COMPARATIVE ANALYSIS OF LUMPED MODEL AND NTGK MODEL APPROACHES FOR LI-ION BATTERIES

Vedat TEKIN[1], Aykut KARAKOR[2], S. Aykut KORKMAZ[3,4], C. Ozgur COLPAN[1], M. Akif EZAN,[1,5], M. Umut KARAOGLAN[1,5], Aytunc EREK[1], Erdal CETKİN[6]*
[1]Department of Mechanical Engineering, Dokuz Eylul University, Buca, Izmir, Türkiye
[2]Department of Mechanical Engineering, Manisa Celal Bayar University, Muradiye, Manisa, Türkiye
[3]Department of Marine Engineering, Dokuz Eylül University, Buca, Izmir, Türkiye
[4]Maritime Engineering, University of Southampton, Southampton, UK
[5]Dokuz Eylul University, Energy Application and Research Center (EUAM), Buca, Izmir, Türkiye
[6]Department of Mechanical Engineering, Izmir Institute of Technology, Urla, Izmir, Türkiye
[*]Corresponding author e-mail: vedat.tekin@ogr.deu.edu.tr

ABSTRACT

Battery performance/lifetime gains attention especially due to increased number of electric vehicles (EVs) which suffers from relatively low range. In EVs, battery performance is one of the most important parameters affecting driving range. Therefore, the literature has been focusing on the studies with the aim of battery performance enhancement. The main objective of a battery thermal management system (BTMS) is to keep the battery within the ideal operating temperature range. For Li-Ion batteries, this range can be considered between 15°C and 45°C. Li-Ion batteries (LIBs) are the most promising power source for pure electric vehicles (EVs) and hybrid electric vehicles (HEVs) due to the batteries' high specific energy, low self-discharge rate, low weight, long lifecycle, and no memory effect. Three topologies of cells are used in EV batteries: cylindrical, prismatic and pouch-type. These cells have advantages and disadvantages in terms of energy storage capacity, cooling characteristics and footprint. BTMS can be modelled with different assumptions depending on the solution accuracy, algorithm structure and computational speed parameters. This study investigates the cooling performance of cold plate based BTMS for batteries with different geometric structures in different modelling methods. The main objective of this study is to simulate cell temperature change, heat generation and state of charge in different BTMS models for batteries with different cell geometries using cold plate. In our study, BTMS simulated the battery current drawn, operating voltage, state of charge, heat generation, heat generation and time-dependent variation in cell temperature for a LIB battery consisting of 14 series of 2 parallel pouch cells with a capacity of 3.3 kWh and a LIB battery consisting of 32 series of 2 parallel cylindrical cells with a capacity of 6.9 kWh using a lumped model in MATLAB/Simulink and the Newman, Tiedemann, Gu and Kim (NTGK) model in ANSYS-FLUENT. This study not only contributes to the advancement of thermal management in electric vehicles, but also provides a basis for the optimization of cooling performance for batteries of different geometries used in electric vehicles in different BTMS models.

Keywords: Battery Thermal Management System, Cold Plate Technology, Thermal Optimization, NTGK Model, Lumped Model

1. INTRODUCTION

LIBs, which are electrochemical energy storage devices, are used in many different fields, for example electric vehicles. These batteries, which have different geometric properties due to their different usage areas and different energy capacities, are one of the most important parts in terms of providing power to electric vehicles. Overheating of LIBs is a serious problem. To prevent thermal runaway and decrease in the performance of the batteries, it is necessary to keep the temperature between 15°C - 45 °C. Battery thermal management systems, which can be classified as air, PCM and liquid cooled, aim to bring LIBs to optimum operating temperature. There are models such as Newman Pseudo-2D, Equivalent Circuit Model, NTGK as well as simplified models such as Lumped method to model batteries. Lamrani et al., (2021) developed a simplified model to numerically investigate the 6 series of 4 parallel cylindrical battery packs containing PCM and showed that the simplified model can be used with reasonable accuracy in BTMS. Sevilgen et al., (2023) investigated three different cold plate designs for thermal management of the battery pack modelled by the NTGK method at different discharge rates. They showed that in terms of the temperature difference at different locations of the battery module, the multi-channel cold plate is more suitable, especially for high discharge rates. Kalkan et al., (2022) obtained the optimum values of different design variables (channel width, distance between branches, channel depth, number of crossovers in branches and coolant low rate) to optimise the maximum battery temperature, maximum temperature difference on the battery surface and pressure drops in the channels. Zahng et al., (2020) proposed a cold plate with channels for thermal management of a 6 series 4 parallel pyrolytic battery modelled by NTGK method. As a result of their analyses with different discharge rates and different fluid inlet rates, they have shown that the cooling system they proposed keeps the battery at optimum operating temperature. Fan et al., (2024) proposed a cold plate with channels for thermal management of a 6 series 4 parallel prismatic battery modelled by NTGK method. As a result of their analyses with different discharge rates and different fluid inlet rates, they have shown that the cooling system they proposed keeps the battery at optimum operating temperature. In this study, two battery modelling methods, NTGK method and Lumped model, will be compared with each other using ANSYS – FLUENT and MATLAB/Simulink. The thermal management of the battery will be realized by Cold plate application, which is a non-direct contact liquid cooling method.

2. MATERIAL AND METHODS

In this study, a Li-Ion Pouch Type battery module consisting of 28 cells (14 series and 2 parallel) with a capacity of 3.3 kWh was used. The technical specifications of the battery module are provided in Table 1 (Farasis Energy, 2023), and these data were used as references in the conducted research.

Table 1: Characteristics of battery cells at 25°C and 1 C-Rate (Farasis Energy, 2023)

Characteristic	**Value**
Mass of battery cell (g)	505
Length of battery cell (mm)	230.5
Width of battery cell (mm)	161
Thickness of battery cell (mm)	6.16
Cell heat capacity (J kg^{-1} K^{-1})	1040
Nominal capacity (Ah)	29.3
Nominal voltage (V)	3.58
Nominal energy (Wh)	105

In this study, parameters such as maximum battery temperature, temperature difference inside the battery, cooling effect of the cold plate on the battery, temperature difference across the cold plate and battery efficiency are investigated for the reference battery at different C-rate values. The battery thermal management system is modelled in MATLAB/Simulink using a lumped method and in ANSYS/Fluent using the NTGK method. The data obtained with the lumped model and NTGK method are used as boundary conditions for CFD analysis in ANSYS/Fluent. By defining the heat flux on the CAD designed cold plates in spider web and serpentine geometries, the amount of heat transferred to the cold plate, the temperature rise in the cold plate, and the heat dissipation and cooling performance on the cold plate surface are analysed. The studies were carried out assuming the input parameters given in Table 2.

Table 2. Input Parameters

Parameters	**Value**
Refrigerant Inlet Temperature (°C)	10
Refrigerant Inlet Flow Rate (g s^{-1})	7
Spider Web Cold Plate Total Channel Area (m^2)	0.217
Serpentine Cold Plate Total Channel Area (m^2)	0.206
Ambient Temperature (°C)	25
Initial Temperature of the Battery (°C)	20
Initial SOC Value of the Battery (%)	85

2.1. Simplified Battery Heat Transfer Model

The assumptions considered when reducing the physical problem to a mathematical model are as follows:

- Heat generation inside the battery is equal in each cell.
- The convection coefficients on the lateral surfaces of the battery module are the same.
- The heat generation in the cells does not depend on the temperature.

The top surface of the battery is assumed to be adiabatic.

Based on these assumptions, the energy equation of the battery is written as follows:

$$(mc_p)_b \frac{\partial T_b}{\partial t} = Q_t + Q_{loss} \tag{1}$$

where, m_b is the battery mass, $c_{p,b}$ is the specific heat capacity of the battery, Q_b is the total amount of heat generated by the battery and Q_{loss} is the total heat dissipated from the battery.

$$Q_t = Q_{irr} + Q_{rev} \tag{2}$$

where Q_{irr} is the heat generation from electrical energy and Q_{rev} is the heat generated due to reversibility during the charging and discharging processes of the battery. In the lumped model, reversible effects can be neglected.

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

where I is the electrical current, and R is the internal electrical resistance.

$$Q_{loss} = Q_{coldplate} + Q_{convection} = U\, A_s\, \Delta T_{LMTD} \tag{4}$$

where Q_{loss} is the heat removed from the coil by conduction and convection, $Q_{coldplate}$ is the heat transferred to the cold plate by conduction and $Q_{convection}$ is the heat removed from the lateral surfaces to the air. U is the total heat transfer coefficient, A_S is the heat transfer area and ΔT_{LMTD} is the logarithmic mean temperature difference.

2.2. NTGK Battery Heat Transfer Model

The NTGK model is an empirical electrochemical model (Kwon et al., 2006). The volumetric current transfer rate is expressed as follow,

$$j_{ECh} = \alpha Y[U - (\varphi_+ - \varphi_-)] \tag{5}$$

where α is the specific area of the electrode plate, φ_+ and φ_- are the phase potentials for the positive and negative electrodes, respectively, and j_{ECh} is the volumetric current. Where U and Y are the model parameters of the battery discharge depth functions

$$U = \left(\sum_{n=0}^{5} a_n (DOD)^n\right) - C_1(T - T_{ref}) \tag{6}$$

$$Y = \left(\sum_{n=0}^{5} b_n (DOD)^n\right) exp\left[-C_2(\frac{1}{T} - \frac{1}{T_{ref}})\right] \tag{7}$$

For a given battery, the voltage current response curve is obtained by experiment and then determined by the curve that fits the data. Here, C_1 and C_2 are NTGK model specific parameters. T is the existing temperature of the battery and T_{ref} is the reference temperature of the battery. DOD, which represents the depth of discharge of the battery, is expressed as follows.

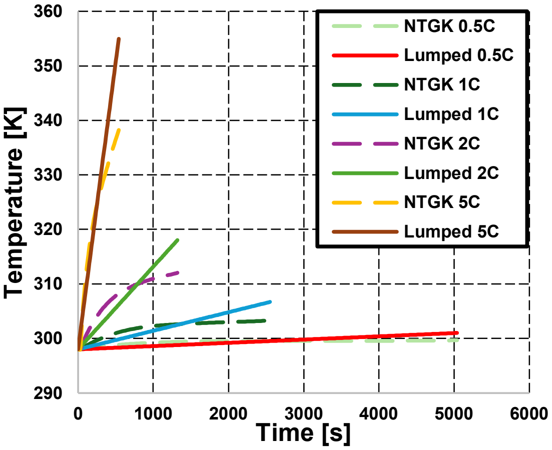
$$DOD = \frac{Vol}{3600 Q_{nominal}} \int_0^t j dt \tag{8}$$

where Vol is the battery volume and $Q_{nominal}$ is the total electrical capacity of the battery. The heat of electrochemical reaction is shown in Eq. Here, the first term is the heat due to voltage and the second term is due to entropic heat.

$$\dot{q}_{ECh} = j_{ECh}\left[U - (\varphi_+ - \varphi_-) - T\frac{dU}{dT}\right] \tag{9}$$

3. RESULTS AND DISCUSSION

BTMS can be designed with complex but highly accurate models such as NTGK as well as simplified but fast models such as Lumped method. In this study, where the NTGK method and Lumped method are compared, the maximum cell temperature of the battery and the heating performance of the cold plate for 0.5C, 1C, 2C and 5C rates are evaluated by assuming an initial temperature of 25 °C and an initial SOC value of 85%. It is observed that as the C-rate value increases, the maximum cell temperature increases and the cooling performance decreases. When the results obtained from the NTGK method and Lumped method were compared, a difference of 1.95% was found.



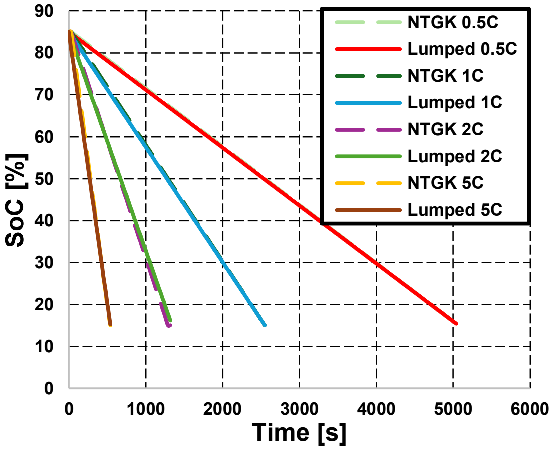


Table 1: Temperature change in Lumped and NTGK models at different C-Rate

Table 2: Soc change of Lumped and NTGK models at different C-Rate

4. CONCLUSIONS

In this study, the cooling performance of a spider web cold plate BTMS under different c-ratio is compared for the NTGK method and the Lumped method. A difference of 2.25% between the results obtained from the two models was observed and the usability of the Lumped model was determined. In future studies, it is aimed to conduct experimental and numerical studies for different battery types and different cold plate designs.

ACKNOWLEDGEMENT

This research was supported by Dokuz Eylul University's Scientific Research Projects with project number FBA-2023-2996.

5. REFERENCES

Fan, L., Li, J., Chen, Y., Zhou, D., Jiang, Z., & Sun, J. (2024). Study on the cooling performance of a new secondary flow serpentine liquid cooling plate used for lithium battery thermal management. International Journal of Heat and Mass Transfer, 218. https://doi.org/10.1016/j.ijheatmasstransfer.2023.124711

Farasis Energy. Farasis Battery Module Technical Specifications Module 14S2P Configuration P32Cells. Confidential document; 2022.

Kalkan, O., Celen, A., & Bakirci, K. (2022). Multi-objective optimization of a mini channeled cold plate for using thermal management of a Li-Ion battery. Energy, 251. https://doi.org/10.1016/j.energy.2022.123949

Kwon, K. H., Shin, C. B., Kang, T. H., & Kim, C. S. (2006). A two-dimensional modeling of a lithium-polymer battery. Journal of Power Sources, 163(1 SPEC. ISS.), 151–157. https://doi.org/10.1016/j.jpowsour.2006.03.012

Lamrani, B., Lebrouhi, B. E., Khattari, Y., & Kousksou, T. (2021). A simplified thermal model for a lithium-ion battery pack with phase change material thermal management system. Journal of Energy Storage, 44, 103377. https://doi.org/10.1016/J.EST.2021.103377

Sevilgen, G., Dursun, H., & Kılıç, M. (2023). Experimental and Numerical Investigations on the Thermal Performance of Three Different Cold Plates Designed for the Electrical Vehicle Battery Module. Sustainability (Switzerland), 15(19). https://doi.org/10.3390/su151914162

Zhang, H., Li, C., Zhang, R., Lin, Y., & Fang, H. (2020). Thermal analysis of a 6s4p Lithium-ion battery pack cooled by cold plates based on a multi-domain modeling framework. Applied Thermal Engineering, 173. https://doi.org/10.1016/j.applthermaleng.2020.115216