https://doi.org/10.31871/WJRR.16.6.13
World Journal of Research and Review (WJRR)
ISSN: 2455-3956, Volume-16, Issue-6, June 2023 Pages 16-22

An Overview of Battery Cooling Systems for Electric Vehicles

Nguyen Tien Han, Nguyen Thi Hong Ngoc, Nguyen Dinh Tan, Tran Duc Hoang, Nguyen Thanh Cong, Le Van Quynh

***Abstract*— In order to improve the performance of electric vehicle batteries, the battery thermal management system (BTMs) always ensures that the temperature inside the battery is kept in the optimal range. The cooling system for the battery is one of the important systems to ensure that the battery's temperature is within the optimal temperature range. Some cooling systems applied to electric vehicle batteries include Air Cooling (AC), Liquid Cooling (LC), Refrigerant Direct Cooling (RDC), Cooling System using Phase Change Material (PCM), Thermoelectric Cooling (TC), Heat Pipe Cooling (HPC), Hybrid Cooling (HC). A detailed review on the battery cooling systems is discussed in this paper. The study results have shown the advantages and disadvantages of battery cooling systems being applied on electric vehicles. In addition, the study results could provide ideas for researchers in the field of electric vehicle battery cooling**

***Index Terms*—Electric vehicle, battery, cooling system, thermal management system.**

I. Introduction

Electric vehicles are used to replace traditional vehicle in the near future throughout the cities of countries around the world. Researchers have been focusing on perfecting technologies such as battery technology, energy system, electric drive, safety system and comfort system of electric vehicles. However, battery technology is considered by researchers as a core technology in the development of electric vehicle technology, energy storage and thermal safety of the battery are two important issues in this core technology, a battery thermal management has become one of the remaining issues that must be appropriately handled to ensure robust EV design. Starting from researching safer and more durable battery cells that can resist thermal exposure, battery packing design has also become important to avoid thermal events causing an explosion or at least to prevent fatal loss if the explosion occurs. An optimal battery packing design can maintain the battery cell temperature at the most favorable range which is 25–40◦C, with a temperature difference in each battery cell of 5◦C at the maximum, which is considered the best working temperature. The fundamental problems of the battery thermal management systems (BTMSs) in electric vehicles (EVs) discussed in general [1]. A comprehensive review classifying comparatively the existing and upcoming battery management systems discussed, which could be seen as a first look into the future BTMSs for automotive applications [2]. Several cooling systems such as Air Cooling (AC), Liquid Cooling (LC), Refrigerant Direct Cooling (RDC), Cooling System using Phase Change Material (PCM), Thermoelectric Cooling (TC), Heat Pipe Cooling (HPC), Hybrid Cooling (HC) are commonly used in EVs [3]: (i) Air Cooling (AC), this solution has a number of advantages such as simplicity, low cost, electrical safety, light weight, no worry of leakage, easier maintenance, etc. [4, 5]. However, it cannot meet the requirements of high temperature working environment, need to cool the battery pack with large capacity and high charge and discharge cycle. To overcome these limitations, forced-air convection cooling method uses cooling fans [7, 8], airflow [9, 10], and fin structure [11]; (ii) Liquid Cooling (LC), a thermal model for the pouch battery pack with liquid cooling is developed for thermal analysis of various pack designs [12]. A liquid cooling system for lithium-ion battery with changing contact surface is designed to keep battery working in a cool environment [13]; (iii) Refrigerant Direct Cooling (RDC), RDC also could be applied to battery thermal safety synergy control for its potential in emergency cooling of spaying and prevention overheating or thermal runaway propagation which means that refrigerant-based direct cooling should develop a cross-coupling controlling strategy to realize the synergy control both for BTM and BTM with enhanced safety [14, 15]. A direct refrigerant cooling using conventional R134a and environmentally friendly R1234yf for lithium-ion batteries of electric vehicles proposed to investigate without changing the model structure [15]. The performance improvement of a novel direct two-phase refrigerant cooling over a conventional liquid cooling for traction batteries of EVs was proposed to investigate [16]; (iv) Cooling System using Phase Change Material (PCM) is commonly used in the study of battery thermal management system (BTMS). Active liquid cooling was also combined with copper foam/paraffin composite phase change material (CPCM) to provide extra cooling ability [17]. The paraffin/aluminum foam composite phase change material (PCM) was investigated experimentally. The experimental results indicate that paraffin/ aluminum foam composite PCM had an ideal cooling effect in limiting the temperature rise of the Li-ion battery during the discharge process [18]; (v) Thermoelectric Cooling (TC) uses the Peltier effect to create a heat flux at the junction of two different types of materials. A thermoelectric

Nguyen Tien Han, HaNoi University of Industry, Ha Noi, Vietnam
Nguyen Thi Hong Ngoc, Faculty of Vehicle and Energy Engineering, Thai Nguyen University of Technology, Thai Nguyen, Vietnam
Nguyen Dinh Tan, Faculty of Mechanical Engineering, East Asia University of Technology, Bac Ninh, Vietnam
Tran Duc Hoang, Faculty of Vehicle and Energy Engineering, Thai Nguyen University of Technology, Thai Nguyen, Vietnam
Le Van Quynh, Faculty of Vehicle and Energy Engineering, Thai Nguyen University of Technology, Thai Nguyen, Vietnam
Nguyen Thanh Cong, Faculty of Vehicle and Energy Engineering, Thai Nguyen University of Technology, Thai Nguyen, Vietnam

generator (TEG) coupled with forced convection (F-C) was designed as an effective and feasible cooling system for a battery thermal management system [19]. Heat pipes were applied to BTMS for EVs, in order to facilitate its introduction to the market, by highlighting the strengths as well as the improvements that must be made [20]. An electric–thermal coupling model of a cylindrical Panasonic 21700 battery was proposed by using offline parameter identification method to investigate the efficiency of heat pipes [21]; and (vi) Hybrid Cooling (HC), some research results have shown that air, liquid, PCM, HP and refrigeration cooling are capable of maintaining battery pack thermal management within the desired range, but it has also been found that the limitations of a single technique limit achieving the best possible performance in battery thermal management. In order to integrate the advantages and overcome the disadvantages of a single cooling method, the combination of two or more cooling systems called mixed cooling has been researched and developed by the researchers. More hybrid cooling methods adopting different basic methods are being designed to meet EVs requirements. The phase change material (PCM)-based hybrid cooling system was proposed for the battery thermal management system consisting of 25 commercial Sony-18650 cells arranged in a cubical battery pack [22]. The performance of a hybrid air-phase change material (PCM) cooled lithium-ion battery module at various air inflow velocity (U_0 = 0–0.1 m/s) and different thickness of PCM encapsulation (t = 1–3 mm) for 1C, 2C and 5C discharge rates was proposed to achieve the best thermal performance and long cycle life of these batteries [23]. Some of these systems are analyzed in detail below

II. Battery Cooling Systems

A. *Air cooling*

The different air cooling strategies were investigated by changing the relative positions of air flow inlet and outlet to acquire the best cooling way [24] and the results indicate that the cooling performance of inlet and outlet located on the different sides is better than on the same side and the use of the baffle plate can highly improve the thermal performance of air cooling strategies with the lateral inlet and outlet. Schematic of simulation results is shown Fig.1. The modules, equipped with a forced-air cooling system, were charged at 1 C-rate and discharged at 1, 1.5, and 2 C-rates for three cycles in each test [25]. The cooling efficiency of the air-cooled BTMS was improved through designing the flow pattern of the system and an optimization strategy was proposed to optimize the positions of the inlet region and the outlet region for cooling efficiency improvement of the system [26]. Compared to the symmetrical system, the maximum cell temperature difference of the optimized BTMS was reduced by 1.7 K with the power consumption decreased by 12%. Schematic of the parallel air-cooled BTMS with Z-type flow is shown in Fig.2.

The natural convection of this battery cooling system has the advantages of simplicity, low cost, and natural convection as the main heat dissipation process. The disadvantage is that the wind force is uncontrollable. Compared with natural convection, forced convection is more reliable and easier to maintain, so it has become a common battery cooling system. However, the disadvantage of forced convection is that the temperature distribution in the battery is uneven. Due to the characteristics of the air itself, the cooling effect has certain limitations. The advantages of air-cooled thermal management include: safety and reliability during operation, simple materials required and easy to implement, and timely and effective ventilation when harmful gases are generated [27].

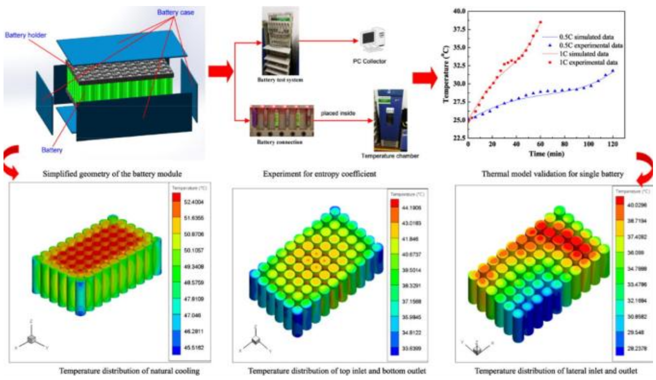

Figure 1. Schematic of simulation results [24]

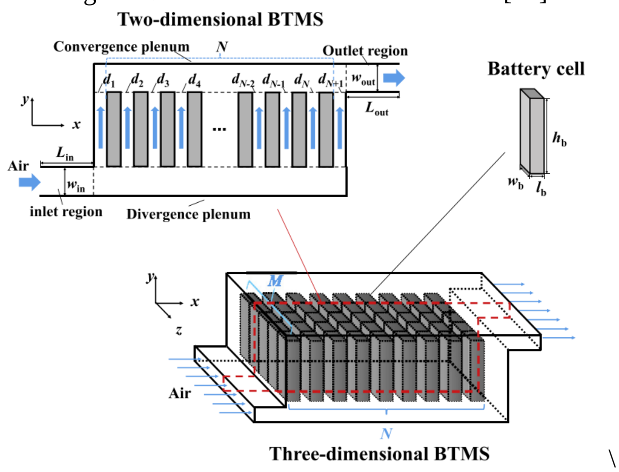

Figure 2. Schematic of the parallel air-cooled BTMS with Z-type flow [26]

B. *Liquid cooling*

Liquid cooling is a powerful way to keep the battery temperature in a proper range. A novel modular liquid-cooled system for batteries and carried out the numerical simulation and experiment to study the effect of coolant flow rate and cooling mode on the thermal behavior of the battery module was presented to improve the temperature uniformity of the battery module in a certain flow range. The modular structure could be suitable for industrial batch production and group the batteries flexibly to meet the actual demand and the study results provided a 2 new approach for the modular design of liquid-cooled battery thermal management system [28]. The temperature distribution of different flow direction layouts is shown Fig.3. A novel liquid cooling based thermal management system for the cylindrical lithium-ion battery module with variable contact surface was designed to to study the effects of aluminum block length and velocity on the thermal performance in the way of simulation [29]. The schematic of liquid cooling system for the battery module is shown in Fig. 4

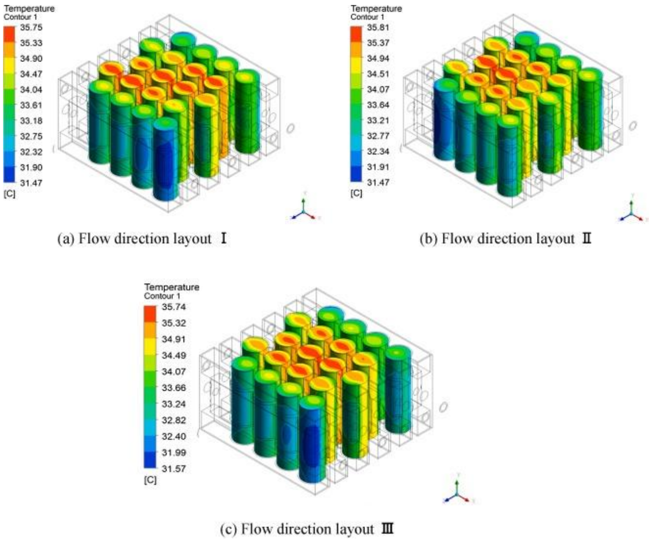

Figure 3. Temperature distribution of different flow direction layouts [28]

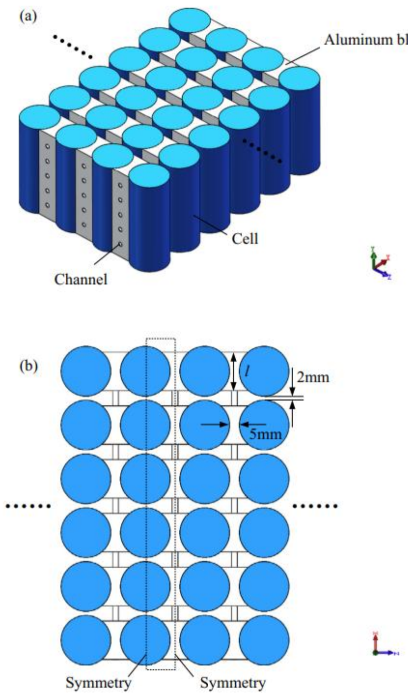

Figure 4. Schematic of liquid cooling system for the battery module [29]

A new kind of coolant, liquid metal, was proposed to be used for the thermal management of the battery pack. Mathematical analysis and numerical simulations were conducted to evaluate the cooling capability, pump power consumption and module temperature uniformity of the liquid metal cooling system, in comparison with that of water cooling [30].

The liquid-cooled battery cooling system has a good effect and can effectively reduce the working temperature and local temperature difference of the battery. At the same time, there are also adverse effects such as complex system structure, relatively large mass, liquid leakage, and frequent maintenance. However, in the electric vehicle thermal management system that requires relatively strict battery working conditions and prioritizes thermal management, the liquid-cooled battery cooling system has more obvious advantages than air-cooled.

C. *Refrigerant direct cooling*

The direct refrigerant cooling system consists of either a vapor compression or an absorption system. A novel discrete model based on an electro-thermal coupling method and thermal resistance network to analyze the local temperature control performance of refrigerant direct cooling and liquid cooling systems under real operating scenarios with acceptable computing time and accuracy and the results shown that the phase change of the refrigerant in the refrigerant direct cooling plate significantly affects the temperature control performance [31]. A thermal management system (TMS) based on R134a refrigerant was proposed using mathematical one-dimension simulation method to analyze the feasibility of mainly working modes, including battery preheating mode, mixed heating mode, low-temperature mixed heating mode [32]. The typical applications on electric vehicles of direct cooling were also investigated, and more productions are under research [33] and synthesize research results in the field of cooling for electric vehicle batteries. A novel direct two-phase refrigerant cooling over a conventional liquid cooling for traction batteries of EVs was proposed to investigate the performance improvement. The two-phase refrigerant cooling satisfies the maximum cell temperature limit of 45°C even under harsh environmental conditions and the study results have shown that the two-phase refrigerant cooling provides 16.1% higher battery capacity and 15.0% lower internal resistance compared with the liquid cooling under harsh environmental conditions [34]. The schematics of battery cooling systems of direct two-phase refrigerant cooling is shown Fig.5 and the experimental setup is shown Fig.6.

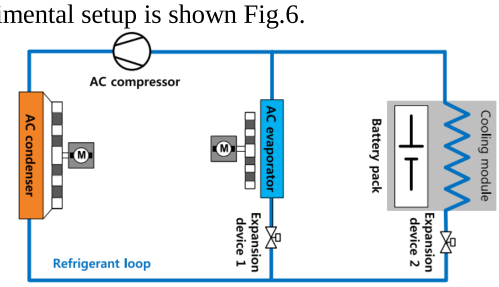

Figure 5. Schematics of battery cooling systems of direct two-phase refrigerant cooling [34]

Advantages of refrigerant direct cooling for batteries is simpler in structure, which can effectively reduce the weight of the BTMS and improve the energy density and economy of the power system. The refrigerant direct cooling with boiling heat transfer has several significant advantages in higher heat fluxes with evaporative.

D. *Phase Change Material*

A phase-change material (PCM) is a substance which releases/absorbs sufficient energy at phase transition to provide useful heat or cooling. Phase Change Materials are ideal products for thermal management solutions. The previous developments introducing PCMs for EVs battery cooling was proposed to enhance PCMs efficiency in those systems [35].

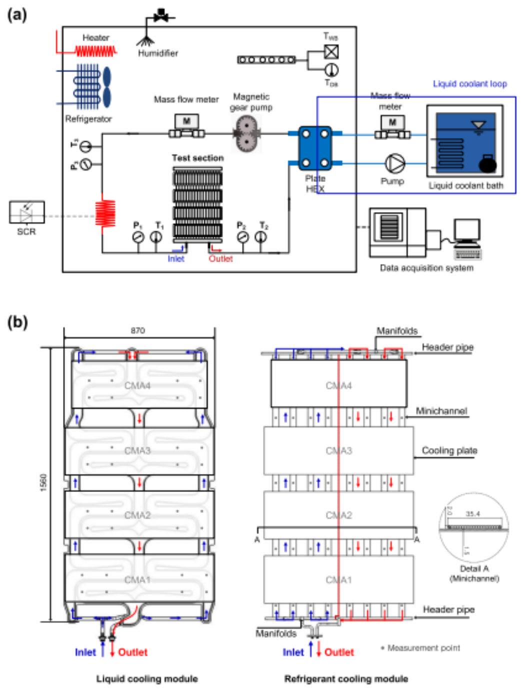

Figure 6. Schematics of (a) experimental setup and (b) tested cooling modules [34]

The thermal conductivity enhancement of PCM44, an eutectic mixture of Mg (NO3) 26H2O –MgCl26H2O –NH4NO3, using carbon fibers has been investigated [36]. The phase change materials (PCM) in Li-ion batteries for electric vehicle and scooter applications were propose and analyze the thermal characterization of Li-ion battery modules [37] and a new design using commercially available high-power Li-ion batteries (HPPC 18650) with a PCM thermal management system was proposed in this work as an alternative to NiMH batteries. The schematic of the proposed battery module is shown Fig.7.

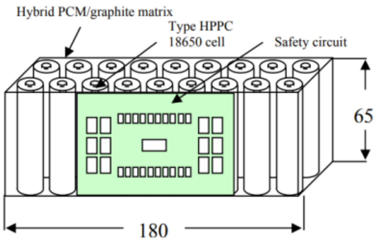

Figure 7. Schematics of the PCM/Li-Ion Battery Module [37].

The physical state of PCM changes with temperature. During the phase change process, the temperature range is small, but the latent heat absorbed or released is large. PCMs have the advantages of small volume change, large latent heat, and good stability. PCM relies on its own high latent heat capacity, however when the temperature exceeds its own melting point, the cooling performance of PCM will decrease significantly.

E. *Thermoelectric Cooling*

Thermoelectric cooling (TEC) is a new technology that has the potential to revolutionize the way things are kept cold. An experimental investigation was performed on an advanced battery thermal management system for emerging electric vehicles using thermoelectric cooling [38]. the experimental test shows that the battery surface temperature drops around 43°C (from 55 °C to 12 °C) using TEC-based water cooling system for a single cell with copper holder when 40 V is supplied to the heater and 12 V to the TEC module. Schematic illustration of the used single unit of TEC system for BTMS is shown Fig.8

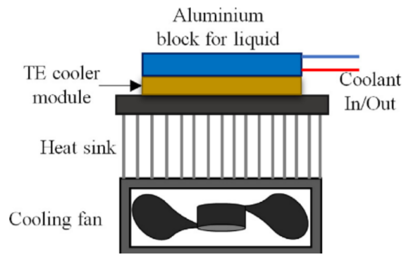

Figure 8. Schematic illustration of the used single unit of TEC system for BTMS [38]

The 3D thermal model of a high power lithium ion battery and the TEC was elaborated to investigate the performance of a thermal management system for a lithium ion battery pack [39]. The simulation model of the TEC is shown Fig.9.

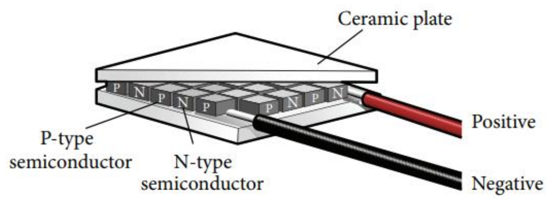

FIGURE 1: Schematic diagram of the TEC.

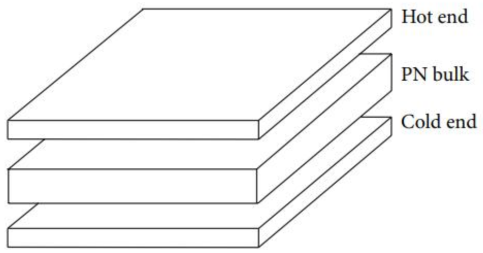

Figure 9. The simulation model of the TEC

TEC technology has many advantages over the conventional vapor-compression cooling systems. The main disadvantages of thermoelectric cooling are the high cost and low energy efficiency, which has restricted its application to cases where system cost and energy efficiency are less important than energy availability, system reliability and quiet operation environment.

F. *Heat Pipe Cooling*

Heating pipe (HP) is a high-efficiency heat exchange element that uses the phase change of the medium in the pipe to absorb and release heat. A heat pipe and wet cooling combined BTM system was developed to handle the thermal surge of lithium-ion batteries during high rate operations and examine the cooling effects of the combined BTM system, and its performance was compared with other four types of heat pipe involved BTM systems and natural convection cooling method [40]. Schematic illustrations of 8 Ah battery pack with heat pipes are shown Fig.10. Among the temperature collection points, T_1 to T_6 are used to measure the temperature gradient in pack level and T_a to T_e are used to test the center cell temperature uniformity

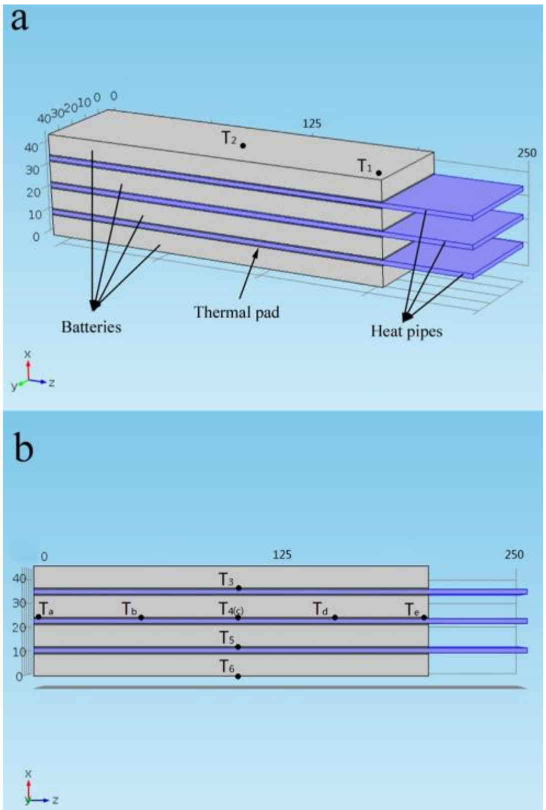

Figure 10. Schematic illustrations of 8 Ah battery pack with heat pipes [40].

Numerical model was built and verified to study the efficiency of the new design. Compared with traditional air cooling, the proposed design has an advantage in maximum temperature control. The maximum temperatures are 16.93℃, 26.07℃ and 36.27℃ for 1C, 2C and 3C discharging, respectively [41]. A battery thermal management system using a heat pipe was established and a significant number of battery discharging experiments were conducted under various conditions using the offline parameter identification method. The study results have shown that the changing refrigerant temperature can achieve a better thermal management effect under suitable ambient temperature conditions [42].

Heat pipes have become one of the important battery cooling system for electronic equipment due to their good heat flux variability, thermal conductivity, density variability, heat flow direction reversibility, excellent constant temperature thermal performance, and environmental adaptability. Compared with other battery cooling system, the heat pipe has a stronger heat transfer capacity, but it does not mean that its heat load can be increased infinitely.

G. *Hybrid Cooling*

Hybrid cool is the combination of two or more cooling systems together to take advantage of their advantages. The hybrid cooling system has proved to be an energy saving technology for electric vehicle batteries. A novel coupled thermal management with phase changed material (PCM) and liquid pipe was proposed and numerically investigated for prismatic LiFePO4 battery pack [43]. Study results showed that the coupled system exhibited good cooling performance even at ambient temperature of 45◦C, which suppressed the maximum temperature and temperature difference of battery pack to 47.6◦C and 4.5◦C, respectively. The schematic diagram of experimental system and thermalcouples locations in single battery is shown Fig.11.

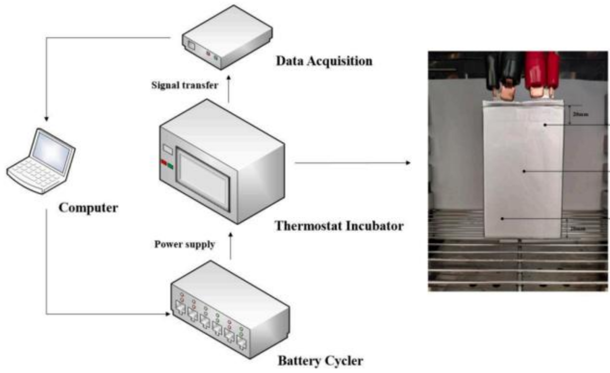

Figure 11. Schematic diagram of experimental system and thermalcouples locations in single battery [43].

A hybrid TMS (HTMS) using phase change materials (PCM) and six flat heat pipes was proposed to maintain the temperature profile below 40°C under a high current rate of 150 A for 1400 s profile without any pause [44]. The study results reveal that the HTMS was an exceptionally robust cooling system since it reduces the T_1 temperature by 35% compared to the natural convection case study, while the heat pipe TMS can reduce the T_1 temperature by 15% compared to the same case study. The flow diagram of the experimental test bench is shown in Fig.12.

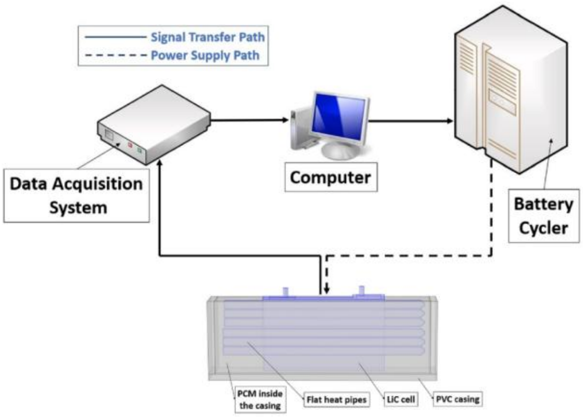

Figure 12. The flow diagram of the experimental test bench [44]

A hybrid system that the combining phase change materials with forced-air cooling was proposed for analysis by both numerical and experimental methods. The schematic of experiment is shown Fig.13.

A R134a-based circulating-cooling BTMS with frequency conversion control was implemented to investigate its thermal management performance. The flow rate of the refrigerant is changeable by adjusting the frequency of the refrigerant circulation pump. The cooling system with finned-tubes was specially designed for a 18,650-type lithium-ion battery module. The thermal behavior of the battery module, cycling under various conditions, were carefully tested and analyzed [46]. Geometric dimensions and positions of thermocouples, together with the structure of the battery module are shown in Fig. 14. In the future, the hybrid cooling system will be widely used for BTMSs of EV manufacturers in the world.

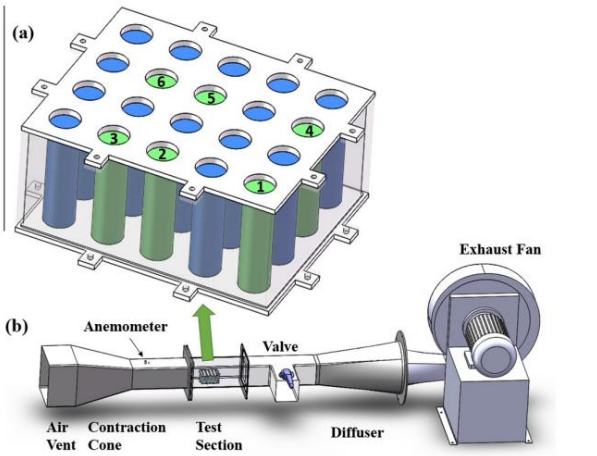

Figure 13. Schematic of experiment [45], (a) A 5S4P battery pack, temperature of six cells (marked in green) was measured through K-type thermo-couples; (b) structure of the air channel.

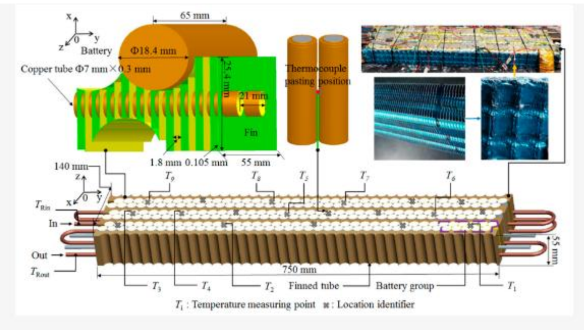

Figure 14. Schematic of the battery module [46].

III. Conclusion

Some cooling systems applied to electric vehicle batteries include Air Cooling (AC), Liquid Cooling (LC), Refrigerant Direct Cooling (RDC), Cooling System using Phase Change Material (PCM), Thermoelectric Cooling (TC), Heat Pipe Cooling (HPC), Hybrid Cooling (HC) were synthesized and analyzed based on the research results of the references. The analysis results have shown the advantages and disadvantages of battery cooling systems for electric vehicles. In addition, the study results could provide researchers with ideas in the field of battery cooling for electric vehicle.

Acknowledgment

This research was supported financially by Thai Nguyen University of Technology, TNUT, Viet Nam.

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Nguyen Tien Han received the Ph.D degree in Internal Combustion Engine Engineering from Hanoi University of Science and Technology, Ha Noi, Vietnam. He is currently a high-quality lecturer at the Ha Noi University of Industry, Viet Nam. His current research interests include Energy Engineering, New Energy and Dynamics of Systems.

Nguyen Thi Hong Ngoc received bachelor's degree in Hanoi University of Industry, Viet Nam in 2019. Now she is a teaching assistant at the Department of Automotive Engineering, Faculty of Vehicle and Energy Engineering, Thai Nguyen University of Technology, Viet Nam. Her current research interests include Electric vehicle technology, Electric vehicle battery, Optimal design and control.

Nguyen Dinh Tan received his Ph.D. degree in Hanoi University of Science and Technology, Viet Nam in 2018. Now he is a lecturer in Faculty of Mechanical Engineering, East Asia University of Technology, Bac Ninh, Vietnam. His current research interests include Manufacturing technology, Lubricating and cooling, Vehicle dynamics, Optimal design and control

Tran Duc Hoang received bachelor's degree in Thai Nguyen University of Technology, Viet Nam in 2011. Now he is a teaching assistant at the Department of Automotive Engineering, Faculty of Vehicle and Energy Engineering, Thai Nguyen University of Technology, Viet Nam. His current research interests include Vehicle dynamics, Vehicle vibration and noise, Optimal design and control.

Nguyen Thanh Cong received MSc. degree in Mechanical Engineering from Thai Nguyen University of Technology, Thai Nguyen, Viet Nam. He is currently a lecturer at Department of Heat and Refrigeration Engineering, Faculty of Vehicle and Energy Engineering, Thai Nguyen University of Technology, Viet Nam, Viet Nam. His current research interests include Vibration and noise, Heat and heat transfer in engineering.

Le Van Quynh received his Ph.D. degree in School of Mechanical Engineering, Southeast University, China in 2013. Now he is an Associate Professor at the Department of Automotive Engineering, Faculty of Automotive and Power Machinery Engineering, Thai Nguyen University of Technology, Viet Nam. His current research interests include Vehicle dynamics, Vehicle vibration and noise, Optimal design and control.