Research Progress of Nanofluid Heat Pipes in Automotive Lithium-ion Battery Heat Management Technology

Xinyu Wang,* Yanan Zhao, Yezhu Jin

School of Mechanical Engineering, North China University of Water Resources and Electric Power, Zhengzhou, Henan 450045, China

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Power batteries are a crucial component of electric vehicles and other electric equipment. Their long-term high-rate discharge generates a lot of heat, which can lead to battery failure, shortened battery life, and even safety accidents if not managed properly. Due to its high thermal conductivity, the heat pipe can quickly conduct heat away from the battery and separate the heat source from the heat sink. In addition, due to its excellent isothermal performance, the heat pipe can also achieve the characteristics of low-temperature preheating and high-temperature cooling of the power battery by reducing the inhomogeneity of the battery temperature field to reduce the temperature difference. In this paper, we review the current state of the art in thermal management of automotive lithium-ion battery, and highlight the current state of thermal management of batteries based on the combination of nanofluids and heat pipes. Finally, the development of nanofluidic heat pipes in lithium-ion battery heat management systems is prospected.

Key Words: Battery heat management; Heat pipe; Nanofluid heat pipe; Lithium-ion battery

Introduction

As one of the pillars of development, energy plays a decisive role in social and economic development. But with the overuse of traditional fossil energy, global warming, and frequent haze, people pay more and more attention to environmental problems in recent years. Countries have recognized the need for energy transition, and electric vehicles have become a strategic choice [1]. Because of its high energy density and long service life, the lithium-ion battery has become the mainstream of electric vehicle power cells and has a great development prospect in the automotive industry [2]. With the development of lithium-ion battery technology and the support of national policies, the sales of electric vehicles are increasing, so the demand for lithium-ion batteries is also increasing [3]. According to the 2022 Green Battery Annual Conference and the 1,000 people conference on lithium-ion new energy in China, global power lithium-ion battery shipments will be 685.3GWh in 2022. It is expected to reach about 1.7 TWh in 2025, this is 1.5 times more than in 2022 (Figure 1).

*Corresponding author: 1278792329@qq.com

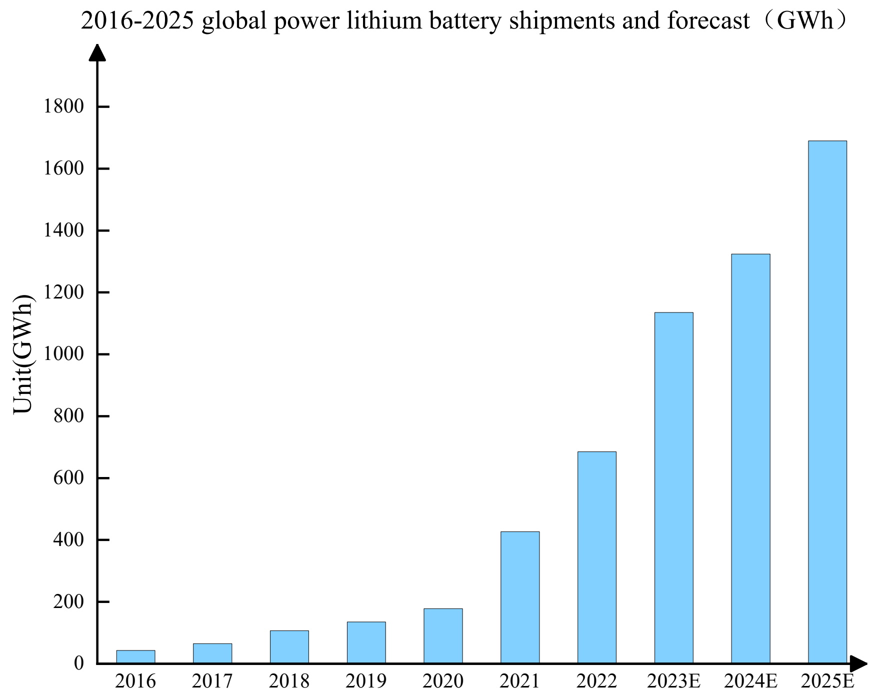


Figure 1. Global shipments of lithium batteries

However, behind the high sales volume is also hidden a huge security risk. In recent years, with the gradual maturity of lithium-ion battery technology, the increasing energy density of lithium-ion batteries and the increasing number of batteries used, electric vehicles have experienced frequent spontaneous combustion accidents [4]. According to statistics, in the first quarter of 2022 alone, there were 640 spontaneous combustion accidents of electric vehicles, an increase of 31% year-on-year, including many well-known brands such as Jády, Tesla, and Xiaopeng. Some safety incidents are shown in Table 1. Most of these spontaneous combustion accidents are caused by the overheating of the battery pack and the out-of-control heating of the battery, which leads to the rupture of the battery case. These accidents seriously threaten the safety of drivers and passengers and draw people's attention to the safety of lithium batteries.

Table 1. Statistics on domestic electric vehicle spontaneous combustion accidents in the first half of 2022

Date of accident	Brand	Type of battery	Event
7.22	Tesla	Ternary lithium battery	The car caught fire after the crash
7.14	Weimar	Ternary lithium battery	Fire during charging
7.5	Roc	Ternary lithium battery	The car caught fire after the crash
7.3	Roewe	Ternary lithium battery	A fire broke out while driving
6.14	Byd	Lithium iron phosphate battery	Stationary parking (caused by car owner modification)
6.6	Byd	Lithium iron phosphate battery	A fire broke out while driving

The lithium-ion battery is mainly composed of five parts: positive pole, negative pole, electrolyte, diaphragm, and shell [5] (as shown in Figure 2). At the same time, the heat generation of lithium batteries mainly comes from the electrochemical reaction heat during charging and the ohmic internal resistance joule heat during discharge [6]. According to research, the temperature of lithium-ion batteries has a great impact on their life. At 20~40 ℃, the battery life will be shortened by 60 days for each degree of temperature increase [7]. When the temperature is too high, the solid electrolyte facial mask (SEI film) in the lithium-ion battery will accelerate the decomposition and generate gas in the battery, thus causing the battery to break or even fire [8]. If the lithium battery catches fire, it will not only damage the car but also cause unnecessary casualties. Therefore, the selection of an appropriate thermal management system and the research on lithium-ion battery cooling systems are of great significance in improving the performance and economy of electric vehicles [9].

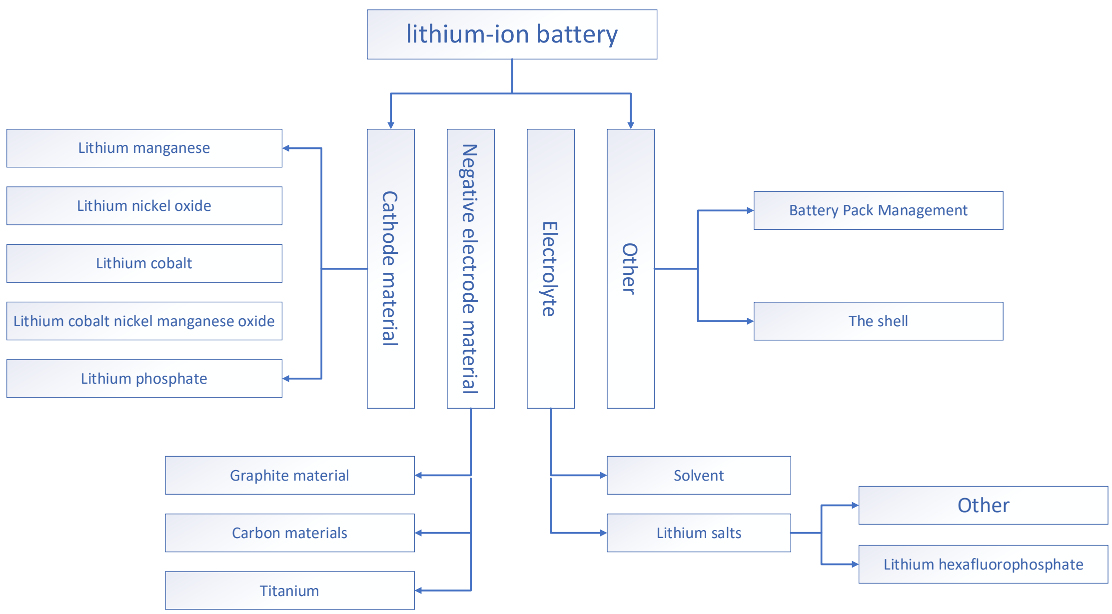


Figure 2. Structure diagram of lithium battery.

Common Battery Cooling Technology

There are five common battery cooling technologies: air cooling, liquid cooling, refrigerant direct cooling, phase change material cooling, and heat pipe cooling [10]. Among them, the cooling mode of air, liquid, and refrigerant is active cooling, and the phase change materials and heat pipes are passive cooling (as shown in Figure 3). This article will describe four methods of cooling: air cooling, liquid cooling, phase change material cooling, and heat pipe cooling, with emphasis on the research status of nanofluid heat pipe cooling technology in lithium ion vehicle batteries.

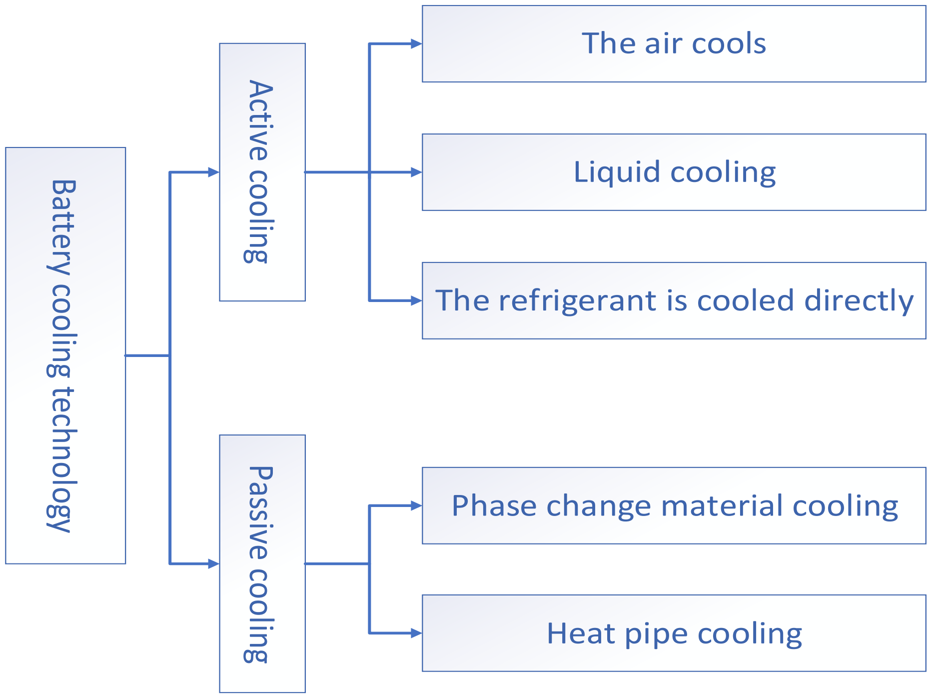


Figure 3. Classification of battery cooling technology.

Air Cooling

Air cooling includes natural convection and forced convection. Natural convection is to use the natural flow of external air to make the airflow through each surface of the battery, thus achieving the cooling effect. Forced convection generally uses fans to extract external air and control wind speed to achieve the effect of battery cooling. Compared with natural air convection, forced convection is more controllable for battery cooling. Because air cooling has the characteristics of low cost, easy maintenance, small use space and simple design, air cooling has always been a common cooling method in battery thermal management systems.

There are two ways to dissipate heat in the air duct: series and parallel [11] (as shown in Figure 4). It is easy to know from Figure 4 (a) that the heat dissipation of the series air duct will lead to the phenomenon of low inlet temperature and high outlet temperature, and the whole temperature field is uneven. Compared with the series air duct, the airflow of each part is the same, and the temperature distribution is relatively uniform. For example, Honda Insight and Toyota RAV-4 adopt the parallel air duct design.

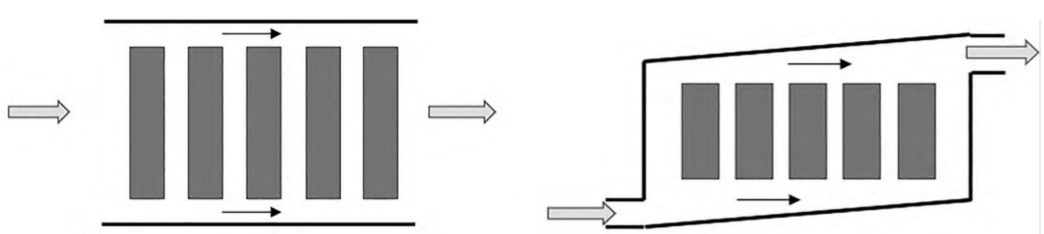


Figure 4. a) Series air duct b) Parallel air duct

The key to the quality of air cooling technology is the size of the air inlet and the quality of the air channel. Therefore, the improvement and optimization of air ducts and the arrangement of batteries are the main research directions of air cooling. However, in essence, although air cooling has a simple structure and saves space, it has a low thermal conductivity and absorbs less heat than the same volume of liquid. Therefore, air cooling is currently mainly used for the cooling requirements of low-power and small-volume battery packs. With the continuous development of lithium-ion batteries, air cooling is gradually difficult to meet the required technical requirements [12].

Liquid Cooling

The heat transfer coefficient of liquid is greater than that of gas. Under high load, the cooling effect of liquid is better than that of gas. When liquid cooling is used at the same time, the volume is smaller and the space is saved [13]. There are two types of liquid cooling: direct cooling and indirect cooling [14]. Direct cooling is to directly contact the coolant with the object to be cooled, or even completely soak the object to achieve the purpose of cooling. The advantage of direct cooling is that it can maintain the constant temperature of the object to be cooled, and the overall temperature difference is small. The disadvantage is that it has high requirements for the type of cooling liquid. The more commonly used cooling liquid is mineral oil and glycol. Indirect cooling is generally achieved by winding an infusion pipe with coolant inside the object to be cooled, or by using a cooling plate without direct contact with the object. Indirect cooling has fewer restrictions on the type of coolant, but it needs a series of supporting equipment, which is not conducive to the lightweight design of vehicles [15].

Due to the risk of liquid leakage from direct cooling and the high requirements for cooling medium insulation. Currently, the indirect cooling method is mostly used, as shown in Figure 5, the bottom plate cooling system is the mainstream of current liquid cooling research. In the research of liquid plate cooling, Jiaqiang *et at.* [16] designed a rectangular channel coolant plate, and the study showed that the average temperature of the power cell was the lowest when the width of the rectangular channel was 45 mm, the height was 5 mm, the number of channels was 4, and the coolant flow rate was 0.07 m/s. Among these four influencing parameters, the number of channels has the greatest effect on the cell temperature, and the size of the rectangular channels has the least effect on the cell temperature. In addition, the heat transfer performance of the coolant, *i.e.,* the thermal conductivity of the coolant, is also an important factor affecting the cooling effect. Maxwell [17] was the first to propose increasing the percentage of solid particles in the liquid to enhance the thermal conductivity of the coolant. However, solid particles tended to accumulate in coolants with low flow rates and cause blockages. Therefore, the use of smaller particles (*i.e.*, nanoparticles) may improve this problem. For example, Deng *et al.* [18] added nanoparticles to water, which led to improved cooling. Eastman *et al.* [19] added Cu nanoparticles with a volume fraction of 0.3% to a glycol solution, and the resulting nanofluid thermal conductivity was improved by 40%. According to the experimental data, the cooling effect of the coolant is better than that of water using nanofluids at low flow rates. At fast flow rates, water cooling is better than nanofluid.

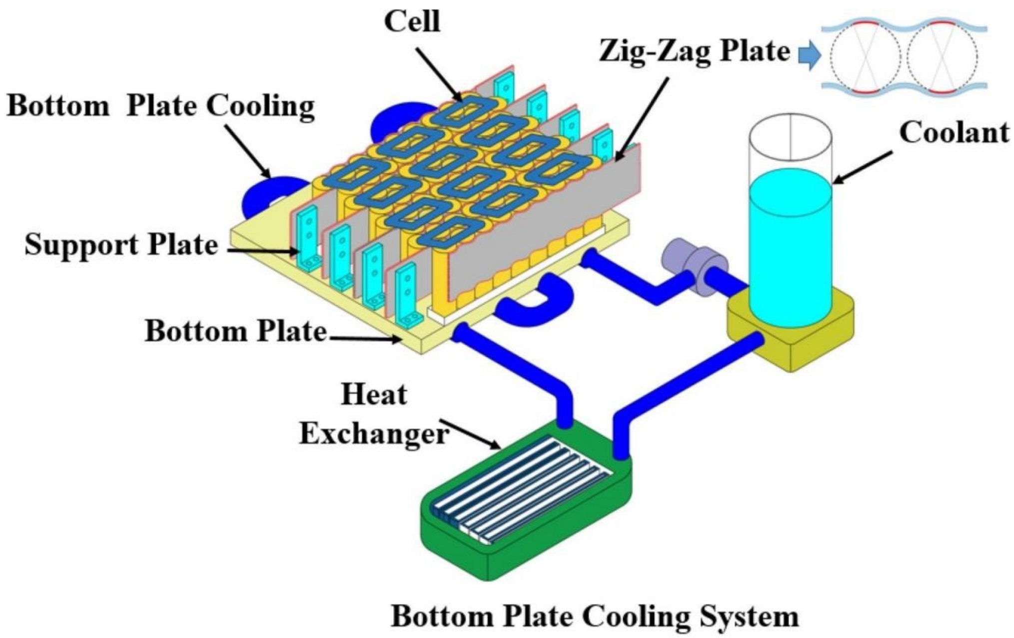


Figure 5. Bottom plate liquid cooling system [20].

Phase Change Material Cooling

With the change of temperature, the material whose state also changes is called phase change materials (PCM). Phase-change materials can absorb or release a large amount of heat under a small temperature change. Therefore, the cooling technology of phase-change materials absorbs the heat generated by battery charging and discharging during phase change through this characteristic of phase-change materials [21]. Phase change materials can be divided into solid-solid, solid-liquid, solid-gas and liquid-gas phase change materials according to the form and process of phase change, and can be divided into organic phase change materials and inorganic phase change materials according to the composition of the materials. Phase change materials, which are clean, pollution-free and heat storage capacity, are widely used in construction, clothing, refrigeration, aerospace, military, communications, power and other industries. In the cooling of lithium-ion batteries, paraffin is a phase change material that has been studied extensively. Schematic diagram of phase change material cooling in the battery is shown in Figure 6.

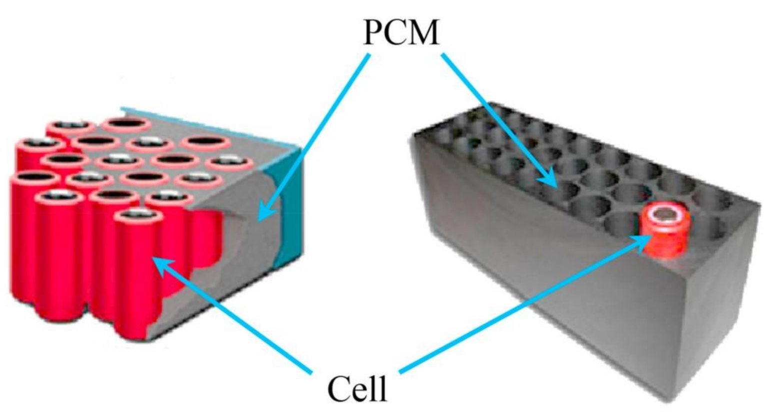


Figure 6. Phase-change material cooling system [22].

According to the research, under the condition of high temperatures and high discharge rates, the use of phase change material cooling is better than the use of air cooling. At the same time, phase change material cooling does not need a fan, which reduces the power compared with air cooling. Zou *et al*. [23] have prepared multi-walled carbon nanotubes (MWCNT), graphene-based, and MWCNT/graphene-based composite phase change materials (PCM) and carried out experimental studies. The results showed that the thermal conductivity of PCM was increased by 31.8%, 55.4%, and 124%, respectively, Compared with that of graphene-based PCM, MWCNT-based PCM, and pure PCM. The composite PCM shows great potential in thermal management of li-ion power batteries. Due to the low thermal conductivity of paraffin, Jiang *et al*. [24] combined graphene with paraffin to make graphene-paraffin composite phase change material (CPCM). The results showed that the composite material of graphene and paraffin can significantly reduce the temperature rise of lithium-ion batteries, and has an excellent performance in controlling the temperature uniformity of the battery pack. In addition, there are also studies on the structure of PCM, phase change materials, and other materials. Weng *et al*. [25] studied the thickness of phase change cooling and found that when the thickness of the PCM module is 10 mm, the cooling effect is the best. Choudhai *et al*. [26] combined phase change materials with fins, which reduced the battery temperature by 9.28%.

Phase change material cooling has simple structure, easy to manufacture and low cost, but there are a series of technical problems. Phase change material cooling belongs to passive cooling. When working in a long time and high temperature environment, timely heat dissipation is required, otherwise there is a risk of complete melting, leading to failure of the cooling system. At the same time, PCM melting will lead to volume increase and risk of leakage. In the research of phase change materials, the practicability of single phase change material is not high. It is necessary to focus on the research of composite phase change materials to obtain a safer and more effective phase change cooling system.

Heat Pipe Cooling

The heat pipe is efficient heat transfer equipment, developed by NASA in the early 1960s, used for heat pipe cooling systems in spacecraft. It is heat transfer equipment that can efficiently transfer heat under high-temperature and low-temperature environments. It has the advantages of fast heat transfer speed, high heat transfer efficiency and small thermal resistance, and is widely used in various heat management fields.

Heat pipe (HP) is a kind of passive cooling equipment. In most cases, it does not need to consume any external energy [27]. As shown in the cross-section of the conventional heat pipe in Figure 7, the heat pipe is composed of three parts: evaporation section, thermal insulation section, and condensation section. The working medium is usually liquid, forming a two-phase flow state of steam and liquid in the pipe. According to the thermodynamic principle, when a heat source heats one end of a heat pipe, the working medium inside the pipe vaporizes, carrying the absorbed heat to the other end, where it condenses into liquid, transferring the heat to the surrounding environment.

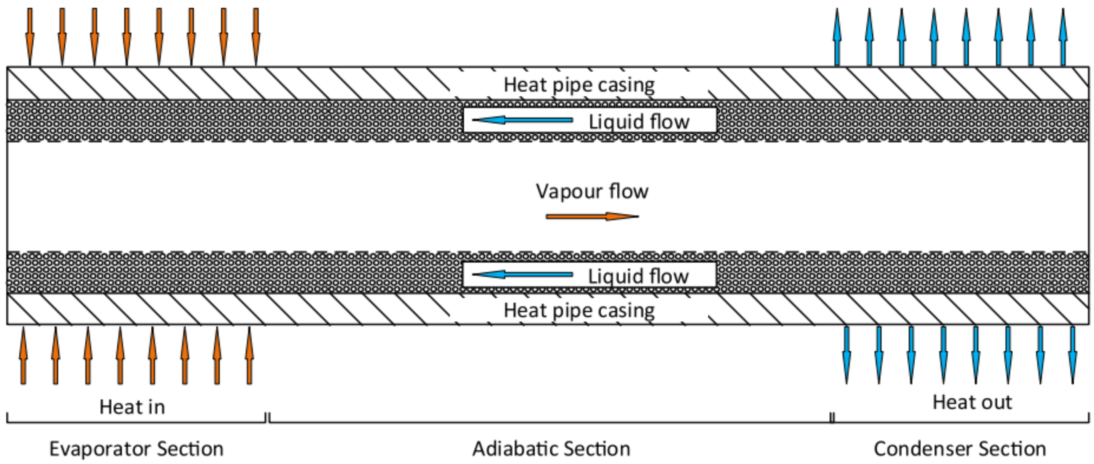


Figure. 7. Cross-section of a conventional heat pipe[28].

The heat pipe has been widely used in aerospace, electronics, machinery, and other fields due to its simple structure, reliable operation, and high heat transfer efficiency. For example, in spacecraft, a heat pipe can effectively control the temperature of spacecraft and prevent electronic components from overheating, thus improving the reliability and life of spacecraft. In electronic equipment, a heat pipe can effectively dissipate heat and protect electronic components from high temperature, thus improving the performance and life of electronic equipment. It has broad application prospects and huge development potential. For example, Mbulu *et al.* [29] developed a battery thermal management system (BTMS) based on heat pipes, as shown in Figure 8. The system uses L-shaped and I-shaped heat pipes instead of traditional battery clamps. The evaporator part absorbs heat from the aluminum plate surface, while the condenser part transfers heat to the copper bracket. With water as the cooling medium, the heat pipe is tested at 30, 40, 50, and 60W input power, and the condenser is cooled with 0.0167, 0.0333, and 0.05kg/s mass flow. The results show that the designed BTMS based on heat pipe can keep the maximum temperature (T_{max}) below 55℃ and the temperature difference at both ends of the battery even at the maximum input power(Δ T) Keep below 5℃.

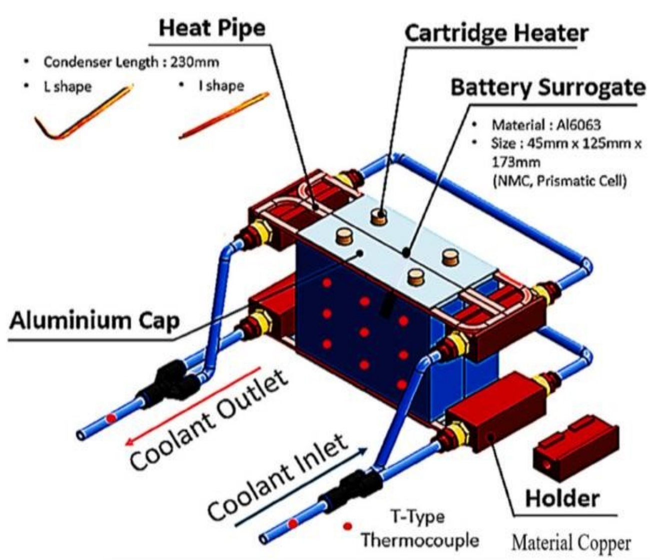


Figure 8. Battery BTMS based on L-shaped/I-shaped heat pipe [40].

Zhang and Wei [30] studied a heat pipe cooling system for square cells, which uses flat heat pipes to cool the battery pack. The results are shown in Figure 9. Compared with natural convection cooling and aluminum plate cooling, the maximum temperature difference is reduced by 73.7% and 50.1%, respectively. The use of a flat heat pipe can effectively reduce the maximum temperature and temperature difference of the battery while reducing energy consumption.

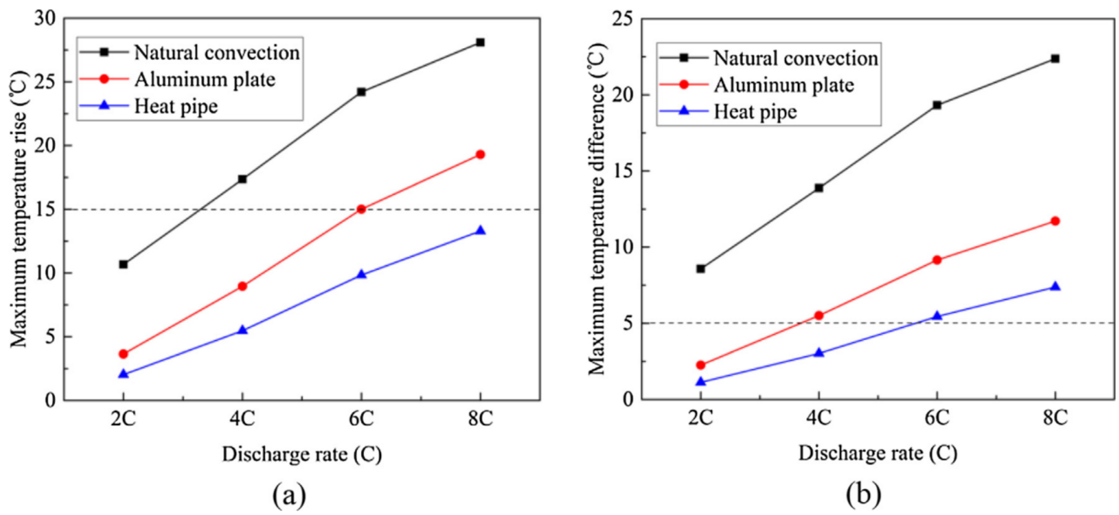


Figure 9. The maximum temperature rise and difference of the battery pack using different heat dissipation methods: (a) max temperature rise and (b) max temperature difference [30].

Battery Thermal Management System Based on Nano-fluid Heat Pipe

Nanofluid is a mixture of nanoparticles, molecules, and liquids with special physical and chemical properties [31]. As shown in Figure 10, nanofluids are widely used in various fields, such as biomedicine, material science, environmental science, energy engineering, etc. [32]. Compared with traditional fluids, nanofluids have a larger specific surface area and higher surface activity because their particle size is at the nanometer level. These characteristics make nanofluids show different properties from traditional fluids in terms of heat conduction, friction resistance, viscosity, etc. In addition, nanofluids also have good thermal stability and chemical stability, enabling them to operate stably under high temperatures, high pressure, and chemical corrosion environment. At the same time, nanofluids show outstanding characteristics in improving boiling heat transfer performance. Therefore, the method of applying nanofluids to heat pipes to improve the heat transfer efficiency of heat pipes came into being.

Baheta *et al.* [33] studied the effect of copper nanofluid with an average particle size of 20 nm and particle concentration of 0-4% on the heat transfer performance of cylindrical heat pipes. The results show that the thermal resistance of the heat pipe is reduced by 17.5% and the performance of the heat pipe is improved when the concentration of water-based copper nanofluid is 4% and the heat input is 100W. Reji *et al.* [34] used deionized water and aluminum (Al) nanofluids as heat transfer media in the heat pipe and conducted research in the range of heat input values from 40W to 200W. The results are shown in Figure 11. Compared with deionized water, the performance of siphon heat pipe using Al nanofluid is improved by 41%, and the maximum efficiency can reach 88% when the dip angle of the heat pipe is 60°.

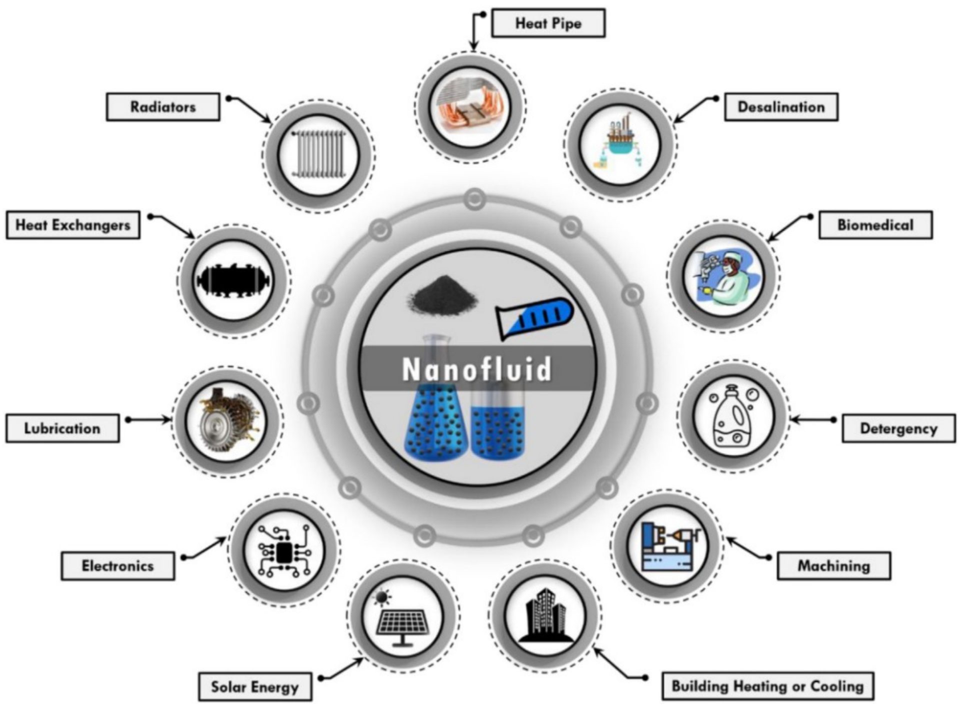


Figure 10. Nanofluid applications in different areas [32].

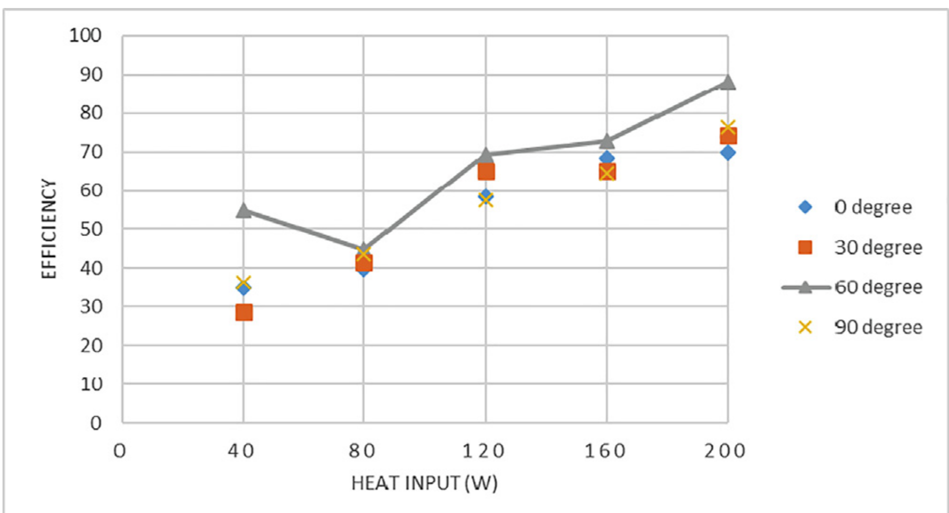


Figure 11. Effificiency of Heat Pipe with Nano Fluid [34].

Riehl *et al.* [35] studied and analyzed the loop heat pipe (LHP) using nickel oxide (NiO)-water (H_2O) nanofluid and the pulsating heat pipe using copper oxide (CuO)-water (H_2O) nanofluid, and compared the performance of the two with that of the loop heat pipe and pulsating heat pipe using deionized water. The results showed that LHP and OHP using nanofluid have higher heat transfer performance than the base fluid, The performance has been improved to different degrees. Zhang *et al.* [36] used the experimental device as shown in Figure 12 to carry out visualization experiments on SiO_2-H_2O nanofluid pulsating heat pipes with concentrations of 0.5 wt%, 1.0 wt%, 1.5 wt%, and 2.0 wt%, respectively using high-speed cameras. The results show that the addition of nanoparticles increases the instantaneous driving force of the working fluid, promotes the phase change of the working fluid of the pulsating heat pipe, is conducive to the reflux of the condensate, and improves the performance of the heat pipe. When the heating power is 50W and the concentration is 1.0 wt%, the maximum heat transfer efficiency of the heat pipe can be increased by 40.1%.

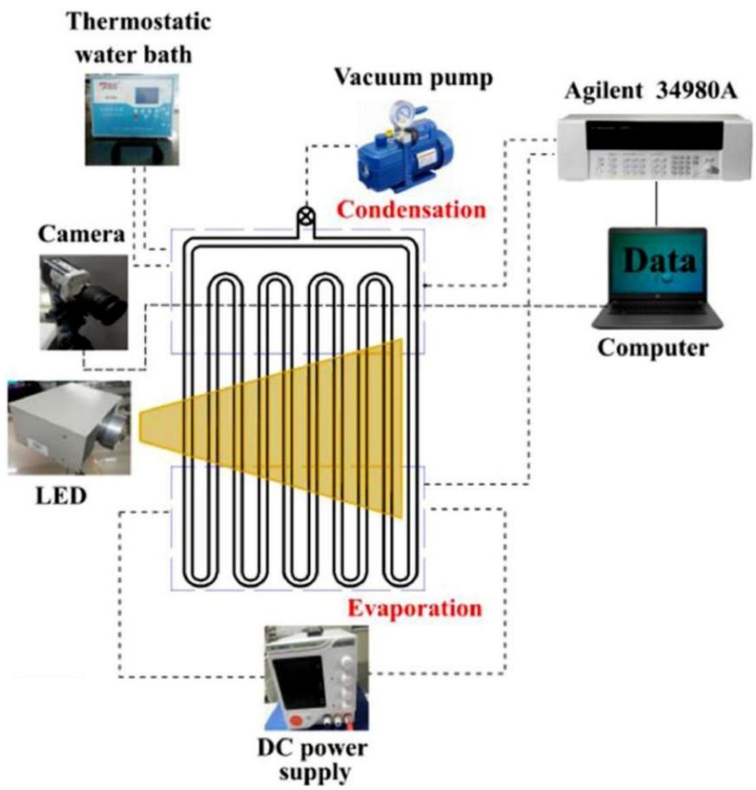


Figure. 12. Schematics of experimental apparatus[36].

To sum up, as a new type of working medium, nanofluid can greatly improve the heat transfer efficiency of heat pipe by selecting the appropriate nanofluid combined with heat pipe. The nanofluid heat pipe combines the advantages of the two and has a broader application prospect in the field of heat transfer. For example, it is of great significance to apply the nanofluid heat pipe to the thermal cooling of batteries [37].

Nasir *et al.* [38] conducted an experimental and numerical study on the application of alumina (Al_2O_3) nanofluid heat pipes in a lithium-ion battery thermal management system (HPTMS). The results showed that the battery temperature was reduced by 7.28°C (1.5%), when using 4.44 vol% alumina nanofluid heat pipe at a thermal load of 30 W, as shown in Figure 13a. In addition, at 30 W, 1.5 vol% alumina nanofluid was able to reduce the thermal resistance of the heat pipe from 0.4677 °C/W to 0.394 °C/W (15% reduction), as shown in Figure 13b.

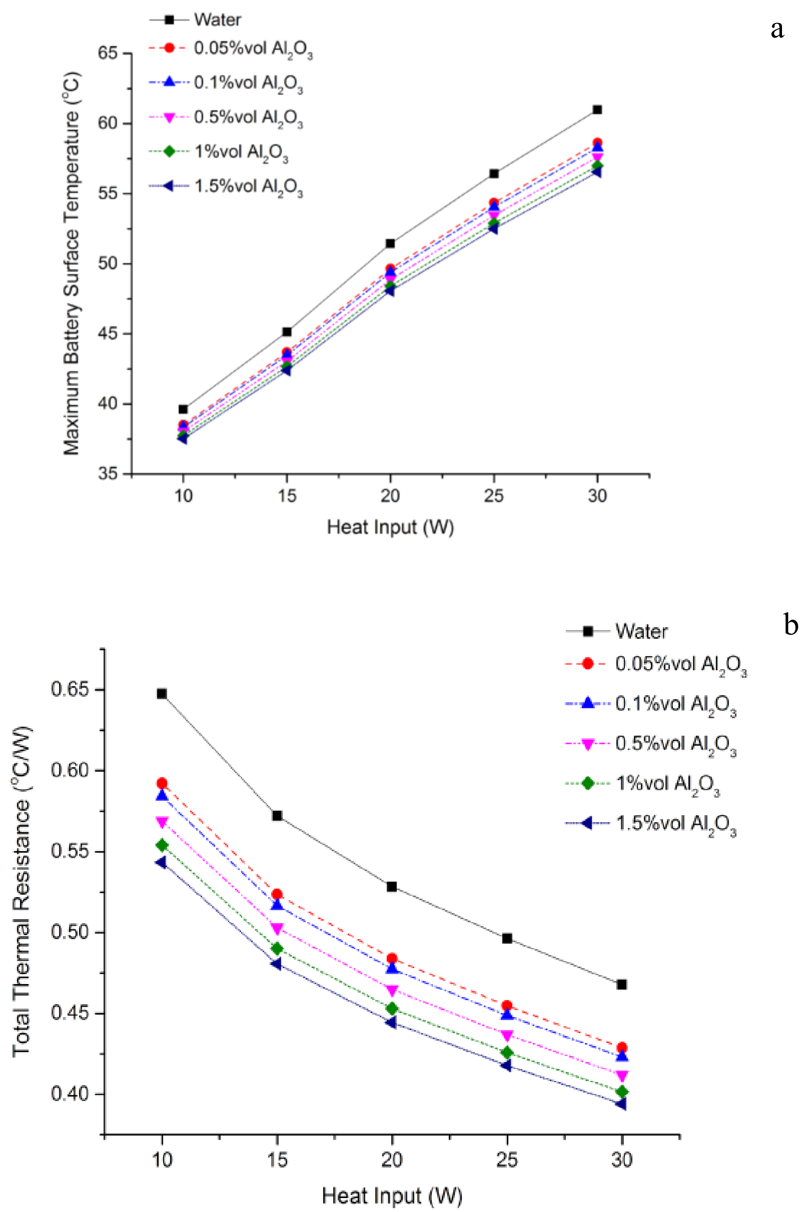


Figure 13. a) Maximum battery surface temperature at different heat inputs, b) Thermal resistance of HPTMS at different heat inputs [38]

Zhou *et al.* [39] proposed a mixed cooling system, which is an oscillating heat pipe (OHP) composed of a copper plate evaporator with six parallel circular channels and a capillary copper tube condenser. They used the ethanol solution of carbon nanotubes (CNTs) as the working fluid of the oscillating heat pipe, with the mass concentration ranging from 0.05 wt% to 0.5 wt%. The experimental results show that the cooling system with a concentration of 0.2 wt% maintains a thermal resistance of 0.066 °C/W and an average evaporator temperature of 43.1°C. Figure 14 shows the average temperature change of the power input analog battery pack from 8 to 56 W under different CNT concentrations. Obviously, the use of carbon nanotube nanofluids has greatly reduced the average temperature of the battery pack.

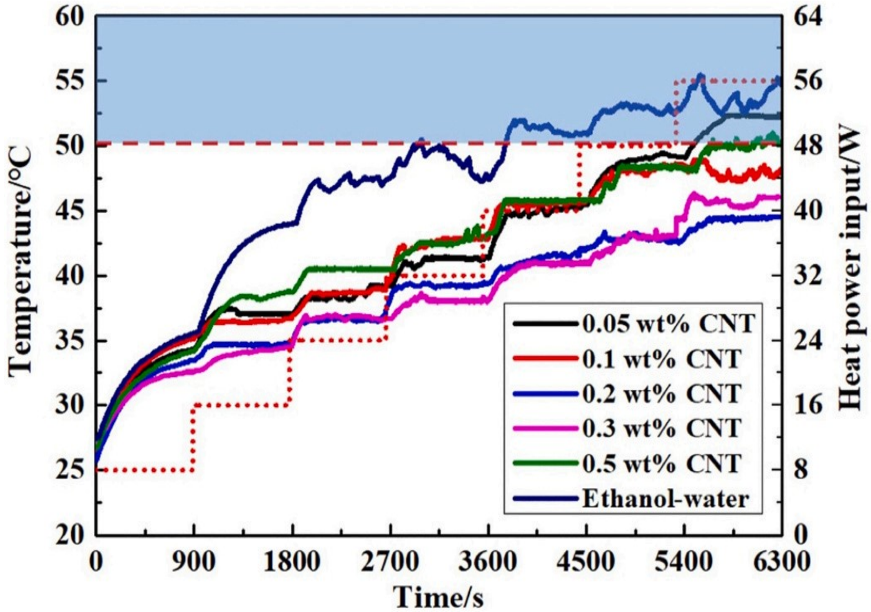
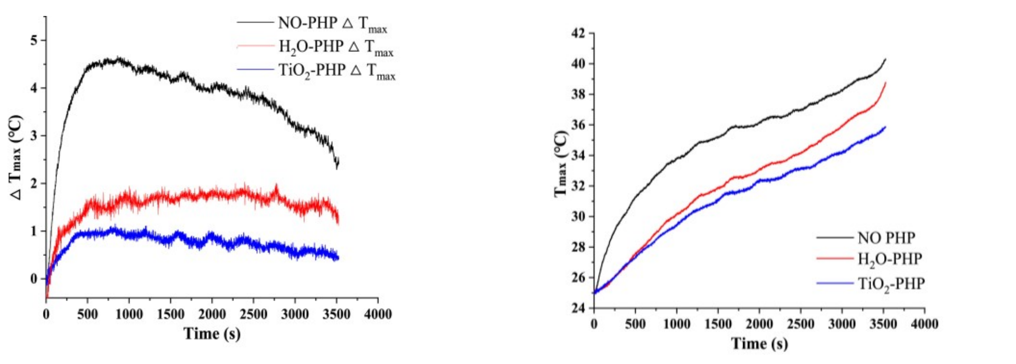


Figure 14. Average temperature variation for hybrid cooling system with at different mass concentrations [39].

Chen *et al.* [40] applied TiO_2 nanofluid as the working fluid in the thermal management system of lithium-ion batteries in vehicles with pulsating heat pipe (PHP) and compared three thermal management modes (no PHP, H_2O-PHP, and TiO_2 PHP) at 25℃ ambient temperature and 1C. The results are shown in Figure 15. When there is no PHP, H_2O-PHP, and TiO_2-PHP are used, the maximum temperature T_{max} of the battery surface is 40.31℃, 38.78℃, and 35.86 ℃ respectively. During continuous discharge, the maximum temperature gradient ΔTmax is 4.67℃, 2.03 ℃ and 1.15℃, respectively. Therefore, the pulse heat pipe battery thermal management system using TiO_2 nanofluid can effectively reduce the temperature of the battery pack and improve the uniformity of the surface temperature.



(a) Variation curve of maximum temperature difference ΔT_{max} over time. (b) Variation curve of the maximum temperature of the battery T_{max} over time

Figure 15. Variation curves of battery temperature over time under diffferent modes of heat dissipation [40]

Patel *et al.* [41] applied the hybrid nanofluid loop heat pipe (LHP) of 5% alumina (Al_2O_3)-water (H_2O) nanofluid and 1% titanium dioxide (TiO_2) in the battery thermal management system. The results show that compared with the other two working fluids, the loop heat pipe mixed with nanofluids has better thermal management performance, and can reduce the heat of the battery simulator to 47 °C under the operating limit of the lithium-ion battery. As shown in Figure 16, when heating at 40 W, compared with nanofluid and base fluid, the mixed nanofluid can provide a temperature drop of about 15.8 °C, and the performance of the heat pipe is improved by 12%.

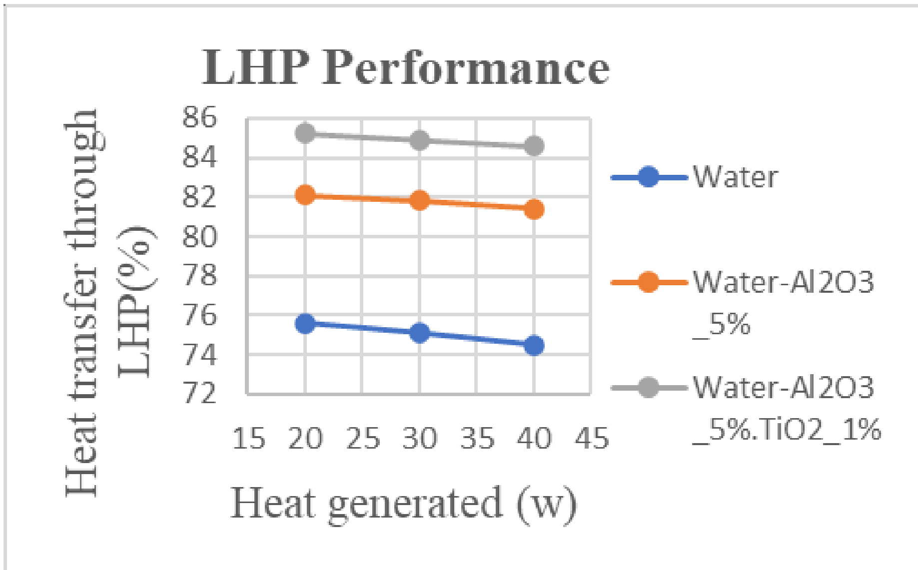


Figure 16. Loop heat pipe performance [41]

Smaisim *et al.* [42] applied the nanofluid loop heat pipe with the working fluid of graphene oxide (GO)-water to the thermal management system of lithium-ion batteries in automobiles, and carried out experimental research and simulation analysis. The results show that the maximum temperature is 49°C, 52°C, 52°C and 52.5°C at the filling ratio of 20%, 35%, 50% and 65%, which is basically consistent with the experimental results of 52.5°C, 52°C, 49.8°C and 46°C, effectively reducing the temperature of the battery pack.

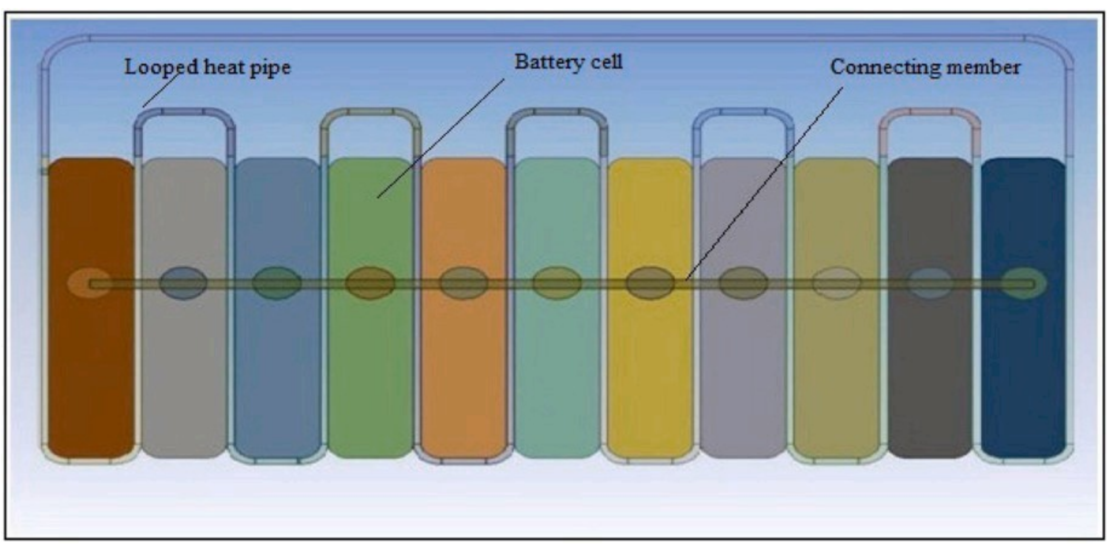


Figure. 17. Arrangement of Li-ion battery cells with heat pipe[42].

Figure 18 shows the line diagram of the micro-heat pipe with the experimental device. Narayanasamy *et al.* [43] applied the annular micro-heat pipe with acetone, deionized water, and graphene oxide nanofluid as the working fluid to the lithium-ion battery thermal management system. Their research results show that compared with acetone and deionized water, the thermal conductivity of tetrahydrofuran-graphene nanofluid is increased by 61%, thus speeding up the heat transfer rate and reducing the thermal resistance range by 0.09-0.64 °C/W.

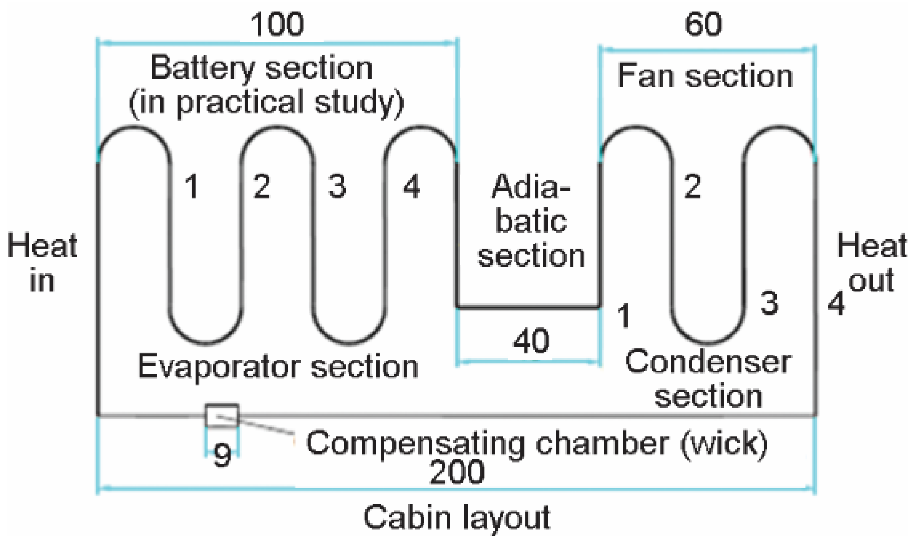


Figure 18. Line diagram of micro-heat pipe [43].

CONCLUSIONS

This paper reviews the research on the application of nanofluid heat pipe in lithium battery thermal management system in recent years, and it is known through the literature that using nanofluid as the workpiece of heat pipe can improve the thermal efficiency, reduce the thermal resistance and improve the heat transfer performance of heat pipe. The application of nanofluid heat pipe in the battery thermal management system can largely improve the uniformity of battery temperature distribution and effectively control the maximum temperature of the battery, which has great application prospects.

According to the literature, the following suggestions are put forward for the future research on the thermal management system of nanofluid heat pipe batteries:

1. Because the working principle and structure of nanofluid heat pipe are similar to that of the heat pipe, and it is easy to use with other cooling methods, domestic and foreign scholars should strengthen the research on the coupling of nanofluid heat pipe with air cooling, liquid cooling, and other battery thermal management technologies.
2. Domestic and foreign scholars mainly focus on the heat transfer performance of nanofluid heat pipe battery heat management technology using nanofluid heat pipe, but little on the time-dependent characteristics of nanofluid heat pipe battery heat pipe systems. Therefore, it is necessary to conduct in-depth research on the service life of nanofluid heat pipes in the battery heat management system and the stability of nanofluid.

3. Compared with the battery thermal management system using a single nanofluid heat pipe, the hybrid nanofluid loop heat pipe (LHP) battery thermal management system studied by Patel *et al.* [41] in the literature shows that the hybrid nanofluid heat pipe battery thermal management system performs better than the single nanofluid heat pipe battery thermal management system. Therefore, the battery thermal management system of hybrid nanofluid heat pipe will be an important research direction for future scholars.

CONFLICTS OF INTEREST

The authors declare that there is no conflict of interests regarding the publication of this paper.

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