PARAMETRIC INVESTIGATION OF IMMERSION TYPE THERMAL MANAGEMENT SYSTEM OF LI-ION POUCH BATTERY MODULE

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ABSTRACT

Lithium-ion batteries (LIBs) used in electric vehicles (EVs) have attracted considerable attention from researchers due to their higher energy density, promising energy efficiency, and longer cyclic lifetime. However, at temperatures exceeding the operating range of these types of batteries (25–45 °C), they pose a serious reduction in performance and a threat to safety. Accordingly, it is vital to identify and design an effective battery thermal management system (BTMS). This study aims to model and evaluate the use of an immersion-type BTMS, which rejects the excess heat from the battery by forced convection of a dielectric liquid. A numerical model has been developed using the lumped-capacitance method to calculate the temperature rise in the LIB at constant discharge rates of 0.5 C, 1 C, and 2 C. Parametric simulations have been carried out in the MATLAB/Simulink environment to investigate the effect of different flow rates of dielectric fluid (0.003, 0.006, 0.012, 0.018, 0.0036 and 0.072 kg/s) used for the thermal management of a pouch type battery module consisting of 28 cells (14 series and 2 parallel). In addition to providing effective cooling, immersion-type BTMS stands out compared to other liquid-based cooling systems in delivering high battery efficiency, simplicity of design, and reliability. As a result of the simulations, it is found that if at least a flow rate of 0.036 kg/s is selected, the battery can be maintained within the optimum operating temperature even at a high discharge rate of 2 C. It is concluded that immersion-type BTMS is an effective method, especially in EVs that require high power.

Keywords: Lithium-ion battery, Battery thermal management, Direct liquid cooling, Immersion cooling, Lumped model, Simplified battery model

1 INTRODUCTION

With the increasing use of fossil fuels in parallel with the rapidly growing world population, air pollution, global warming and similar environmental problems are occurring. To overcome this problem, the use of alternative energy types has become a necessity (Zou et al., 2020). The use of electric vehicles (EVs) instead of internal combustion engine vehicles, which have a serious place in our daily lives, is an important step towards a cleaner environment (Yu & Li, 2019).

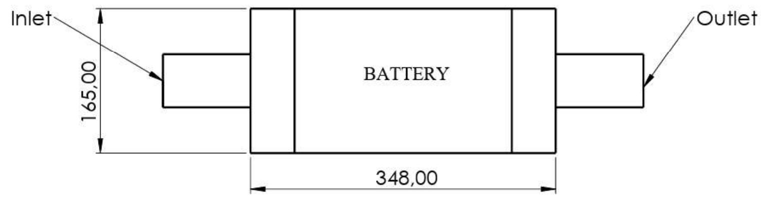
The energy required by EVs is provided by Lithium-ion batteries (LIBs), which are electrochemical energy storage devices. LIBs stand out with their high volumetric energy density, improved lifetime, and reliability (Jiang et al., 2022). In addition to these advantages, the most serious problem of LIBs is overheating. If the battery temperature exceeds the optimum operating temperature range of the battery (25–45 °C), a serious decrease in battery performance and even thermal runaway occurs. Effective thermal management is critical to ensuring the safety, performance, and longevity of LIBs in EVs (Ren et al., 2019). Battery thermal management systems (BTMSs) are being developed to keep the battery at a specific temperature range. Although there are different classifications, it is possible to classify them as air, phase change material, and liquid-based BTMSs. Liquid-based cooling systems, which can be in direct liquid contact or indirect contact, have a lower average temperature of the battery compared to other BTMS. The immersion type BTMS, which provides efficient cooling of the battery by direct immersion in the dielectric fluid, improves the performance and lifetime of the batteries with high heat transfer efficiency and homogeneous temperature distribution (Dubey et al., 2021). For these reasons, liquid-based BTMS stands out from others, especially in systems with high power requirements. For the non-direct contact liquid-based cooling method, researchers have paid particular attention to the design of the flow channels in cold plate applications (Chen et al., 2022; Ozden et al., 2017).

Some researchers have conducted analyses by using computational fluid dynamics method to investigate the effects of immersion type BTMS. In an experimental study conducted with pouch type batteries, it was shown that the temperature difference between the cells was reduced by creating flow channels between the battery cells with a direct contact BTMS system (Larrañaga-Ezeiza et al., 2022). In the experimental and numerical study carried out to increase the cooling efficiency and hydraulic performance in pouch type batteries, the structural design of the battery module was carried out by placing graphite fin and pass sections between the cells (Choi et al., 2023). In the literature, there are various simplified battery modelling approaches, and the most widely used are the equivalent circuit model and NTGK (Newman, Tiedemann, Gu, and Kim) model. Simplified models aim to evaluate battery performance with lower computational cost and acceptable accuracy.

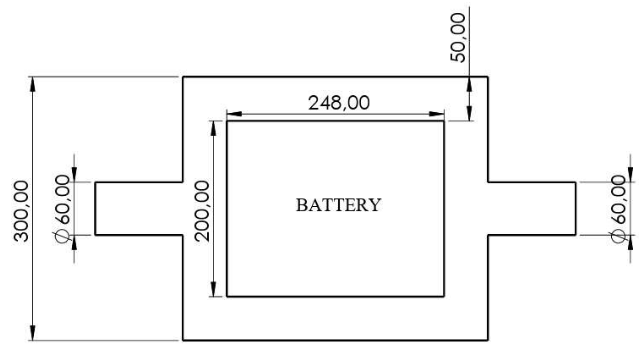
This study aims to model and evaluate the application of an immersion-type BTMS that dissipates excess heat from the battery through forced convection of a dielectric liquid. According to the literature, it is seen that there are few studies on immersion type thermal management system and different models are required especially for pouch type batteries. A pouch-type battery module containing 28 cells (14 series and 2 parallel) was modeled as a lumped system, and the effects of immersion-type thermal management depending on different parameters, such as mass flow rate and discharging rate, were investigated.

2 METHODS

The battery module consists of 28 pouch-type cells. The main features of this module are given in Table 1. These characteristics are the data of a module consisting of Farasis P32B cells. The internal resistance value of the battery is taken from Farasis (Farasis, 2023) depending on the state of charge (SOC) of the battery. The top and side views of the immersion tank are given in Figure 1. The immersion tank is 300 mm in width, 348 mm in length, and 165 mm in height. The fluid inlet and outlet ports have an inner diameter of 60 mm. The battery module has an aluminum shell with a thickness of $t_{Al} = 5$ mm. The battery module has a width of 200 mm, a length of 248 mm and a height of 165 mm. Novec 700 was used as dielectric fluid to cool the battery and its properties are given in Table 2. The initial temperature of the battery is 25 °C and the inlet temperature of the fluid is 20°C.



(a)



(b)

Figure 1: Dimensions [mm] of the Immersion cooling system: **(a)** Side view, **(b)** Top view

Table 1: Characteristics of battery cells at 25 °C and 1 C-Rate (Farasis, 2022)

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

Table 2: Characteristics of Novec 7000 Engineered Fluid (3M, 2021)

Characteristic	Value
Density (kg m^{-3})	1400
Thermal conductivity (W m^{-1} K^{-1})	0.075
Specific heat capacity (J kg^{-1} K^{-1})	1300
Kinematic viscosity (m^2 s^{-1})	0.32×10^{-6}

2.1 Simplified Battery Heat Transfer Model

A simplified heat transfer model for the battery is developed to characterize the transient behavior of the immersed cooling system with acceptable accuracy and reduced computational time. The assumptions considered in the model are as follows,

- Each cell in the battery has an identical temperature.
- The average convection coefficient of the fluid around the battery module is uniform.
- Heat generation inside the battery cells are uniform.

- Heat transfer occurs by convection from the four lateral surfaces of the battery module. The top and bottom surfaces of the battery module are assumed to be adiabatic.

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

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

In this expression, m_b is the battery mass, $c_{p,b}$ is the specific heat capacity of the battery, Q_t is the total amount of heat generated by the battery and Q_{loss} is the total amount of heat transferred by the dielectric fluid. The heat generation term is represented in the following equation (Lamrani et al., 2021):

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

Q_{irr} arises from the Joule effect and corresponds to the conversion of electrical energy into heat. This term is expressed as follows,

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

where I and R are electrical current and internal electrical resistance, respectively. Q_{rev} given in Eq. 2 causes structural changes in the electrodes during the charging and discharging processes of the battery, resulting in entropy change of lithium ions (Liu et al., 2024). These changes that cause heat production and consumption are called reversible effects and are expressed as follows,

$$Q_{rev} = -IT\frac{dE_{oc}}{dT} \tag{4}$$

where E_{oc} is the open circuit voltage, $\frac{dE_{oc}}{dT}$ represents the entropy coefficient and depends on the state of battery charge (SOC). By following the recent works of, this effect is neglected in the current simplified model. The reason for this neglect is that heat generated of reversible heat is much smaller than irreversible heat (He et al., 2023; Jia et al., 2024). Another important expression is the state of charge of the battery, which is stated below,

$$SOC(t) = SOC(t_0) \mp \frac{\int_0^t I(t)dt}{C_{nom}} \tag{5}$$

where $SOC(t_0)$ indicates the initial state charge of the battery and C_{nom} is the nominal capacity of the battery. In this equation, the negative sign indicates the discharge state, and the positive sign indicates the charge state.

2.2 Immersion Type Thermal Management System Model

The heat transfer between the battery and dielectric fluid is simply defined with the following well-known expression,

$$Q_{loss} = U\, A_s\, \Delta T_{LMTD} \tag{6}$$

where U is the total heat transfer coefficient, A is the surface area exposed to the forced convection, and ΔT_{LMTD} is the logarithmic mean temperature difference. To make a more accurate approach to the temperature difference, it is found as the logarithmic mean temperature difference with the following equation:

$$\Delta T_{LMTD} = \frac{(T_b - T_{inlet,f}) - (T_b - T_{outlet,f})}{\ln\frac{(T_b - T_{inlet,f})}{(T_b - T_{outlet,f})}} \tag{7}$$

where T_b, $T_{inlet,f}$, $T_{outlet,f}$ are battery temperature, fluid inlet temperature, and fluid outlet temperature, respectively. The UA in this equation is expressed in terms of the thermal resistance,

$$UA_s = \frac{1}{R_t} \tag{8}$$

The total thermal resistance is the sum of the conduction and convection thermal resistances for this system. R_{cond} represents thermal resistance by conduction and R_{conv} represents thermal resistance by convection.

$$R_t = R_{conv} + R_{cond} \tag{9}$$

$$R_{conv} = \frac{1}{h_{ave}\, A_s} \tag{10}$$

where h_{ave} is the average convection heat transfer coefficient, A_s is surface area.

$$R_{cond} = \frac{t_{Al}}{k_{Al}\, A_{Al}} \tag{11}$$

where t_{Al} is the thickness of the aluminum, k_{Al} coefficient of thermal conductivity of aluminum, A_{Al} surface area of aluminum. The temperature of the fluid leaving the immersion tank is found by the equation given below for the case of constant surface temperature.

$$\frac{T_{f,out} - T_b}{T_{f,inlet} - T_b} = exp\left(\frac{-h_{ave}\, A_s}{\dot{m}\, c_{p,f}}\right) \tag{12}$$

In this equation, $\dot{m}$ represents the mass flow rate of the fluid and $c_{p,f}$ represents the specific heat of the fluid. The average convection coefficient at the battery surface was found by Nusselt correlation (Han et al., 2023).

3 RESULTS AND DISCUSSION

In this study, the transient thermal response of the battery module is numerically determined at four different discharge currents and six mass flow rates. A total of 18 analyses are conducted to discuss the influence of working parameters on temperature variations. At the initial state, it is assumed that the battery is fully charged with a SOC of 100%, and the analyses proceed until the complete discharge is obtained. Four discharging rates of 0.5 C, 1 C, and 2 C are analyzed. Finding the appropriate flow rate for the system is of great importance as increasing the flow rate affects the pumping power and operating costs. The current study aims to evaluate the influence of the working mass flow rate on the battery temperature. It is observed that the battery temperature is in the optimum operating range at each flow rate. When we examine Figures 2, 3, and 4 we observe that the temperature of the battery increases as the C-Rate increases. For a discharge rate of 0.5 C, the battery reaches 33.47 °C at a mass flow rate of 0.03 kg/s, while the temperature is found to be 26.12 °C when the flow rate is increased to 0.072 kg/s. For the highest discharge rate of 2 C-Rate, the maximum temperature of the battery is 63.73 °C at a mass flow rate of 0.003 kg/s and 39.64 °C at a mass flow rate of 0.072 kg/s. In this situation, a mass flow rate of more than 0.036 kg/s is required not to exceed the optimum operating temperature of the battery.

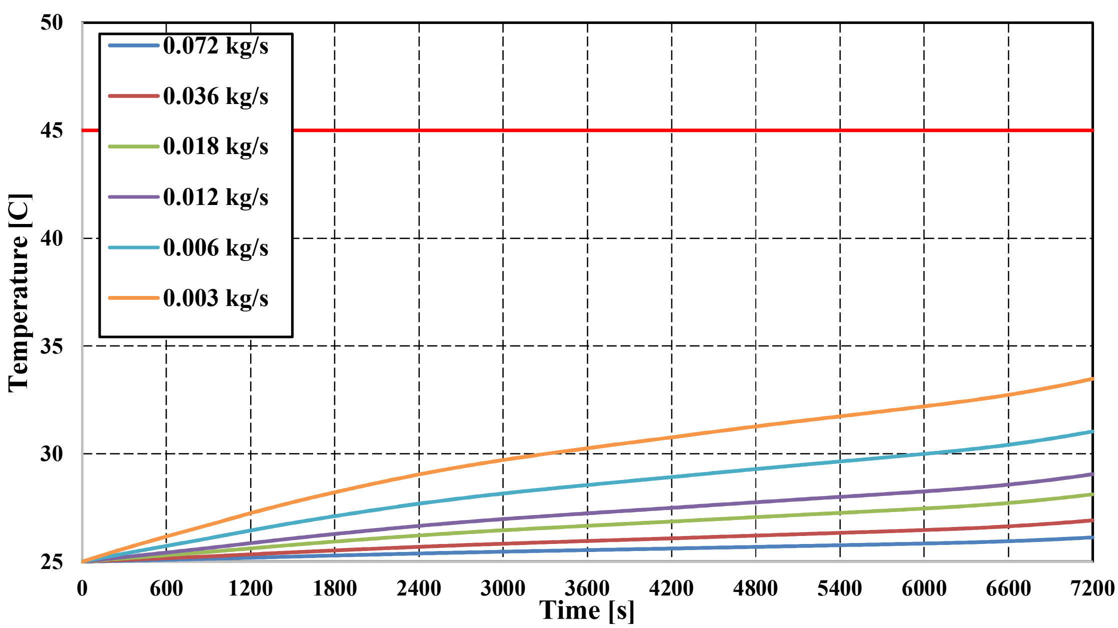


Figure 2: 0.5 C discharge current for different flow rates for the discharge current of the battery temperature change over time

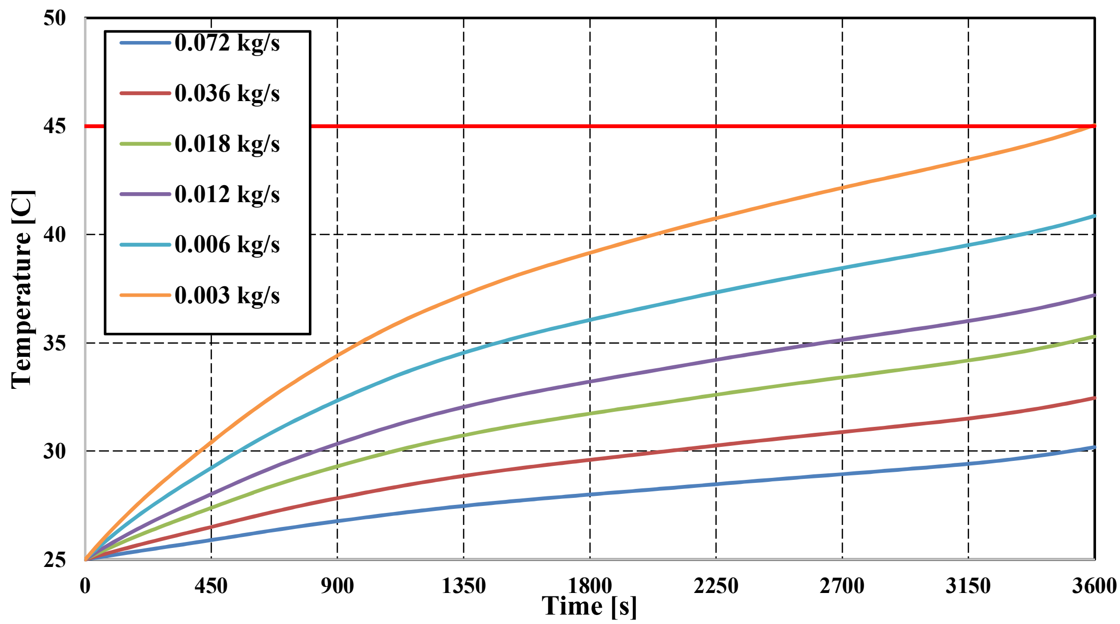


Figure 3: 1 C discharge current for different flow rates for the discharge current of the battery temperature change over time

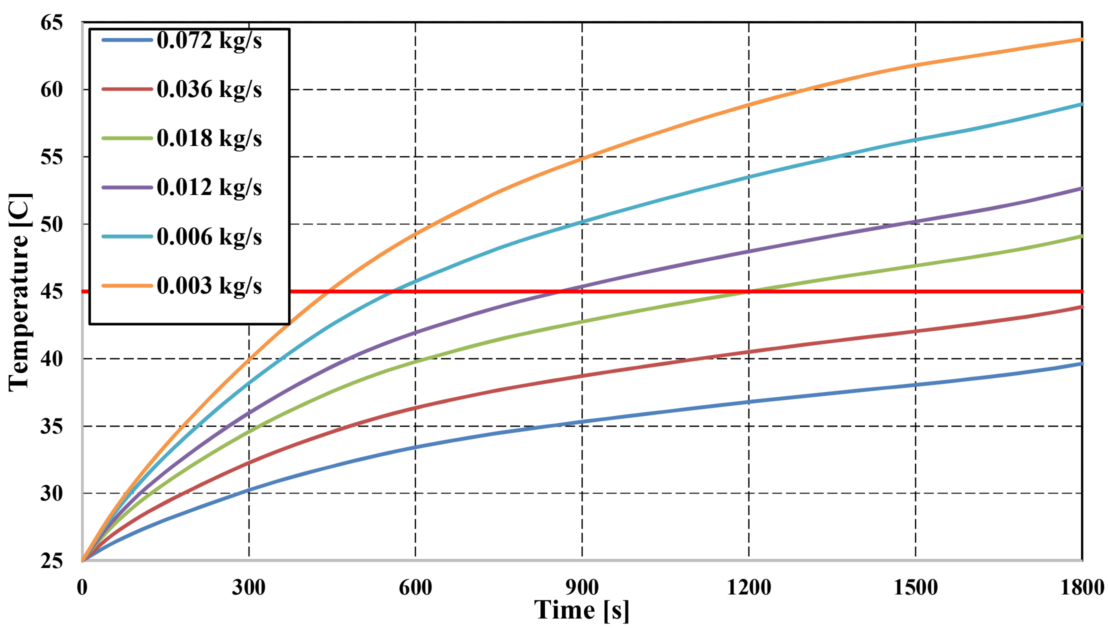


Figure 5: 2 C discharge current for different flow rates for the discharge current of the battery temperature change over time

Table 3: The battery module discharge times for various C-Rates values

Characteristic	Value
0.5	7200
1	3600
2	1800

4 CONCLUSIONS

This study develops a simplified model for an immersion thermal management system and battery module. The time-wise variations of battery temperature under different flow rates and battery charge rates are analyzed. Considering the outputs of the study, it is expected to be useful in understanding the immersion thermal management system and pave the way for the commercial use of the method. In addition, issues such as the cost, weight, and lifetime of the dielectric fluid and the sealing of the immersion tank need to be addressed, and it is aimed to investigate this method in more depth with experimental studies in future studies.

NOMENCLATURE

A_{Al}	the surface area of aluminum (m^2)
A_s	convection surface area (m^2)
$c_{p,b}$	battery specific heat capacity (J kg^{-1} K^{-1})
$c_{p,f}$	specific heat capacity fluid (J kg^{-1} K^{-1})
E_{oc}	open circuit voltage (V)
h_{ave}	convection heat transfer coefficient (W m^{-2} K^{-1})
I	electrical current (A)
k_{Al}	coefficient of thermal conductivity of aluminum (W m^{-1} K^{-1})
$\dot{m}$	the mass flow rate of fluid (kg s^{-1})
m_b	battery mass (kg)
Q_{loss}	total amount of heat transferred by the cooling system (W)
Q_{irr}	irreversible heat generation (W)
Q_{rev}	reversible heat generation (W)
Q_t	the total amount of heat generated by the battery (W)
R	internal electrical resistance (Ω)
R_{cond}	conduction thermal resistance (K W^{-1})
R_{conv}	convection thermal resistance (K W^{-1})
R_{total}	total thermal resistance (K W^{-1})
t_{Al}	the thickness of the aluminum (m)
T_b	battery temperature (K) or (°C)
$T_{f,inlet}$	the inlet temperature of the fluid (K)
$T_{f,out}$	the outlet temperature of the fluid (K)
ΔT_{LMTD}	logarithmic mean temperature difference
U	total heat transfer coefficient (W m^{-2} K^{-1})

Subscript

BTMS	Battery thermal management system
EV	Electric vehicles
LIB	Lithium-ion batteries
SOC	State of charge

Al	aluminum
ave	average
b	battery
$cond$	conduction
$conv$	convection
f	fluid
irr	irreversible
rev	reversible
s	surface
t	total

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REFERENCES

3M. 3M^{TM} Novec^{TM} 7000 Engineered Fluid. Confidential document; 2021

Chen, Y., Chen, K., Dong, Y., & Wu, X. (2022). Bidirectional symmetrical parallel mini-channel cold plate for energy efficient cooling of large battery packs. *Energy*, *242*. https://doi.org/10.1016/j.energy.2021.122553

Choi, H., Lee, H., Kim, J., & Lee, H. (2023). Hybrid single-phase immersion cooling structure for battery thermal management under fast-charging conditions. *Energy Conversion and Management*, *287*. https://doi.org/10.1016/j.enconman.2023.117053

Dubey, P., Pulugundla, G., & Srouji, A. K. (2021). Direct comparison of immersion and cold-plate based cooling for automotive li-ion battery modules. *Energies*, *14*(5). https://doi.org/10.3390/en14051259

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

Farasis Energy. P29F Cell Technical Overview. Confidential document; 2023.

Han, J. W., Garud, K. S., Kang, E. H., & Lee, M. Y. (2023). Numerical Study on Heat Transfer Characteristics of Dielectric Fluid Immersion Cooling with Fin Structures for Lithium-Ion Batteries. *Symmetry*, *15*(1). https://doi.org/10.3390/sym15010092

He, J., Sazzad Hosen, M., Youssef, R., Kalogiannis, T., Van Mierlo, J., & Berecibar, M. (2023). A lumped electro-thermal model for a battery module with a novel hybrid cooling system. *Applied Thermal Engineering*, *221*. https://doi.org/10.1016/j.applthermaleng.2022.119874

Jia, T., Zhang, Y., Ma, C., Yu, H., & Hu, S. (2024). The early warning for thermal runaway of lithium-ion batteries based on internal and external temperature model. *Journal of Energy Storage*, *83*. https://doi.org/10.1016/j.est.2024.110690

Jiang, Z. Y., Li, H. B., Qu, Z. G., & Zhang, J. F. (2022). Recent progress in lithium-ion battery thermal management for a wide range of temperature and abuse conditions. In *International Journal of Hydrogen Energy* (Vol. 47, Issue 15, pp. 9428–9459). Elsevier Ltd. https://doi.org/10.1016/j.ijhydene.2022.01.008

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

Larrañaga-Ezeiza, M., Vertiz, G., Arroiabe, P. F., Martinez-Agirre, M., & Berasategi, J. (2022). A novel direct liquid cooling strategy for electric vehicles focused on pouch type battery cells. *Applied Thermal Engineering*, *216*, 118869. https://doi.org/10.1016/J.APPLTHERMALENG.2022.118869

Liu, J., Yadav, S., Salman, M., Chavan, S., & Kim, S. C. (2024). Review of thermal coupled battery models and parameter identification for lithium-ion battery heat generation in EV battery thermal management system. In *International Journal of Heat and Mass Transfer* (Vol. 218). Elsevier Ltd. https://doi.org/10.1016/j.ijheatmasstransfer.2023.124748

Ozden, A., Ercelik, M., Ouellette, D., Colpan, C. O., Ganjehsarabi, H., & Hamdullahpur, F. (2017). Designing, modeling and performance investigation of bio-inspired flow field based DMFCs. *International Journal of Hydrogen Energy*, *42*(33), 21546–21558. https://doi.org/10.1016/j.ijhydene.2017.01.007

Ren, D., Hsu, H., Li, R., Feng, X., Guo, D., Han, X., Lu, L., He, X., Gao, S., Hou, J., Li, Y., Wang, Y., & Ouyang, M. (2019). A comparative investigation of aging effects on thermal runaway behavior of lithium-ion batteries. *ETransportation*, *2*. https://doi.org/10.1016/j.etran.2019.100034

Yu, L., & Li, Y. P. (2019). A flexible-possibilistic stochastic programming method for planning municipal-scale energy system through introducing renewable energies and electric vehicles. *Journal of Cleaner Production*, *207*, 772–787. https://doi.org/10.1016/j.jclepro.2018.10.006

Zou, J., Han, N., Yan, J., Feng, Q., Wang, Y., Zhao, Z., Fan, J., Zeng, L., Li, H., & Wang, H. (2020). Electrochemical Compression Technologies for High-Pressure Hydrogen: Current Status, Challenges and Perspective. In *Electrochemical Energy Reviews* (Vol. 3, Issue 4, pp. 690–729). Springer Science and Business Media B.V. https://doi.org/10.1007/s41918-020-00077-0