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Three dimensional numerical validation and investigation on air cooling system of Li-ion battery used in hybrid electric vehicles

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Abstract The lithium ion batteries are most commonly used in hybrid electric vehicles for obtaining high energy density among the condemnatory issues that have been in automotive industry. As the thermal management system is very prominent in automotive batteries, an effective design consideration is to be carefully opted for cooling the battery. Especially, a forced cooling is followed as an empirical choice rather than natural cooling in the automotive industry. In this paper, a three dimensional battery pack with multiple cells and cooling passages is modelled and validated to maximize the durability and battery performance. An enumerated design of air-cooled system is validated from the literature and then numerically investigated the overall distribution of the temperature with different cases by changing the positions of the inlets and outlets of the battery to satisfy the thermal specification requirements of the battery. Since, a distinctive battery system is used in hybrid electric vehicle which contains multiple cells in parallel, cooling efficiency is accomplished by a uniform diffusion of air flow in the coolant passages which dissipates the heat evolved from the individual lithium-ion battery cell. The above four cases are compared and demonstrated that the efficient cooling performance is attained with the one inlet and one outlet which are placed at the opposite sides of the battery. This is acquired because, the faster the air flow rate, the more the system cools due to the high temperature dissipation.

Keywords: Temperature, cooling efficiency, fluid air, air flow rate, air cooling



1. Introduction

The common expectation from the hybrid electrical vehicles is to provide wide driving range and sensible refueling time for the modern hybrid passenger vehicles. The greatest advantage of these vehicles is the usage of smaller gasoline engine and the motor compared to the conventional and electric vehicles. In the hybrid vehicles the output power is obtained by the combination of powers of the gasoline engine and the motor. So these vehicles yield higher efficiency which is equal to the efficiency of the electric vehicles with the small sized motors. The dual purpose motor/generator promotes the regenerative braking in which the kinetic energy is recovered and used for charging the battery. Therefore, the batteries are needed to put up electrical currents as high as possible [2] for many charging and discharging cycles. The greatest power and energy is provided by lithium batteries in hybrid electric vehicle applications. For achieving the high voltage of the battery, the cells in the battery are chained in series to effectively run the hybrid electric vehicles [3].

Generally, in the lithium ion batteries the flow is happened in between the electrodes. During charging, the lithium ions shift from anode to cathode and in discharging, the lithium ions directly shift from cathode to anode. In the typical lithium ion battery lithium is used as anode and nickel oxide, cobalt, or manganese is used as cathode. In order to acquire more energy density of the battery the various electrolyte materials are explored [4]. In general there are two types of lithium ion batteries, one which uses the liquid or gel type of electrolyte and the other uses the solid polymer which acts as separator as well as electrolyte. The organic solution of electrolyte contains various solvents which show volatility and flammability [5] characters. The battery life depends on the calendar life in which the permanent loss of the capacity is observed. Not only high density but also safety and long durability issues commercialize the hybrid electric vehicles [6].

Because of potential overheating [7] and exposure to more temperature [8-10] the battery undergoes very fast degradation. So, an appropriate cooling system is designed to maintain optimum battery temperature in various operating conditions [9] on which the life span of the battery is depended. Every 1^oC rise in temperature leads in reducing the life span of the battery by two months [11]. The battery temperature should be kept below 40^o C and the difference in the temperature should be below 5^o C [12]. Various cooling strategies are used in thermal management systems such as air cooling (natural air cooling, forced air cooling and indirect cooling), liquid cooling(direct and indirect liquid cooling) using water, acetone, refrigerants etc [14,15], air conditioning cooling and phase change phenomena cooling by using heat pipe [16]and PCM systems [18]are examined to enhance the cooling efficiency. A new technique is introduced by changing the phase of the material [17].In natural and forced convection circumstances the simulations have been processed for obtaining the heat dissipation and generation rates [8].

Wu et al [19] proposed the most effective cooling system in which forced air convection with heat pipe is used for controlling the high temperature of the battery. *Mahamud and park* [11] suggested a reciprocating air flow cooling system for reducing maximum temperature in cell and for enhancing the temperature uniformity. *Karimi and Li* [13] introduced another effective cooling system in which the distribution of forced convection is effective, cost effective and also maintains the uniform temperature and voltage across the battery. Air ventilation in some batteries is important for sending out the dangerous gases [20,21]. As the cooling is essential for battery thermal management system, various improved cooling techniques have been proposed effectively. Since air is the surrounding medium of the passenger vehicle, a better cooling system is recommended which reduces the cost and weight of the battery. Separate ventilation is provided in the front area of the passenger vehicle as entrance of the air which provides better cooling. In this paper, a forced air cooling system is used for the lithium-ion battery in hybrid electric vehicles for the various boundary parameters. And numerical simulation is carried out to attain the overall temperature distribution of the battery cells and coolant passages in the system.

2. Methodology

The validated battery system in this paper consists of 72 battery cells and 74 coolant passages. The coolant passages are placed in middle of the battery cells for dispelling the heat flux. A rectangular manifold is considered for both the inlet and outlet of the battery system. The battery cells considered in the system are prismatic in nature. The complete dimensions of the model has clearly mentioned in the below table [1].

Table 1. The dimensions of the battery system

	Length(mm)	Breadth(mm)	Height(mm)
Battery system	225	191	787
Coolant passages	3	65	151
Manifolds	--	--	20

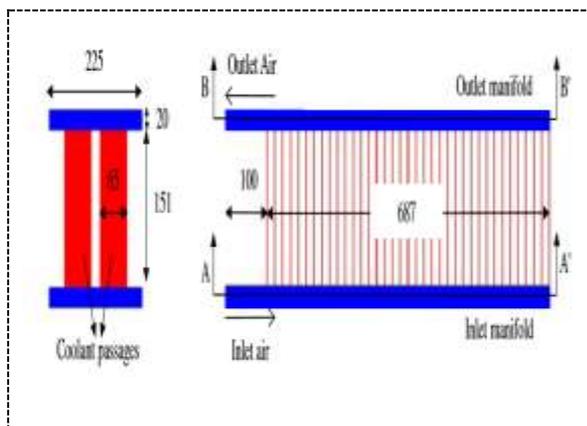


Figure 1. Dimensions of the battery system

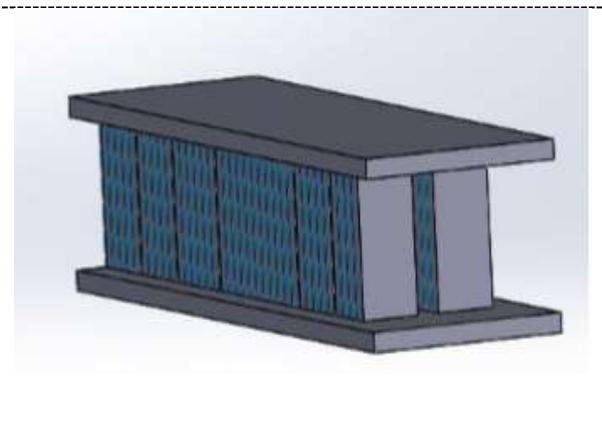


Figure 2. The solid works model

The above geometry taken from the literature [1] is modelled in the Solid works and further taken to the numerical simulations. The geometry modelled in the solid works is then imported to cfd modelling tool ICEM CFD. In this, the whole geometry is specified and named accordingly. The blocking and the tetrahedral mesh of the considered design have obtained. The following figures show the modelled and meshed geometry in ICEM CFD.

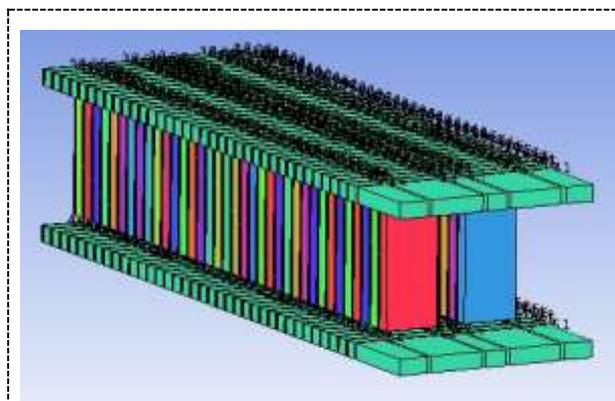


Figure 3. ICEM CFD geometry

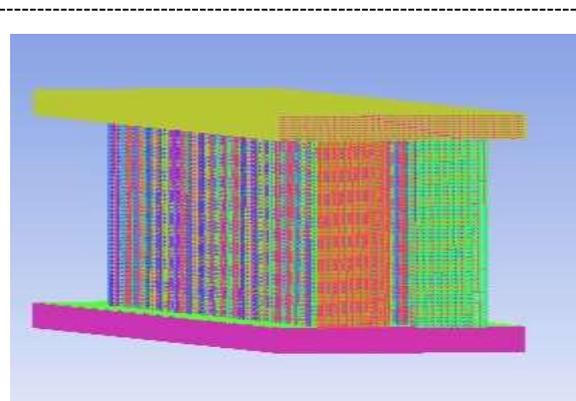


Figure 4. Meshed geometry

The final meshed model of the battery system is imported in to the ANSYS CFX where the considered model is simulated and numerically investigated. In the pre -processor of CFX the material properties and the boundary conditions are provided and simulated. The inlet temperature of the battery system is considered as 313 K. Air with the mass flow rate $0.045 \text{ kg sec}^{-1}$ [1] is blown from the inlet of the battery system. The material of the battery is taken as aluminium from the literature. The following table shows the boundary conditions and the material properties of the model. In this paper, four cases are considered by changing the direction of the fluid air in the inlets and the outlets. The first case (validation) consists of single inlet and outlet which are placed on the identical sides of the battery. In the second case two inlets and two outlets are taken on the opposite sides of the battery. In the third case only one inlet and one outlet is taken on the opposite sides of the battery. The above four cases are simulated in the pre-processor of CFX and numerically investigated.

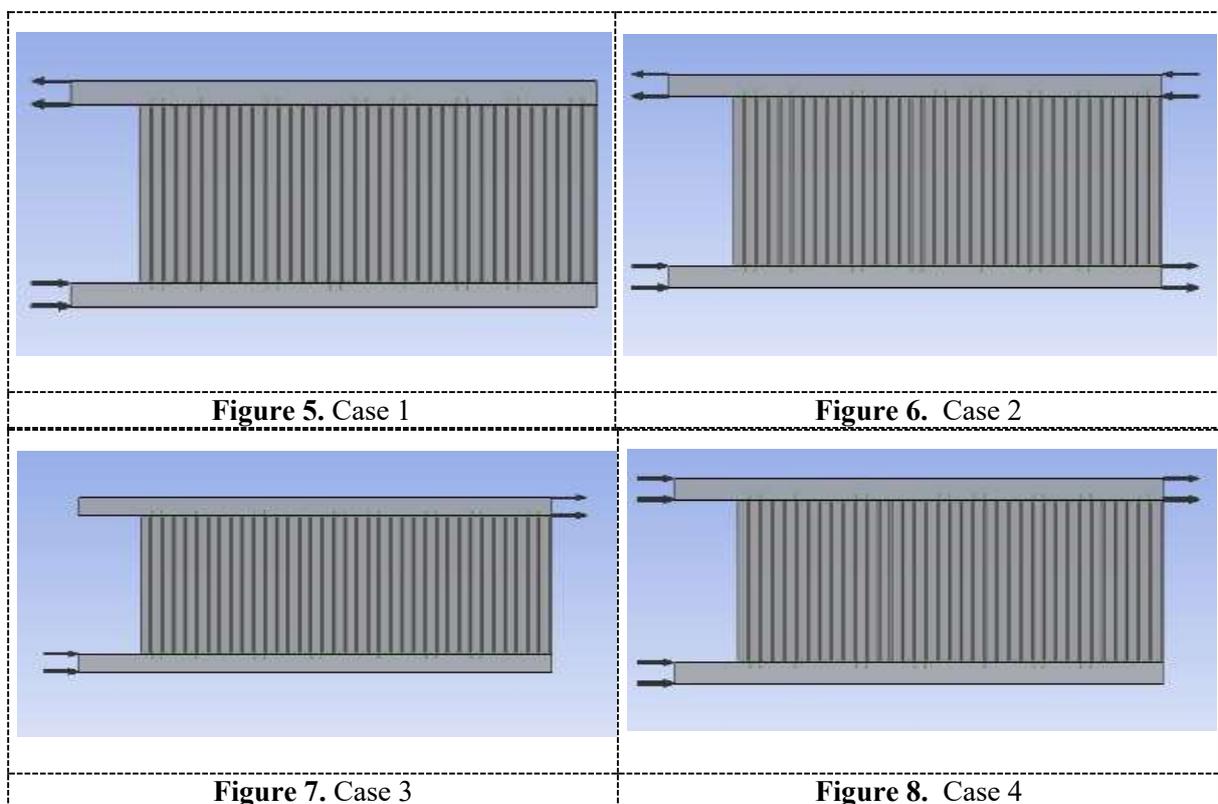
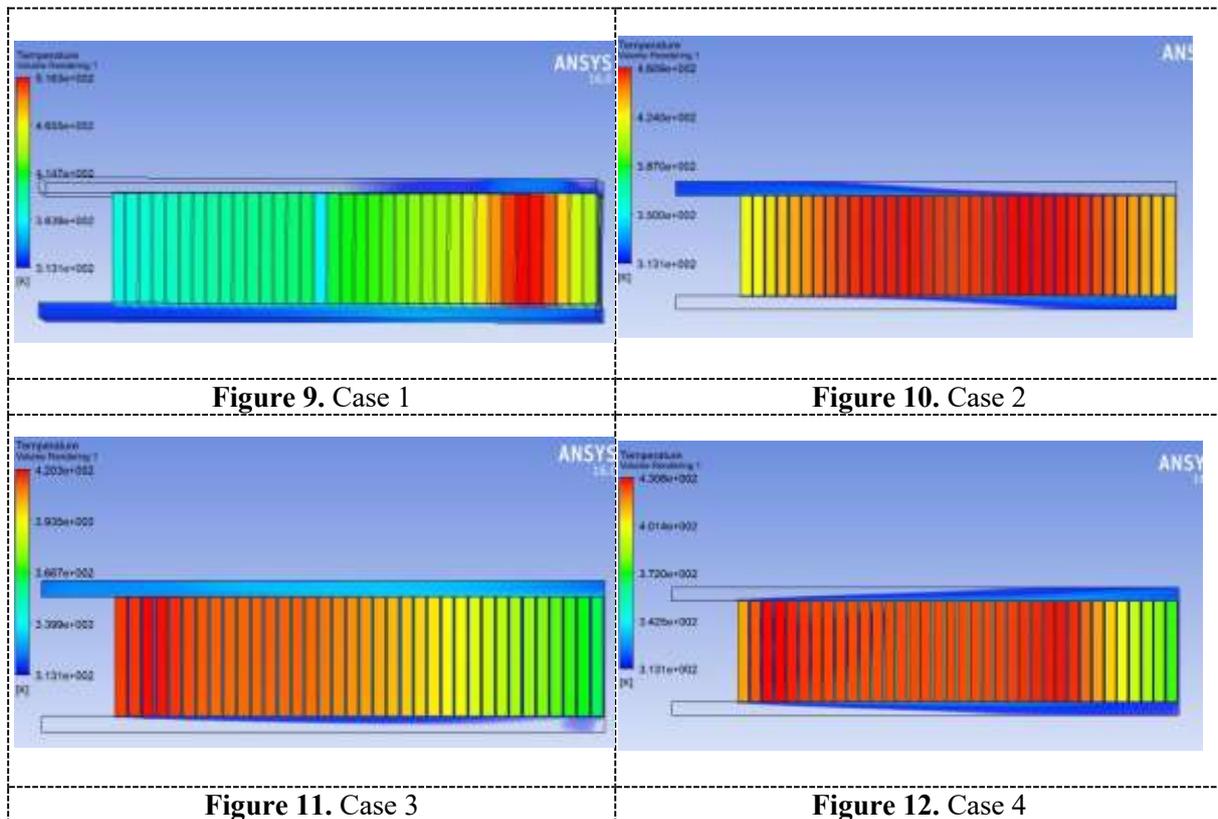


Table 2. The material properties of the battery and air

	Fluid air	Battery cell
Density	1.184	2700
Dynamic viscosity	1.98×10^{-5}	---
Specific heat	1003	900
Thermal conductivity	435	240
Heat flux	--	254

3. Results and Discussions

The overall temperature distribution is obtained by conducting the numerical simulations for the four cases and the optimized design for the fluid flow is predicted. The required results can be extracted in the post-processor of the CFX.



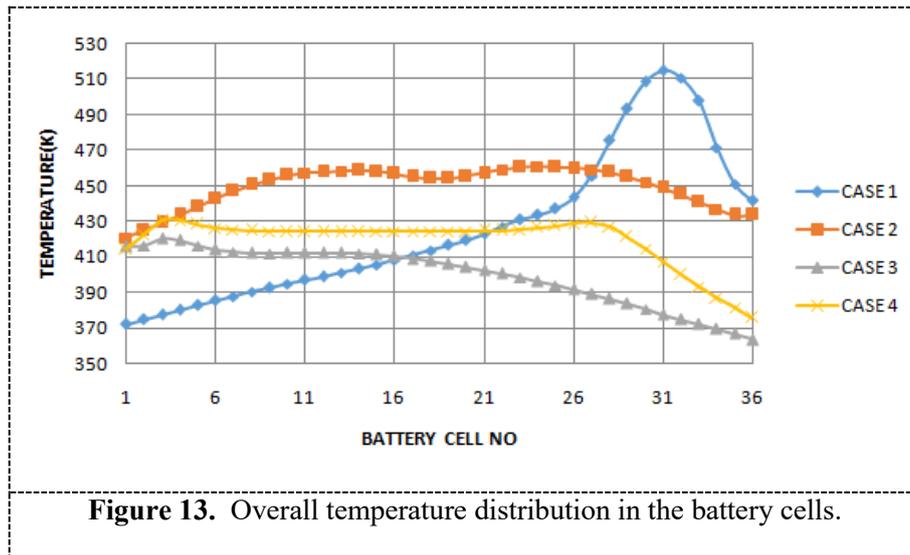
The numbering of the cells and the coolant passages in the battery is given from the inlet manifold. The effective cooling is required for the lithium ion battery to obtain the optimum parameters. In the validation the air flows across the channels of the battery and reaches the top portion by cooling the cells of the battery. The hot air comes out from the top manifold which is in the opposite direction of the inlet flow. The heat transfer takes place in the whole battery and thereafter the temperature of the cells gets decreased. The amount of heat transfer directly depends on the air flow rate in the corresponding coolant passages. The outermost cells temperature is very critical due to its inefficient flow rates in the passages. So, the temperature of these cells increases.

The fluid air temperature in the first case is noted as 322.28 K and the highest temperature of the battery is 516 K observed at the 31st and the 67th cells of the battery. The lowest temperature is 372 K observed at the 1st and the 37th cells of the battery. The temperature distribution directly affects the battery SOC and the discharge rates. The temperature variation between the cells is higher than the desired threshold values of the battery which does not yield the optimum parameters.

In the second case the recorded fluid air temperature is 319.04 K. The highest and the lowest temperatures are 460 K and 420 K observed at the 24th, 60th and the 1st, 37th cells.

In the fourth case the noted fluid air temperature is 319.93 K. The highest and the lowest temperatures are 430 K and 375 K observed at the 4th, 40th and the 36th, 72nd cells of the battery. For the sake of obtaining the utmost cooling ability, there should be the uniform temperature distribution in between the cells. The above requirements are obtained in the third case where the fluid air temperature is 321.71 K. And the highest and the lowest temperatures are 420 K and 363 K observed at the 3rd, 39th and the

36th, 72nd cells of the battery. The temperature diffusion graph is plotted only for 1-36 cells because the same trend is followed by the 37-72 cells. The battery cells temperatures are plotted and compared for the four cases in the following figure.



4. Conclusions

The forced air cooling in the hybrid electric vehicles for the battery system is mostly suggested because of its low cost, compactness and the adaptable design. The different configurations of the air flow are developed and numerically calculated in this study. The recommended cooling performance is attained by providing one inlet and one outlet at the opposite sides of the battery. In the third case temperature consistency is obtained. This investigation can be further carried out by using forced convection with heat pipe which decreases the temperature and also obtain the temperature consistency. The simulations that have been done in this paper can further carried by introducing the tapered inlet and outlet manifolds which even more decrease the temperatures of the battery. It is anticipated that the above approach will be the standard one not only for the hybrid electric vehicles but also for the electric vehicles and fuel cell vehicles in which the battery cells are used.

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