International Journal of Mechanical, Industrial and Aerospace Sciences
ISSN: 2517-9950
Vol:7, No:10, 2013

Heat Generation Rate and Computational Simulation for Li-Ion Battery Module

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Abstract**—**In recent years Li-Ion batteries getting more attention among the Electrical Vehicles (EV) and Hybrid Electrical Vehicles (HEV) energy storage. Li-Ion has shown extended power density and light weight compared to other batteries readily available in the market. One of the major drawbacks in Li-Ion batteries is their sensitivity to the temperature. If the working temperature is beyond the limit, that could affect seriously on the durability and performance of Li-Ion battery. Thus Battery Thermal Management (BTM) is the most essential in adapting Li-Ion battery to the EVs and HEVs.

Keywords**—**Li-Ion battery, HEV/EV, battery thermal management, heat generation rate.

I. INTRODUCTION

THERE has been increased interest in Hybrid Electrical Vehicles (HEV) and Electrical Vehicles (EV) due to various sustainability concerns like greenhouse gases and exhausting fossil fuels. At present, Ultracapacitors, High-Speed Flywheels and Batteries are considered to be the most promising Energy Storage Systems (ESS). Among these Lithium based batteries have shown higherspecific energy, specific power thus considered as major source of electrical energy storage for the powertrains used for HEV/EVs [1]. In earlier generation of HEVs, Nickel-Metal Hydride (N-MH) batteries were used due to their low price and reasonable energy density. However Li-Ion batteries showing extended efficiency, high energy density and higher cycle life than any other batteries available in the market today [2]. Thus Li-Ion batteries are most obvious choice for HEV and EVs. Fig. 1 shows the prospective battery technologies for electrical power vehicles at present and for the future [3].

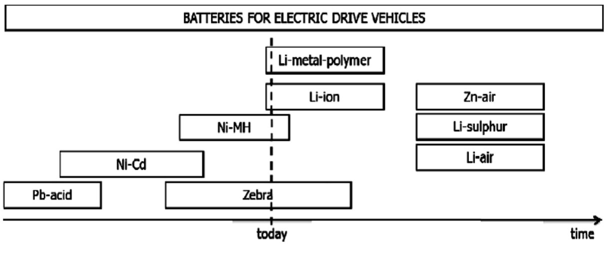

Fig. 1 Technology paths and different states of development [3]

Although Li-Ion batteries are with the high performance they are also very sensitive in nature. Repeated charge and discharge cycles and working temperature kind of factors have major impact on the SOC, SOH and life of Li-Ion battery. Thus battery management system (BMS) is inevitable for any applications using Li-Ion battery to obtain the maximum efficiency.

An effective cooling system is most essential for every battery pack installed in an EV or HEV that could maintain the operating temperature for better SOC, SOH and life of Li-Ion batteries. Pesaran A. proposed various thermal management systems for a battery pack considering both air and liquid as cooling medium [4]. Heat generation rate for a given battery pack is an important factor that controls the thermal analysis.

The main purpose of the study is to carry out an experiment to investigate the heat generation rate for the Li-Ion battery module used for an EV.

II. EXPERIMENTAL SETUP

In general calorimeters are used to determine the heat generated by the batteries [4], in case of Muhammad, the battery heat generation is approximated by the sum of (i) Joule (irreversible) and (ii) entropic (reversible) heats [5]. Alaouiin his paper, estimated heat generated from electric energy balance $\eta_{disch} = E_{char}/E_{disch}$, where η_{disch} is the discharge efficiency, $E_{char}$is the charging energy to the Li-ion cell, and E_{disch} is the energy discharged from the cell. The cell was charged at constant current/constant voltage method [6].

A comparison and correlation of calorimetric method and potentiometric method was studied by Eddahech et al. [7]. It is understood that the heat capacity of the battery cell is determined using calorimeter and there by heat generation will be calculated using the total weight of the battery whereas in potentiometric estimation is based on joule heating and entropy change.

Fig. 2 Li-Ion Battery Module

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TABLE I
LI-ION BATTERY SPECIFICATIONS

Item	Specification
Weight	Approximately 4.8kg
Cell Dimension	Thickness : 11.3mm Width : 167 mm Length : 335 mm
Normal Capacity	86 Ah @ 0.5C
Normal Voltage	(1C) 7.5V
Standard Charging Current	1C
Standard Discharging Current	1C
Max. Continuous Charging Current	172A
Max. Continuous Discharging Current	460A @ SOC50, 30Sec, 25°C
Max. Plus Discharging Current	600A
Working Temperature	-20~50°C
Module Dimension	Thickness : 53.6mm Width : 184.2mm Length : 360.2mm

In the present work a li-ion battery module as in Fig. 2 was considered for the analysis. Specification of the battery is stated in Table I. The main objective of the works is to determine the heat generation rate for the battery module.

In this experiment, battery is assumed to be discharge with 43A current at 0.5C which last about two hours. A Galvanostat device was used to determine the resistance inside the module, which was measure approximately 10 mΩ as in Fig. 3.

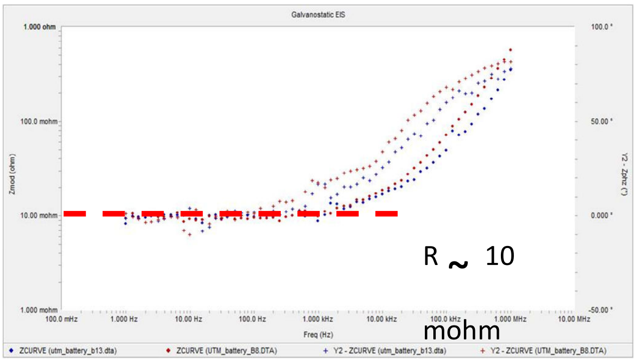

Fig. 3 Resistance in the battery module

As mentioned in the works of Mahamud [5] and Eddahech et al. [7], battery heat generation rate was estimated based on joule heating and entropy change. The formula of entropic loss, Q_{rev} and Joule heating, Q_{irr} is given by:

$$S_{r,I} = Q_{rev} + Q_{irr} \tag{1}$$

$$Q_{rev} = -IT\frac{dE}{dT} \tag{2}$$

$$Q_{irr} = I^2R \tag{3}$$

where,

$S_{r,i}$ = heat generated in J
Q_{rev} = reversible entropic loss in J
Q_{irr} = irreversible Joule heating in J
T = Battery temperature in K
$-\frac{dE}{dT}$ = Entropic coefficient
I = discharge current in Amp
R = internal electric resistance

Experiment was conducted at room temperature of 301K, the batteries used for this study is assumed to have a same characteristic as the batteries used by Mahamud's study thus average entropic coefficient was considered as -0.3 mV.K^{-1}[5].

With the data provided above, the heat generated by four batteries, $S_{r,I}$ in a module is calculated and the value is 34W and it is equivalent to 9560.5Wm^{-3} heat generated based on the volume of a module.

III. CFD SIMULATION

Computational simulation was carried to on thermal management. In total thirteen batteries were used in the battery pack and the arrangement was shown as in Fig. 4. Similar model was created using Solidworks, and meshing was done by Ansys meshing tools as shown in Fig. 5.

Fig. 4 Battery module arrangement within the EV boot

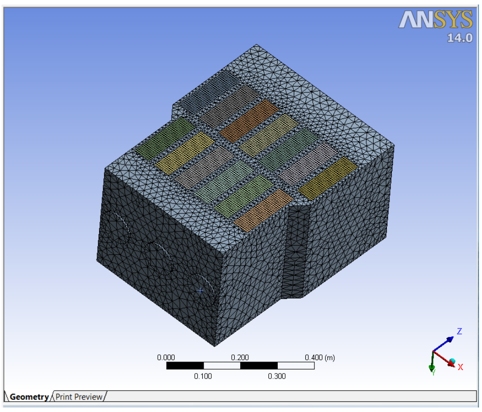

Fig. 5 CFD mesh for battery pack

Ansys Fluent was used to solve the fluid dynamics simulations considering 30CFM, 60CFM and 90CFM flow rated fan at the inlet.

IV. RESULTS AND DISCUSSION

There were three holes on one side and four holes for other side for air ventilation. Initially CFD model was created considering three fans fixed to the three holes side and assumed to push air through the battery modules, so that the air could exit through four holes. This model was repeated for three flow rate conditions with 30CFM, 60 CFM and 90CFM, respective temperature profiles were analyzed to fit the two important criteria stated below.

a. The operating temperature should be within 20°C to 40°C [8]
b. The temperature variation among the battery modules to be within 5°C [8]

Temperature profiles for various flow rates are shown in Figs. 6-8. Table II can illustrate the maximum temperature, minimum temperature and temperature difference among the modules for various flow rates.

TABLE II
TEMPERATURE PROFILES

Flow Rate	T_{max}	T_{min}	ΔT
30 CFM	50°C	45°C	5°C
60 CFM	45°C	41°C	4°C
90 CFM	43°C	40°C	3°C

From Table II it can be noticed that 30 CFM flow rate can control the temperature near to 50°C and the temperature difference **ΔT** is about 5°C. However the 60 CFM and 90 CFM flow rate could show improvement in **ΔT**, but all the three flow rates fail to satisfy the first criteria to keep temperature bellow 40°C.

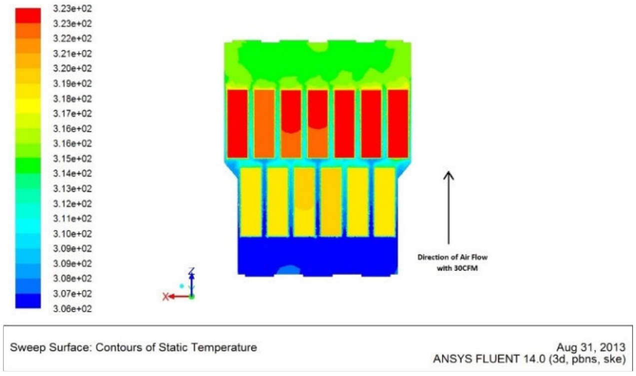

Fig. 6 Temperature profile for battery modules with 30CFM flow rate

Thus the flow direction and number of fans were changed to opposite side. This time with 4 fans pushing the air into the battery pack and letting air to exit from three holes on the other side.

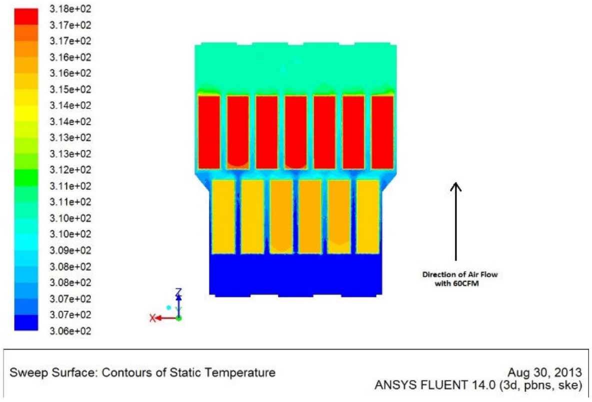

Fig. 7 Temperature profile for battery modules with 60CFM flow rate

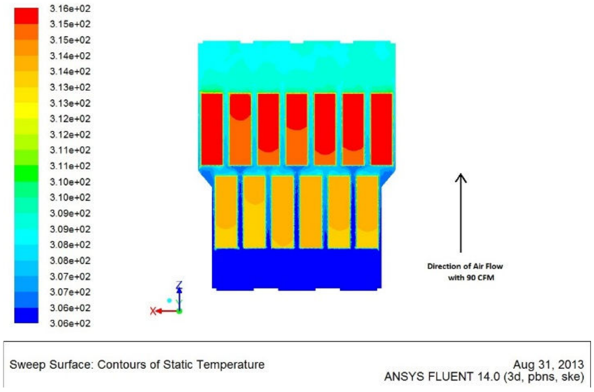

Fig. 8 Temperature profile for battery modules with 90CFM flow rate

Temperature profile for this condition is illustrated in Fig. 9. It can be noticed that most of the battery modules are near to 40°C except a few with 41°C. However the **ΔT** was maintained to 1°C, which means more even distribution of temperature among the modules.

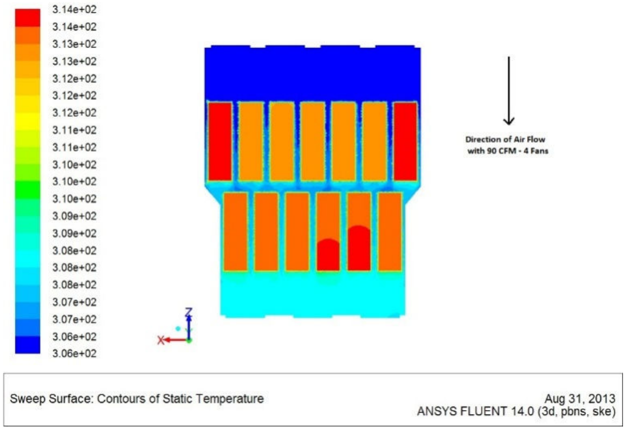

Fig. 9 Temperature profile for battery modules with 90CFM flow rate 4 fans

Table III illustrates the comparison between 3-fans push versus 4-fans push with 90 CFM architecture results. It clearly indicates that the first rows of battery modules could maintain 40°C for both the cases as minimum temperature recorded. With 4-fan architecture, battery modules in the second row could get more supply of air to apply better cooling, thus they could maintain 2° less (max temperature of 41°C) compared with 3-fans architecture.

TABLE III
TEMPERATURE PROFILES WITH 90 CFM FANS

Architecture	T_{max}	T_{min}	ΔT
3-fans push air	43°C	40°C	3°C
4-fans push air	41°C	40°C	1°C

According to Pesaran and Keyser in their work, at 22°C, discharging from 80% to 50% SOC, the heat generation rate was 0.13, 10.5, and 41.6 Watts for C/1, 5C, and 10C discharge rates, respectively. As the state of charge and temperature decreased, the heat generation rate increased, which was shown in Fig. 10 [9]. Thus the heat generation rate of 8 Watts/cell which was considered in current work could assume to happen at 22°C with SOC of 45%.

In current simulation ambient temperature considered was 33°C which is far below than 22°C and temperature raise in the battery modules could be less than 40°C. Thus 90CFM fan with 4-fans pushing air architecture was a best judgment to keep the battery modules with in working temperature as well as not to consume high battery power for battery thermal management.

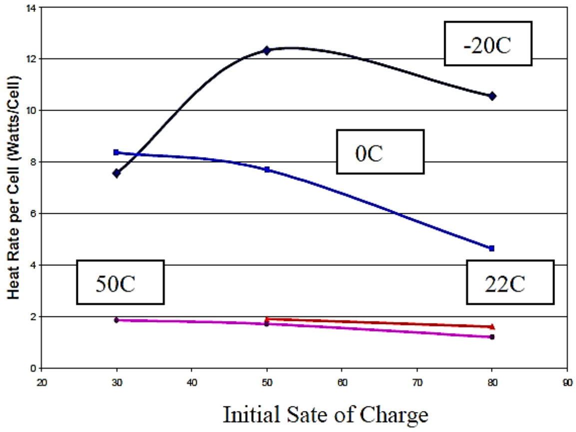

Fig. 10 Heat generation rate at various SOC and Temperature levels [9]

V.CONCLUSION

We observed that, heat generation rate is most important factor that influences the design of battery thermal management system. While estimating the heat generated using entropic loss and joule heating, the internal resistance of the battery module is most important to know.

While simulating the battery pack for the temperature management under computational modeling, Ansys Fluent was used as the solver. It was noticed that for the battery pack designed to fit in the electrical vehicle boot, the model with four fans at 90 CFM could provide the best cooling mechanism than all other mechanisms that were tried.

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