Journal of Advanced Research in Fluid Mechanics and Thermal Sciences

Journal homepage:
https://semarakilmu.com.my/journals/index.php/fluid_mechanics_thermal_sciences/index
ISSN: 2289-7879

Forced Air Cooling for Battery Module on Series Connected Batteries: Temperature Variation Due to Non-Uniform Flow Across Channel

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ARTICLE INFO

Article history:
Received 10 August 2023
Received in revised form 24 October 2023
Accepted 5 November 2023
Available online 15 November 2023

Keywords:
Lihtium-ion battery; heat transfer; CFD

ABSTRACT

Cells in battery pack for electric vehicle are typically connected in series to meet system voltage requirement. In series connection, each cell will experience identical amount of current drawn, therefore the amount of heat generation for each cell will be relatively similar. Nevertheless, this depends on the cell internal resistance which causes joule heating. To mitigate increase in temperature in the pack, cooling system is necessary. Forced air cooling is the most straightforward cooling system as it pulls cool air from inside the vehicle cabin, and the air will be channeled through cooling routes in the battery module. Typically, the cell located close to the inlet of the cooling system gets the maximum cooling rate, and the cooling capacity reduces as air passes towards the last cell in the module. Two cooling designs are explored in which air velocity is varied by changing the cross-sectional area of inlet air whilst keeping the same mass flow rate. This causes the inlet air velocity to change, to which the airspeed for a small air inlet will be higher than a larger inlet. It shows that higher air speed promotes better cooling only at the first and last cell in the module with a temperature gradient up to 15°C. A battery module with a higher cross-sectional area provides a more uniform heat transfer rate whereby the individual cell temperature is relatively similar with 50% more consistent than the smaller cross-sectional area. This demonstrates that having a higher air speed is not the key attribute in determining the cooling factor of a battery module/pack.

1. Introduction

Internal combustion engines (ICE) have held a dominant position in fleet vehicles for generations. The maturity of this technology is evidenced by its widespread adoption across several applications. However, with regard to air quality, specifically in urban areas where transit plays a significant role in the economy, it is imperative to mitigate carbon emissions. Therefore, it is imperative to identify

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https://doi.org/10.37934/arfmts.111.1.226236

a feasible resolution to reduce carbon emissions in the transportation sector. Implementing electrification in powertrain systems offers a potential solution for addressing the primary limitation of utilising internal combustion engines. Nevertheless, the widespread adoption of entirely electric vehicles would present specific challenges, particularly with driver behaviour. Hence, implementing powertrain hybridisation may serve as a temporary measure before transitioning towards a more extensive level of electrification.

Electric cars and hybrid emerge as disruptive forces in the automobile industry, positioning themselves as the preferred alternative for future transportation. This shift is driven by a growing global preoccupation with the causes and consequences of climate change, as well as significant advancements in portable battery technology, particularly lithium-ion batteries. While battery-powered electric vehicles may not wholly eradicate greenhouse gas emissions in transportation, they possess the capacity to mitigate daily tailpipe emissions. Within the transportation industry, it has been approximated that most of the existing cars in operation are reliant on conventional carbon-based fuel sources. Comparative analysis was conducted and showed that battery electric vehicle gives better comparison fuel economy as compared to plug-in-hybrid and normal internal combustion engine as stated by Anida *et al.,* [1]. The limited temperature range within which lithium-ion batteries can effectively operate presents a significant obstacle to the widespread adoption of electric vehicles. The operation cycle of Lithium-ion Batteries generates internal heat, which poses significant challenges in terms of safety and performance as described by Razi *et al.,* [2] and Ardani *et al.,* [3]. These challenges include the dissolution of electrolytes at elevated temperatures as described by Gu and Wang [4] and reduced energy and battery power output at extremely low temperatures as shown by Liu *et al.,* [5]. Battery thermal management systems facilitate the maintenance of lithium-ion cells within a battery pack at their designated operating temperatures. Furthermore, gauging energy content in the battery pack posed huge challenges. This is mainly due to highly dynamic nature of the battery operation. Omairi and Ismail [6] implemented multi-layer perceptron to track state of charge of battery rather than using the typical coulomb counting. This allows better tracking with respect to rapid change of the battery dynamics.

Implementing a cooling system for battery packs or modules is widely prevalent, especially in electric and hybrid vehicles as described by Jiaqiang *et al.,* [7], Tong *et al.,* [8], and Wang *et al.,* [9]. This observation underscores the increasing popularity of the system, as it is driven by the substantial power consumption of battery systems, resulting in the huge dissipation of heat. Two distinct categories of cooling systems exist, specifically passive and active. The latter employs a feedback mechanism to regulate the operation of the cooling system, enabling it to be turned on or off as needed as technically described by Brand *et al.,* [10]. Furthermore, these findings are also supported by Herninda *et al.,* [11] and Singh *et al.,* [12]. Determining temperature within a battery module/pack is contingent upon the specific location at which the measurement is being conducted. The utilisation of this technology results in energy conservation for cooling purposes, yet the control mechanism employed for feedback presents a considerable level of complexity as presented by Saw *et al.,* [13]. In contrast, a passive cooling system does not necessitate an extensive control system. Typically, a phase change material is wrapped around the cell surface which will absorb heat from the cell and suppress the temperate increase as conducted by WafirulHadi *et al.,* [14]. Additionally, active cooling employs circulation of a cooling liquid within the battery module or pack as described by Akinlabi and Solyali [15] and Al Shdaifat *et al.,* [16]. The cooling effectiveness of the method typically depends on the Nusselt number as described by Ansari *et al.,* [17]. Higher Nusselt number promotes higher foced convection coefficient which essentially increases rate of heat removal at solid surface. Subsequently, the rate of heat removal can be improved by using nanofluid as a cooling medium. Nanofluid or hybrid nanofluid improves thermal performance especialy with combination of microhcannel which is exensively decribed by Jowsey *et al.,* [18] and Che Sidik *et al.,* [19]. Adding nanoparticle in coling medium essentially allows more heat to be trafferred from heat source. This indirecty increases Nusselt number hence improve heat transfer via forced convection that highlighted by Elfaghi *et al.,* [20].

The circulation of a cooling liquid within a battery module or pack is controlled by fans or compressors, which govern the mass flow rate. A high mass flow rate is preferable to mitigate the temperature rise that occurs during periods of high discharge load. Lithium-ion batteries exhibit favourable performance characteristics in elevated temperatures; nevertheless, extended exposure to such conditions can lead to a decline in battery longevity as described by Liu *et al.,* [5] and Wang and Zhao [21]. It is worth noting that the optimal operational temperature range for lithium-ion batteries lies within 0 to 50°C. However, subjecting the Li-ion battery to high temperatures during the charging process can result in battery degradation as described by Tong *et al.,* [22]. Charging a battery in low-temperature conditions has led to an elevation in the battery's internal resistance. Consequently, this increase in resistance has been found to contribute to a lengthened and decelerated charging duration [23].

Prolonged charge discharge will deteriorate the battery, and this impact is pronounced if the depth of discharge is higher [24]. A high C-rate promotes a higher rate of degradation. This would eventually exacerbate if the cooling system of the battery module/pack cannot maintain a safe temperature window. The role of the cooling system is not only keeping the cell at a safe operating temperature. It also must be able to keep the temperature between cells as close as possible. Temperature variation across battery pack/module is inevitable. However, this should be kept as low as possible to minimize degradation. A case study has been conducted at Kolej Komuniti Kepala Batas, where the voltage across the battery module from Toyota Prius-C is measured. This battery module has been used for quite some time, and it has a cooling inlet from one side, as shown in Figure 1. Continuous usage has caused the battery voltages to vary. As such, batteries that are closed to cooling inlet possess lower voltage as shown in Figure 2. This could be due to differences in cooling capability across the battery module. This work analyses temperature variation across batteries for large and small air-cooling system openings. The process is conducted through computational fluid dynamic simulation to evaluate temperature variation across battery modules.

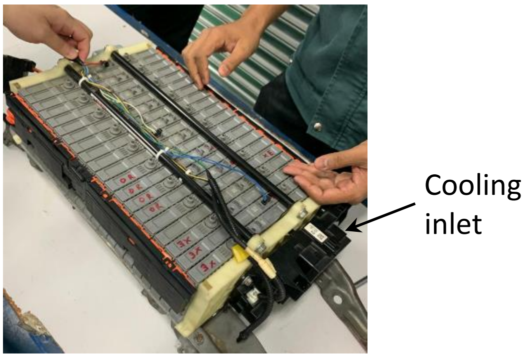


Fig. 1. Toyota Prius-C battery module at Kolej Komuniti Kepala Batas

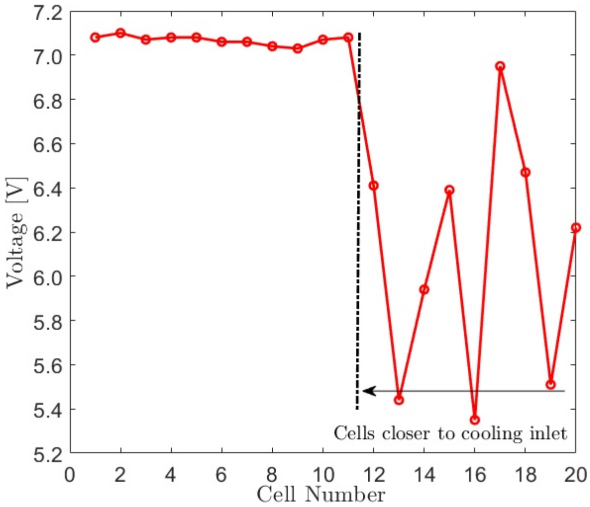


Fig. 2. Cell voltage variation across the Prius-C battery module at Kolej Komuniti Kepala Batas

2. Modelling Configurations

The simulation is conducted with only 15 cells per module, which is slightly less than the number of cells that can be found in the actual Prius-C battery, with 28 cells per module. Table 1 summarizes the physical parameters used in this study, which is extracted from Razi *et al.,* [2]. The cell dimensions relatively match the size of the Prius-C battery. Therefore, it is chosen for the analysis to essentially replicate the physical condition experienced in the Prius-C battery module. This study aims to investigate the impact of airspeed on the temperature of the cells in the module. In order to achieve this, the inlet size of the module is varied in two sizes, as shown in Figure 3 and Figure 4 for small and large openings, respectively.

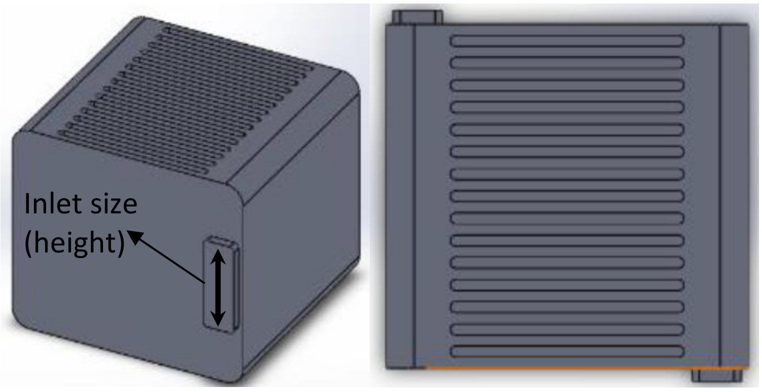


Fig. 3. Battery module small opening

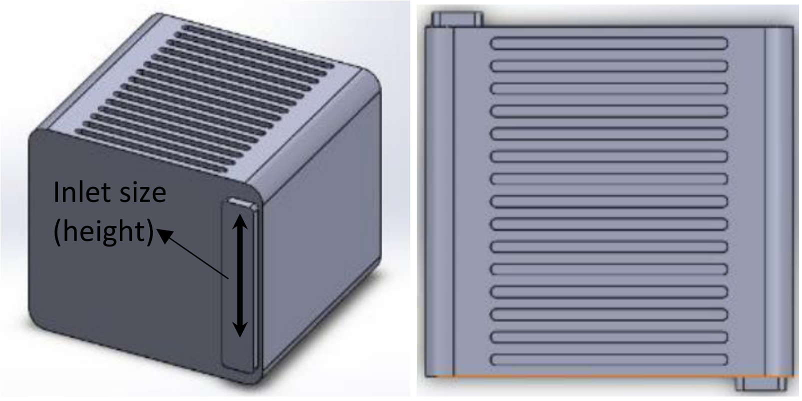


Fig. 4. Battery module with large opening

Table 1
Battery module physical parameters

Battery dimension	160mm X 220mm X 8mm
Pack dimension	200 mm X 230 mm X 248 mm
Gap between cell	8 mm
Number of cell per module	15 cells
Inlet area	3500 mm^2 (Small opening) 6650 mm^2 (Large opening)

The outer surface of the battery module is insulated to thoroughly investigate the impact of air cooling on the battery surface. This is mathematically represented by Eq. (2), in which the heat carried by the air will not be rejected through the wall of the battery module. The heat generated by each of the cells is assumed to be constant with a value of 0.5 watts [3]. This value is applied constantly across all of the cells. Due to the air constantly flowing in the battery module, heat from the cell surface is rejected via forced convection, represented by Eq. (1). The heat transfer coefficient is estimated to be within the forced convection region, which is 25 W/m^2.^{o}C. In order to probe the temperature variation of the cell, a three-dimensional heat conduction equation represented by Eq. (3) is solved, and this equation is applied to each of the cells.

$$\mathrm{q_{convection}} = \mathrm{hA_s(T_s - T_{air})} \tag{1}$$

$$\mathrm{q_{wall}} = {}^{\mathrm{dT}}\!/_{\mathrm{dx}} = {}^{\mathrm{dT}}\!/_{\mathrm{dy}} = {}^{\mathrm{dT}}\!/_{\mathrm{dz}} = 0 \tag{2}$$

$$\mathrm{\rho C_p V \frac{dT}{dt} = k_x \frac{d^2T}{dx^2} + k_y \frac{d^2T}{dy^2} + k_z \frac{d^2T}{dz^2} + q} \tag{3}$$

The applied mass flow rate is kept constant for both battery module designs with a value of 0.001 kg/s [4]. By keeping the mass flow rate constant, changing the size of the air cooling inlet section would eventually affect the inlet air speed for the cooling of the battery module. The direction of air is illustrated in Figure 5. The model uses k-ω sst turbulence model coupled with an energy equation to solve for temperature.

The Semi-Implicit Method for Pressure-linked Linked Equations (SIMPLE) technique is used as a numerical procedure for solving the Navier–Stokes equations in computational fluid dynamics. This technique is used to tackle various fluid flow and heat transfer problems. The k-omega SST model provides a better prediction of flow separation than most RANS models and accounts for its good behavior in adverse pressure gradients. It can account for the transport of the principal shear stress in adverse pressure gradient boundary layers. This model also has the best prediction on narrow areas. Therefore, it is deemed suitable for this geometry because the gap between cells is relatively narrow.

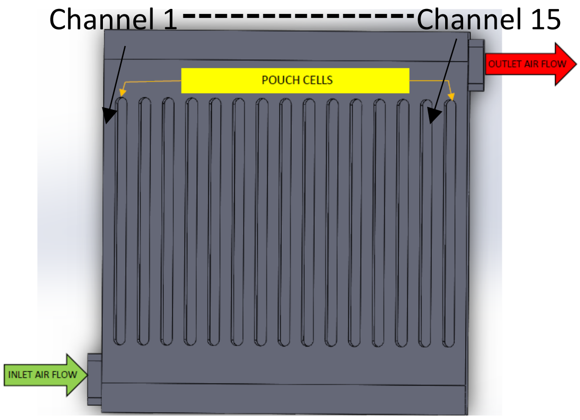
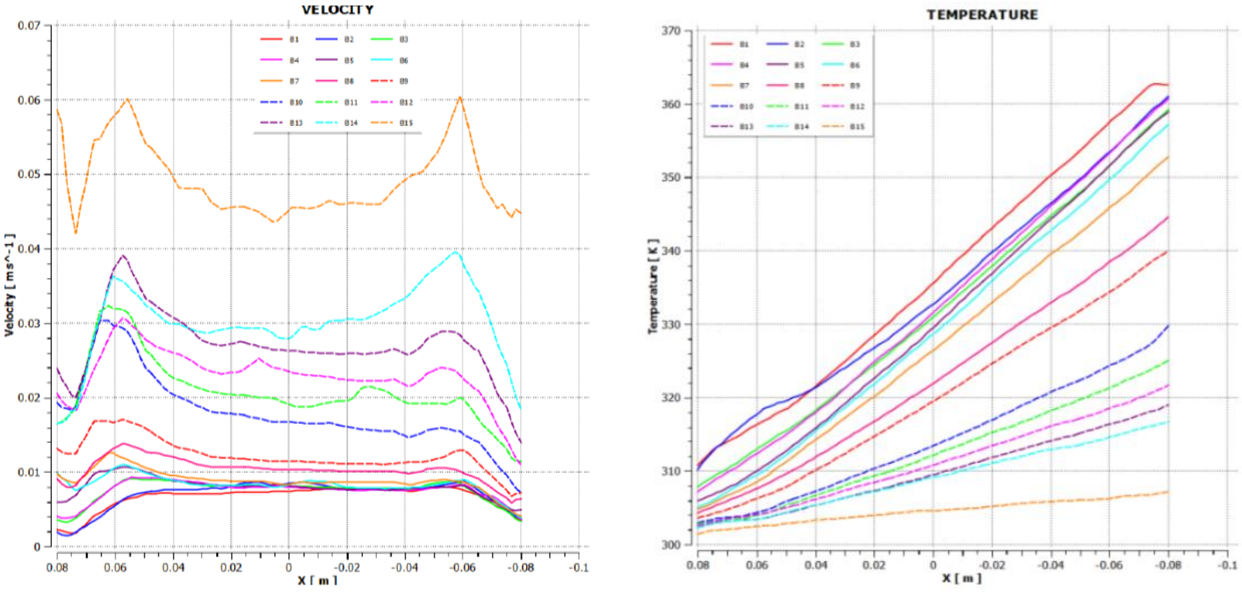


Fig. 5. Air flow direction

3. Temperature Profile Evaluation

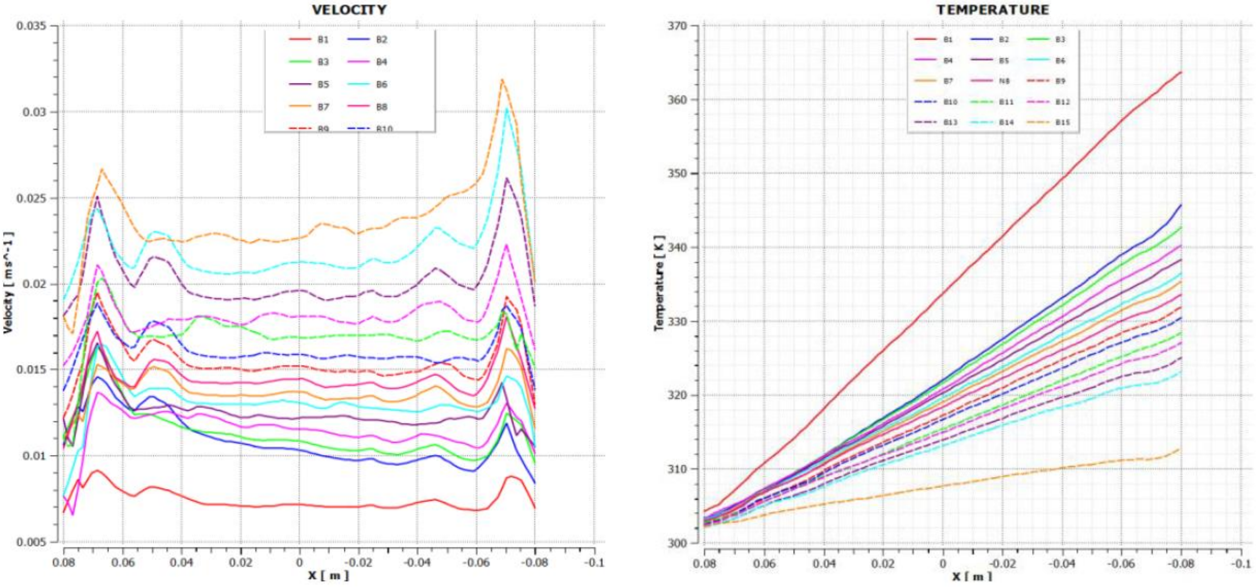
The simulated air flow is conducted with a mass flow rate of 0.001 kg/s; therefore, the effective air speed is 0.1232 m/s and 0.2348 m/s for the case of small and larger openings, respectively. As the airspeed increases, the cooling rate increases due to an increase in Nusselt number. This would eventually increase the local heat transfer rate at the cell's surface. The air inlet temperature for both cases is set to 300K. Gaps or channels between cells are filled with forced air in which heat from the cell's surface is taken by forced air convection. Variations in airspeed can be seen in Figure 6(a) and Figure 7(a) for small and large openings, respectively.

A small opening causes airspeed to increase, and therefore, each of the channels experienced relatively higher airspeed as compared to the case of a large opening. These effects promote large cooling capability, particularly at the point where the air starts to enter each of the channels. Figure 6(b) and Figure 7(b) illustrate the average cell surface temperature. It can be seen that the cell surface temperature increases linearly from the point of air entering to the air exiting, particularly at each air channel. This is mainly due to constantly applied heat generation, and when the airspeed enters the channel, the cell surface closest to the air inlet receives a higher rate of cooling. The air enters at a relatively lower temperature; hence, when the air travels, the first edge of the battery surface gets the maximum cooling effect. The higher temperature difference in this region promotes higher heat loss through forced convection. As the air travels along the cell surface, the air temperature increases, eventually reducing the temperature difference between the air and battery surface. An increase in temperature differences reduces the ability of heat rejection on the cell surface. This is manifested by a linear increase of cell surface temperature from the air inlet to the air exit of each channel. At higher velocities, regions show lower battery temperatures. When the velocity increases, the Nusselt number increases. As the Nusselt number increases, the heat convection rate will also increase. As the Nusselt number increases, the heat convection rate will also increase, eventually resulting in higher heat convection rates.



(a) (b)

Fig. 6. Temperature and velocity pattern for small opening



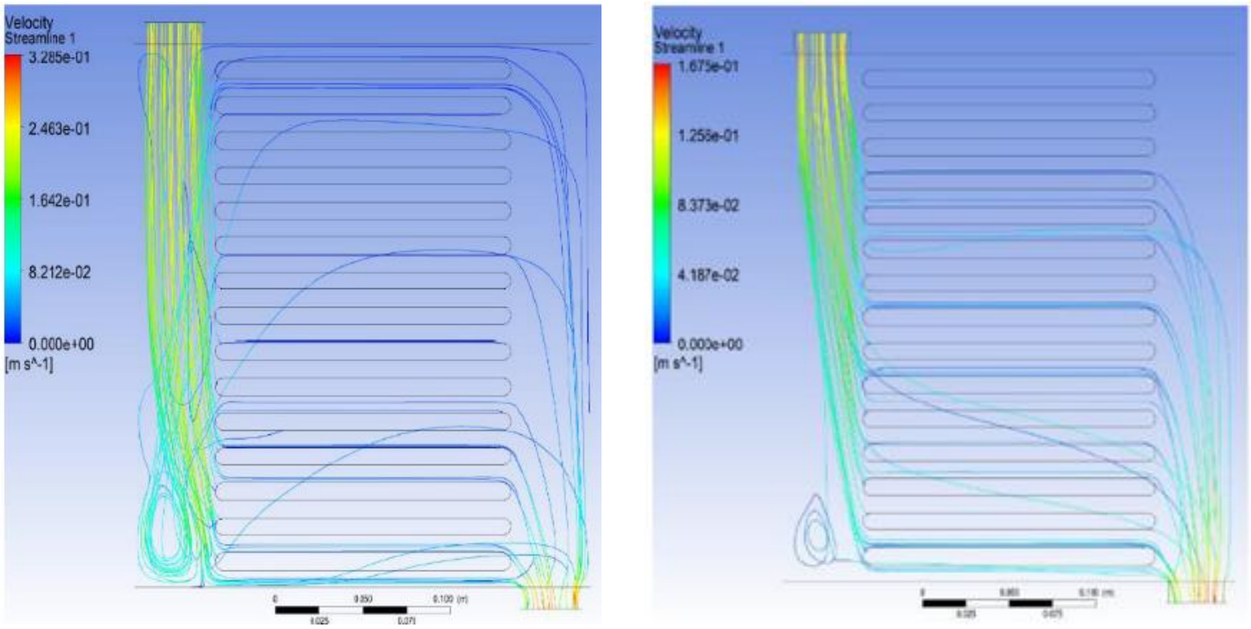
(a) (b)

Fig. 7. Temperature and velocity pattern for large opening

Due to higher air speed for the case of a small opening, the average cell temperature is smaller than that of a large opening. The lowest cell surface temperatures are 34^{o}C and 39^{o}C for small and large openings, respectively. On the other hand, the highest temperatures are 89^{o}C and 91^{o}C for cases of small and large openings, respectively. This shows that a small opening promotes higher cooling rates; if the performance of the battery module is concerned, the lowest temperature is not necessarily better. The module/pack batteries should have similar temperatures to avoid local current deviation during charge and discharge. The operating current depends on the cell temperature, in which a high temperature will allow a higher current rate. Therefore, when a cell has a significant temperature difference in the battery module, cells with higher temperatures will be charged/discharged at relatively higher rates than other cells. Although this study shows that the battery module with a large opening possesses a higher average temperature, the cells' temperatures in the module are relatively close, and the differences between cells are narrow. Module with a small opening has a larger temperature difference between cells. Higher airspeed increases the cooling rate. However, non-uniform airflow entering each channel creates significant temperature uniformity across the battery module.

4. Airflow Evaluation

Air for battery cooling is forced to flow through each channel that houses the battery in between. The airspeed is higher in the case of the small opening. In general, higher air speed promotes a higher rate of cooling. However, higher air speed carries relatively higher momentum. This causes only approximately one-third of the channel to receive adequate airflow, particularly the channel close to the outlet port. This causes average cell temperatures close to the outlet port to have lower temperatures than cells at another channel, as shown in Figure 8. High variation of airspeed causes considerable temperature uniformity whereby most cells possess a high average temperature at the inlet location compared to cells towards the exit. Inadequate airflow in this section causes a drop in cooling capability. Small opening forces the airspeed to increase, eventually creating higher cooling capability. However, a large temperature gradient across the battery module is manifested due to non-uniform airflow, as shown in Figure 9. On the other hand, a large opening causes the airflow to be divided relatively even, reducing the temperature gradient across the battery module.



(a) (b)

Fig. 8. Velocity contour for: (a) Small opening, (b) Large opening

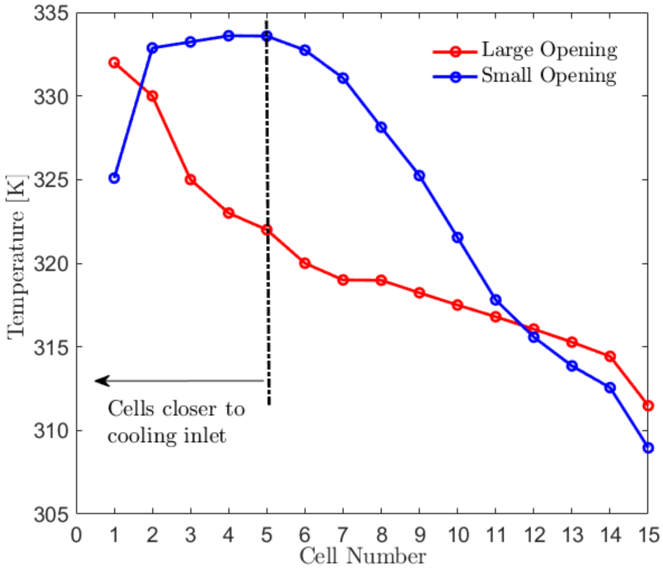


Fig. 9. Temperature and velocity contour for large opening

5. Conclusions

The simulation was conducted to predict temperature variation across battery pack aimed at two cases. The small inlet flange showed higher cooling capability due to higher airspeed. However, it created highly non-uniform temperatures across the battery pack, eventually hampering its performance over prolonged usage. On the contrary, a large flange provided more temperature uniformity across the battery pack as the temperature difference between cells in this setup was relatively narrow. Nevertheless, a large flange's cooling capability was comparatively low compared to a small flange. In essence, higher air speed provided higher cooling capability; however, it caused significant temperature non-uniformity across the battery pack. Therefore, it is crucial to balance between cooling capability and temperature uniformity in which the airspeed and gap between channels need to be optimized to balance these two figures of merits.

Acknowledgement

This work was funded by the Ministry of Higher Education under Fundamental Research Grant Scheme (FRGS/1/2020/TK0/UTM/02/111).

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