Thermal Management System Analysis Concentrate on Air Forced Cooling for Small Space Compartment and Heat Load

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Abstract. Battery thermal management system (BTMS) plays an important thing as to control of the battery thermal behaviours. Recently, most of the manufacturer either in automobile, motorcycle, and electric vehicle (EV) industry are using this application of BTMS for their product. It is because BTMS promising the extend the period and lifespan of the battery and the battery system controlling the temperature distribution and circulation on the system. Lithium-ion battery is one of the common usages in BTMS. Lithium-ion battery promising the goals such as higher performance, better cycle stability, and improved protection are being followed with the selection and engineering of acceptable electrode materials. It also shows a goal for future such as high of the energy storage due to higher energy density by weight among other rechargeable batteries. However, there still have factor that are limiting the performance/application when using lithium-ion as battery thermal management system (BTMS). For example, the performance, cost, life, and protection of the battery. The main reason is therefore important in order to achieve optimum efficiency when working under different conditions. Hence, the best range of temperature and the cooling capacity of lithium-ion battery need to evaluate in order to increasing the lifespan of lithium-ion battery at the same time can increasing the performance of the cell. This study found that the higher the velocity of air, the higher the cooling capacity that gain from the surrounding. It also was strongly related to the dry bulb temperature of surrounding air.

1. Introduction

Range extended electric vehicle (REEV) Seri Perlis Motorcycle is being develop by UniMAP-MODENAS-MIMOS. The BTMS is fully responsible by researchers from UniMAP. This is to determine the best cooling system that can be install into the REEV Seri Perlis Development by comparing and investigate the cooling capacity, total input power, and improve the efficiency of the system. The battery thermal management system (BTMS) plays an important thing as to control of the battery thermal behaviours. The objectives of a battery thermal management system (BTMS) are to extend the period and lifespan of Lithium-Ion battery and therefore the battery system controlling the temperature distribution and circulation. In particular, BTMS is required once the cells are liable to high charging and discharging rates and once the vehicle is running at terribly high or very low ambient temperatures. However, according to [1] an operating temperature of the battery exceed 50°C can cause damage or decreasing the lifetime of the batteries. The efficiency of the battery become decrease as the temperature rise while charge/discharge activity. The best efficiency will determine if the battery is operating under the temperature range [2]. The disadvantage of the lithium-ion battery is operating at high temperature will cause the battery safety problems, leakage and decrease the cell efficiency [3].
important consideration for the battery pack is weight, size, reliability, and cost, must then be taken into application of the battery packs [4]. A BTMS ensures that the temperature of the battery cells does not exceed the defined limits the temperature variation between all cells and modules in the pack is within the optimal range to ensure that all applicable parameters are monitored and managed and that sufficient safety measures are in place to avoid thermal leakage [5], and [6]. The previous research suggests the best operating temperature range of lithium-ion batteries [7] suggest that Lead-acid, NiMH and lithium-ion where the best operating temperature of cell is between 25°C and 40°C for good balance between performance and lifespan of the battery [5] suggest the temperature range for lithium-ion is to be below 50°C. [8] The lithium-ion cells should operate lower than 60°C to prevent thermal runaway, which starts endanger battery safety at the range of the temperature within 70°C to 100°C. [7] Suggest the best range of working temperature of the battery is within 15°C to 35°C. This research will focus on air cooling, considering the usage condition, even other researcher [9] suggested that using liquid cooling with nanofluids as working fluid is the best in terms of efficiency. It is also suggested that the most important issue to be precaution is safety of the electric vehicle [10].

2. Methodology
This chapter presents the methodology involved in this research to achieve all the objectives. This section is divided into two section which is experimental setup and Computational fluid Dynamic (CFD) simulation. The section will be discussing about the calculating and determine the cooling capacity of the lithium-ion battery, while experimental setup for the air-cooling system also to determine the cooling capacity.

2.1 Experimental Setup
The setup consists of tested Lithium-ion battery, ducting system, blower 1, blower 2, temperature controller, data logger switch unit and others detector of the thermal condition. The setup was designed to calculate the cooling capacity, temperature difference, and cooling load of the Li-ion battery with change in the temperature and air velocity according to the condition of experimental.

![Figure 1 Schematic diagram of experimental setup](image1)

The lithium-ion battery is place into the ducting system. The initial temperature, last temperature and the relative humidity is test by using thermo-hygrometer. By using the selected velocity, the air will flow into the ducting system as illustrated in Figure 1. In this experimental, 10 point of thermocouple is place at the testing area to collect the temperature reading every 15 second of data as shown in Figure 2. The 6 point is place at the surface of the tank, which is at the top, bottom, left, right, front, and back. 2 point of thermocouple is placed at the inlet and outlet of the testing area while another 2 point of thermocouple is place at the inlet of water flow into the tank and outlet of water flow from the tank into the temperature controller.
The purpose of the 10 point of thermocouple is to read the temperature data every 15 second of the experiment. 6 point of the thermocouple that place at the surface of the tank that to measure and to ensure the desired temperature which is 40°C is maintain along the experiment is running. 2 points at inlet and outlet of the testing area is to read the temperature after the testing condition. Another 2 thermocouple which is place at water inlet and outlet is to ensure the water temperature that come from the temperature controller is maintain 40°C to supply into the tank as display as Lithium-ion battery. There will be 5 condition that will be tested in this experimental. The condition is shown in Table 1 below.

| Condition | Velocity (m/s) |
|-----------|---------------|
| Condition 1 | 1.55 m/s     |
| Condition 2 | 1.96 m/s     |
| Condition 3 | 2.21 m/s     |
| Condition 4 | 7.27 m/s     |
| Condition 5 | 7.44 m/s     |

2.2 Computational Fluid Dynamic (CFD) Simulation
The simulation result of testing condition during experiment using computational fluid dynamic (CFD) is discussed in this subsection. The simulation work to examine the efficiency of the cooling system in transferring heat from the surface of the battery to the ambient has been conducted. The simulation was done for intake air velocity of 10km/h until 100 km/h with increment 10km/h for each condition. The temperature inlet is set at 35°C, and battery surface temperature at 40°C.

Detail results for each air velocity intake is provided in this subsection. In this section, a typical air intake at each of condition is simulated, and the results will be discussed to determine the efficiency of the designed cooling system. In this section, 3 conditions will be explained according to testing principle which 10 km/h, 50 km/h and 100 km/h is to evaluate the result after undergoing the simulation.

2.3 Numerical Solution
This calculation is based on the velocity of air flow within the vicinity of the surface of battery compartment with variance of 0 – 100 km/h. The air is considered as dry (no moisture). The cooling capacity of the system can be calculated by using equation 1 using the control volume method, and with an assumption that the air is at steady flow, flowing uniformly along all surfaces of the battery.

\[ \dot{Q} = \dot{m}C_p\Delta T \]  

Where;
\[ \dot{m} = \rho vA \]
\[ V = \frac{\dot{m}}{\rho} \]
with battery compartment volume = (195 mm × 195 mm × 150 mm)
\[ \dot{Q} \] = Cooling Capacity (kW)
\[ v \] = Velocity of air (m/s)
\[ V \] = Volume flow rate of air (m³/s)
\[ \dot{m} \] = mass flow rate of air (kg/s)
\[ C_p \] = specific heat of air (kJ/kg. °C)
\[ \rho \] = density of air (kg/m³)
\[ A \] = Inlet ducting area (m²)
\[ \Delta T \] = Temperature differential of air between inlet and outlet of duct (assumption 2 °C of differential)

The simulation numeric formulation that shall be used in this project stage is similar to the above understanding concept, i.e., using Navier Stokes equation concept with dry air as the working fluid and create a pressure differential through the flow systems. From there the temperature of energy (enthalpy) carried by the air will be differentiated with the inlet and outlet condition.
3. Result and Discussion
In this section, the discussion and data are presented. The cooling capacity of the lithium-ion battery is calculated. The performance between the air-cooling system and CFD simulation was compared in this chapter in terms of cooling capacity and total input power.

3.1 CFD Simulation
The simulation result of testing condition during experiment using computational fluid dynamic (CFD) is discussed in this subsection. The simulation work to examine the efficiency of the cooling system in transferring heat from the surface of the battery to the ambient has been conducted. The simulation was done for intake air velocity of 10km/h until 100 km/h with increment 10km/h of each increasing. The temperature inlet is set at 35 °C, and battery surface temperature at 40 °C. Detail results for each air velocity intake is provided in this subsection. In this section, 3 condition which is 10km/h, 50km/h and 100km/h of a typical air intake is simulated, and the results will be discussed to determine the efficiency of the designed cooling system.

3.1.1 Condition 1 (10km/h)
Figure 3 depict the view and result of the contours, air stream vector trajectory and magnitude distribution as the air flow inside the ducting through the surfaces of the battery. Additionally, from these figures, the temperature differential of air before and after the gaining heat from the battery is quite low which not more than 1°C.

3.1.2 Condition 5 (50km/h)
Figure 4 depict the view and result of the contours, air stream vector trajectory and magnitude distribution as the air flow inside the ducting through the surfaces of the battery. As displayed in velocity figure, there are contours that shows the velocity of the system. It can be seen there are heat transfer occur after the air through the lithium-ion battery where the magnitude is close to 0 m/s and creating eddies at top, below and front of lithium-ion battery which will causes damaging the efficiency of cooling system. A small amount of temperature differential could be seen at surrounding air that flows near to surfaces of the battery and it is not well distributed. These locations are highlighted by the blue arrows/colours in the figures.

Figure 3 depict the (a) Air flow velocity, (b) Velocity stream trajectory and (c) temperature distribution in the ducting for 10km/h air intake

Figure 4 depict the (a) Air flow velocity, (b) Velocity stream trajectory and (c) temperature distribution in the ducting for 50km/h air intake
3.1.3 Condition 10 (100km/h)

Figure 5 depict the view and result of the contours, air stream vector trajectory and magnitude distribution as the air flow inside the ducting through the surfaces of the battery. As displayed in these figures, there are approximately three positions that show stagnation condition. A small amount of temperature differential could be seen at surrounding air that flows near to surfaces of the battery and it is not well distributed because of the higher velocity that supply into the ducting. These locations are highlighted by the blue arrows/colours in the figures.

![Figure 5](image)

**Figure 5** depict the (a) Air flow velocity, (b) Velocity stream trajectory and (c) temperature distribution in the ducting for 100 km/h air intake

3.3 Cooling capacity from simulation

The result of cooling capacity was obtained by using data from the simulation which undergoes the ducting system and heat transfer between air and lithium-ion battery. This data was evaluated to compare the simulation calculated data and theoretical calculation data. In theoretical, the temperature differential was assuming to be 2°C while the temperature differential of simulation was obtained after the simulation is done. The data was taking at outlet of the ducting system. Table 3 shows the result of cooling capacity from the simulation while figure 6 shows the graph between the cooling capacity and velocity which was obtained from the simulation part.

| velocity (m/s) | density (kg/m3) | area (m2) | Mass flow rate (kg/s) | \(C_p\) (kJ/kg.K) | Temperature differential (°C) | Cooling capacity, \(Q\) (kW) | Cooling capacity, \(Q\) (W) |
|---------------|----------------|----------|----------------------|-----------------|------------------------------|---------------------------|---------------------------|
| 2.78          | 0.230          |          | 0.46                 | 0.105           |                              | 105                       |                           |
| 5.56          | 0.460          |          | 0.40                 | 0.184           |                              | 184                       |                           |
| 8.33          | 0.690          |          | 0.37                 | 0.259           |                              | 259                       |                           |
| 11.11         | 0.920          |          | 0.34                 | 0.314           |                              | 314                       |                           |
| 13.89         | 1.225          | 0.068    | 1.150                | 1.005           | 0.33                         | 381                       |                           |
| 16.67         | 1.380          |          | 0.32                 | 0.455           |                              | 455                       |                           |
| 19.44         | 1.610          |          | 0.32                 | 0.518           |                              | 518                       |                           |
| 22.22         | 1.840          |          | 0.31                 | 0.573           |                              | 573                       |                           |
| 25.00         | 2.070          |          | 0.30                 | 0.624           |                              | 624                       |                           |
| 27.78         | 2.300          |          | 0.28                 | 0.647           |                              | 647                       |                           |

![Figure 6](image)

**Figure 6** Result of cooling capacity from simulation
3.4 Cooling capacity from experimental

Table 2 and table 3 shows the result of the cooling capacity which obtained from experimental and simulation. The parameter needs to calculate the cooling load of the battery is temperature inlet, temperature outlet (ΔT), mass flow rate of air (ṁ), density of air and water (ρ), specific heat capacity of air and water (Cp), velocity of air flow (v), area of the ducting flow (A), enthalpy (h) where enthalpy will be finding into the psychometric chart using the relative humidity and temperature. The enthalpy will be use if the moist air is selected as air flowing medium. The parameter of condition was mentioned at section 3.1 above. The result is shown in Figure 7 where it can be seen that the increasing pattern of cooling capacity with increasing the velocity of air.

Table 3 Result of cooling capacity from the experimental

| Condition | Density of air (kg/m³) | Specific heat capacity of air (kJ/kg.c) | Area (m²) | Velocity (m/s) | Mass flow rate (kg/s) | Total Cooling capacity (w) |
|-----------|------------------------|----------------------------------------|-----------|----------------|-----------------------|---------------------------|
| 1         |                        |                                        |           | 1.55           | 0.13                  | 19.94                     |
| 2         |                        |                                        |           | 1.96           | 0.16                  | 25.72                     |
| 3         | 1.225                  | 1.005                                  | 0.0676    | 2.22           | 0.18                  | 101.06                    |
| 4         |                        |                                        |           | 7.27           | 0.60                  | 221.88                    |
| 5         |                        |                                        |           | 7.44           | 0.62                  | 234.68                    |

![Cooling capacity vs Velocity of simulation result](image)

3.5 Discussion

In this section, a discussion about the comparison between the cooling capacity of theoretical and the cooling capacity of the experimental was discussed in terms of cooling capacity and velocity. From the Figure 8, it can be seen that the higher the velocity of the intake or the velocity that supply into the ducting system, the higher the cooling capacity that release by the lithium-ion battery to the surrounding. Figure 8 shows the line graph and dotted graph which the line graph represents the cooling capacity of theoretical and dotted graph represent the cooling capacity from experimental. It can be seen at the certain velocity, the cooling capacity that release by the lithium-ion battery was enough. Hence, at initial and earlier of the velocity, it was not resembling the calculation but when the velocity is achieved 8km/h, the cooling capacity shows increasing till 101W. This graph also proved that the higher the velocity intake, the higher the cooling capacity of the system. It shows at 26.2 and 26.7 km/h, the cooling capacity of the system is higher than cooling capacity of the theoretical.
Figure 8 Cooling capacity vs Velocity of theoretical and experimental

4. Conclusion
At the end of this research, the cooling capacity of air that depicts of Lithium-ion battery had been investigated and compared successfully based on different condition velocity of air, ambient temperature, and relative humidity. This study found that the higher the velocity of air, the higher the cooling capacity that gain from the surrounding. It also was strongly related to the Tdb of surrounding air and relative humidity either outdoor or indoor of experimental testing area. In other words, the changes in Tdb are almost the same with the changes in enthalpy. The changes in enthalpy play an important role in heat transfer, which mostly depends on the changes of temperature dry bulb, Tdb. The lower the enthalpy value, the better the heat transfer, which results in lower rate of cooling capacity of air. The findings of the experiment provide new perspectives on the relationship between inlet temperature condition of theoretical and experimental and the velocity of air. Detail results for each air velocity intake was shows that the higher velocity intake that supply into the testing area the better the outlet temperature that will obtained. The result shows the rise ±1 at thermal behaviour i.e surface maximum temperature and final outlet temperature. Based on the temperature distribution that had been discussed, a small amount of temperature differential could be seen at surrounding air that flows near to surfaces of the battery and it is not well distributed. This is due to heat transfer that occur between lithium-ion battery and air surrounding.

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