Journal of Emerging Technologies and Industrial Applications
Vol. 1 No. 2 (2022) pp. 1-8
e-ISSN: 2948-507X

Journal homepage: https://jetia.mbot.org.my/index.php/jetia/index

Analysis of the Cooling System in Battery Pack of Electrical Vehicles

Noor Hajar Mohd Khair[1], Amir Khalid[1*], Shahruizwan Sharudin[1], Muhamad Asri Azizul[1], Rahmah Mahmudin[1], Shaiful Fadzil Zainal Abidin[1], Zuraidah Ngadiron[2], Rifqi Irzuan Abdul Jalal[3]

[1]Centre of Automotive and Powertrain Technology, Faculty of Engineering Technology, Universiti Tun Hussein Onn Malaysia, 84600 Pagoh, Johor, Malaysia
[2]Faculty of Engineering Technology,
Universiti Tun Hussein Onn Malaysia, 84600 Pagoh, Johor, Malaysia
[3]Universiti Kuala Lumpur - Malaysia France Institute (UniKL MFI), Section 14, Jalan Damai, Seksyen 14, 43650 Bandar Baru Bangi, Selangor.

Abstract: Many people are aware that our environment is getting worse from day to day due to air pollution, mainly from the on-road vehicles. To combat this problem, electric vehicles (EVs) such as hybrid electric vehicles (HEVs) and fuel cell hybrid electric vehicles (FCHEVs) were introduced. Cooling system for the battery pack in electrical vehicles is crucial, as the battery will have a poor performance if it is too hot. High temperature can cause fast aging of the battery. This review paper is to discuss the cooling system has an effect on the performance of the battery pack in electrical vehicles (EVs). From previous research findings and several methods can be used to solve this problem, either through simulations or experiments. Simulations usually run by computer software such as computational fluid dynamics (CFD) or finite element model (FEM) using mesh models. Most researchers prefer to choose simulations rather than experiments because it can save a lot of cost. As a result, battery pack in EVs needs to have cooling system, so that all the systems can run smoothly and efficient.

Received 15 June 2022; Accepted 10 October 2022; Available online 15 December 2022

Keywords: Cooling System, Battery Pack, Electrical Vehicles, fuel cell, hybrid

*Corresponding Author:

[1]Centre of Automotive and Powertrain Technology,
Faculty of Engineering Technology,
Universiti Tun Hussein Onn Malaysia, 84600 Pagoh, Johor, Malaysia
Email: amirk@uthm.edu.my

1. Introduction

In this modern era, many people are aware that our environment is getting worse from day to day due to air pollution, mainly from the on-road vehicles. To combat this problem, electric vehicles (EVs) are created, i.e., hybrid electric vehicles (HEVs) and fuel cell hybrid electric vehicles (FCHEVs) [1-5]. Another reason to opt for EVs, is because the conventional internal combustion (IC) engines run on fuel and fossil fuels, which are non-renewable energy. It will be used until the vehicle run out of fuel and as substitution, powered battery is used. Electric powered vehicles use battery pack as their main source of energy. Although EVs have not polluting gas emission while operating and have high energy efficiency, the heat management of the battery pack is a huge downside for the EVs [6-11].

Currently, the most commonly used battery in EVs is the Lithium-ion (Li-ion) batteries as shown in Figure 1. Li-ion batteries have greater power and specific energy compared to Lead Acid and Nickel Metal Hydrides (Ni-MH) batteries [1,13]. The life of Li-ion batteries decreases when the temperature is high, while power and energy capabilities decline at cold temperature. These limit the range of driving and performance of EVs [14,15]. The desirable temperature for Li-ion batteries to operate is in the range between 25 to 45°C [16]. Cooling system for battery in electric vehicles is important because it affect the safety, battery life and battery performance [17-18]. The rising of temperature due to heat generated in the battery will reduce the performance [17]. Therefore, this review paper also discuss the thermal management of the battery pack in EVs, methods of cooling battery pack in EVs and modelling of battery cooling system in EVs.

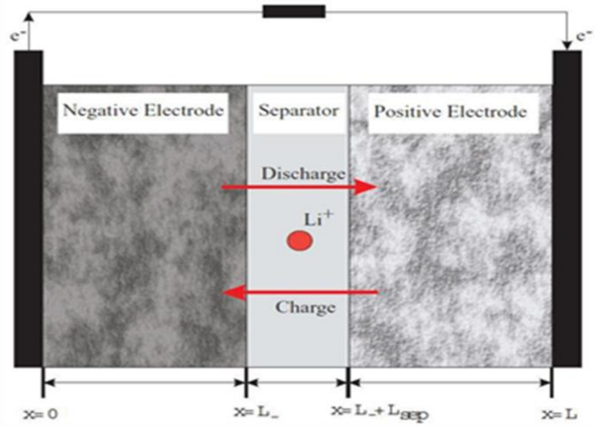


Fig. 1: Schematic drawing of Lithium-ion battery cell [12]

The arrangement of the cooling system of electrical vehicles battery pack is shown in Figure 2 [16]. This experiment is on liquid boiling cooling versus air cooling. In the external heat exchanger, the coolant liquid is heated and vapored gas is cooled down and condensed. The charging and discharging cycles are done 5 times. Charging is done by the constant current charge followed by the constant voltage charge, while discharging is done by the constant current. Experiments are carried out by 10ºC and 20ºC charging/discharging rates and the time for a full discharge is 6 minutes and 3 minutes respectively.

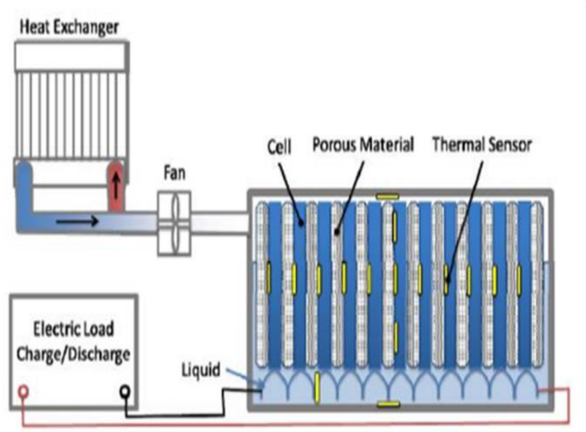


Fig. 2: Cooling system of electrical vehicles battery pack construction [16]

2. Discussion

2.1 Thermal Management of the Battery Pack in Electrical Vehicles

Figure 3 (a) and (b) show the overall pictures of temperature distribution in the battery pack at the end of discharge for rate of 2ºC [19]. Both battery packs are using air as cooling medium and left for 24 minutes in respective methods. The differences between the two are the battery pack in Figure 3 (a) use natural convection with heat transfer coefficient, h = 7 W/m^2°C and air velocity, V_{air} = 0.01 m/s, whereas the battery pack in Figure 3 (b) is tested using forced convection with h = 50 W/m^2°C and V_{air} = 1 m/s. Referring to the results, the value of h and V_{air} for battery pack in Figure 3 (a) is smaller and the heat removing process for the battery pack is not so efficient compared to battery pack in Figure 3 (b), which have better uniformity in terms of temperature.

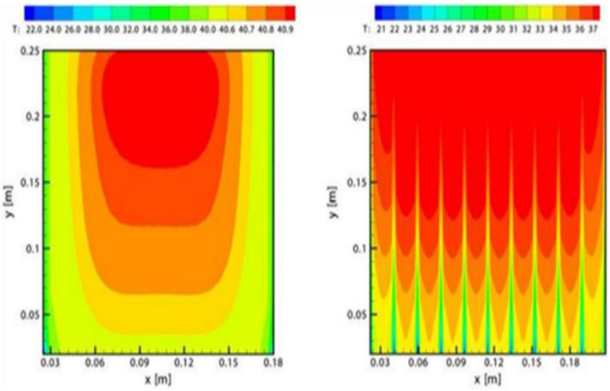
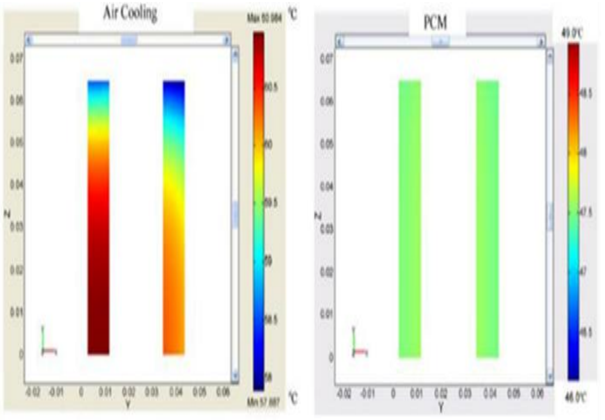


Fig. 3: Overall picture of temperature distribution in the battery pack at the end of discharge for a rate of 2ºC with cooling medium of (a) natural convection and (b) forced convection [19]

Meanwhile, Figure 4 shows the temperature profile of two adjacent cells with different methods of cooling; (a) is by air-cooled, whereas in (b) is using phase change material (PCM) [20]. PCM cooling method gives better thermal management for cooling system as the colour indicator is green with a little bit yellow showing more cooler condition compared to the battery pack in Figure 4 (a) which indicates hot condition by red colour indicator. However, the temperature for battery pack in Figure 4 (b) is around 47.5°C, but still do not reach the high temperature, which can affect the performance and efficiency of Li-ion battery pack.

Published by MBOT Publishing
https://jetia.mbot.org.my/index.php/jetia/index



(a) (b)

Fig. 4: Temperature profiles in two adjacent cells when applied (a) air-cooling and (b) passive cooling [20]

Figure 5 shows an illustration of a simulation using computational fluid dynamics (CFD) with thermal runaway in a battery pack [21]. The ignition starts as shown in illustration number 1 where the cell at the bottom left corner draws high current and overheated. Afterwards, the heat will progress to other cells as shown in the illustrations numbered 2, 3 and 4 until the whole battery pack ignites. The ignition will cause the temperature of the battery pack to increase as depicted by the temperature profile in Figure 5. The changing of temperature is indicated by the different colours used in the profile.

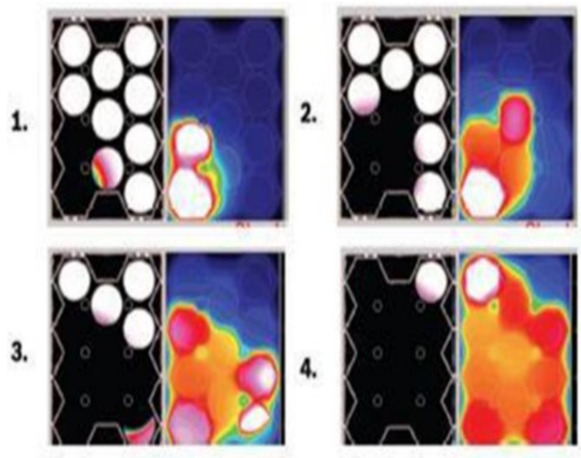
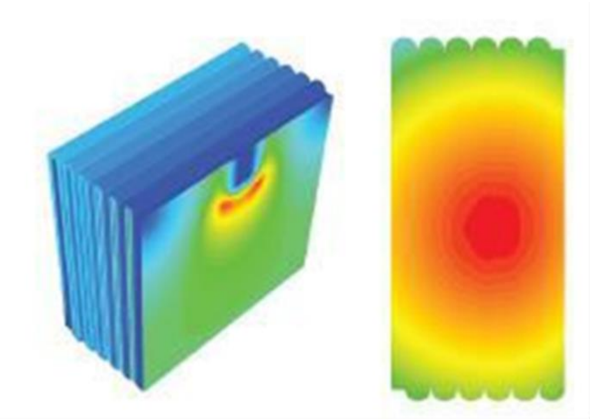


Fig. 5: An illustration of thermal runaway in a battery pack [21]

Furthermore, Figure 6 shows battery pack models based on joule heating experimental data [22]. The model on Figure 6 (a) can predict current density distribution, while the model on Figure 6 (b) is used to predict the resulting temperature distribution within a battery cell. From the observation, temperature profiles for higher temperature in the battery pack is indicated by red colour, which occurs in the middle surface of each battery cell, while the coolest temperature is indicated by blue colour arises in the outer surface of each battery cell.



(a) (b)

Fig. 6: Models based on joule heating experimental data can predict (a) current density distribution and (b) the resulting temperature distribution within a battery cell [22]

3.2 Methods of Cooling Battery Pack in Electrical Vehicles

3.2.1 Series and Parallel Cooling

Figure 7 shows a comparison between the series and parallel flow thermal analysis in the cell of HEV battery pack [23]. The y-axis represents maximum temperature in each cell for both flows, while the x-axis represents the time taken for the analysis.

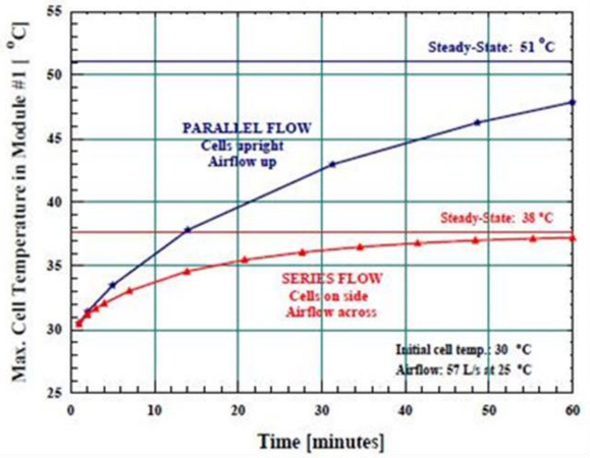


Fig. 7: Transient and steady-state thermal analysis of the first module in a 12-module Optima battery pack for a parallel HEV [23]

For parallel flow, the cells in the battery pack are arranged upright, so the airflow that goes through the cells is in an upward direction. On the other hand, for series flow, the cells are arranged side by side and the air that cools the battery pack will flow across the cells. From the figure, it obviously states that parallel flow has higher maximum cell temperature when it is running compared to the series flow, which means when the cells of the battery pack is in series flow it will reach the steady

Published by MBOT Publishing
https://jetia.mbot.org.my/index.php/jetia/index

state faster. This condition proves that battery pack that use series flow is much better compared to parallel flow.

3.2.2 Air Cooling and Phase Change Material (PCM) Cooling

Figure 8 shows temperature against time for plug-in hybrid electric vehicles (PHEV) for 20 battery packs [20]. Both initial temperatures are equal which are at 40ºC. The red line represents air cooling with h = 6 W/ m^2K, whereas the blue line represent PCM cooling. According to the figure, it shows that as time increases, temperature for both cooling type also increase. In comparison, when the battery pack is cooled using airflow, the temperature increase abruptly but by using PCM cooling, the temperature increase in a small amount and the increment of the temperature of the battery pack is almost constant after 200 seconds. This is because PCM reflects the heat absorption at the surroundings of the cells in the battery pack. This shows that using PCM cooling method is way better.

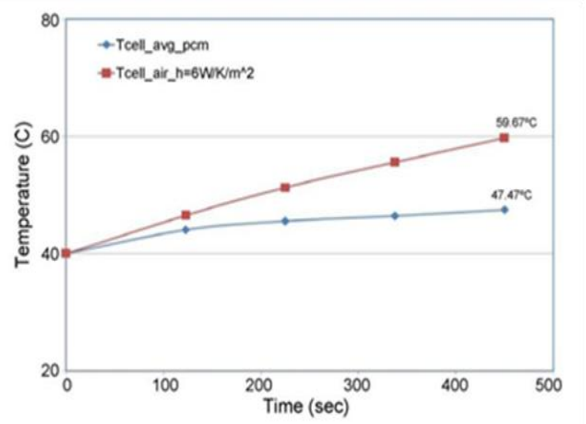


Fig. 8: Cell temperature increases for plug in hybrid electric vehicle (PHEV)-20 battery pack under stressed condition [20]

3.2.3 Active Cooling and Passive Cooling

Figure 9 and 10 show types of cooling methods, which is an active and passive cooling method in EVs respectively [24]. Both active and passive cooling methods are using outside air as their cooling medium. The difference between active and passive cooling method is that, the passive cooling have cabin air for the returned air from the exhaust, while the returned air for active cooling have to return back to the inlet of outside air.

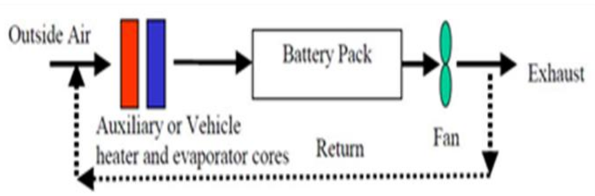


Fig. 9: Active Heating and Cooling [24]

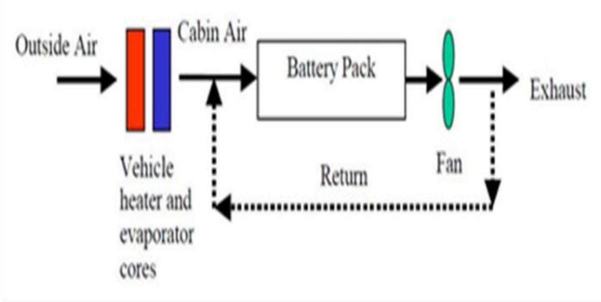
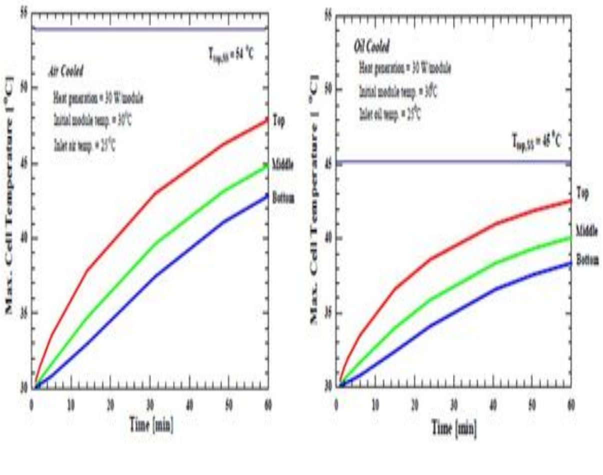


Fig. 10: Passive Heating and Cooling [24]

3.2.4 Air cooling & Oil Cooling

Figure 11 shows the transient and steady-state comparison of cooling an Optima module with liquid or air based on a similar parasitic pump/fan power [23]. The battery pack in Figure 11 (a) used air cooling, while in Figure 11 (b) used oil cooling. The y-axis represents the maximum cell temperature and the x-axis represents time taken in minutes. The initial temperature of the battery pack is 30ºC for both cooling methods and 25ºC for initial temperature of both air and oil.

Figure 11 (a) and (b) show that when the time increases, the maximum cell temperature also increases. The top, middle and bottom lines in red, green and blue respectively are showing the vertical location of the cells in the battery pack which is the top layer, middle layer and bottom layer. It shows that oil cooling method have a better heat transfer compared to air cooling method.



(a) (b)

Fig. 11: Transient and steady-state comparison of cooling an Optima module with (a) liquid or (b) air based on a similar parasitic pump/fan power [23]

3.2.5 Large and Small Aspect Ratio

Figure 12 shows the comparison results for heating rectangular battery packs using different aspect ratios, which are large and small. Each aspect ratio is tested

Published by MBOT Publishing
https://jetia.mbot.org.my/index.php/jetia/index

using core and jacket heating [25]. The energy input is 6.62 Wh/kg and the experiment ran for 2 minutes. The vertical axis represents the temperature of battery pack and the horizontal axis represents time taken in seconds. The figure shows that the longer the time, the temperature will be higher. In comparison of core heating, it shows that large aspect ratio have lower temperature than the small aspect ratio. Meanwhile, for jacket heating, the large aspect ratio has higher temperature compared to small aspect ratio. However, comparison between core and jacket heating indicates that jacket heating have relatively lower temperature and from the overall analysis, jacket heating with small aspect ratio have the lowest temperature after being cooled.

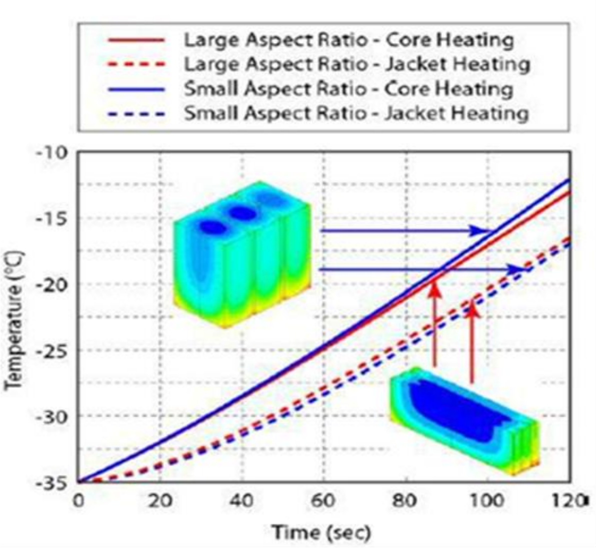


Fig. 12: Comparing results of heating two rectangular batteries with different aspect ratios for heating rate [25]

3.3 Modelling and Analysis of Battery Pack Cooling System in Electrical Vehicles

Figure 13 shows the detailed computational fluid dynamics (CFD) thermal model of the cold plates which is used to extract the pressure losses, convective heat transfer coefficient and the thermal resistance of the cold plates for different mass flow rates [26]. Specific for low Reynolds number turbulence models have been utilized to acquire an exact description of the hydrodynamic and convective heat transfer case inside the complex small channels in the cold plates. The model has been numerically and experimentally established.

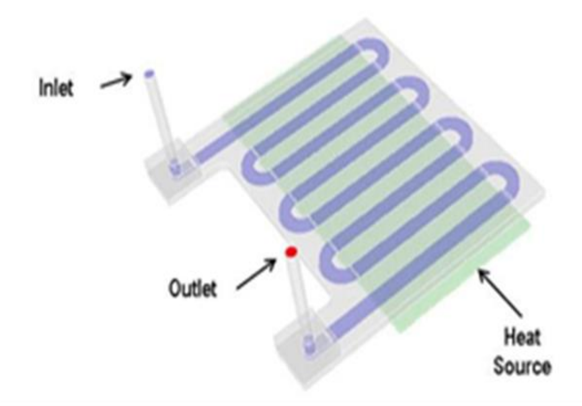


Fig. 13: Detailed CFD model for the cold plates of battery pack [26]

Meanwhile, Table 1 shows that the temperature of the battery pack is affected by the diameter of the cooling channels [27]. These results were obtained from combining 1D network solver, 3D heat transfer and computational fluid dynamics (CFD) modeling method, in order to find the optimized cooling systems. The bigger diameter leads to higher temperature difference (DT) within the cells of the battery pack. The difference of the average temperature from the first battery cell to the last one also increases with the diameter of cooling channel.

Table 1: Temperature change for different diameter of cooling channels [27]

Channel Diameter (mm)	Maximum DT within Cell (C)	Difference of Avg Temperature from 1st to Last (C)
1.00	2.42	1.22
1.25	2.52	1.35
1.50	2.63	1.50
1.75	2.74	1.67
2.00	2.88	1.90
2.25	3.05	2.11
2.50	3.17	2.40
2.75	3.40	2.76
3.00	3.54	3.06

The computational fluid dynamics (CFD) using mesh models of series ventilation in Figure 14 (a) and (b) compared the temperature distribution of the battery pack with and without cooling system [25-27]. The cooling system for this model is by using fan to cool off the battery pack. In Figure 14 (a), when the cooling of battery is not considered, temperature increased by 21.87°C. The battery will work in bad condition, and it will accelerate aging, if the maximum temperature exceeds 50°C, which is very hazardous.

Published by MBOT Publishing
https://jetia.mbot.org.my/index.php/jetia/index

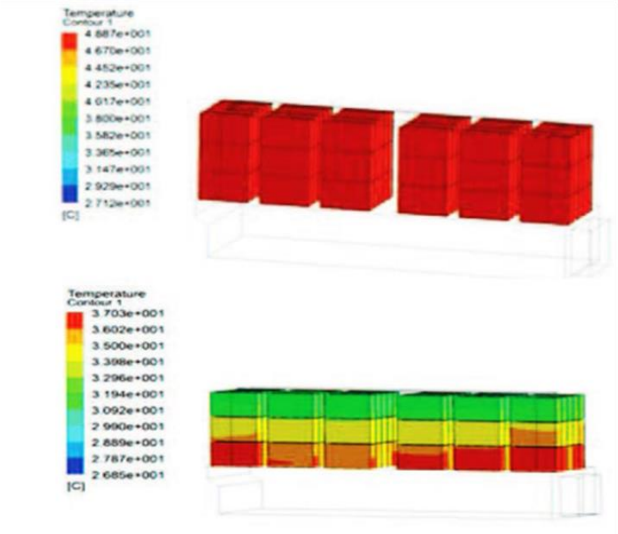


Fig. 14: Temperature distribution at battery surfaces (a) without cooling system and (b) considering the cooling system. [25-27]

On the other hand, based on Figure 14 (b), after the fan is turned on, maximum temperature falls to 37℃, indirectly meets the working condition which is in the range of 25-40℃. On the downside, the range of temperature difference among the cells rose, which shows the temperature consistency of battery pack becomes bad. Explicitly, the lowest temperature is in the first layer and consequently, it increase in each layer below it, because the cooling air is heated when flowing through each of the layers when using series ventilation.

Figure 15 (a) and (b) show the ANSYS CFD model for similar battery model but with different diameter and length of gap between each cell. In Figure 15 (a), the cells have smaller diameter, so the gap between the cells are bigger. However, the cells in Figure 15 (b) have larger diameter, which makes the gap between the cells smaller [25-27]. According to Figure 15 (a), the first and last cell experienced smaller heat transfer coefficient because the velocity is lower due to lesser blockages in the neighbourhood cells. Without CFD analysis, this could have been overlooked because generally, the first cell will be cooler than the others. The smaller gaps between the cells in Figure 15 (b) cause in higher velocity, which means greater heat transfer coefficient. Therefore, this cell configuration at the battery pack will be cooler compared to the smaller diameter because it has more uniform temperature distribution and lower temperature values.

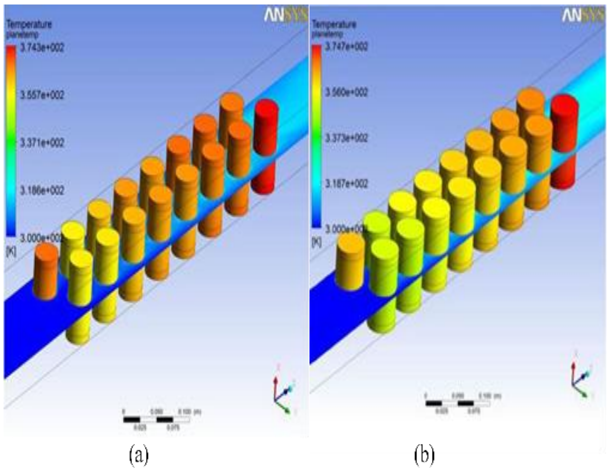


Fig. 15: Temperature distribution of a 16-cell battery model (a) with smaller diameter and (b) with larger diameter.[25-27]

4. Conclusion

Nowadays, battery pack plays an important role for green vehicles concept, since it replaced the fuels such as gasoline oil or diesel. Therefore, a well design thermal management system is required to regulate the battery pack temperature evenly. Production of EVs requires different methods of cooling for the battery packs, in order to allow it to operate in all climates because the life and performance differs according to the surroundings. By using liquid as cooling/heating medium, it gives a better effectiveness to the thermal management system. Generally, for parallel HEVs, an air thermal management system is adequate, whereas for EVs and series HEVs, liquid-based systems may be required for optimum thermal performance. Li-ion batteries also need a good thermal management system because of the safety and low temperature performance concerns [9]. The location of the battery pack may also have a strong impact on the type of battery thermal management required by the battery, and whether the pack should be air cooled or liquid cooled.

Acknowledgement

The authors would like to thank the Ministry of Higher Education (MOHE) for supporting this research under the Fundamental Research Grant Scheme No. FRGS/1/2019/TK10/UTHM/02/10 Vot K224 and also Research Fund Universiti Tun Hussein Onn Malaysia (H793).

References

[1] M. Mousavi, S. Hoque, S. Rahnamayan, I. Dincer and G. F. Naterer, "Optimal design of an air-cooling system for a Li-Ion battery pack in Electric Vehicles with a genetic algorithm," 2011 IEEE Congress of Evolutionary Computation (CEC), New Orleans, LA, pp. 1848-1855, 2011.

[2] Jaat, N., Azizul, M.A., Khalid, A., Jais, M.H.A., Abidin, S.F.Z., Mustaffa, N., Ishak, I.A., Manshoor, B., Didane, D.H., Zahari, I. (2021). Investigation of Performance Characteristics of Plastic Pyrolysis Oil and Crude Palm Oil Fuel on Diesel Engine. International Journal of Engineering Trends and Technology, 69 (12), pp. 312-318.

[3] Abidin, S.F.Z., Khalid, A., Zanalli, S., Zahari, I., Jalal, R.I.A., Abas, M.A., Koten, H. (2021). The effect of 48V mild hybrid technology on fuel consumption of a passenger car by using simulation cycle. Case Studies in Thermal Engineering, 28, art. no. 101492

[4] Abidin, S.F.Z., Rodzi, S.N.A.M., Khalid, A., Zahari, I., Jalal, R.I.A., Abas, M.A. (2021). Reducing fuel consumption of a passenger car towards energy efficient vehicle by using belted alternator startertechnology. (2021) International Journal of Engineering Trends and Technology, 69 (9), pp. 116-123.

[5] Ishak, I.A., Ali, M.S.M., Sakri, F.M., Zulkifli, F.H., Darlis, N., Mahmudin, R., Abidin, S.F.Z., Azizul, M.A., Sulaiman, S., Samiran, N.A., Khalid, A. (2019). Aerodynamic characteristics around a generic train moving on different embankments under the influence of crosswind. Journal of Advanced Research in Fluid Mechanics and Thermal Sciences, 61 (1), pp. 106-128.

[6] Khalid, A., Jaat, N., Zainal Abidin, S. F. ., Mohamed Sunar, N., Jacob, D. . W. ., & Amirnordin, S. H. (2022). Influences of Algae Biodiesel on Ignition Delay, Combustion Process and Heat Release of Diesel Combustion. Journal of Emerging Technologies and Industrial Applications, 1(1).

[7] Darlis, N. ., Mohammad Aris, M. H. ., Azizul, M. A. ., Ishak, I. A., Sulaiman, S. ., Mahmudin, R., & Andsaler, A. . (2022). HVAC CFD Analysis of Air Flow and Temperature Distribution inside Passenger Compartment. Journal of Emerging Technologies and Industrial Applications, 1(1).

[8] Baharol Maji, D. S., & Mustaffa, N. (2021). CFD Analysis of Rear-Spoilers Effectiveness on Sedan Vehicle in Compliance with Malaysia National Speed Limit. Fuel, Mixture Formation and Combustion Process, 3(1).

[9] Mat Yasin, M. H., Salleh, M. R., Ali, M. H., & Mamat, R. (2022). Characterization of Physical Properties for Diesel-alcohol and Biodiesel-alcohol Blends. Fuel, Mixture Formation and Combustion Process, 4(1).

[10] Khaifullizan, M. N. N., Jaat, N., Zainal Abidin, S. F., Darlis, N., & Zahari, I. (2021). Effect of Intake Air Temperature on Engine Performance and Fuel Consumption of Passenger Car. Fuel, Mixture Formation and Combustion Process, 3(2).

[11] C. C. Chan, A. Bouscayrol and K. Chen, "Electric, Hybrid, and Fuel-Cell Vehicles: Architectures and Modeling," in IEEE Transactions on Vehicular Technology, vol. 59, no. 2, pp. 589-598, Feb. 2010.

[12] P. Amiribavandpour, W. Shen and A. Kapoor, "Development of Thermal-Electrochemical Model for Lithium Ion 18650 Battery Packs in Electric Vehicles," 2013 IEEE Vehicle Power and Propulsion Conference (VPPC), Beijing, pp. 1-5, 2013.

[13] Y. K. Tan, J. C. Mao and K. J. Tseng, "Modelling of battery temperature effect on electrical characteristics of Li-ion battery in hybrid electric vehicle," 2011 IEEE Ninth International Conference on Power Electronics and Drive Systems, Singapore, pp. 637-642, 2011.

[14] Pesaran, A.A., G.-H. Kim, and M. Keyser, “Integration Issues of Cells into Battery Packs for Plug-in and Hybrid Electric Vehicles,” 24th International Batteries, Hybrid Fuel Cell Electric Vehicle Symposium, Stavanger, Norway, May 2009.

[15] Shim, J., R. Kostecki, T. Richardson, X. Song, and K. Striebel, “Electrochemical Analysis for Cycle Performance and Capacity Fading of A Lithium-ion Battery Cycled at Elevated Temperature,” Journal of Power Sources, vol. 112, no. 1, pp. 222-230, 2002.

[16] H. Hirano, T. Tajima, T. Hasegawa, T. Sekiguchi and M. Uchino, "Boiling Liquid Battery Cooling for Electric Vehicle," 2014 IEEE Conference and Expo Transportation Electrification Asia-Pacific (ITEC Asia-Pacific), Beijing, pp. 1-4, 2014.

[17] R. Kumar and N. Khare, "Smart Instrument for Automotive Battery Application," 2012 Fourth International Conference on Computational Intelligence and Communication Networks, Mathura, pp. 671-675, 2012.

[18] X. Hu, S. Lin, S. Stanton and W. Lian, "A Foster Network Thermal Model for HEV/EV Battery Modeling," in IEEE Transactions on Industry Applications, vol. 47, no. 4, pp. 1692-1699, July-Aug. 2011.

[19] Karimi, G. and X. Li, “Thermal management of lithium-ion batteries for electric vehicles,” International Journal of Energy Research, vol. 37, no. 1, pp. 13-24, 2013.

[20] Kizilel, R., R. Sabbah, J.R. Selman, and S. Al-Hallaj, “An alternative cooling system to enhance the safety of Li-ion battery packs,” Journal of Power Sources, vol. 194, no. 2, pp. 1105-1112, 2009.

[21] Smyshlyaev, A., M. Krstic, N. Chaturvedi, J. Ahmed, and A. Kojic, “PDE model for thermal dynamics of a large Li-ion battery pack,” American Control Conference (ACC), 2011.

[22] Hu, X., “Battery Thermal Management in Electric Vehicles,” ANSYS Journal Article, pp. 1-6, 2013

[23] Pesaran, A.A., M. Keyser, and S. Burch, “An Approach for Designing Thermal Management Systems for Electric and Hybrid Vehicle Battery Packs,” Fourth Vehicle Thermal Management Systems Conference and Exhibition, London, UK, May 1999.

[24] Pesaran, A.A., “Battery Thermal Management in EVs and HEVs: Issues and Solutions,” Advanced Automotive Battery Conference, Nevada, 2001.

[25] Pesaran, A., A. Vlahinos, and T. Stuart, “Cooling and Preheating of Batteries in Hybrid Electric Vehicles,” The 6th ASME-JSME Thermal Engineering Joint Conference, Hawaii, 2003.

[26] N. Nieto, J. Gastelurrutia, L. Díaz and F. Blanco, "Thermal management systems' design methodology

Published by MBOT Publishing
https://jetia.mbot.org.my/index.php/jetia/index

for transport applications," 2013 World Electric Vehicle Symposium and Exhibition (EVS27), Barcelona, pp. 1-9, 2013.

[27] H. Lewis, B. Zandi, G. Lewis and S. Ketkar, "Variable fidelity methodology for thermal battery modeling," 13th InterSociety Conference on Thermal and Thermomechanical Phenomena in Electronic Systems, San Diego, CA, pp. 975-984, 2012.

Published by MBOT Publishing
https://jetia.mbot.org.my/index.php/jetia/index