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Thermal Modelling of Battery Pack of an Electric Vehicle using Computational Fluid Dynamics

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ABSTRACT

As Today, conventional engines are being replaced by electric vehicles due to environmental concerns and concern about the exhaustion of fossil fuels. Li-ion cells are often used in EV's because of their high energy density. The thermal behaviour of the batteries is crucial not only for safety operation but also for their capacity and life. This article focusses primarily on the effect of inclusion of conductive material and conditioned air on the battery module. A three-dimensional flow and thermal analysis of an air-cooled module that contains prismatic lithium-ion cells fitted in aluminum structure. The flow and thermal simulation is carried out at the peak discharge of the batteries i.e. 2C rating [17] using a commercial CFD package. The results are compared with the base line model analysis which is performed with same parameters. The temperature is decreased by 7.2ºC on average for the addition of fins to the battery module. The increased load on the AC unit is calculated as well when the air is directed to battery module and sufficient modifications for the system are suggested.

KEYWORDS: Battery thermal management; Li-ion batteries; CFD; Air-cooling; HVAC cooling.

Introduction

Environmental pollution and energy crisis are serious threats now a days. The usage of fossil fuels is increasing rapidly due to global demands for energy resources and improvements in economic levels. BP statistical Review of World Energy 2016[1] and BP Energy Outlook 2016[2] statistics show that world oil usage raised by 1.9 million barrels per day, almost equivalent to two-third of transportation sector use. For the reduction of fossil fuels emissions, build clean energy like EV's an environmentally friendly model than traditional IC engines systems[3].

The crucial part of clean energy vehicle implementation is to find a suitable unitformenergy storage that can meet high driving requirements. Various types of battery systems, such as leadacid, nickel based sodium-based, and lithium-ion (lithium-ion) batteries, have been proposed[4]. Because of their high energy and power density, extended life and low self-discharge levels, Li-ion batteries are among the most chosen devices for EV's. These are widely used in wristwatches, smartphones, laptops and many other portable electronic devices from these important factors[5]. Depending on the space and functionality, car manufacturers will use different battery designs and geometric shapes. A single cell is not sufficient in actual use to supply the energy and power needed for the vehicle operation. At present most battery packs for hybrid electric vehicles (HEV) are cooled by air. The cabin air conditioner is removed through the battery by a secondary fan blower mechanism. A double water loading method poses the problems of correct transfer of air from the rear of the cabinas of machine's view point, there are double airflow circuits inside car. Conditioner's primary circuit is centred on a low negative suction pressure. Main HVAC system feeds the battery module situated at backside of vehicle with power exchange circuit and secondary air flow. Both air flow circuits are controlled by the pressure difference. The point of view of the complete unit, it is to decrease the requirement of air flow. This allows the low negative pressure created by blower fan is less, thus increasing the reverse flow of air to the front AC system, particularly on recirculation mode.

The lesser airflow essential necessity helps maintain sound levels down due to lesser operational speeds. The problems of battery's thermal architecture need to betackled at both part and device level[6]. The BTMS main requirement is to maintain within the module and battery pack a feasible range of temperature and uniform distribution of temperature[7]. Pesaran et al. (2001), the system must meet requirements: removal of heat from the battery module by cooling, maintenance of battery temperature under lower temperature conditions, isolation to prevent sudden changes in temperature, and exhaust ventilation suitable for expelling hazardous gases[8]. BTMS not only have to maintain the batteries within this ideal operable range but also have to make sure that the distribution of temperature within the individual cell and the battery is consistent.

It must be very compact, very light, low cost, high reliability, easy maintenance, low consumption of parasite energy and simple packaging[9,10]. The ideal temperature range for lithium-ion battery packs was found to be in the range 20 and 40 °C[11]. Battery cooling systems can be classified many ways. First, it is classified on cooling medium employed like air cooling, liquid cooling and PCM cooling[12]. The other parameter is the consumption of power, where passive cooling can be used with ambient conditions, while active cooling should be provided with an energy source[13]. Finally, overt cooling or indirect cooling are other forms of whether or not there is direct contact with the cooling medium[14].

Also, BTMS can be used without the vapor compression process with different cooling methods such as BTMS with the vapor compression cycle (VCC) or BTMS. Cabin air or direct HVAC system is used by the system that includes VCC. While the principle of PCM cooling, heat pipe cooling and cooling of thermoelectric elements is used by another. A car air conditioning system's VCC is used to provide drivers with comfort at all times. In many electric vehicles, therefore, the combination of these two systems is used because it can be used for existing systems[15]. However, due to its high-power consumption, such an integrated system is not advisable, which can even increase the battery temperature. In many cases, it is strongly favoured due to simplicity of an air-cooling system. Within the forced air-cooling system Nonetheless, extensive parametric literature studies are lacking consider the effects of geometrical parameters routinely and fan energy on cooling capacity.

Battery Heat Dissipation Model

According to Bernardi et al.[16] the heat generated by battery is given below. Temperature is considered to be uniform in the battery, its energy balance equation includes mixing, phase change, ambient heat, electrical work, reactions and heat capacity changes to cause temperature change over time. For the case of Li-ion cells equation is simplified in to following form.

$$\dot{Q}g = I^2 . R_{int} + I.T. \frac{\partial Uavg}{\partial t}$$

$\dot{Q}g$ is total heat generation rate, I is the discharge current, T is battery temperature and $\frac{\partial Uavg}{\partial t}$ is entropy heat generation.

TABLE 1

Polynomial expression coefficient.

Coefficients	3C	2C
A1	3.2235×10^{-12}	1.2578×10^{-13}
A2	-8.2542×10^{-9}	-4.8310×10^{-10}
A3	7.7851×10^{-6}	6.8347×10^{-7}
A4	-3.2303×10^{-3}	-4.2934×10^{-4}
A5	0.6157	0.1216
A6	148414.7651	-17.7630
A7	7.7851×10^{-6}	66623.3365

Problem Formulation

The simulation is based on an air-cooled module containing LiFePo4 cells mounted between the aluminium fins in the present investigation. The fin structure is as shown in figure 1.

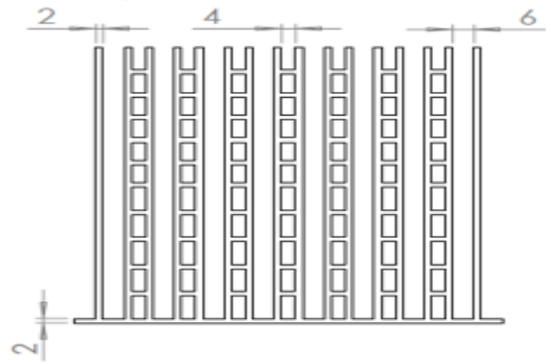

Fig. 1. Aluminium Fin structure with dimensions.

With a 2C energy level, the cells are discharged. Within the aluminum frame, the eight prismatic cells are arranged vertically with evenly spaced spaces between adjacent cells as shown in the figure 1. Two cooling fans were positioned to blow air to through the module. Cells are numbered from 1 to 8, with 1 and 8 being extreme cells, 4 and 5 being the fan's nearest medium.

$$\dot{Q}g = A_1t^6 + A_2 t^5 + A_3 t^4 + A_4 t^3 + A_5 t^2 + A_6 t + A_7$$

The first term in equation is called polarization heat and can be calculated by adding the battery's internal resistance and the current's square. According to the entropic transition, the next term is the reversible entropic heat. Produced heat depends on temperature, charging status, depth of discharge and discharge rate. Heat liberated by a $LiFePo_4$ battery with a capacity of 40Ah and voltage 3.2 V as a function of time is formulated by Li[11] by experimentally finding the internal resistance and entropic coefficient various rates of discharge and proposed a polynomial equation. The coefficients for the polynomial expression are mentioned in the table below and variable t represents time.

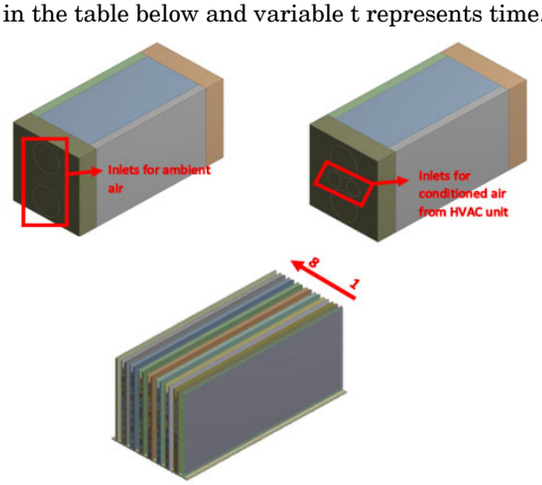

Fig. 2. (left to right) (a) Domain for normal operation, (b) Domain for AC bleed air, (c) Arrangement of batteries.

Then the air stream exits the device through two output ports in front of the fans that are exposed to the atmosphere. In order to facilitate the study, the design does not include cell tabs. Fan boundary condition is

considered as inlet (circle) a constant velocity limit condition, while the outputs were defined as the limit conditions of the pressure output. The adiabatic boundary condition of non-slip wall was given to other domain walls. For this modelling project, the measurements of the prismatic cells and the cell's thermos physical properties were used from analysis of Fan et al[17]. The dimensions and thermo-physical properties listed in Table 2.

TABLE 2

Specifications of battery.

Specification	Value
Battery dimensions	6*145*255 (tabs excluded)
Density (kg/m^3)	2335
Specific heat capacity (J kg^{-1} K^{-1})	745
Thermal conductivity (W m^{-1} K^{-1})	27

The module was assumed to operate with a 2C discharge level for 600s and to add a heat generation frequency to the battery. The gap in the module between the adjacent cells (d) was equivalent to 5 mm. For three separate streams, that is, 30 CFM, 40 CFM and 50 CFM, the air velocity levied at the port of entry is considered. AC purge of the HVAC unit at 10 CFM also investigated the battery temperature. The transfer of radiation considered to be insignificant in this simulation.

Methodology

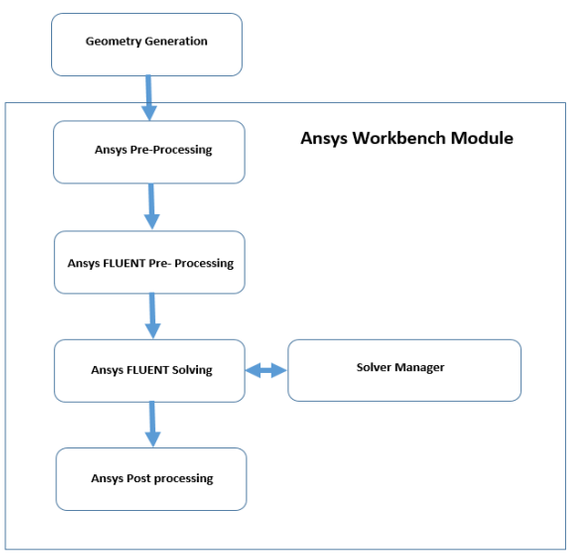

Fig. 3. CFD Methodology.

Numerical Solution

Simulations involving fluid flow were carried out extensively through the use of techniques and codes for computational fluid dynamics. ANSYS Fluent has been used in this study. The domain of computing for the simulation is meshed with hexahedral cells. The k-epsilon turbulence equation was opted and SIMPLE algorithm is solver. The fins are assigned with aluminium material and a new material with battery properties was created and assigned to battery. The internal heat generation was given to the batteries of magnitude 63884.34 W/m^3 (heat generated at 2C discharge rate for 600 seconds). The transient analysis was performed for 240 seconds and the convergence criterion was defined in such a way that the flow and thermal energy residuals of the governing equations are below 10^{-4} and 10^{-6}, respectively. The ambient temperature of air is considered as 35°C and the AC air to bleed in to the module is at 15°C (with 30% RH) from the figure.

A simulation is performed to find out the impact of

1. Temperature distribution on batteries without fins
2. Temperature distribution on batteries with fins
3. The above conditions are also analysed with AC bleed from HVAC unit with a flow rate of 10 CFM.

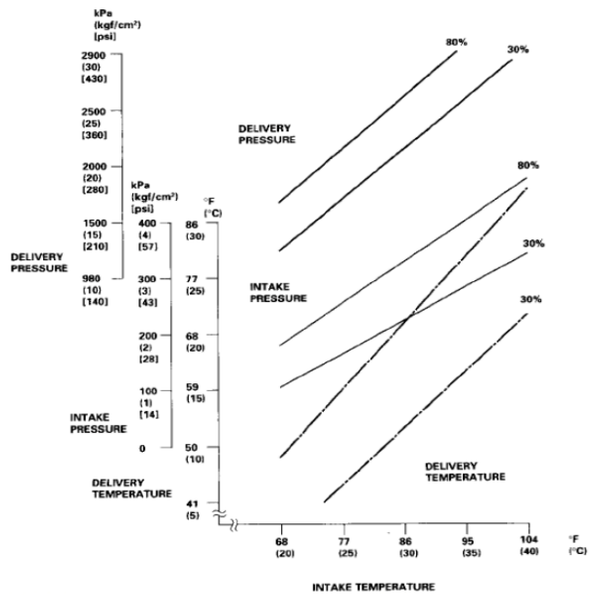

Fig. 4. Automobile AC unit characteristics (source: Honda Accord AC Unit characteristics).

These criteria are then compared based on the rise of temperature on individual batteries, uniformity of temperature fields and the fan power required for maintaining the temperature.

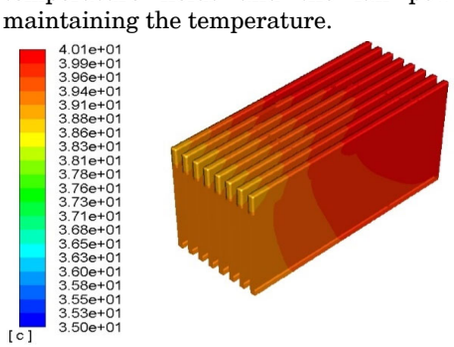

Fig. 5. Temperature distribution of the batteries after 240 s for the flow of 30 CFM.

Results and Discussions

The above case corresponds to the simulation with 30 CFM flow rate at normal operation, after the discharge

process (t = 600 s), the thermal distributions on the battery module is shown in above figure.Maximum temperature in eight cells is 40.1°C, which was found near the exit at the other end of each cell. To compare the temperature distribution information of every cell, average temperature within a cell and maximum temperature generated in each case are tabulated below.

TABLE 3

Maximum temperature for all conditions.

CFM	With Fins		Without Fins	
	Normal operation	With AC bleed	Normal operation	With AC bleed
30	40.1	34.1	46.4	43.9
40	37.9	31.1	46.2	43.9
50	37.5	29	46	39.5

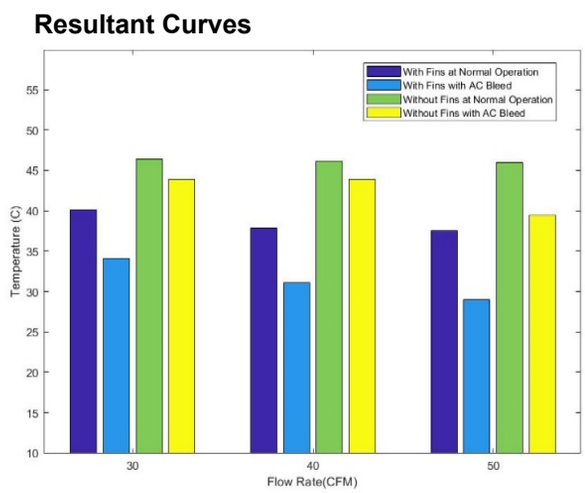

Fig. 6. Maximum temperature plots for variable CFM.

The peak temperature on the battery is dropped by 6.5°C with the addition of fins to the battery pack for flow rate of 30 CFM. The additional increase of the flow rate doesn't have considerable effect on the temperature of the battery for 40 CFM and 50 CFM even with the fins. There is considerable decrease in the temperatures of the model with fins compared to the both operations.

TABLE 4

Average temperature of each cell stacked in fins.

Condition	1	2	3	4	5	6	7	8
30 CFM Normal operation	39.4	39.4	39.1	38.9	39.0	39.2	39.4	39.5
40CFM Normal operation	37.3	37.3	37.4	37.3	37.4	37.4	37.4	37.5
50 CFM Normal operation	37.1	37.1	37.1	37.05	37.08	37.1	37.1	37.1
30 CFM With AC	30.5	29.6	29.4	29.7	29.4	29.4	30.1	29.9
40 CFM With AC	28.4	27.2	27.7	26.9	26.9	27.2	27.9	28.2
50 CFM With AC	26.5	27.6	27.1	26.8	26.8	26.6	27.3	28.3

The average temperatures of each battery are tabulated above and the battery pairs 1-8, 2-7, 3-4, 5-6 are displaying the temperatures in symmetric behaviour in the case of normal operation while for the AC bleed condition the temperatures are fluctuated for above mentioned pairs in the range of 2 to 3°C.

The ideal temperature range for lithium-ion battery packs was found to be in the range 20 and 40 °C, where the temperature in simulation without the fins is exceeding the safety limit. For the AC bleed condition, the battery temperatures are below the restricted level and the low temperatures are observed on the batteries 3 and 6 compared to others. This might be due to the arrangement of the batteries parallel to AC duct, where they are directly affected to conditioned air.

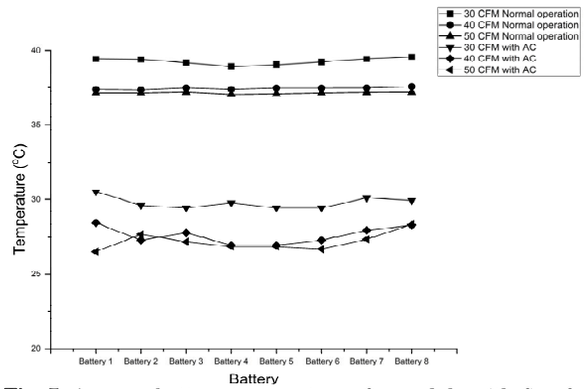

Fig. 7. Average battery temperatures for module with fins for both operating conditions.

TABLE 5

Average temperature of each cell without fins for both operating conditions.

Operation	1	2	3	4	5	6	7	8
30 CFM Normal operation	45.1	44.2	43.8	43.6	43.6	43.7	44.2	45.0
40CFM Normal operation	45.2	43.7	43.5	43.3	43.4	43.9	44.4	45.2
50 CFM Normal operation	44.5	43.4	42.8	42.6	42.4	43.0	43.5	44.1
30 CFM With AC	39.5	35.4	33.7	34.4	34.4	34.5	35.4	39.3
40 CFM With AC	39.2	35.9	34.2	34.9	35.6	34.7	37.8	40.9
50 CFM With AC	36.2	35.4	29.2	35.4	35.4	31.5	35.4	38.4

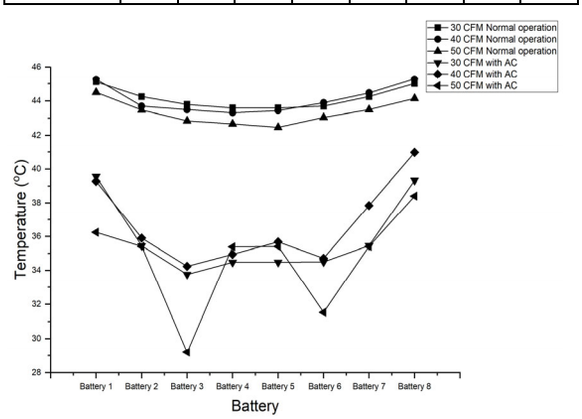

Fig. 8. Battery average temperatures for module without fins for both operating conditions.

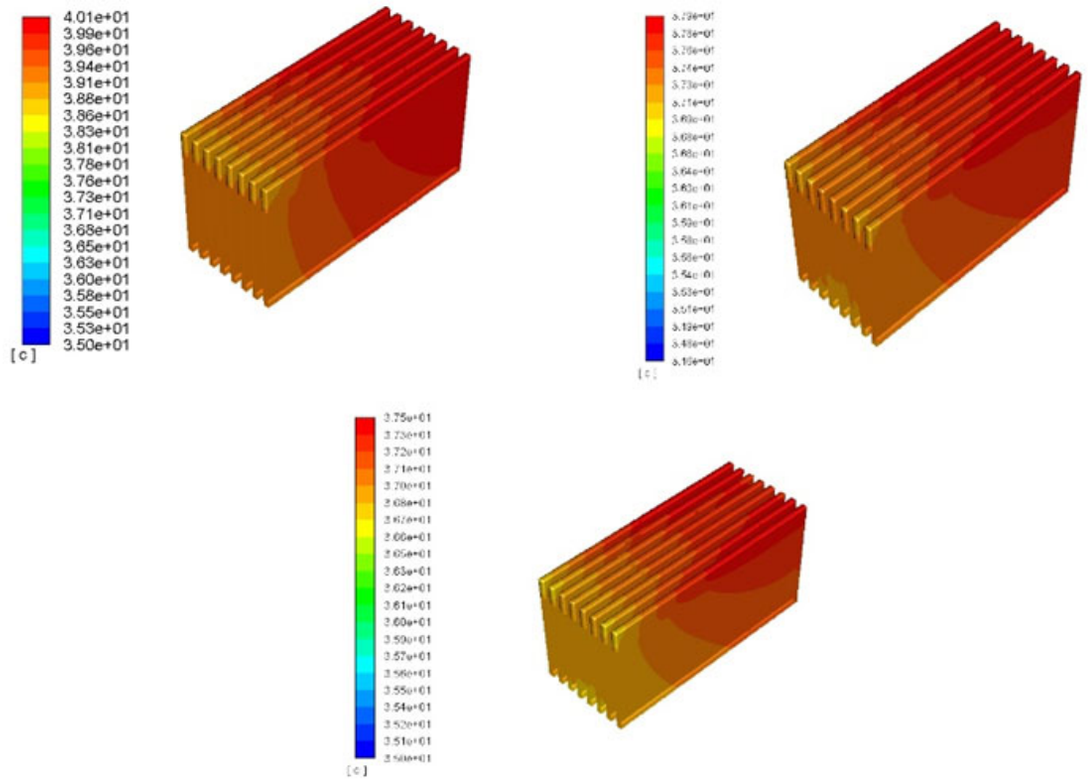

Fig. 9. (left to right)Battery temperature profile for the module with fins at normal operation (a) 30CFM, (b)40CFM, (c) 50CFM.

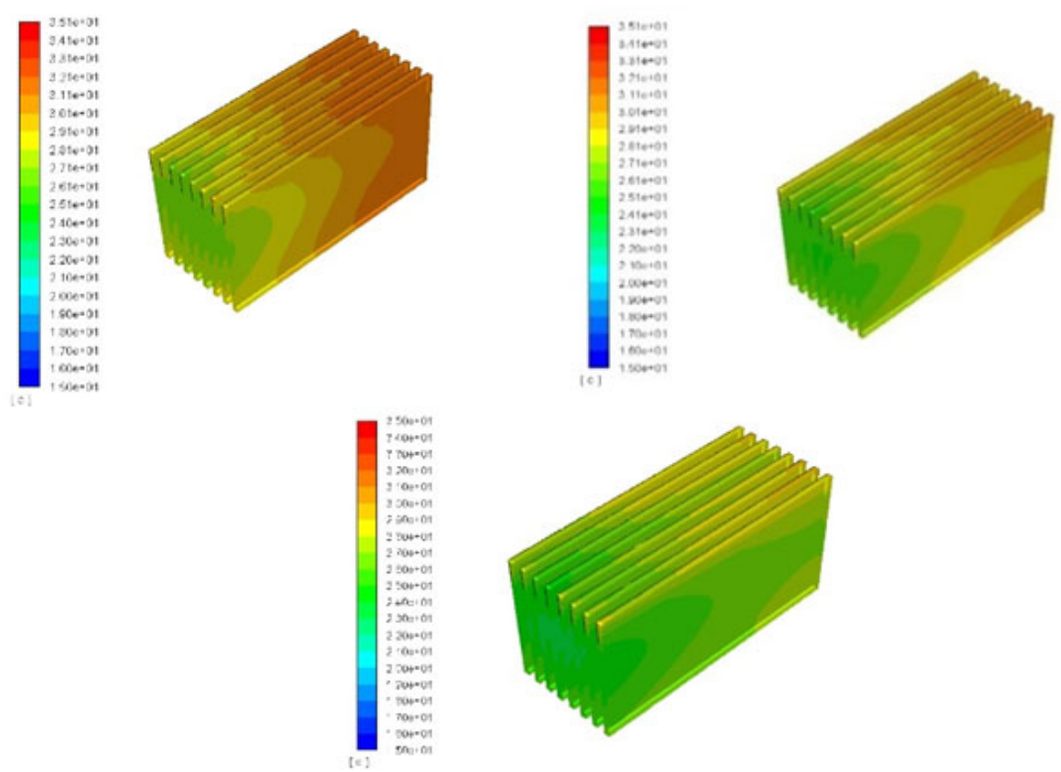

Fig. 10. (left to right) Battery temperature profile for the module with fins and with AC bleed (a) 30CFM, (b) 40CFM, (c) 50CFM.

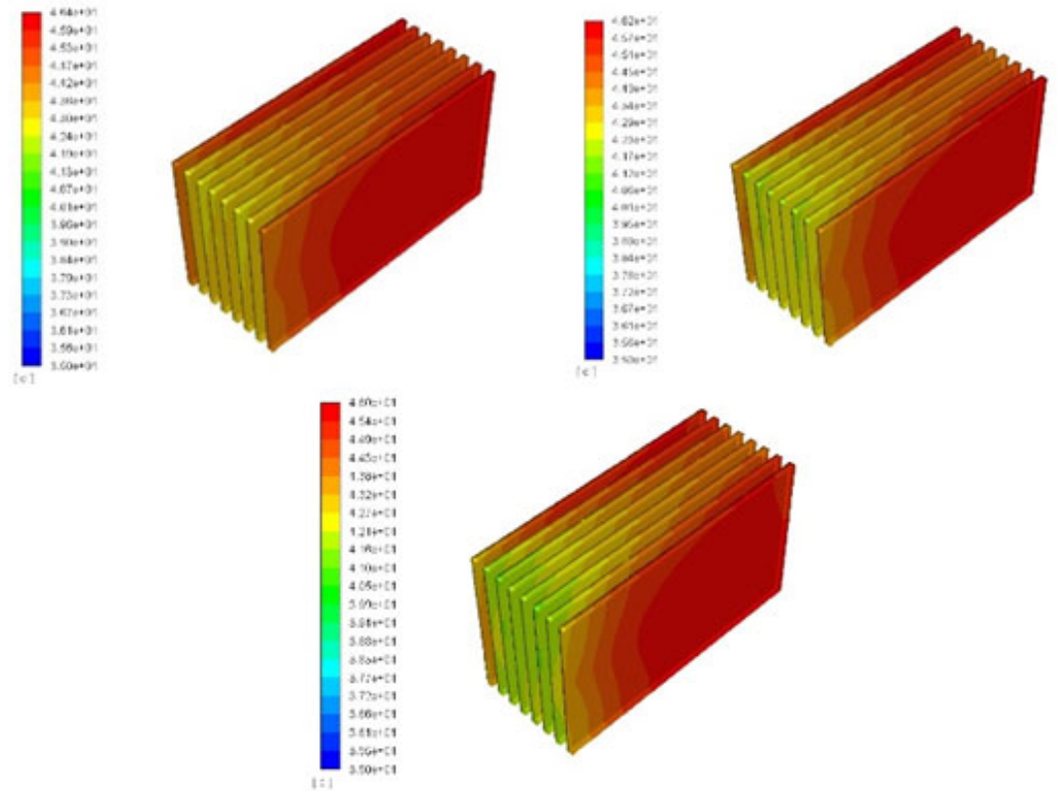

Fig. 11. (left to right) Battery temperature profile for the module without fins at normal operation (a) 30CFM, (b) 40CFM, (c) 50CFM.

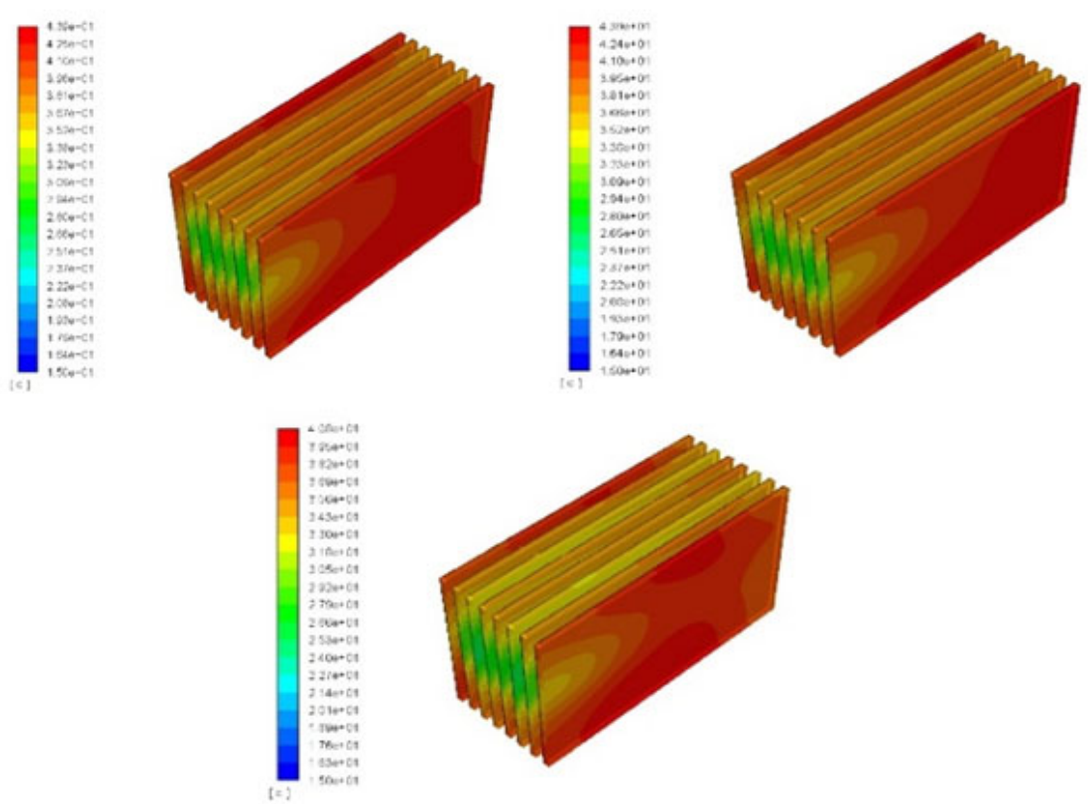

Fig. 12. (left to right) Battery temperature profile for the module without fins and with AC bleed (a) 30CFM, (b) 40CFM, (c) 50CFM.

Calculating the Fan Power

The pressure drop is calculated across the inlets and outlets from the fluent post processing tool to predict the fan power required for the model with fin structure. The values are tabulated below:

TABLE 6

Power required for fan.

Condition	CFM	Pressure drop (Pascal)	Power (W)
Normal operation	30	9	0.126
	40	27.5	0.495
	50	48.7	1.1201

Thermal Load on AC

As we are cooling the battery with the conditioned air drawn directly from the HAVC unit of an automobile, the capacity of the HAVC unit has to be increased as per the demand. The amount of the heat removed from the module for each and every condition is tabulated below.

TABLE 7

Heat removed from the battery module.

CFM	With Fins		Without Fins	
	Normal Operation	With AC bleed	Normal Operation	With AC bleed
30	487	591	291	521
40	496	651	396	633
50	614	709	658	665

Ragesh et al[18] considered a clustered model of a standard vehicle cabin and established a comparison based on experiments conducted on some vehicles that could be used for general validation. The model's numerical formulation can also be summarized as:

$$\dot{Q}_{Total} = \dot{Q}_{Met} + \dot{Q}_{Dir} + \dot{Q}_{Dif} + \dot{Q}_{Ref} + \dot{Q}_{Amb} + \dot{Q}_{Exh} + \dot{Q}_{Eng} + \dot{Q}_{Ven} + \dot{Q}_{AC}$$

$$\dot{Q}_{Total} = 240 + 1000 + 190 + 0 - 200 + 0 + 0 - 1000 - 2800$$

$$\dot{Q}_{Total} = -2570\ W$$

Cooling capacity = $\frac{\dot{Q}_{Total}}{3.517*1000}$ = 0.74 TR

By the addition of battery unit heat load to the above total load, the cooling capacity is

$$\dot{Q}_{Total} = 2570\ W + 709\ W = 3279\ W$$

Cooling Capacity= $\frac{\dot{Q}_{Total}}{3.517*1000}$ = 3279/3.517*1000

= **0.93 TR**

The total HVAC system has to be redesigned for 0.93 TR for the handling of BTMS working on the AC bleed.

Conclusions

The effects of using the fins for thermal management of the battery with ambient air and HVAC bleed air on the battery module have been investigated at different flow rates and thus conclusive observations can be made

Firstly, for the existing module without any fins (even spacing) and with conditioned air:

- Conventional air cooling is not efficient for improved heat dissipation for the 2C discharge frequency. The heat generated is above 40 °C at all flows and remains unchanged even when the flow increases.
- The minimum temperature for the AC bleed operation is 39.5 °C and it is possible to observe uneven distribution of temperature on the battery. This can have a serious impact on the battery's safety.

Hence the conventional cooling techniques cannot handle the thermal management of the $LiFePo_4$ batteries at high continuous discharge rate (600 seconds).

Module with fins,

- The fins can effectively dissipate the heat with the same battery discharge rate and the same flow rates. The temperature difference is 6.5 °C, 6.8 °C and 8.5 °C at a flow rate of 30 CFM, 40 CFM and 50 CFM. The profile of the battery temperature is constant throughout the length. The temperature of 30 CFM indicates a slightly higher temperature increase for each cell, but the temperature is more uniform.
- For the AC bleed operation, exhibits the battery temperatures are above the safety line and resulting temperature profiles are uniform throughout the length of battery.

The uniformity of the battery temperature can be achieved with the addition of fins and the safe operating conditions can be calculated. Because the ambient temperature is 35°C, the air conditioning bleed supply can be blocked at lower temperatures, thus by decreasing the load on the HVAC system

Modification of the HVAC unit

In the present study, under severe summer conditions, we assumed the general heat load conditions for a mid-sized hatchback. The extra load is applied to the standardized load to be handled by the HVAC system and the capacity increase is calculated. Including the heat load of the battery in the HVAC unit increases the unit's capacity by 25.6%.

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