

Heat Conduction Modelling of Battery Thermal Management System for Electric Vehicle



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Abstract A battery thermal management system is crucial for electric-vehicle (EV) and hybrid-vehicle (HV) battery packs to operate effectively in all climates. Battery packs are critical components of electric vehicles. The system is designed for higher life cycles utilization. However, temperature affects the performance and life span of the batteries. Keep the temperatures distribution low within the operating temperature range among all modules and battery cells is the main factor to increase the life of the battery system. This paper studied the effects of having the ventilation system by positioning the air inlets and outlets with and without heat sink as greater heat dissipates among battery packs. The heat dissipation and temperature distribution determine the battery life span. A computational fluid dynamics model was created for the purpose to analyze the temperature distribution and airflow profile. The battery pack was designed to keep the compartment smaller but with better cooling efficiency. The results show that the locations and shapes of inlets and outlets have a significant impact on battery heat dissipation. A strategy was proposed to minimize the temperature variation of the battery cells compartment. The temperature changes between the highest and lowest ones for the evaluated event are reduced from 26.04 to 23.67 °C and the heat dissipation rate is improved by 9.10%.

Keywords Electric vehicle · Computational Fluid Dynamic and Battery Thermal Management System

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1 Introduction on Electric Vehicle

People have paid great attention to global warming, which is recognized mainly because of greenhouse gas emissions from fossil fuel combustion. Electric vehicles (EVs) are the mainstream of future transport vehicles to help ease global warming and the depletion of crude oil. A battery pack as the main power source of EV is required to meet high energy and power density, long life cycle, long lifetime, and so on. Lithium-ion batteries are one of the common energy storage systems for electric vehicles. Generally, the battery pack has several battery modules or cells in series and/or in parallel to achieve the required voltage and capacity. In the case of long-distance travel, the vehicle would be equipped with a larger battery pack and therefore a large amount of heat. Single-cell overheating and failure can occur and degrade the performance of the entire pack; therefore, a favorable ventilation system design can quickly remove the enormous heat generated by high power demand (hard acceleration, climbing, etc.) and maintain the performance of the battery pack. The common ventilation systems are air-cooling, liquid-cooling, phase change cooling, or any combination. Air cooling system has the advantages of simple structure, lightweight, low cost, easy maintenance and repair, and no liquid leakage problems. It is suitable for electric vehicles. Temperature affects the battery's performance and lifespan. Well distributed temperatures within the operating temperature range amongst all modules and battery cells are one of the key factors to prolong battery life.

High temperatures degrade the life of the Li-ion batteries, while cold temperatures reduce the power and energy performance of the EVs, thus limiting the driving range and performance of the EVs[1]. Li-ion batteries using olivine-type lithium-iron-phosphate (LiFePO₄) cathode have attracted a great deal of attention as a power source for EVs and HVs due to their low material cost and non-toxicity. Their weakness, however, is the temperature that affects their performance, safety, and life. Both [2] and [3] reported that, although the capacity increases as the operating temperature are raised, the degree of capacity fade also increases. Both reported poor performance at low operating temperatures.

The battery design optimization is used to maintain the batteries operating at a desirable temperature range, thus preventing them from exceeding the high-temperature limit that can damage the batteries or reduce their life. Moreover, the uneven temperature distribution in the battery pack leads to unbalanced battery cells and reduced performance. Several battery optimizations, use mainly air cooling [3], liquid cooling [4] or phase-change materials (PCMs) [5].

2 Electric Vehicle Technology Review

Battery Electric Vehicles (BEVs) have an internal energy source an electric motor powered by electrical batteries located in the vehicle. The powertrain gives BEV

the possibility to utilize with zero emissions at the place of use. Many of the engineered solutions embraced for the construction of BEVs also make use of the “energy recovery” technologies that allow the electric motor to be used both as a source of propulsion and as a generator when braking or when the vehicle moves freely under gravitational action. The advantages of using BEV in traffic are the high torque of the electric motor that is distributed to the wheels and the simpler air resistance (and deceleration) compared to the internal combustion engine (ICE) vehicles. BEVs also do not emit noise while using an electric motor and do not generate environmental pollution [6]. The aspects make BEVs the ideal vehicles to be used in cities and urban areas.

On the other hand, the actual terminal voltage of the battery E_{cmf} detracts from the electromotive balance force (electrode potential) due to the electrochemical polarization of the battery. This method yields Q_p heat, which is a loss of energy during the polarization of the battery charge and discharge. $Q_p = I^2R_p$, where R_p is the polarization resistance that is associated with the polarization process. Finally, the Joule heat Q_j is generated due to the internal ohm resistance of the battery the heat generated during the charging/discharge process is $Q_j = I^2R_i$, where R_i is the internal ohm resistance of the Li-ion cell.

Xu et. al. conducted a CFD and observational heat transfer performance study of the symmetrical fractal silicon thin-film network under-stimulation [7]. The results showed that the heat transfer rate at pulsation frequency (2–10 and 30–40 Hz) increased by 25–40 percent and was significantly greater than that at (10–20 Hz) when the Re number remained constant. By raising the Re number, the enhancement factors dropped significantly from 40 to 5% for the above frequency range, as opposed to steady-state cases. Doubling the frequency of Re caused a drop in the wall temperature and an increase in the number of Nu. There was no big variation in the pressure drop between steady and pulsed flow cases [7].

Yu et. al. have studied numerically the effect of agitator plates inserted within the HS channels to enhance the heat transfer by antagonism [8]. Periodic motion in the radial direction generated by the agitator plate increased the thermal efficiency. Maximum heat transfer results and insights were approximately 61% by agitation. They tracked a sharp enhancement in heat transfer on the base surface as the size of the tip gap between the agitator plate and the channel was reduced. On the other hand, there was no effect of the size of the tip gap observed on the heat transfer on the side walls. Higher thermal conductivity rate from the channel wall was measured when the amplitude or frequency of the agitator plate risen. It can be seen that there was very limited research in this area of research the cooling mechanism used to remove heat from heat sinks is one way of categorizing heat sinks. It can be divided into two categories [9]. Passive heat sinks are used either in natural convection implementations or in applications where heat dissipation does not rely on a demarcated airflow supply. Typical height at heat inlet: 10 mm to large. Standard load limit 5–50 W. Semi-Active Heat Sinks leverage existing fans in the system. Typical height at heat inlet: -10 mm. Load limit 15–25 W. Active Heat Sinks use designated fans for their use, such as ventilator heat sinks in either impingement or vertical streams. This type of heat sink usually involves mechanically moving components, and its

reliability depends heavily on the reliability of the moving parts [10]. The heat sink is the most critical part of the proposed. It must have a large size to have a small thermal resistance value and a volume and weight that can be tolerated for EV applications. The heat sink absorbs the power pumped from battery cold surfaces and the heat generated by itself. Heat sink performance affects the system's highest possible temperature range and excellent thermal stability [2]. The heat sink selected should be capable of dissipating the power generated by the Lead-acid cell ($Q_c = 6 \text{ W}$).

CFD can provide insight into flow patterns that are difficult, expensive, or impossible to study using methodological approaches. Experiments can provide a quantitative description of flow phenomena using observations for one quantity at a time, at a limited set of characteristics and times. If a full-scale model is not obtainable or is not practical, scale models or dummy models may be used. Experiments may have a limited range of problems and operating conditions. Simulations can predict flow profiles by applying computer-aided CFD software for all desired parameters, with a function of space and time, and virtually any problem and realistic operating conditions. For confirmation, the results may need to be validated. To maintain the reliability of the mesh size, the length of the fluid may need to be affirmed. We used CFD post-processing software, SOLIDWORK, in this study. The mesh size of 5 mm is chosen for the whole pack.

3 Methodology of Electrical Vehicle Battery Pack Simulation

3.1 Heat Transfer Analysis

An analysis on battery thermal management was conducted through computational fluid dynamic (CFD) flow simulation to obtain the heat flow, making the study of the thermal analysis overall. The heat sink performance considered the material thermal conductivity, compartment geometry, fin-type, heat transfer coefficient, airflow rate, and ducting components arrangement. A conceptual approach can be made to evaluate the surface performance of the heat sink (Fig. 1).

Alternatively, thermal performance may be measured experimentally by the temperature sensing approach. This chapter will discuss the mentioned methods for the determination of the thermal effect to the battery compartment of the electric vehicle system. Aluminum alloys are the most common and effective heat sink materials which are in this study specifically choose aluminum alloys 6061 grade (Table 1).

The fin shape of a heat sink can significantly impact its ability to distribute thermal energy into the environment. The quantity and size of the fin determine the efficiency of the heat transfer components as a medium to release the heat faster. For a better concept design, the fins are not in any cover but attach to a flat solid aluminum plate. This is a way to increase the opening surface area to the air.

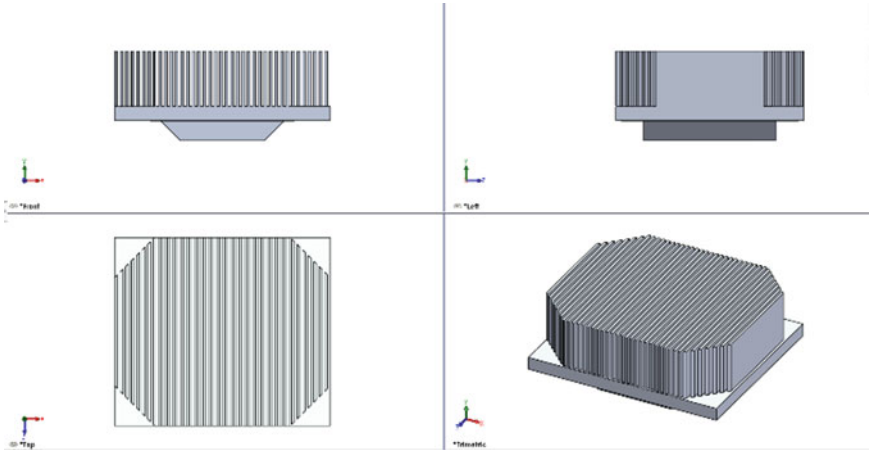


Fig. 1 Flat straight fin heat sink

Table 1 Heat properties

Properties	Description
Thermal load (heat power)	6.0 W
Power	576 W
Convection coefficient	28 W/(m ² K)
Temperature	303 K
Material	Aluminum Grade 6061

3.2 Computational Fluid Dynamic (CFD) Analysis

To obtain the airflow simulation on the battery pack thermal management, a simulation is performed by using SOLIDWORK flow simulation 2020. The input data and mesh generate should be recognized for the software to perform simulation. In SOLIDWORKS flow simulation a wizard study is created, and the properties for the material involved is being set as shown in Table 2.

The heat sink was selected as the component which the material is aluminum 6061 while the battery pack casing was made up of alloy substance. The heat generation mode of CFD was selected which aligns with the airflow investigation study and the

Table 2 CFD basis assumption

Properties	Description
Model type	Linear elastic isotropic
Default failure criterion	Maximum Von Mises stress
Specific heat	900 J/(kg K)
Mass density	2700 kg/m ³

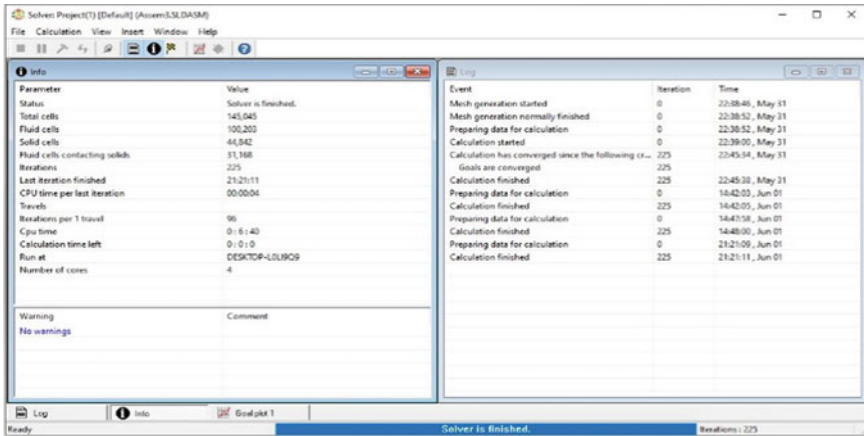
Table 3 CFD properties and setup

Parameter	Description
Mode	Heat generation rate
Coordinate system	Global coordinate system
Heat generation rate	6.0 W
Flow parameters	Inlet flow vector direction: normal to face
Thermodynamic parameters	Environment pressure: 101,325.00 Pa
Turbulence parameters	Turbulence intensity and length Intensity: 0.10% Length: 0.003 m

fluid condition was set up as an air parameter. In CFD analysis, two types of goals were set which were the global goal and surface goals, both goals were selected in an average type of goal to be calculated. Global goal mainly focused on the fluid temperature, overall compartment temperature, and wall temperature. Detailed of the setup are tabulated in Table 3 while the mesh properties are specified in Table 4.

Before the CFD simulation being run, all opening sections of the geometry must be closed as a defined boundary condition. The feature was constructed by inserting a lid feature and the size of the computational domain need to be greater than the battery pack compartment

Table 4 CFD mesh properties and setup



4 Battery Pack with Heat Sink

Figure 2 shows the installation of PID fan controller assembly with heat sink being placed on top of the battery component, this section shows how the arrangement of the battery thermal management is set up. Mainly two cases were focused and highlighted. The first one has simulated the inlet air intake without the heat sink meanwhile for the second case study was the heatsink that was placed on top of the battery compartment.

The idea is to maintain a constant temperature by controlling the speed of a fan by changing its supply voltage. It uses a PID (Proportional-Integral-Derivative) control algorithm to calculate the adequate power % to apply to the fan, through a PWM controlled MOSFET. The goal design builds a system to maintain the right temperature at the battery pack. It can be used in any forced ventilation application though.

Figure 3 shows the geometrical configuration of a plate-fin sink with a horizontal inlet cooling flow. Both the base size and the width are 50 mm. The total heat dissipation of 6 W is uniformly applied over the base plate of the heat sink with a base thickness of 20 mm. The thermal conductivity of the heat sink is 200 W/m K. The ambient air temperature is 25 °C. The conductivity of the air is 0.0267 W/m K and the air density is 1.177 kg/m. The task is to determine the maximum temperature on the heat sink to operate at the optimum range. This material Aluminium alloys 6061 with thermal conductivity values of 201 W/m K is operated with a thermal load (heat power) of 6 W which we get by using the online micro calculator in determining the thermal load.

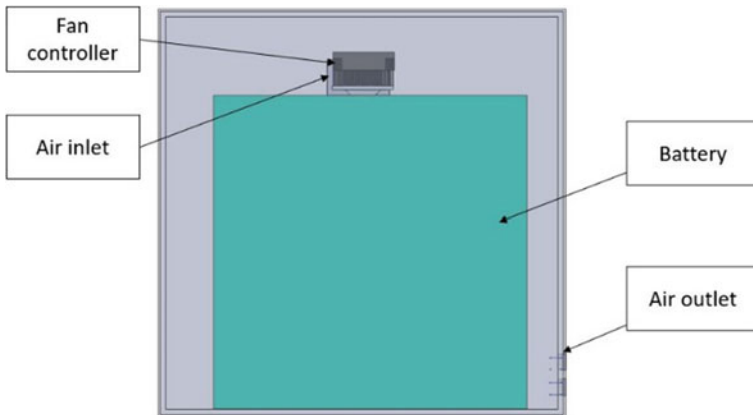


Fig. 2 Components arrangement of the EV battery pack

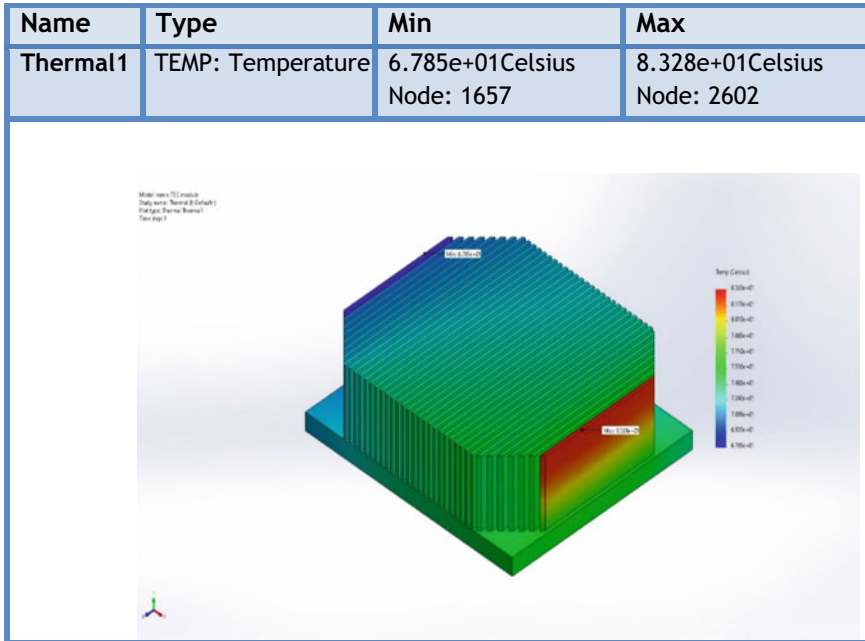


Fig. 3 Heat sink thermal temperature distribution

5 Flow Trajectories

Figure 4 shows the streamline arrow of the first case study whereas the fan blower only without heatsink is being placed up at the inlet of air intake. As can be seen in the figure the streamline is in a cool state, but the air streamlines are not uniformly from the air inlet through the fan and exit through the outer lid. The streamline of the airflow at 6.0 W is illustrated below.

Figure 5 shows the streamline arrow of the second case study whereas the fan blower and heatsink were being placed on top of the battery compartment. As can be seen in the figure, the streamline is in a cool state where the heat is dissipating uniformly from the air inlet through the fan and exits through the outer lid. The streamline of the airflow at 6.0 W.

From the parametric analysis on the power rate, the fan speed, and the location of the heatsink on the thermal performance, it is found that the temperature distribution among the battery cells is not even within the battery module for the first case study. It was found that even the authors change the three key parameters in a large range, the temperatures on the rear battery cells are still larger than those on the front battery cells.

However, the temperature uniformity distribution for the second case study which shows a greater airflow distribution and the heat dissipation flow has a great impact on the capacity and battery cycle life. Extensive studies have shown that a high



Fig. 4 First case of the CFD simulation without heat sink

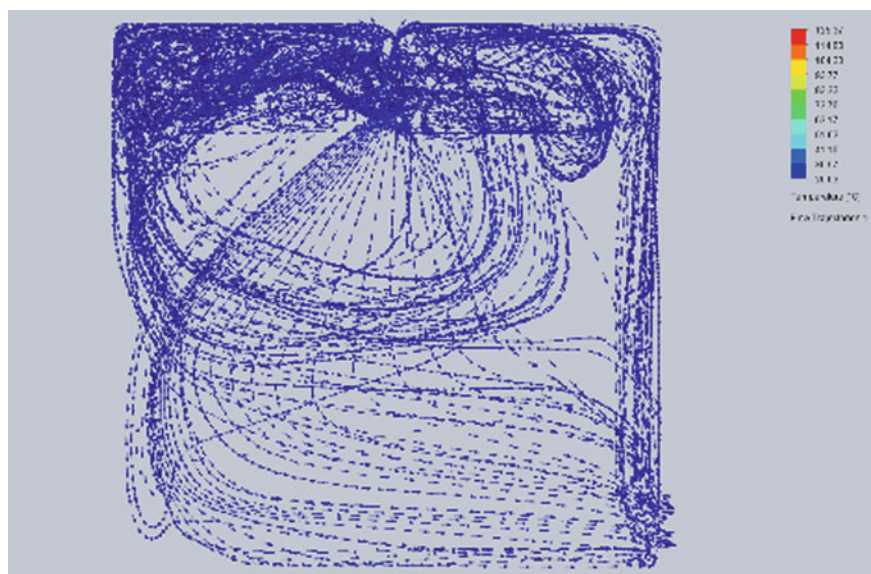


Fig. 5 Second case of the CFD simulation with heat sink

temperature will accelerate the degradation of the capacity and shorten the life cycle (Fig. 6).

The temperature uniformity of a single battery cell is affected by its intrinsic properties, such as electrode and electrolyte materials, thermal conductivity, battery dimensions, and extrinsic factors like convection heat transfer coefficient and media. The temperature uniformity of a battery module is affected by the passage spacing size, cooling air, manifold configuration, and others.

Based on Fig. 7, due to the heat taken away by the cooling air, the cooling air temperature plays an important role in the temperature on the battery cell. The figure shows the specific heat and thermal conductivity of the heatsink that is being placed in the battery pack.

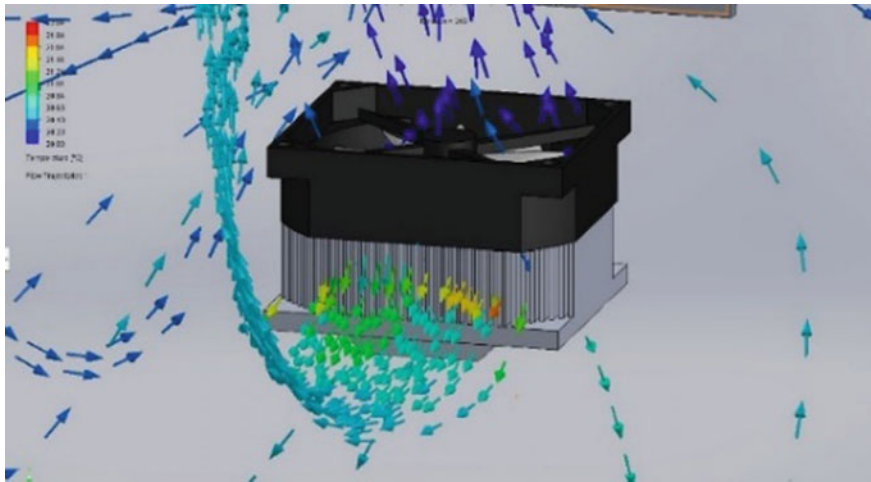


Fig. 6 Second case CFD simulation focused on heat sink

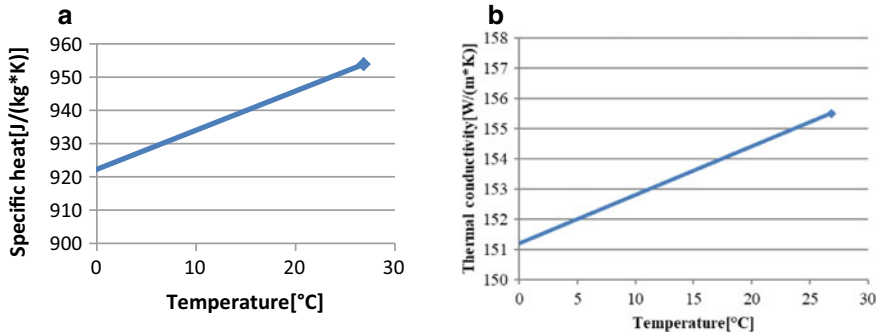


Fig. 7 a Specific heat of heat sink, b thermal conductivity heat sink

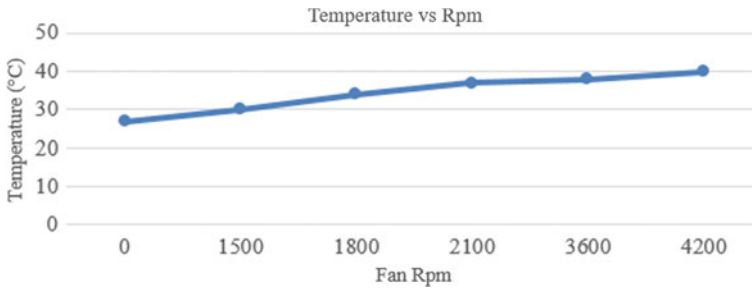


Fig. 8 Temperature versus RPM graph

During the study on the 1 case it shows, due to the pressure drop in the manifold, it is challenging to eliminate the pressure difference when the inlet is being placed as the fan blower for the battery pack. This causes the flow area of each passage to be another factor that largely affects the distribution of the passage heat flow. Thus, the heatsink fan blower is placed on top of the battery because it shows a greater uniform of airflow streamlines, causing the temperature to drop greater.

Figure 8 shows the temperature of the surrounding in the battery pack, when the temperature sensor detects an increase of heat, the fan speed or Rpm will increase radiantly with temperature. The Figure shows the increases in the temperature that triggers the fan speed.

The thermal efficiency of the optimized battery pack based on the maximum and minimum temperature is gain from the heat sink dissipation. The heat-sink can reduce 2.37 °C or 9.10% more dissipation performed around the battery compartment.

6 Conclusions

This study presents a heat sink and PID fan as a type of air-cooling ventilation system for an electric scooter battery pack that differs from the typical ventilation system by relocating cooling air inlets and outlets, modifying inlet forms, and combining with a PID fan system to the battery pack. According to simulation results, the design of battery ventilation can effectively reduce the maximum temperature and the maximum temperature difference in the pack, the temperature difference between the highest and lowest ones for the evaluated event is reduced from 26.04 to 23.67 °C and the heat dissipation rate is improved with 9.10%. The uniformity of the temperature distribution has an improvement of 9.10%. which eventually extends the service cycles of the battery cells and enhances the reliability of the battery pack. As to the conceptual design stage, with the help of the CFD simulation technology, one can quickly predict the result of the ventilation system design which shortens the development process to achieve the purpose of cost-saving.

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References

1. Shkarah AJ et al (2013). A 3D numerical study of heat transfer in a single-phase micro-channel heat sink using graphene, aluminum and silicon as substrates. *Int Commun Heat Mass Transf* 108–115
2. Fan YZ (2021) Optimization of cooling strategies for an electric vehicle in high-temperature environment. *Appl Thermal Eng*
3. Li H-Y, Chen K-Y (2007) Thermal performance of plate-fin heat sinks under confined impinging jet conditions. *Int J Heat Mass Transf* 50:1963–1970
4. Li H-Y, Chao S-M (2009) Measurement of performance of plate-fin heat sinks with cross flow cooling. *Int J Heat Mass Transf* 52:2949–2955
5. Lee C, Chen R (2015) Optimal self-tuning PID controller based on low power consumption for a server fan cooling system. *Sensors*
6. Lee DW (2014) Development of BLDC motor and multi-blade fan for HEV battery cooling system. *Int J Autom Technol*
7. Liu M et al (2011) Experimental study on liquid flow and heat transfer in micro square pin fin heat sink. *Int J Heat Mass Transf* 54:5602–5611
8. Pesaran AA (2001) Battery thermal management in EV and HEVs: issues and solutions. *Battery Man* 43(5):34–49
9. Qu Z et al (2012) Passive thermal management using metal foam saturated with phase change material in a heat sink. *Int Commun Heat Mass Transf* 39:1546–1549
10. Pesaran A, Keyser M, Burch S (1999) An approach for designing thermal management systems for electric and hybrid vehicle battery packs. National Renewable Energy Laboratory, Golden