Influence of Geometry Changes on the Radial Cooling Performance of Lithium-ion Battery

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Abstract

With the exponential rise of the electric vehicles in the field of automobile sector, the use of lithium-ion battery (LIB) has been increased to several folds. The performance and life cycle of LIBs is governed by its temperature during operation. Therefore, studies related to the prediction of thermal behavior of operating LIB is gaining worldwide attention nowadays. The thermal behavior of LIB under different charging and discharging rates are predicted experimentally and numerically. The present work includes the thermal analysis of cylindrical LIB at 1C rate of discharge using three-dimension (3D) multipartition thermal model. The influence of geometric changes on the cooling performance, using radial cooling approach, is analyzed for two convective heat transfer coefficients (h=20 and 50 W/m^{2}K).The numerical results are validated by the published experimental data. Present work compares the average surface temperature for three different geometries (datum geometry-DG i.e. 18650 LIB, large geometry-LG and small geometry-SG) of LIB subjected to radial convective cooling. Subsequently, the temperature heterogeneity in terms of radial temperature gradient for 1C discharge rate is compared. The results show that average surface temperature of DG is minimum, while radial temperature heterogeneity is minimum for LG.

Keywords: Lithium-ion battery, multipartition model, battery geometry, radial cooling, heat transfer coefficient, average surface temperature, radial temperature gradient.

1. INTRODUCTION

Lithium-ion cylindrical batteries (LIB) have been widely considered as an energy storage device for battery electric vehicles (BEV), hybrid electric vehicles (HEV), and plug-in hybrid electric vehicles (PHEV) etc, due to their high power density, high specific energy, high reliability, low self-discharge rate, as well as low cost [1,2]. However, LIB exhibit high sensitivity to temperature [3, 4]. As reported in some studies, the internal resistance of the battery will increase noticeably at low temperatures, which result in the reduction of battery specific energy and power significantly. In the charge/discharge process, considerable heat is generated in the battery[5,6]. Effect of temperature on the life of LIB is very crucial [7] and some studies depicts that even a single degree increase in the temperature can reduce the life of battery significantly [8-10].

It is to be noted that, prediction of internal temperature variation of a battery for different rate of charging and discharging with the help of experiment is possible[11], but the real time situation of a battery during its operation when assembled as pack and module in an vehicle or device is difficult. Therefore, the numerical modelling is crucial to enhance the understanding of thermal aspects of battery. Finite element method, lumped analysis or electro chemical methods are some techniques which can be used for the simulation of battery thermal behaviour[11-14]. However, they have their own limitation and assumptions. Further, development of appropriate phenomenological models to simulate thermal behaviour of batteries can be battery electrode dependent that vary with different battery technologies [15, 16]. It is computationally expensive to have predictions of thermal behaviour accurately while battery is in operation. A comparatively less computational 3D model using the approach of equivalent circuit network (ECN) for thermal management is performed by coding on python[17]. However, to increase the accuracy level multi partition modelling using FEM for thermal analysis is an emerging approach[18-20].The 3D multi partition cylindrical model has been used and integrated with finite element method to investigate the internal temperature variation for different geometries.

In the present work, radial convective cooling is taken into the consideration with heat transfer coefficient equals to 20 W/m^{2}K (natural) and 50 W/m^{2}K (forced) and the effect of cooling is checked for three different types of geometry to find out the best geometry among the three with minimum average surface temperature and radial temperature gradient. The thermal behaviour of battery is different at different charging and discharging rate. The surface temperature and radial temperature gradient variation over the time for 1C discharge rate is numerically predicted and compared for the considered geometries. Discharge rate is taken into consideration rather than charging rate in the present work as, during charging, the endothermic reaction take place inside the battery. On the other hand, during the discharge process, exothermic reaction takes place, due to which the rise in temperature and temperature heterogeneity is high in battery[3, 11].

2. MATERIALS AND METHODS

Three different geometries considering multi partition model approach is designed to study the thermal behavior at 1C discharge rate. The multipartition model of a battery consist of five parts i.e. positive terminal, negative terminal, jelly roll, cell cap and cell steel can. Separately all parts are designed and assembled to carry out the thermal transient analysis using convective heat transfer cooling method in ANSYS platform.

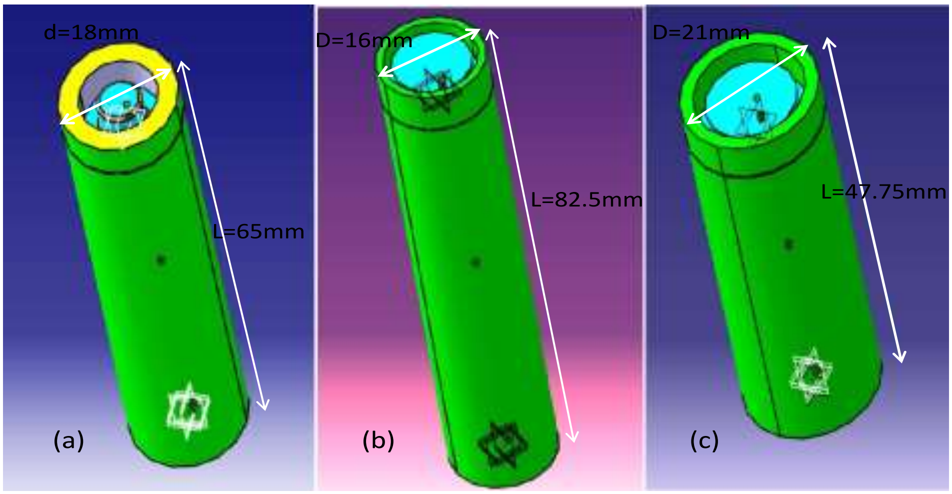


Figure 1. (a) Datum geometry (DG) i.e. 18650 LIB, (b) large geometry (LG) and (c) small geometry (SG).

In presented work three types of geometry is taken. The first one is Li-ion 18650 cylindrical battery with pre known dimensions of 18 mm diameter and 65 mm length and in paper this geometry is abbreviated as datum geometry (DG). In second geometry length has been increased and diameter has been decreased while keeping the volume constant and this geometry is abbreviated as large geometry (LG), in next geometry diameter has been increased and length has been decreased while keeping the volume constant and this geometry is abbreviated as small geometry (SG). The dimensions and data are tabulated in Table1.

Table 1. Diameter and length of different geometry

Geometries	Length (mm)	Diameter (mm)	Volume (mm^3)
DG	65	18	16520
LG	82.5	16	16520
SG	47.75	21	16520

From the above assembly design and dimensions table, it can be observed that different geometry has been found out by changing the dimensions while keeping the volume constant.

2.1 Thermo physical properties of different components of battery

As discussed earlier, three-dimensional (3D) multipartition model is considered, as compared to lumped model multipartition model give more accurate results[13]. Here a transient thermal analysis has been performed for 1C discharge rate (discharging in 3600 seconds). Mainly five components are taken to constitute multipartition model i.e. positive terminal, negative terminal, cap, jelly-roll and cell can. The orthotropic thermal conductivity has been taken for the jelly-roll as per cylindrical coordinate system and rest all other components are provided with isotropic properties. The variation of temperature in jelly-roll is very crucial, jelly-roll plays the major contribution in radial temperature gradient.

Table 2. Thermo physical properties of all different component used in battery[13]

Components	Material	Density (kg/m^3)	Heat capacity (J/kg K)	Thermal conductivity (W/m K)
Positive terminal	Aluminum	2719	871	202.4
Negative Terminal	Nickel	8900	460.6	91.74
Jelly roll	Electrode &Separator	2440	1210	K_r=1.1, K_z=K_q=12.5
Cap	PTC	3455	565.5	30
Steel Can	Steel	8030	502.48	16.27

2.2 Heat generation for different component

Cap, positive terminal and negative terminal having a constant internal heat generation whereas internal heat generation for the jelly roll is dependent on rate of charging and discharging, it will give different value for different rate of charge/discharge[13]. Heat generation of jelly-roll mainly depends on its internal resistance and internal resistance of jelly-roll varies with state of charge and discharge. By tracking the variation of internal resistance, we can get the data related to internal heat generation for different rate of charge and discharge. Here the analysis is limited to 1C discharge rate. The plot of volumetric heat generation v/s time for 1C is given in Figure 2.

Table 3. Component wise heat generation [13]

Components	Heat generation(mW/mm^3) for 1C
Cap	0.147
Positive Terminal	0.214
Negative Terminal	0.671

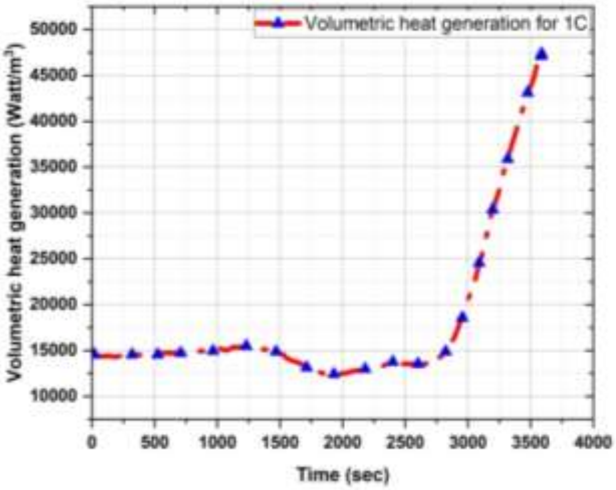


Figure 2. Volumetric heat generation of Jelly-roll at 1C discharge rate[13]

The volumetric heat generation for jelly-roll is plotted versus time, from the curve it can be observed that at the end of discharging i.e. in between 2500 to 3600 seconds the variation is large, from the above observation this can be said that at higher value of depth of discharge the heat generation is high. The variation heat generation with time can be seen in Figure 2.

2.3 Validation study

The thermal model is validated from the published experimental [13] cooling performace data for Li-ion 18650 battery which is also assumed as a datum geometry (DG). The percentage error in experimental and simulated result is less then 5 % the comparision graph is also ploted (Figure 3).

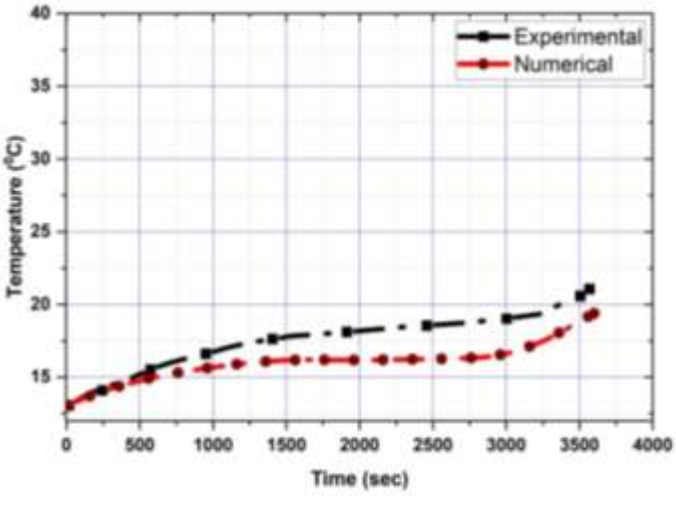


Figure 3. Numerical and experimental battery surface average temperature at 1C for DG i.e. LIB 18650. Experimental data are taken from the study Yang et al[13]

3. RESULTS AND DISCUSSION

After designing the battery model as per table 1 for DG, LG and SG, the multipartition heat generation transient thermal analysis is performed in ANSYS. The input parameters of table 2 and 3 and convective heat transfer values are provided to predict the average surface temperature. The results are shown in figure 3.

From the figure 4, it is observed that the average surface temperature for all the three geometry is different and it is maximum for SG at h=50 W/m^{2}K, which is 17.474 ℃. The maximum surface temperature for the LG and DG is 16.577℃ and 16.269℃ respectively. From the obtained results one can conclude that radial cooling approach for DG is good in terms of average surface temperature after 1 hour of cooling.

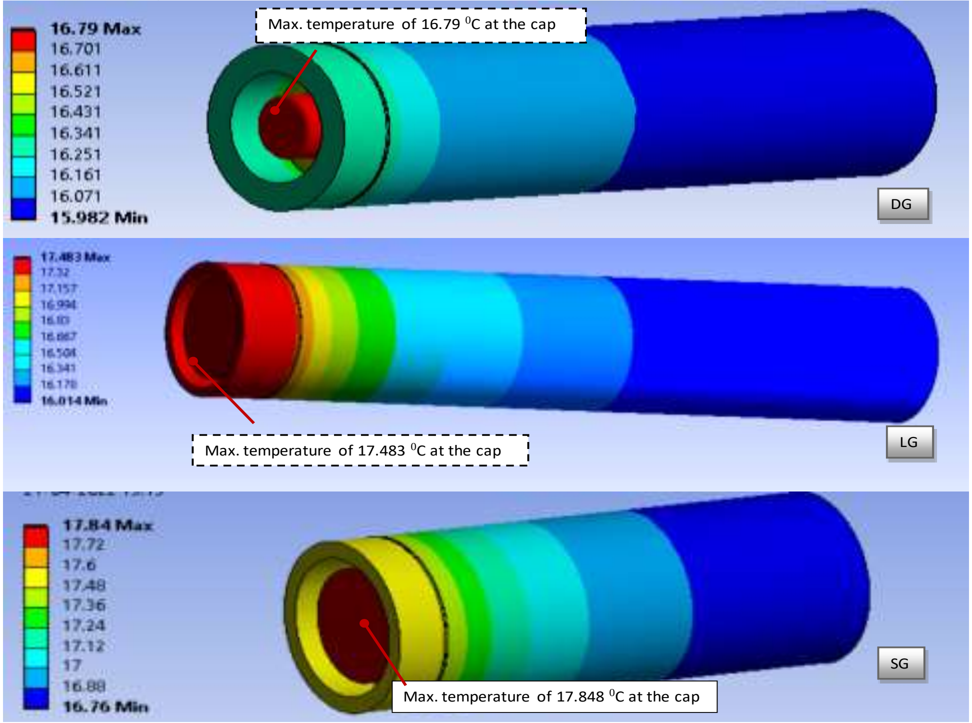
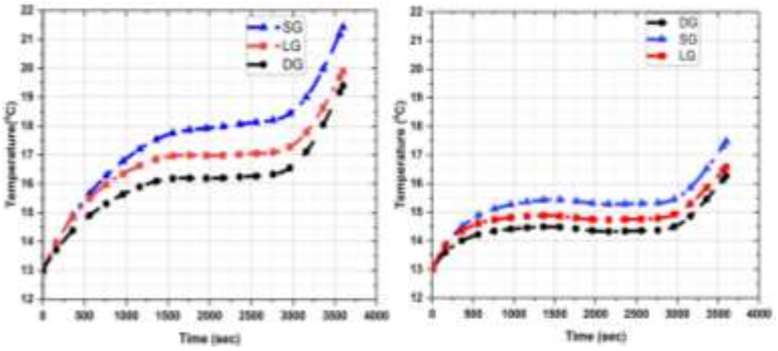


Figure 4. Average surface temperature contour for Datum geometry (DG), Large Geometry (LG), and Small Geometry (SG) at the end of 3600 seconds for 1C discharge rate at h= 50 W/m^{2}K (i.e. forced cooling).



(a) (b)

Figure 5. Variation of average surface temperature with time for 1C discharge rate at (a) h= 20 W/m^{2}K, (b) h=50 W/m^{2}K

The average surface temperature of the considered geometries are predicted and the values are compared in figure 5 for h=20 Watt/m^{2}K and 50 W/m^{2}K, simulating the natural and forced convective cooling.

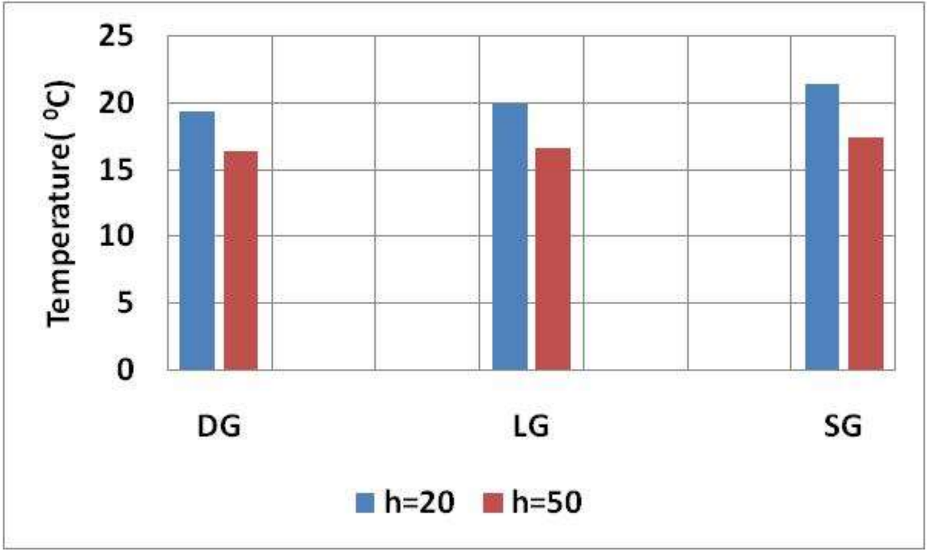
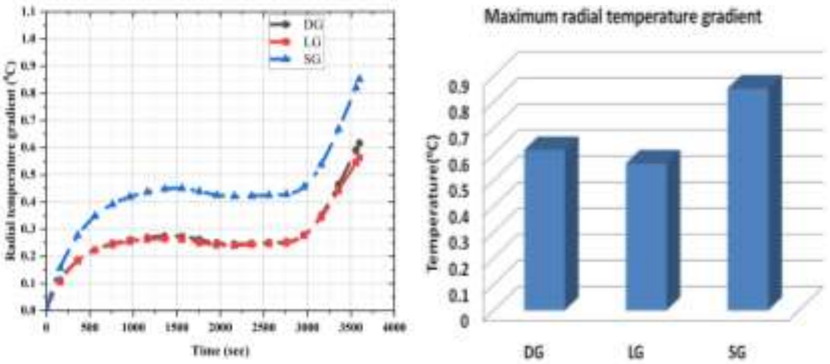


Figure 6. Maximum average surface temperature diffrance for DG, LG and SG for changing the heat transfer cofficient from 20 to 50 W/m^{2}K

As in the analysis when the convective heat transfer cofficient is chnaged from 20 to 50 W/m^{2}K the maximum surface average temperature fall is 2.954℃, 3.321℃ and 3.954℃ for DG, LG, and SG respectively, as shwon in Figure 6. The rate of cooling for the SG type battery on increasing the heat transfer cofficient is higher in comparision with DG and LG. This is because the difference between maximum average surface temperature and ambient temperature is high for SG type battery after natural cooling.



(a) (b)

Figure 7. (a) Variation of radial temperature gradient over the time for h=50W/m^{2}K and, (b) Maximum radial temperature gradient for different geometry for h=50W/m^{2}K.

Radial temperature gradient plot versus time at h=50 W/m^{2}K for radial cooling for all the three geometries is plotted in figure 7(a). This can observe that variation of radial temperature gradient for 1C rate for DG and LG is very close to each other. In figure 7 (b) this can be observed that maximum value of radial temperature gradient is minimum for LG and maximum for SG.

4. CONCLUSION

In the present work, the effect of geometry is clearly seen on radial convective cooling at different values of heat transfer coefficient. The cooling performance, in terms of average surface temperature, is most efficient for DG i.e. for 18650, intermediate for LG and least efficient for SG. It is also observed that, on increasing the value of heat transfer coefficient from 20 to 50 W/m^{2}K the average surface temperature decreases for all the geometries. This can be observed from the above analysis that on increasing the heat transfer coefficient the rate of cooling is increasing. The rate of cooling is highest for SG type batteries at elevated heat transfer coefficient due the high temperature difference between battery surface and ambient.

Radial temperature gradient is an important thermal parameter to analyze the life cycle and working conditions of cells. The non-uniform and high radial temperature gradient is dangerous and deteriorating. From the above analysis it has been observed that the radial temperature gradient is minimum for LG and highest for SG. The result can be different for different types of cooling process for different geometry.

It is inferred from the present approach of radial cooling strategy that by increasing the diameter and decreasing the length of LIB, both the average surface temperature and radial temperature gradient will increase. Conversely, decreasing the diameter and increasing the length of the LIB, the radial temperature gradient will decrease and a very minute rise in average surface temperature will take place. If it is important to keep the radial temperature gradient in limit then LG type geometry can be used and if it is required to keep the average surface temperature low, then DG type batteries is suggested in case of radial convective cooling. Therefore, the present work gives a direction towards improving the cooling efficiency by using the optimum cell geometry.

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