Chapter 31
Effect of Phase Change Material on Thermal Behavior of a Lithium-Ion Battery

Uğur Morali

Nomenclature

NTGK	Newman, Tiedemann, Gu, and Kim
DoD	Depth-of-discharge
PCM	Phase change material

31.1 Introduction

Energy storage materials have been widely used in various applications (hybrid vehicles, hybrid electric vehicles, portable devices, and so on). This could be attributed to their high-energy density and high-power density (Zeng et al. 2021). On the other hand, thermally sensitive structures of lithium-ion batteries restrict their usage in many applications where high discharge rates are needed (Yetik and Karakoc 2020). Lithium ions move from the negative electrode to the positive electrode during the discharge operation. This operation is generally performed under a certain discharge current suggested by the battery manufacturer. Battery temperature may rise under charge and discharge conditions due to the generated heat. The battery temperature above 40 °C has negative influence on the battery performance. Therefore, this increase should be controlled to maximize the battery performance.

Simulations have been used to determine thermal behavior of batteries (Jilte et al. 2021; Kwon et al. 2006). Valuable information in analyzing battery temperature rises can be obtained by using battery thermal models. The thermal behavior of the battery can be explained by applying thermal models providing a cost-effective approach. In the literature, distinct cooling methods have been used to control battery temperature rise. Phase change materials (PCMs) have been widely used in

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U. Morali (✉)
Department of Chemical Engineering, Eskisehir Osmangazi University, Eskisehir, Turkey
e-mail: umorali@ogu.edu.tr

T. H. Karakoc et al. (eds.), *Advances in Electric Aviation*, Sustainable Aviation,
https://doi.org/10.1007/978-3-031-32639-4_31

battery temperature control studies owing to their absorption ability of sensible heat as well as latent heat (Choudhari et al. 2021). Therefore, the use of PCM not only absorbs heat but also may provide a discharge operation at a constant temperature (Sattari et al. 2017).

In this study, the NTGK model was implemented to obtain the battery temperatures of a lithium-ion battery. The battery temperatures are maximum battery temperature, average battery temperature, and minimum battery temperature. The battery temperatures were also obtained using PCM. The effect of using phase change material was analyzed using the numerical results.

31.2 Method

A lithium-ion battery was used to simulate battery thermal behavior. Maximum and minimum battery potentials are 4.20 V and 3.00 V, respectively. The lithium-ion battery was discharged from 4.20 V to 3.00 V at 3C-rate. The ambient temperature was 290 K. The battery surface temperature and phase change material temperature were assumed to be equal to the ambient temperature at the initial stage of simulation. The convective heat transfer coefficient of the battery was assumed to be 5 W/m^2 K. Thermal and physical properties of phase change material was obtained from (Bellia et al. 2013). Density, heat capacity, and thermal conductivity of the PCM are 750 kg/m^3, 2250 J/kg K, and 0.2 W/m K, respectively. Melting heat of the PCM is 270.7 kJ/kg. Solidus and liquidus temperatures are 314.15 K and 317.15 K, respectively.

ANSYS Fluent was used to implement the NTGK model. Expressions of battery temperature are presented in Eqs. (31.1, 31.2, and 31.3):

$$\nabla\left(\sigma + \nabla\phi +\right) = -\left(\mathrm{jECh} - \mathrm{jshort}\right) \tag{31.1}$$

$$\nabla\left(\sigma - \nabla\phi -\right) = \mathrm{jECh} - \mathrm{jshort} \tag{31.2}$$

$$\mathrm{jECh} = \alpha \mathrm{Y}\left[\mathrm{U} - \left(\phi + - \phi -\right)\right] \tag{31.3}$$

where $\sigma +$ and $\sigma -$ are electrical conductivity of positive and negative electrodes, $\phi +$ and $\phi -$ are phase potentials of positive and negative electrodes. *jECh* is produced volumetric current transfer rate. *Jshort* shows current transfer rate. Model parameters, *U* and *Y,* are expressed as follows (Kwon et al. 2006; Kim et al. 2009; Gu 1983):

$$3\mathrm{U} = \alpha_0 + \alpha_1\left(\mathrm{DoD}\right) + \alpha_2\left(\mathrm{DoD}\right)^2 + \alpha_3\left(\mathrm{DoD}\right)^3 \tag{31.4}$$

$$\mathrm{Y} = \alpha 4 + \alpha 5\left(\mathrm{DoD}\right) + \alpha 6\left(\mathrm{DoD}\right) 2 \tag{31.5}$$

where *a*0-*a*6 are the fitting parameters. In this study, the fitting parameters obtained by (Kim et al. 2011) were used to calculate U and Y model parameters.

31.3 Results and Discussion

Figure 31.1 shows the maximum temperature of lithium-ion batteries with PCM and without PCM. The maximum battery temperature of lithium-ion battery was 312.81 K at 5C. This maximum battery temperature was within the normal range of lithium-ion battery performance (313.15 K). The maximum battery temperature was 308.75 K when the PCM was used to control the battery temperature. The average battery temperatures with PCM and without PCM are presented in Fig. 31.2. The average battery temperature at 5C was 311.16 K without PCM, while the average battery temperature with PCM was 306.98 K. Figure 31.3 shows the minimum temperature of lithium-ion batteries with PCM and without PCM. The minimum battery temperature at 5C (309.93 K) without PCM was higher than with PCM (300.96 K). Results demonstrated that the PCM showed a decrease in each battery

Fig. 31.1 Maximum battery temperature at 5C-rate with and without PCM

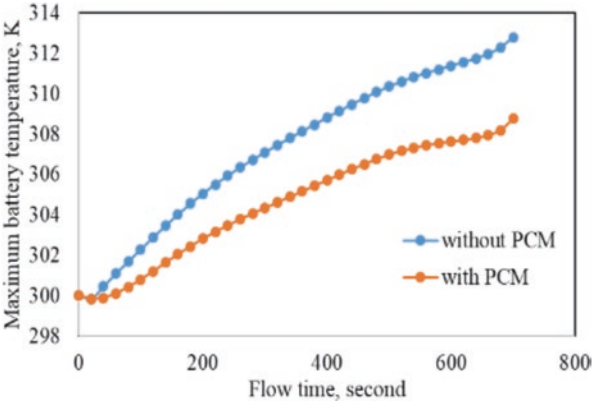
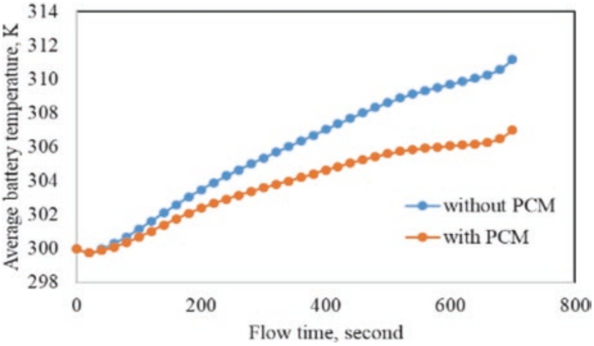


Fig. 31.2 Average battery temperature at 5C-rate with and without PCM



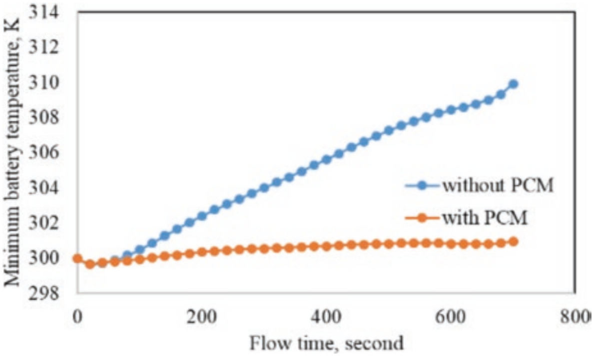


Fig. 31.3 Minimum battery temperature at 5C-rate with and without PCM

temperature. The difference between the minimum battery temperatures with and without PCM was 8.96 K. Moreover, the difference between the average battery temperatures with and without PCM (4.19 K) was higher than the maximum battery temperatures (4.05 K).

Temperature counters for the battery static temperature are presented in Fig. 31.4. The temperature distribution shown in Fig. 31.4a was more heterogeneous than that presented in Fig. 31.4b. In other words, the lithium-ion battery using PCM exhibited a more homogeneous temperature distribution across the battery body. Temperature distribution may affect battery performance. It is anticipated that the performance of the battery using PCM will be higher than the battery without PCM, likely due to homogeneous temperature distribution and restricted temperature rise. It is important to note that the temperature counters in Fig. 31.4 showed the distribution of static temperature at the end of 5C discharge. Results also showed that such a high discharge operation increased battery temperature in a short flow time. The used PCM restricted the temperature rise and allowed heat to dissipate homogeneously across the battery surface.

31.4 Conclusion

The effect of phase change material on battery temperature has been investigated in this study. The battery temperature was obtained using the NTGK model. Results showed that the maximum battery temperature was 312.81 K (without PCM) and 308.75 K (with PCM). The phase change material used reduced the average battery temperature by 1.35%. PCM allowed a relatively homogeneous temperature distribution for the battery discharged at a high rate of 5C compared with the battery without PCM. It is recommended that phase change materials can be used in battery thermal management systems to obtain a homogeneous temperature distribution and to restrict the temperature rise.

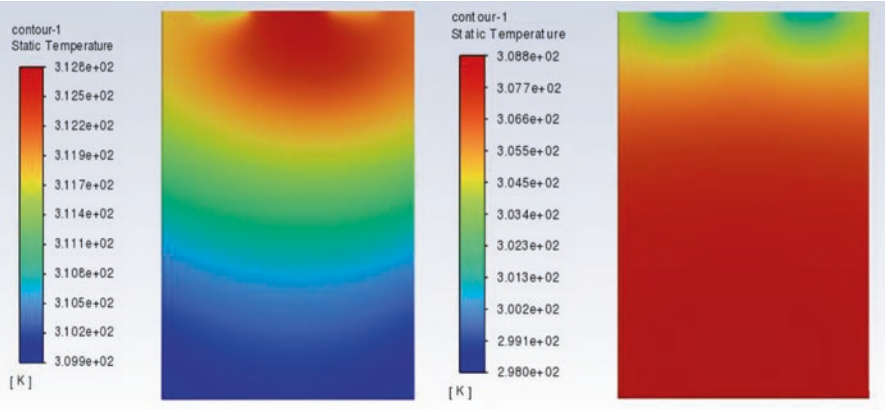


Fig. 31.4 Distribution of static temperature at 5C-rate: (**a**) without PCM; (**b**) with PCM

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