uneven cell gap spacing. The impact of gap spacing and airflow rate on the cooling effectiveness of the existing air-cooled battery module has been thoroughly examined. Another experiment on cylindrical lithium-ion battery module was done by Moghaddam, S.M. [6)] to design optimum BTMS for battery module.

2. Simulation and Case Setup

2.1 Physical Model

Two different types of cell arrangements are studied. The geometrical model and the schematic of 25 Ah lithium-ion pouch cell modules with the cooling domain are shown in Fig. 1 (a) and (b). The battery pack consists of 5 Ah lithium-ion pouch cells with a cooling domain, inlet and outlet. The geometry for both modules are presented in Table 1 and Table 2, respectively. The cell size used in this experiment is 43 mm x 142.5 mm x 11.7 mm, and the heat source size is 14.3 mm x 47.5 mm x 3.9 mm, which is approximately one-third of the cell size. The air inlet and outlet opening for the first cooling domain are 68.5 mm x 10 mm, while the size of the air inlet and outlet opening for the second fluid domain is 98.5 mm x 6.95 mm. The outer cells are 5 mm away from the module case and case bottom for the first module and 10 mm away for the second module.



(a) (b)

Fig. 1: Geometry of pouch lithium-ion pouch cell module with inlet and outlet

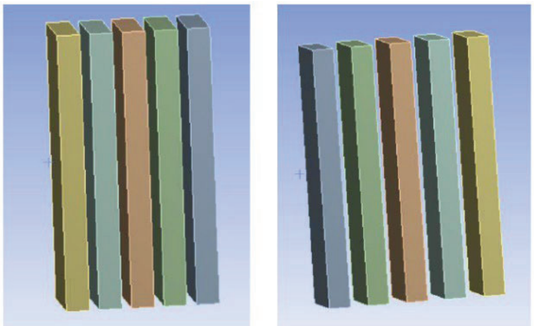
The module has five pouch lithium-ion cells positioned parallels with two different gaps spacing. In a study of battery thermal management systems, Moghaddam, S.M., [6)] conducted an experiment with multiple cell arrangements and gap spacing among cells for cylindrical lithium-ion battery module. A similar concept is repeated for this study, the cooling performance evaluation of pouch type lithium-ion battery module under various cell arrangement and velocity. The first battery module was modelled with 5 mm gap spacing and the overall size of this numerical domain of 53 mm x 142.5 mm x 88.5 mm. While the second geometry's cells arrangement by 10 mm gap spacing with an overall size of the numerical domain of 63 mm x 142.5 mm x 118.5 mm. Figure 2 (a) and (b) show the geometry of cells with the spacing of 5 mm and 10 mm, respectively.

Table 1. Details of pouch cell module with 5-mm gap between cells

Parameter	Dimension
Overall Dimension (mm)	$53 \times 142.5 \times 88.5$
Battery Size (mm)	$43 \times 142.5 \times 11.7$
Heat Source (mm)	$14.3 \times 47.5 \times 3.9$
Air Inlet (mm)	68.5×10
Air Outlet (mm)	68.5×10

Table 2. Details of pouch cell module with 10-mm gap between cells

Parameter	Dimension
Overall Dimension (mm)	63 × 142.5 × 118.5
Battery Size (mm)	43 × 142.5 × 11.7
Heat Source (mm)	14.3 × 47.5 × 3.9
Air Inlet (mm)	98.5 × 6.95
Air Outlet (mm)	98.5 × 6.95



(b) **(b)**

Fig. 2: Cell arrangement: (a) 5-mm gap spacing and (b) 10-mm gap spacing

The ANSYS Fluent that used in this paper is limited to 512,000 cells. Therefore, the meshing cells used in this simulation are within the respective limit. A total of six types mesh were employed to investigate the grid independence test for both cases. After meshing of module with 5 mm gap spacing, elements about 483,082 are generated with 166,155 nodes. Table 3 highlights the details of the mesh with the number of elements. Figure 3 shows that as the element numbers increased from 483,082 to 502,890, and that the average outlet temperature and the average velocity are converged within 0.0013 % and 0.068 % after the element numbers of 483,082. Element with number of 483,082 is selected for battery model with 5 mm spacing and element number of 455,742 for battery module with 10 mm cell spacing respectively for the numerical analysis, considering accuracy as well as computational cost.

Table 3. Details of element for grid independent test of battery module with 5-mm spacing

No of Elements	No of Nodes	Outlet Temperature (K)	Outlet Velocity (m/s)
198,350	66,057	307.178	1.071
239,276	77,500	307.271	1.061
281,781	91,974	307.367	1.049
365,063	122,134	307.470	1.034
483,082	166,155	307.500	1.022
502,890	171,578	307.504	1.022

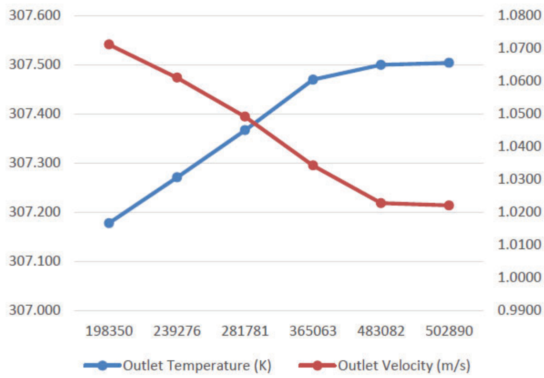


Fig. 3: Mesh independence test of cells with 5 mm spacing

While Table 4 and Figure 4 show the meshing of battery module with 10 mm gap spacing, 455,742 elements are generated with 137,713 nodes and it increased to from 455,742 to 485,866. The average outlet temperature and the average velocity are converged within 0.0006 % and 0.01 % after the element numbers of 485,866.

The cells are assumed to reject heat at a constant rate to simplify the CFD simulation. Hence, related electrochemical reactions can be neglected. Air is perceived as the coolant in this numerical analysis, and the coolant flow is assumed to be incompressible. The cell's thermophysical properties, such as thermal conductivity, specific heat, and viscosity of the coolant, are considered temperature insensitive. Information such as heat flux, heat generation rate and heat transfer coefficient were taken from previous study as the current study focuses on the effect of air velocity on cooling of a pouch lithium-ion battery model. Wang et al. [11] carried out heat generation rate cell about 19,452 W/m² was taken from a study while the heat flux and heat transfer coefficient taken from Jiaqing et al. [10] who investigated the heat dissipation of the power lithium-ion battery module.

Table 4. Details of element for grid independent test of battery module with 10-mm spacing

No of Elements	No of Nodes	Outlet Temperature (K)	Outlet Velocity (m/s)
215,034	59,766	308.923	1.025
260,569	77,024	308.920	1.019
309,781	89,547	308.917	1.015
352,795	104,866	308.914	1.004
455,742	137,713	308.897	0.985
485,866	144,624	308.895	0.984

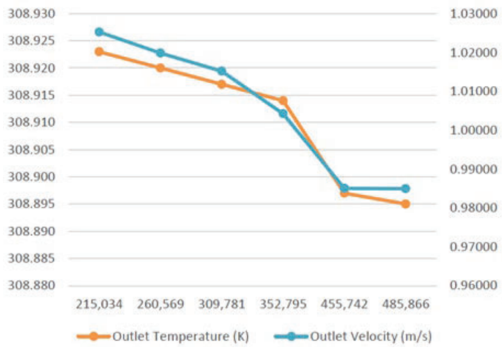


Fig. 4: Mesh independence test of cells with 10 mm spacing

3. Thermal Impact On Cell Module

3.1 Heat Generation On Cell

The heat source of battery cell assumed as constant temperature about 320 K for this study. The chosen temperature is higher as this experiment simulated to evaluate cooling performance for worst-case scenario of battery thermal condition. Figure 5 shows the temperature contour of heat distribution from heat source to battery wall. The heat from heat source transfer to the battery wall by conduction. The heat distribution from heat source to wall is uniform and symmetrical as well. The recorded average temperature at battery wall is 319.6 K. The temperature difference between heat sources to battery wall is 0.348 K. In a study about improvement in cooling performance of the battery thermal management system, Kirad, K., and Chaudhari, M. [12]. obtained the temperature difference about 0.135 K at natural convection boundary conditions. Based on this, the simulation was continued with five pouch lithium-ion cells positioned parallel for the module with 5 mm cell gap spacing and 10 mm cell gap spacing as well.

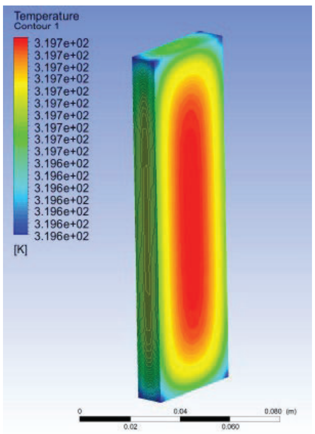


Fig. 5: Temperature distribution of pouch lithium-ion battery from heat source to battery surface

3.2 Outlet Temperature of Battery Module

The average outlet temperature of module of 5 mm cell gap spacing and 10 mm cell gap spacing is shown in Fig. 6. From the results, highest average outlet temperature and temperature difference was recorded at lowest velocity, which is 0.1 m/s for both modules. This is due to the slow heat transfer happened at lowest velocity at steady state condition. However, more heat rejection occurs with inlet temperature of 2 m/s. As air speed increases, the mass flow rate increases, which causes heat to be transferred at higher rates. The increase in turbulence in battery module results in an increase for convection away from the cells. With 10-mm spacing, better heat transfer can be achieved as compared to 5-mm spacing. This is due to bigger fluid domain for heat transfer to happen. In essence, the heat transfers happened more effectively at module of 10-mm cell spacing.

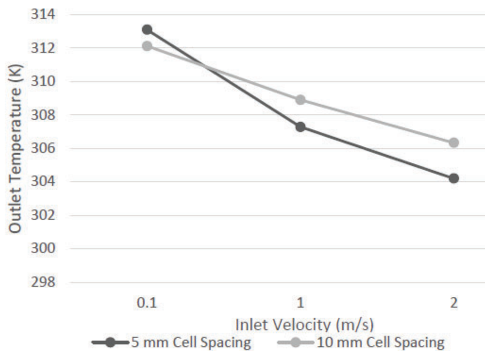


Fig. 6: Average battery surface temperature against inlet velocity

3.3 Surface Temperature Of Battery Module

The average temperature of battery cell surface, fluid domain and module wall were recorded higher at lowest velocity, 0.1 m/s. Additionally, the temperature decreases gradually when the inlet velocity increases. The increase of mass flow rate of fluid as velocity increases will improve the heat transfer rate. This causes the average temperature of the battery surface to increase. In addition, the maximum temperature difference of battery module decreases with the increasing initial spacing. Thus, it can be said that module of 10-mm cell gap spacing has better cooling performance than module of 5-mm cell gap spacing. As a result of difference in heat transfer rate, the average battery surface temperature for 10-mm cell gap spacing is relatively lower than 5-mm as shown in Fig. 7.

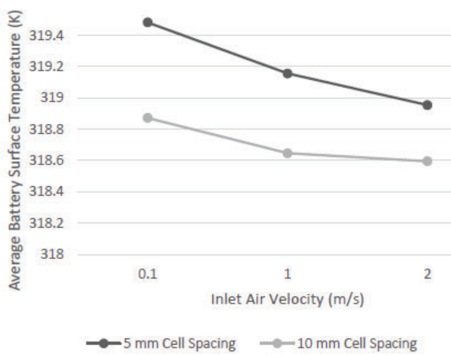
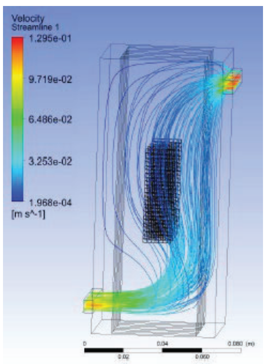


Fig. 7: Average battery surface temperature against inlet velocity

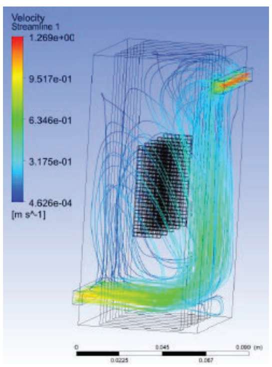
3.4 Streamline of Cooling Air and Impact on Reynolds Number

The velocity streamline for module of 5-mm cell gap spacing and 10-mm cell gap spacing shown in Fig. 8 (a) – (c). The streamline at 0.1 m/s for both module smoother, while the streamline at 1 m/s and 2 m/s are fluctuated. Increase in inlet air velocity will eventually increase the Reynolds Number where flow is moving from laminar to transition zone. This causes the air circulation rate inside the battery module increase. Based on calculated Reynold Number for both modules, module of 5-mm cell gap spacing is higher than module of 10 mm cell gap spacing. The calculated Reynolds Number for module of 5-mm cell gap spacing at 2 m/s is 2389.2, while for the module of 10-mm cell gap spacing at 2 m/s is 1778.8. Although the area of inlet and outlet are same, the perimeter values for both modules are not same. Therefore, the calculated Reynolds Number for module of 10 mm cell gap spacing is lower as the inlet and outlet are shorter and wider.

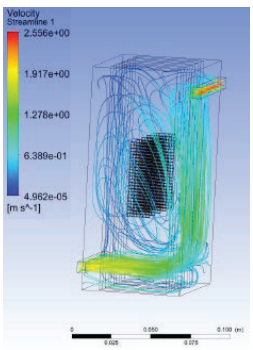
Theoretically, module of 5-mm cell gap spacing has higher turbulence compared to module of 10 mm cell gap spacing. Thus, the heat transfer rate for module of 5-mm cell gap spacing is higher. However, the final cell surface temperature was recorded lowest at module of 10-mm cell gap spacing. This is due to the cell arrangement in which with higher gap spacing allows more air to enter effective cell cooling area and this effect is more dominant the increase of Reynolds number.



(a)



(b)



(c)

Fig. 8: Velocity profile of the air cooling at air speed of : (a) 0.1 m/s , (b) 1 m/s and (c) 2 m/s

4. Conclusion

The pouch type lithium-ion battery module with two cell arrangement is simulated to evaluate the cooling performance under various velocities. The effect of variation of the inlet air velocity (0.1 m/s, 1 m/s and 2 m/s) at constant inlet temperature is reported. Considering the maximum of heat source about 320 K, the cooling performance is better with highest inlet velocity at constant temperature. The battery surface temperature for module of 5-mm cell gap spacing and module of 10-mm cell gap spacing at 0.1 m/s velocity are 319.482 K and 318.872 K, while the battery surface temperature at 2 m/s are 318.954 K and 318.595 K respectively. Increasing the velocity of the inlet air, increase the turbulence flow and decrease the temperature difference. This will also increase the Reynolds number of air moving between the cells. Although the turbulence flow is higher for module of 5-mm cell gap spacing, how highest temperature differences were recorded for module of 10-mm cell gap spacing. This is mainly due to more air is allowed to fill in effective area between cells. High Reynolds number between cells does not play bigger role in giving higher cooling capability. In conclusion, the simulation results show that the overall temperature of the battery module is reduced and the cooling performance improved after optimization of battery module by increasing cell gap spacing and inlet velocity.

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