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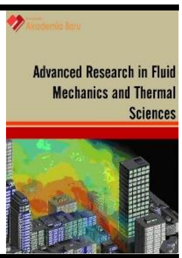

Recent Studies on Lithium-ion Battery Thermal Behaviour for Electric and Hybrid Electric Vehicles: A Review

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ABSTRACT

Environmental issues related to excess greenhouse gases have led to the introduction of electric (EV) and hybrid electric vehicles (HEV). The power source of these vehicles is mainly supplied from a battery specifically Lithium-ion battery (LIB). Lithium-ion battery possesses the characteristic of high power rating, high energy density, and high cycle life. However, this battery suffers from temperature problems, and thus battery thermal management (BTM) is crucial. This paper reviews the existing works related to lithium-ion battery thermal behaviours such as battery heat generation, battery temperature distribution and battery thermal management. Analysis of battery heat generation and temperature distribution is focusing more on single cell temperature behaviour. For battery thermal management, cooling systems such as air-based, liquid based and solid-based are reviewed but special attention has been putting on air-cooling type.

1. Introduction

Land vehicles that available on the road such as cars, busses, trucks, and even motorcycles are increasing in numbers as years passed. This include the increase of internal combustion engine (ICE) usage since most vehicles are powered by the mechanical stroke of an ICE [1]. However, the products produce by burning fossil fuels inside ICE is not environmentally friendly since it produce waste products of excess carbon dioxide during complete combustion and carbon monoxide during incomplete combustion, which will affect the health of humans and contributes to the addition of greenhouse gases [1, 2]. Build-up of greenhouse gases in the lower level of atmosphere traps the heat causing increase of earth temperature and lead to the catastrophic effect of global warming such as rising sea level, droughts, climate changes and flora fauna extinction [3]. Based on a report from Shaukat et al. [4], transportation sector contributes 31% of greenhouse gases emissions and the

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other percentage consist of electricity power sector, industry sector, residential commercial sector and lastly, renewable energy resources sector [4]. Because of this increasing greenhouse gas problem, solution has been made to counter the effects. Some example would be the emergence of green energy such as wind turbines, hydro dam power, and solar power for supplying electricity to the grid [5]. In transportation sector, they have introduced electric vehicle (EV) and hybrid electric vehicle (HEV) that target in reducing the emission of greenhouse gas such as carbon dioxide [5, 6].

In all the architecture of EVs and HEVs, battery is the main component that provides electrical power for the whole systems. The requirements of becoming an electrical storage power supply for this system is to have a high power rating, high density of energy, high life-cycle and safe to be operate [7, 8]. Lithium-ion battery (LIB) types are widely used in the application of EV and HEV nowadays due to its good characteristic that meets the requirements of becoming a power supply storage, plus LIB does not contain any poisonous metals like cadmium, lead or mercury [7-9]. Although LIB possess good characteristic that is suitable for application for EV HEV energy storage, LIB has a major downside related to the effects of temperatures since it will have a great impact on the cell operating efficiency, contribution to cell degradation, reducing lifetime cycle of the battery and increase safety risks [10-13]. Figure 1 shows the relationship of various types of battery, heat responses and ways on managing the dissipation of battery heat.

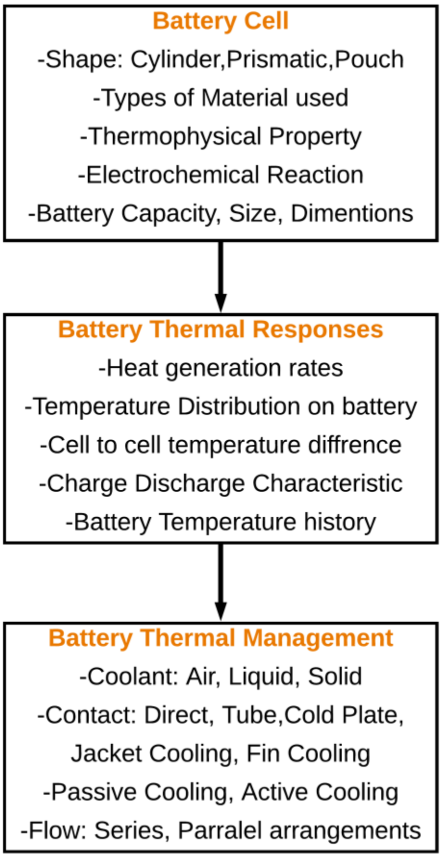

Fig. 1. Flow of Battery thermal management

In this paper, review process has been carried out in these scopes: 1) Introduction of Lithium-ion battery; 2) Battery heat generations; 3) Battery temperature distribution throughout the surface area; 4) Battery thermal management review on air, liquid and solid heat dissipation systems.

2. Battery Heat Generation

There are two sources that contribute to heat generation in lithium-ion battery: 1) Joule effects, where heat is generate when electric charge flows through a resistance. 2) Heat released by electro-chemical reactions [14]. There are also outside parameters that influence the heat generation of lithium-ion battery such as,

- Charge and Discharge current. When higher value of current used for charging and discharging, joule effect presents the strongest contributor of high temperature.
- The State of Charge (SOC) effects. SOC define as the percentage energy remains in the battery. SOC are linked to the electrochemical phenomenon and diffusion of lithium ions.
- Temperature of battery will also affect the electrochemical reactions that can result the internal resistance become decrease.
- The battery material chemistry because some material has great impact on heat.

Study of different current rates for charge and discharge in order to obtain the relationship with temperature is widely done since joule effect become the main heat contributor at higher current rates. The relationship obtain is, higher rates of currents circulates inside a battery, the average battery temperature increase [15-18]. The relationship of current rates and temperature is shown in figure 2. As currents pass through a certain resistance, some energy will loss as heat thus when more currents are supplied, more energy will loss that will contribute into the heat generation from battery.

Second parameter that influences heat generation of lithium-ion battery is the state of charge (SOC) of the battery. Knowing that increase of current rates will lead to higher heat generation and the temperature increase is almost linear. When it comes to end of discharge process or more specifically below 20% of SOC, there is a sudden increase of temperature as shown in figure 3 [19]. The sudden increase of temperature is due to a huge increase of internal resistance at the end of discharge process [19].

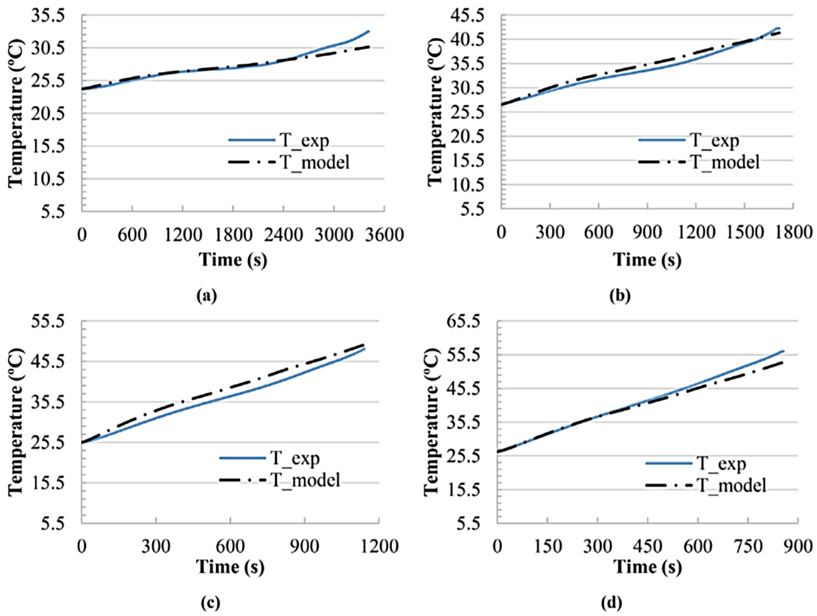

Fig. 2. Average temperatures of the battery pack, a) 1C, b) 2C, c) 3C, d) 4C [15]

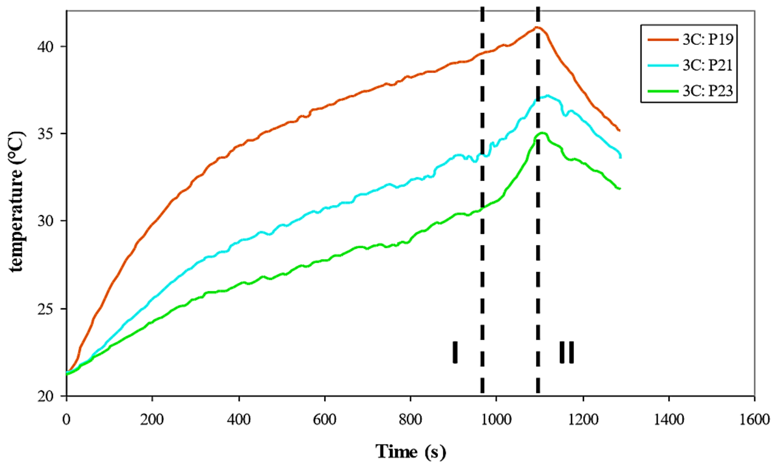

Fig. 3. Cell surface temperature evolution under 3C discharge rate at cooling air velocity of 2 m/s for abuse discharge [19]

3. Battery Temperature Distribution

Temperature at different points on the cell surface is different. This is because lithium-ion are able to move freely inside the electrolyte, thus at certain area that are pack with movement of ions, temperature is higher. Determining the cell-surface temperature distribution is one of the solutions on managing thermal issues on lithium-ion battery [20-22]. The purpose of this method is to find which area that represent higher cell surface temperature. The method is to arrange thermocouples on the cell surface, run the charge or discharge process, then record and compare the temperature of all thermocouples. In figure 4, 3 different types of thermocouples arrangement are presented. The arrangement is based on early hypothesis where heat generated more near the positive and negative terminal due to constrain path of packed lithium-ion. Based on figure 4 (a) and (b) represent the arrangement of 10 thermocouples on each side of the battery cell. Figure 4 (c) Represent the simplified thermocouple placing where only 3 thermocouples on each side of the battery is used. The simplified arrangement is due to early stage of hypothesis that state the area that near positive and negative terminal will experience higher temperature due to constrain path of current flow and high movement of lithium ions thus resulting higher heat generation on that area.

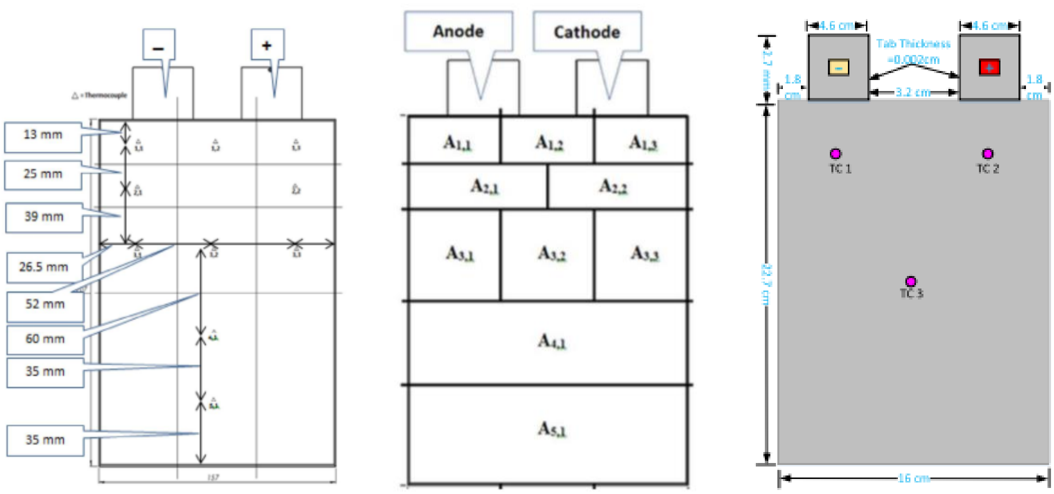

Fig. 4. Arrangement of thermocouple placing [20-22]

The battery is discharge with a constants current of 1C, 2C, 3C and 4C [21]. The result is shown in figure 5, where the battery is discharged at 3C current rate and surrounding temperature remains constant at 25°C. At the beginning of discharged process, temperature at all location is homogenous but as time passes the hot area become significant. At the end of the discharged process, it is concluded that the hot area is near the terminals area.

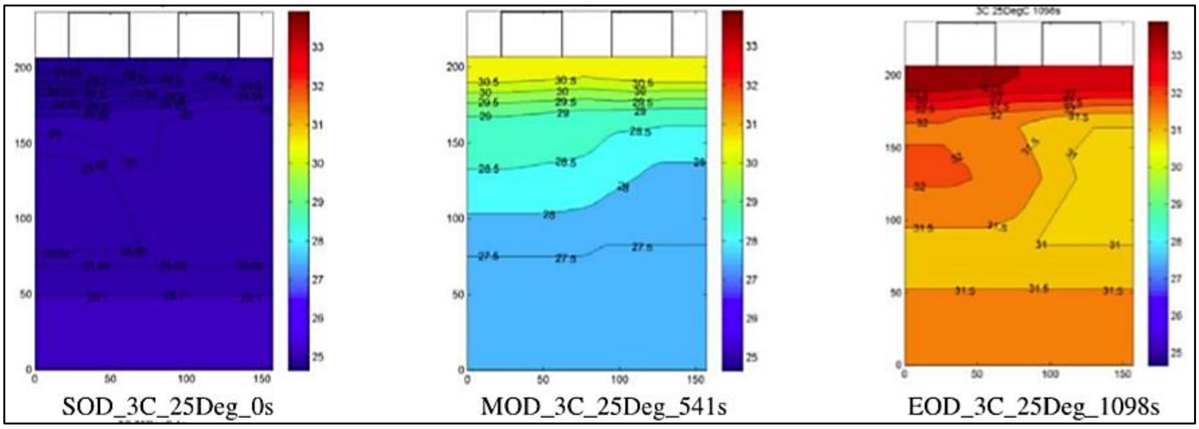

Fig. 5. Temperature distribution on LIB at 3C and 25°C [21]

However, between positive and negative terminal, the temperature is not the same. Based on the review, positive terminal experienced higher temperature compare to negative terminal [20, 21, 23]. In figure 5 and 6, at the end of discharged process, anode or positive terminal generate more heat and it is hotter compare to cathode terminal [20, 21, 23]. Reason due to this temperature variation is that the type of material used for positive and negative terminal. Different material has different value of specific heat capacity. Heat capacity is defined as the amount of heat energy required to raise the temperature by one degree Celsius thus the higher the specific heat capacity value, the slower the heat increase. In positive terminal of lithium-ion battery, normally it consists of Cobalt, Nickel, and Manganese metals while on the negative terminal, lithium or graphite is used. Table 1 shows the types of metal and its specific heat capacity. Based on the table 1, positive terminal materials have lower value of specific heat capacity means that less heat energy required to increase the temperature by one degree Celsius thus the material will experience a temperature increase in a fast rates.

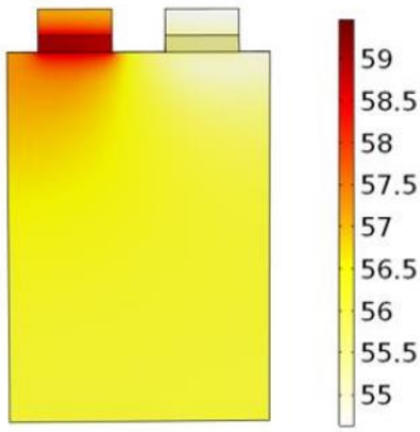

Fig. 6. Temperature on cell surface [23]

Table 1
Types of material and its specific heat capacity

Material types	Specific heat capacity J/(g°C)
Cobalt	0.41868
Nickel	0.50241
Manganese	0.47729
Lithium	3.55871
Graphite	0.72000

4. Battery Thermal Management

When a large amount of battery cells is combined in pack, it will become a battery module. Temperature in a battery module is required to be maintained in a suitable range with temperature between cells should be as uniform as possible. Hence, good heat dissipation is important to achieve this goal. There are three main types of cooling media for battery thermal management, which are air-based, liquid-based and solid-based such as phase change material (PCM). Air and liquid based cooling is an active cooling method because the coolant is the one that carry all the heat to be dissipate while solid-based is a passive cooling method since its only enhance the cooling method for an active medium such as air or liquid to dissipate the heat.

For active cooling, when it comes to a large-scale of cells plus discharging at high discharge rates, the cooling capacity of natural or forced convection with air are barely met the cooling requirements. That is when liquid cooling comes in since liquid-cooling efficiency can be much higher than air-based cooling [24, 25]. However, the main drawback of liquid cooling is its complexity, cost, high maintenance and potential leakage make manufacturers hesitate to use it [24-26] compared to air-based cooling system. In air-based cooling system the application is less complex, less cost needed, and less maintenance issues.

Passive cooling is normally based on solid material. A phase change material (PCM) or heat sink is largely used for enhancing the rate of heat transfer of active cooling. For a simple battery power application, PCM is great for cooling because PCM does not require any power source for cooling purpose however PCM is not suitable for higher temperature cooling and it need an additional support from active cooling to lower down the high temperature.

Selecting a proper battery thermal management is depending on the ease of use, adaptability, heat transfer efficiency, maintenance, duration of life, first cost and annual cost. Different types of cell used (prismatic, cylindrical, pouch) has different cooling setup.

4.1 Air-based cooling

The mechanism of air-based cooling used several fans to drive the air and directly cools the cells by flowing through the surfaces of cells. However, air-based cooling has poor heat capacity and low thermal conductivity, thus it is not proper to be used as cooling medium in BTM but some vehicles consider using this cooling method because of its simplicity of operating, design manufacturing and low cost used [12, 24]. The cooling configurations can be divided as series, parallel, mix series-parallel configurations [12, 24]. The configuration of series and parallel configuration is shown in figure 7 and 8.

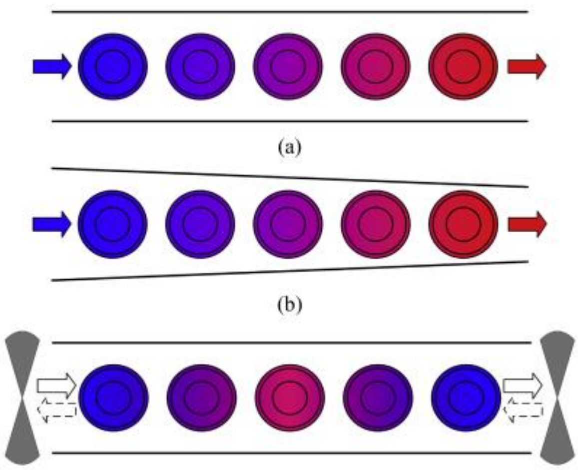

Fig. 7. Air-cooling configuration of Series configuration [24]

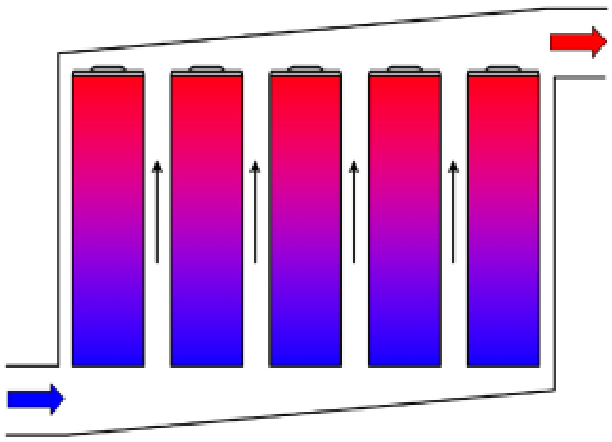

Fig. 8. Air-cooling configuration of Parallel configuration [24]

For series cooling configuration, the temperature of air-coolant may rise due to heat absorption when the air-coolant flows through the series arrangement of cells, and this will result to the cell temperature to cool down. However, for series arrangement, the air flow will pass through cell by cell resulting the first cell near the inlet to be cooled but the cell that is near to the exit is obviously higher since the air-coolant temperature already rise up due to heat dissipation from the cells before [24,27]. Therefore, series arrangement still can reduce the cell temperature but temperature uniformity for all cells cannot be achieved.

The next idea came for pure parallel cooling configuration. The air-coolant flow passing the cells from bottom to top side of the cell or in the opposite way [24,27]. Since the coolant flows past all of the cells at the same time, thus the temperature distribution between cells in a battery pack is more uniform. The key factor in order to achieve the uniform temperature is the flow distribution. An ideal design of the input distributer and outlet collector can evenly distribute the airflow throughout all the cells.

Chen *et al*. [28] has studied the effect of cooling air velocity to the surface temperature of lithium-ion battery. From this study, graph of air temperature versus time in the function of velocity has been plotted and shown in figure 9. Result shows that the temperature will decrease as the velocity of cooling air speed increase because the heat transfers dissipation rate increase. Heat transfer rate is affected by these three parameters, which are, velocity of moving air, dynamic viscosity of air, and thermal conductivity of air. Figure 9 shows that as the velocity increase, temperature will decrease but the difference of temperature become smaller at higher air velocities. This is due to the effect of dynamic viscosity as temperature is low, the dynamic viscosity become high thus more force is needed to move the particle of air.

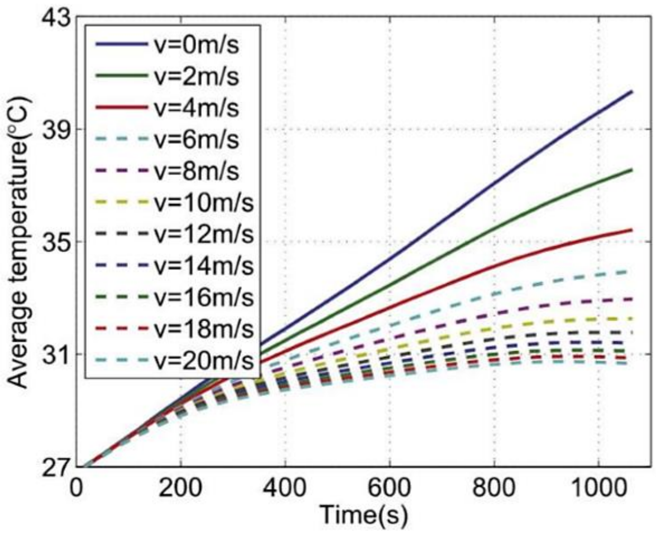

Fig. 9. Graph of air-cooling velocity with temperatures [28]

Arrangements of battery cells play a big role in designing an optimum cooling in battery pack. One parameter is about the cell-to-cell distance, since a battery pack has to be compact so it did not used to much space in hybrid electric vehicles. Yang *et al.* [29] assessed the effects of cylindrical battery arrangements in a pack in terms of temperature behaviour. The variable parameter in this assessment is the distance between the cells and the result is based on maximum temperature and temperature uniformity. Figure 10 shows the plotted graph at different range of gaps between cells that is arrange as in figure 11 and the temperature result.

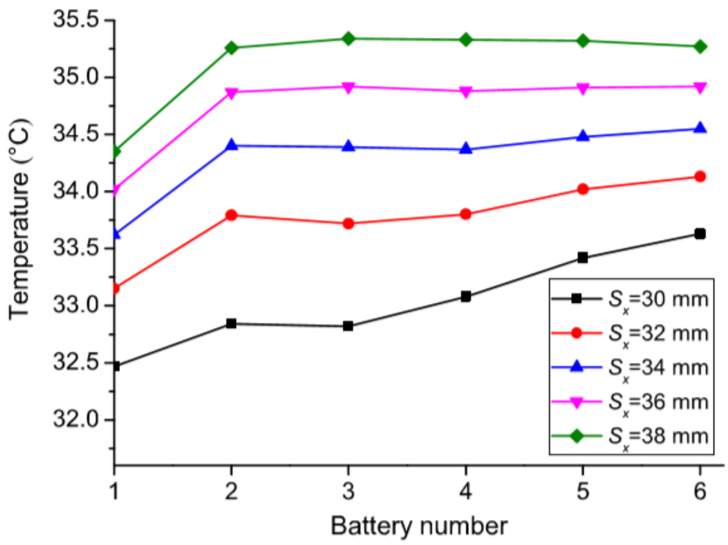

Fig. 10. Graph of batteries temperatures with different gap distances [29]

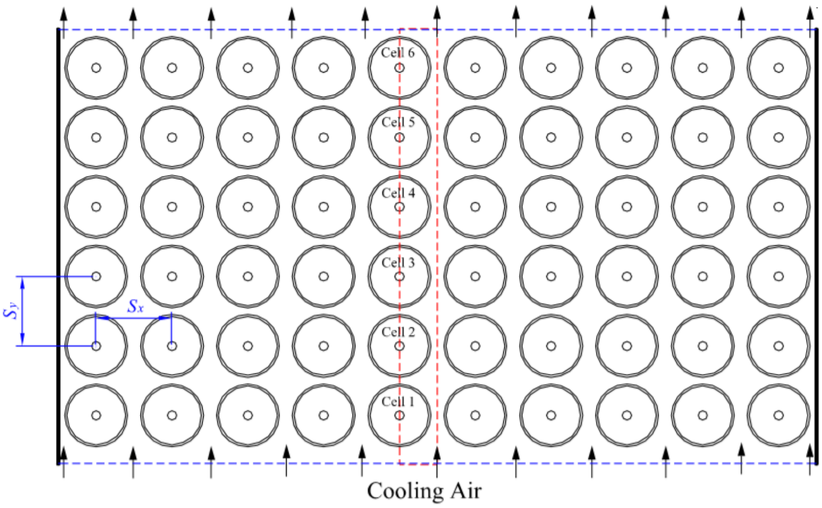

Fig. 11. Schematics of air cooling arrangement [29]

Figure 10 shows the temperature of batteries at the end of discharge. It shows that when the gap between cells become larger, the battery temperature is higher when compared to a smaller gap but the temperature uniformity is improved. Larger gap leads to decrease of air coolant velocity, which lowers down the heat dissipation rate of the battery.

5. Conclusions

Temperature control is crucial in operating lithium-ion battery. Reviews have been conducted on the existing works related to lithium-ion battery thermal behaviours such as battery heat generation, battery temperature distribution and battery thermal management. Battery heat generation trends shows that by increasing the value of current rates, temperature will increase and the major cause is due to joule effects. When an abuse discharged was carries out by discharging below 20% SOC, battery will experience a sudden temperature rise due to huge increase of internal resistance at the end of discharge process. Temperature distribution on a cell surface study shows that temperature is non-homogenous. Normally areas that are near the positive and negative terminal are have higher temperature compared to other location of the battery. Finally, battery thermal management that used cooling systems such as air-based, liquid based, and solid-based are reviewed with the focus is more on air-cooling system. Air-based cooling is a simple method to cool a battery pack and the heat transfer rate can be increase by varying the cooling air speed and optimizing the cells arrangement. Liquid-based cooling provides the best heat dissipation strategy but it require a complex design and require high maintenances as liquid may damage the cells if failure occurs. The performance of air and liquid can be enhanced by merging with a passive system using solid heat sink.

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