Heat Management on LiFePo4 Battery Pack for Eddy Current Brake Energy Storage on Rapid Braking Processes

Nizam, Muhammad
Electrical Engineering Department, Universitas Sebelas Maret

Mufti Reza Aulia Putra
Mechanical Engineering Department, Universitas Sebelas Maret

Inayati
Chemical Engineering Department, Universitas Sebelas Maret

https://doi.org/10.5109/4794171

出版情報：Evergreen. 9 (2), pp.451-456, 2022-06. 九州大学グリーンテクノロジー研究教育センター
バージョン：

EVERGREEN Joint Journal of Novel Carbon Resource Sciences & Green Asia Strategy, Vol. 09, Issue 02, pp451-456, June 2022

Heat Management on LiFePo4 Battery Pack for Eddy Current Brake Energy Storage on Rapid Braking Processes

Muhammad Nizam[1,2,3,*], Mufti Reza Aulia Putra[4], Inayati[5]
[1]Electrical Engineering Department, Universitas Sebelas Maret, Surakarta, Indonesia
[2]National Center for Sustainable Transportation Technology, Bandung, Indonesia
[3]Centre of Excellence for Electrical Energy Storage Technology, Universitas Sebelas Maret, Surakarta, Indonesia
[4]Mechanical Engineering Department, Universitas Sebelas Maret, Surakarta, Indonesia
[5]Chemical Engineering Department, Universitas Sebelas Maret, Surakarta, Indonesia

*Author to whom correspondence should be addressed:
E-mail: muhammad.nizam@staff.uns.ac.id

(Received December 7, 2021; Revised June 3, 2022; accepted June 3, 2022).

Abstract: Electric vehicles are better for the environment. Lithium-ion (Li-ion) battery cells can be used as energy storage. Some uses of the battery are not only used as a power supply for electric motors but are also used in supporting systems such as an additional braking system using Eddy Current Brake (ECB). In general, ECB requires a large current when starting the braking process. At this early stage, the heat will be generated relatively high. During operation, heat is generated, and it will burden the battery's performance. Thus, the heat generated needs to be released into the environment. Careless heat management can have multiple effects, such as fire and, in the worst case, explosion. Battery Thermal Management System (BTMS) needs to be implemented in electric vehicles. There are several methods of thermal management, such as air-cooled and liquid-cooled. The results show that liquid-cooled BTMS is superior in uniform but more complex temperature distribution, and liquid leakage may occur. In comparison, air-cooled BTMS has the advantage of a more accessible system, but the temperature distribution between batteries is not good. Air Cooler can maintain the ideal battery temperature between 20-40 °C.

Keywords: Battery Thermal Management System, heat flux, Thermal Runaway

1. Introduction

There are some vital components of an electric vehicle (EV). One of them is the energy storage system or battery. Generally, we can use lead-acid batteries and lithium-based batteries for EV energy storage. Recently, lithium-ion batteries are known as one of the best energy storages for EVs compared to the lead-acid battery. There are some advantages from lithium battery such as energy characteristics, long life cycle and high power density with low self-discharge [1,2)]. Battery cells as energy storage have several requirements because they are susceptible to temperature. The optimal operating temperature range for this type of battery is 15-35ºC[1,3,4)]. Besides being used as energy storage for electric vehicles, the battery also provides energy for other purposes such as EV accessories or several components such as the Eddy Current Brake (ECB) for braking assistance. On the starting of ECB's has a large current to start the braking process[4)]. In general, electric vehicles will require braking support because their nature does not have the character of an engine brake. Batteries for a significant enough power supply results in high heat generation. If the battery temperature is not maintained correctly, it will reduce battery performance and life cycle. In other words, the battery pack needs to be equipped with a good BTMS to maintain its performance. Excessive heat in the cell battery can cause damage to the battery internals, which can cause the cell battery to explode. This damage can also be affected by the battery's condition, which is not uniform in its heat generation.[5,6)].

BTMS can be divided by the cooling methods: (a) using air for the cooling system, (b) using a liquid cooling system (oil, or coolant), (c) using phase change material (PCM) based cooling system [7)]. Each method has different characteristics that depend on the force cooling methods interaction. The cooling effect using air cooling cannot provide good heat dissipation and sometimes cannot provide cooling requirements of the battery. If the battery is used in extreme environments on the duty cycles [7,8)], it will raise the battery temperature. PCM systems can provide effective heat management and reduce temperature or maintain the battery temperature. However, it has a limitation on the phase change application. Liquid cooling systems will require laminate and better security to prevent battery shorts. In addition, the heavy use of the battery pack will increase the risk of safety issues from the battery. 9). The use of air conditioning will provide cooling that is relatively easier to apply to vehicle with PCM added 10).

Determining the shape of the battery pack requires various considerations. In general, battery packs will be arranged in a relatively narrow area and cause the heat not to be released properly11,12). The battery's temperature will play a significant enough role in the battery's durability13,14). Cell battery operation will be optimized by increasing the efficiency and cycles that can be achieved. All require good temperature management and can increase the ability to dissipate heatt15–17). In the use of electric motorcycle design the dimensions of the battery compartment will be minimal 18). With these limitations, cooling methods such as liquid-cooled and PCM are not suitable. Using air cooling on 2-wheeled vehicle batteries will become easier 19).

Adding air cooling takes some preparation. Adding a fan is the simplest way to applicate an air cooling system20). The cooling process can be adjusted according to the inlet and outlet 5). by adding a fan. The number of outlets and the arrangement method of the battery pack will also affect the cooling capacity of the battery pack 20–22). Apart from being cooler, air cooling also reduces the risk of harmful gases trapped in the battery pack23) In this paper, research on the battery cooling setup and the characteristics of the heat generated will be discussed further. This paper will discuss how the characteristics of incubating using ECB result in high heat generation. When the heat that arises is large enough, it is necessary to cool it to maintain the battery's condition.

2. Equipment and methods

2.1 Equipment

This research applied the finite element method (FEM) analysis. Tests were carried out by simulation on the heat transfer on three discharge rates (1C, 2C, and 3C it will make a different heat flux and affect the different temperatures on the battery's working condition. Commonly we can see that the battery is just used to take 1-2C discharge for electric motorcycle, but in an extreme situation such as fast charging or high-performance bike can be 3C rate 24). The higher the C rate will have an effect when the internal resistance used is high enough. The higher C rate will result in an increase in heat that arises. The battery arrangement can be found in Fig. 1. The condition used is to use a load on the battery using a current load following the use of Electromagnets on the ECB. The condition faced is at the beginning of braking with maximum current, so the character of the heat release when first used will affect the performance of the subsequent braking. When braking is done repeatedly, the battery capacity will decrease, which affects the discharge capability of the battery used.

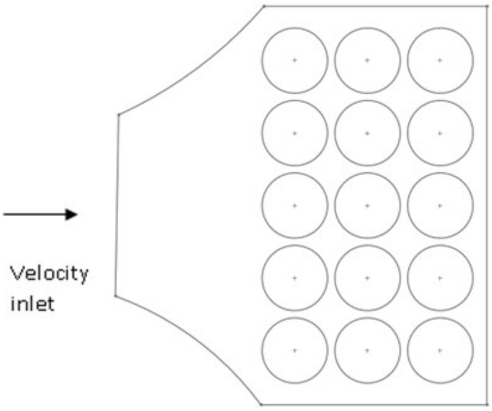


Fig 1. Battery layout

2.2 Methodology

In this research, the model used was the lithium-ion battery type18650 LFP. The cooling process was carried out using an air-cooling system by blowing air into the battery surface. The airflow was varied into four speeds during the simulation process, i.e., 0.5, 1, 1.5, 2 m/s. The use of the reference speed is adjusted to the estimated airflow speed of the cooling fan to be installed. Various battery discharge rates produced heat flux, i.e., the discharge rate was 1C, 2C, and 3C. The heat transfer model of 6 battery cells represents the state and interactions in battery 8). Generated heat by batteries was removed by cooling air, as depicted Fig. 2.

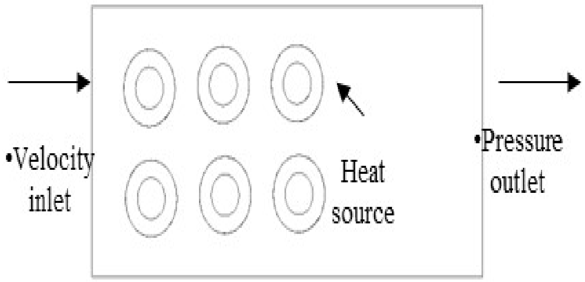


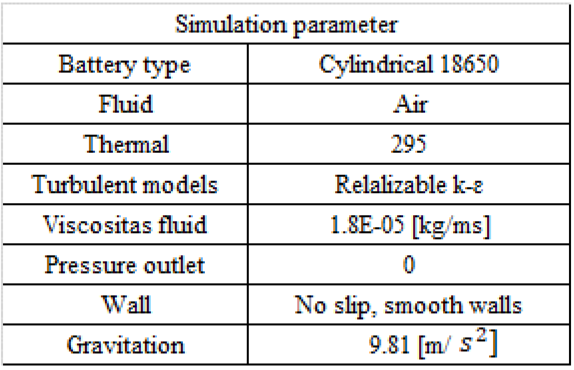
Fig 2. Battery model on FEM

Batteries will generate heat flux due to the discharge process. The battery's temperature will increase when the heat flux is more significant than the air-cooling capacity. A reversible process will appear if the discharge is less than 1C. If the discharge process is more than 1C, the heat generated can be assumed to be an irreversible process 25). The heat generation process can be seen from equation (1),

$$Q_T = Q_e + Q_a \qquad (1)$$

With Q_T is the total heat generated when the battery is used, $Q_e$is the heat in the battery environment, Q_a Does the battery absorb the heat or not by adjusting the Q_eValue by adding cooling like air or oil will maintain the temperature. The battery pack's first row can be assumed using a single pipe characteristic, while in the next row, it can be analyzed using more complex airflow conditions due to the emergence of vortexes. For the value of Re$\leq 10^3$, the vortex generated can be ignored because the effect is relatively small due to the viscous source [25].

Table 1. Simulation parameter



Simulation parameter	
Battery type	Cylindrical 18650
Fluid	Air
Thermal	295
Turbulent models	Relalizable k-ε
Viscositas fluid	1.8E-05 [kg/ms]
Pressure outlet	0
Wall	No slip, smooth walls
Gravitation	9.81 [m/ s^2]

The convective heat transfer is applied in the simulation process using the k-ε model, including the continuity equation (2), momentum equation (3), and energy equation (4).

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_k}(\rho V_k) = 0 \tag{2}$$

$$\frac{DV_j}{Dt} = -\frac{1}{\rho_0}\frac{\partial (P-P_0)}{\partial x_j} + \vartheta \frac{\partial^2 V_j}{a x_k x_k} \tag{3}$$

$$\frac{DT}{t} = a\frac{\partial^2 T}{a x_k x_k} + \frac{v}{c_p}\emptyset_v \tag{4}$$

3. Result and Discussion

After the modeling process, the location of the heat source will be known. The heat distribution when the discharge processes will indicates that the heat generation dominated in the center of the pack. The part of the pack with excessive heat is caused by heat that accumulates from various battery sides. In general, apart from the battery arrangement, heat accumulation is caused by the heat dissipation ability of the pack used.

The addition of a cooling system will be required during the discharge process, and it is known that the heat generated needs to be dissipated more quickly to the environment. The easiest way to increase capacity is to add a fluid flow in the air to help the heat release process

Fig. 3 shows a cooling capability between different discharge rates. The use of an air-cooling system cannot provide good efficiency. Heat absorption capabilities cause it is low than any cooling methods [7]. The difference between the C rate will give an additional heat-released capacity. The heat flux value is strongly influenced by the C rate used. The higher the C rate will affect the heat flux generated. The heat absorption capacity is not much affected by the current air velocity changes. Although there is an increase in the number of contacts between the hot area and the air, the ability to absorb heat by the air is still not good.

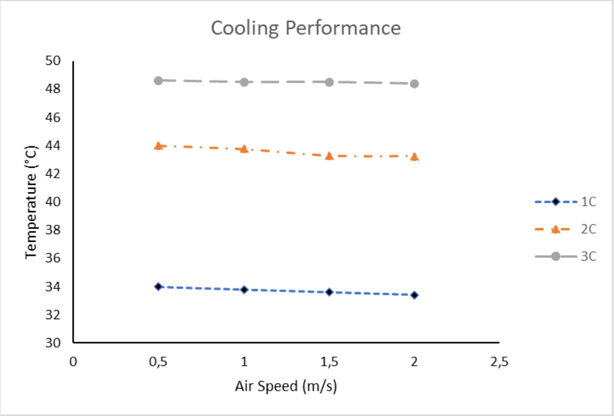


Fig 3. Effect of the cooling system against the discharge rate

Fig. 3 shows that the addition of coolant in the form of air can reduce up to 1.1°C, but it can be seen that the heat release ability is only practical until the 2C rate. The greater the discharge rate, the higher the heat value generated. The use of air as a coolant is the air temperature conditioning, where the air used is at a temperature of 10°C, so the cooling capacity is limited. When the 1C discharge rate, the use of air can still maintain a temperature of 33-34 °C, but when it is more than 2C, the heat is already above 40 °C. Fig 4. shows that when given a flow of air, the heat that occurs on the surface of the battery will be carried away by the air.

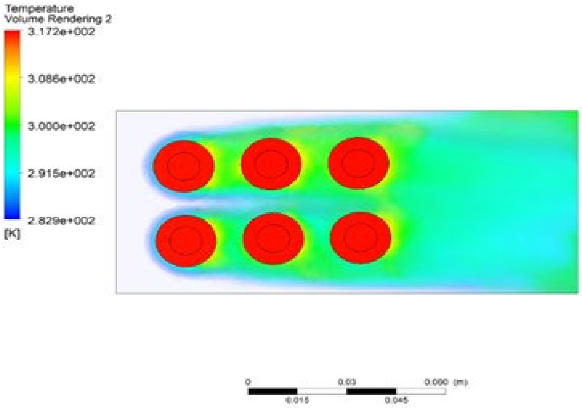


Fig 4. Temperature distribution during the cooling process

The given air velocity will also affect the heat release, which is caused by the flowing air flow having different interactions. In addition to the use of air velocity, the layout of the battery and the distance between the batteries will affect the heat generation and the cooling process from the battery. When the airflow leads to the surface of the battery, it will make contact with the battery. Due to the conservation of mass, the air velocity that passes around the battery will increases. The use of a smaller cross-sectional area will result in the influence of air which will increase the speed of air flow through the battery. The velocity contour has the same flow pattern on both sides because the battery arrangement is carried out on the same line. Air passing on the other side will form the same pattern.

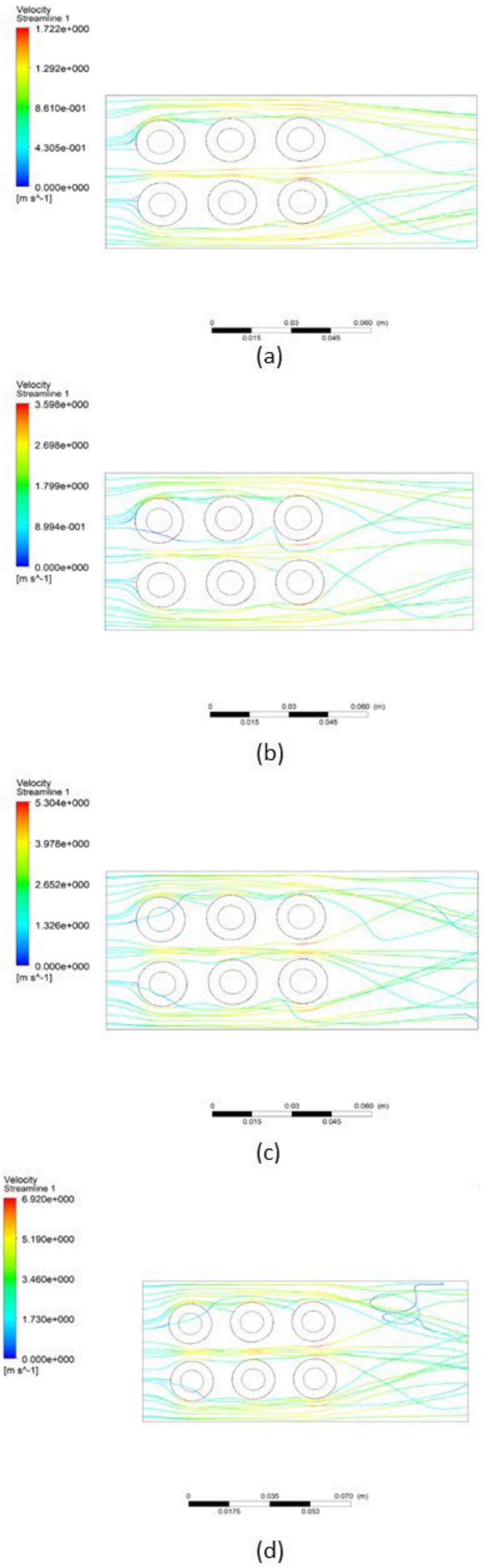


Fig 5. Air dispersion at different speed; (a) 0.5, (b) 1, (c) 1.5, and (d) 2 m/s

Fig. 5 shows the process of fluid flow during the cooling process. Fig. 5(a) shows that the use of 0.5 m/s air velocity provides sufficient interaction with the battery surface, and there is no vortex in the airflow for pictures (b), (c), and (d) high air velocity. The use of high speed will affect the cooling performance. After the first row, the airflow increases the velocity and becomes a vortex. The use of air causes not all surfaces of battery contact with the air to release heat. The heat cannot pass to the air, so the battery's temperature will increase due to cooling capacity being less than the heat generated. The greater the air contact, the greater the heat released to the environment. This condition will facilitate the cooling process needed when the battery will be used to distribute power to the braking system and other systems. The resulting air profile shows almost the same pattern for both sides. The process of air contact with the surface of the battery causes heat to be absorbed by the air flow which causes the air temperature to increase. In the middle between two or more batteries will have a higher air temperature, this is due to the absorption of heat from both sides of the battery. To increase the effectiveness of heat dissipation, it can be done by changing the distance between the batteries to increase contact with the air, besides the addition of the air velocity used will help lower the temperature because high-speed air produces better heat transfer in the battery.

4. Further Projection

Before modifying the cooling system, it is necessary to analyze the heat distribution of the battery module used. In addition, this paper has shown that air conditioning in battery packs can still be optimized. Using the most straightforward setup has maintained the temperature generated in the battery pack as long as it is still below the discharge rate of 1C. The use of air cooling can also be increased by composing the layout of the battery pack used and setting the direction of the inlet and outlet air holes used. With performance considerations, the battery can also be cooled by using a cooler in the storage compartment area

5. Conclusion

From the modeling and analysis process, it is known that an air-cooled battery was only suitable for some cases. There are differences between using a 1C-3C rate of discharge. In the future, research on BTMS can be improved on several parameters, such as using liquid-cooled or improving air cooling capacity by maintaining inlet air temperature at low temperatures. The use of an air-cooling system suits the 1C rate. Above 1C rate, the air could not provide a good battery cooling performance. However, the use of a battery cooler shall keep the battery in the ideal temperature range.

Acknowledgements

This research activity is supported through funding from the Ministry of Research and Technology/BRIN according to the contract Number: 221.1/UN27.22/HK.07.00/2021

Nomenclature

Q_T	total heat generated when the battery is used
Q_e	Heat on environment
Q_a	Heat absorbed
ρ	Amount of quantity q per unit volume
j	The flux of q
t	Time
σ	Generation of q per unit volume per unit time
T	Static temperature
xk	Molar factor
v	velocity

References

1) S. Panchal, I. Dincer, M. Agelin-Chaab, R. Fraser, and M. Fowler, "Experimental and theoretical investigations of heat generation rates for a water cooled lifepo4 battery," *Int. J. Heat Mass Transf.*, **101** 1093–1102 (2016). doi:10.1016/j.ijheatmasstransfer.2016.05.126.
2) M. Nizam, H. Maghfiroh, R.A. Rosadi, and K.D.U. Kusumaputri, "Design of battery management system (bms) for lithium iron phosphate (lfp) battery," *ICEVT 2019 - Proceeding 6th Int. Conf. Electr. Veh. Technol. 2019*, (*November 2019*) 170–174 (2019). doi:10.1109/ICEVT48285.2019.8994002.
3) H. Wang, T. Tao, J. Xu, X. Mei, X. Liu, and P. Gou, "Cooling capacity of a novel modular liquid-cooled battery thermal management system for cylindrical lithium ion batteries," *Appl. Therm. Eng.*, **178** (*February*) 115591 (2020). doi:10.1016/j.applthermaleng.2020.115591.
4) S. Panchal, I. Dincer, M. Agelin-Chaab, R. Fraser, and M. Fowler, "Design and simulation of a lithium-ion battery at large c-rates and varying boundary conditions through heat flux distributions," *Meas. J. Int. Meas. Confed.*, **116** (*September 2017*) 382–390 (2018). doi:10.1016/j.measurement.2017.11.038.
5) Y. Shi, S. Ahmad, H. Liu, K.T. Lau, and J. Zhao, "Optimization of air-cooling technology for lifepo4 battery pack based on deep learning," *J. Power Sources*, **497** (*April*) 229894 (2021). doi:10.1016/j.jpowsour.2021.229894.
6) L. Sheng, H. Zhang, L. Su, Z. Zhang, H. Zhang, K. Li, Y. Fang, and W. Ye, "Effect analysis on thermal profile management of a cylindrical lithium-ion battery utilizing a cellular liquid cooling jacket," *Energy*, **220** 119725 (2021). doi:10.1016/j.energy.2020.119725.
7) Y. Yang, L. Chen, L. Yang, and X. Du, "Numerical study of combined air and phase change cooling for lithium-ion battery during dynamic cycles," *Int. J. Therm. Sci.*, **165** (*March*) 106968 (2021). doi:10.1016/j.ijthermalsci.2021.106968.
8) M. Malik, I. Dincer, M.A. Rosen, M. Mathew, and M. Fowler, "Thermal and electrical performance evaluations of series connected li-ion batteries in a pack with liquid cooling," *Appl. Therm. Eng.*, **129** 472–481 (2018). doi:10.1016/j.applthermaleng.2017.10.029.
9) S. Shahid, and M. Agelin-Chaab, "Analysis of cooling effectiveness and temperature uniformity in a battery pack for cylindrical batteries," *Energies*, **10** (*8*) (2017). doi:10.3390/en10081157.
10) Z. Ling, F. Wang, X. Fang, X. Gao, and Z. Zhang, "A hybrid thermal management system for lithium ion batteries combining phase change materials with forced-air cooling," *Appl. Energy*, **148** 403–409 (2015). doi:10.1016/j.apenergy.2015.03.080.
11) Z.Y. Jiang, Z.G. Qu, and L. Zhou, "Lattice boltzmann simulation of ion and electron transport during the discharge process in a randomly reconstructed porous electrode of a lithium-ion battery," *Int. J. Heat Mass Transf.*, **123** 500–513 (2018). doi:10.1016/j.ijheatmasstransfer.2018.03.004.
12) H. Wang, Y. Wang, F. Hu, W. Shi, X. Hu, H. Li, S. Chen, H. Lin, and C. Jiang, "Heat generation measurement and thermal management with phase change material based on heat flux for high specific energy power battery," *Appl. Therm. Eng.*, **194** (*April*) 117053 (2021). doi:10.1016/j.applthermaleng.2021.117053.
13) Y.Z. Zhang, R. Xiong, H.W. He, X. Qu, and M. Pecht, "Aging characteristics-based health diagnosis and remaining useful life prognostics for lithium-ion batteries," *ETransportation*, **1** 100004 (2019). doi:10.1016/j.etran.2019.100004.
14) H.M. Cho, W.S. Choi, J.Y. Go, S.E. Bae, and H.C. Shin, "A study on time-dependent low temperature power performance of a lithium-ion battery," *J. Power Sources*, **198** 273–280 (2012). doi:10.1016/j.jpowsour.2011.09.111.
15) S. Panchal, R. Khasow, I. Dincer, M. Agelin-Chaab, R. Fraser, and M. Fowler, "Thermal design and simulation of mini-channel cold plate for water cooled large sized prismatic lithium-ion battery," *Appl. Therm. Eng.*, **122** 80–90 (2017). doi:10.1016/j.applthermaleng.2017.05.010.
16) C. Alaoui, "Solid-state thermal management for lithium-ion ev batteries," *IEEE Trans. Veh. Technol.*, **62** (*1*) 98–107 (2013). doi:10.1109/TVT.2012.2214246.
17) Z. Rao, Y. Huo, and X. Liu, "Experimental study of

an ohp-cooled thermal management system for electric vehicle power battery," *Exp. Therm. Fluid Sci.*, **57** 20–26 (2014). doi:10.1016/j.expthermflusci.2014.03.017.

18) M.R.A. Putra, M. Nizam, D.D.D.P. Tjahjana, and H.T. Waloyo, "The effect of air gap on braking performance of eddy current brakes on electric vehicle braking system," *ICEVT 2019 - Proceeding 6th Int. Conf. Electr. Veh. Technol. 2019*, 355–358 (2019). doi:10.1109/ICEVT48285.2019.8993987.
19) H. Liu, Z. Wei, W. He, and J. Zhao, "Thermal issues about li-ion batteries and recent progress in battery thermal management systems: a review," *Energy Convers. Manag.*, **150** (*May*) 304–330 (2017). doi:10.1016/j.enconman.2017.08.016.
20) H. Park, "A design of air flow configuration for cooling lithium ion battery in hybrid electric vehicles," *J. Power Sources*, **239** 30–36 (2013). doi:10.1016/j.jpowsour.2013.03.102.
21) K. Chen, Y. Chen, Y. She, M. Song, S. Wang, and L. Chen, "Construction of effective symmetrical air-cooled system for battery thermal management," *Appl. Therm. Eng.*, **166** (*April 2019*) 114679 (2020). doi:10.1016/j.applthermaleng.2019.114679.
22) K. Kirad, and M. Chaudhari, "Design of cell spacing in lithium-ion battery module for improvement in cooling performance of the battery thermal management system," *J. Power Sources*, **481** (*June 2020*) 229016 (2021). doi:10.1016/j.jpowsour.2020.229016.
23) B.G. Chekuri, P.S. Subhasree Vaskuri, S.S. Kumar Chary, and R.R. Karuppa Thundil, "Three dimensional numerical validation and investigation on air cooling system of li-ion battery used in hybrid electric vehicles," *IOP Conf. Ser. Earth Environ. Sci.*, **312** (*1*) (2019). doi:10.1088/1755-1315/312/1/012025.
24) P. Vyroubal, T. Kazda, J. Maxa, and J. Vondrak, "Analysis of temperature field in lithium ion battery by discharging," *ECS Trans.*, **70** (*1*) 269–273 (2015). doi:10.1149/07001.0269ecst.
25) Z. Wang, W. Fan, and P. Liu, "Simulation of temperature field of lithium battery pack based on computational fluid dynamics," *Energy Procedia*, **105** 3339–3344 (2017). doi:10.1016/j.egypro.2017.03.764.