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Review on Various Techniques of Battery Thermal Management using Heat Pipe

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Key words: Heat pipe, lithium-based batteries, air cooling, liquid cooling, PCM

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Abstract: The present study is an attempt to take an overview of the work done in thermal management of lithium-based batteries using heat pipe assisted air cooling, liquid cooling and PCM (Phase Change Material) based cooling. Heat pipe is an effective heat exchanger device to transfer the heat effectively and has proven its ability in many power electronics devices. Many researchers have done analysis using heat pipe for cooling of the lithium-based batteries both experimentally and numerically for electric vehicle application. In this study, various arrangements of heat pipes with lithium-based batteries are considered with different cooling methods and have discussed its effect on temperature distribution of the battery. Study shows that heat pipe assisted battery cooling is a viable option over battery heating problems.

INTRODUCTION

Electric vehicles are one of the best options to move towards zero-emission road transport system compared to conventional fossil fuel consuming vehicle technology. Lithium-based batteries are widely used in battery electric vehicles because of their high specific energy, specific power, energy density and no maintenance. It is also important to maintain the battery temperature within limits for better cycle-life, energy storage capacity and performance as lithium-based batteries are highly susceptible to thermal runaway at high temperatures. Elevated temperature can ignite extremely flammable electrolytes which may result in explosion, fire, loss of capacity and short circuits of lithium batteries. Hence Battery Thermal Management System (BTMS) is very important for lithium-based batteries. Battery thermal management is done by various cooling methods such as natural or forced air cooling, Liquid cooling and PCM based cooling. Mostly, in electric vehicles liquid cooling is used where in mopeds air cooling is economical. Lithium-ion batteries are first commercialized by the Sony manufacturer in 1991[1]. A lot of progress has happened in lithium battery chemistry to use it in the automotive application from a performance and safety point of view. The lithium-ion battery is best suitable for Electric Vehicles because of high energy for a long-distance covering, high power for peak acceleration, high nominal voltage for high speed and compact battery pack size. But it will need Battery Management System (BMS) to control peak current and to balance cells in the battery pack while charging and discharging. EVs consume battery energy depending upon the drive cycle. Battery discharge rate depends upon speed, acceleration, road gradient, braking and driving pattern. Hence, proper battery management system and battery thermal management system is necessary.

Background: Lithium-ion batteries perform better when the temperature of the battery is between 15°C-35°C and the maximum temperature difference in an individual battery should not exceed 2°C at low load and 5°C at high load[2]. Lithium-ion battery capacity increases with temperature due to increase in its chemical reaction rates. This increase in battery capacity shows that the battery can provide more power at high temperatures[3]. Though at higher temperature lithium batteries provide high power, it hugely impacts its total cycle life. cycle life of the battery suddenly drops down after 50°C Temperature[3]. Various cooling methods researchers are employing to get optimum performance and cycle life of the battery.

Heat generation: Heat generation in the lithium-ion cell is critical for its performance and safety point of view. Lithium-ion cell has internal resistance and when cell charges or discharges, reversible and irreversible heat is generated. If the rate of heat generation goes beyond the rate of heat release then the cell undergoes in its worst condition called as thermal runaway stage. Analytically heat generation can be calculated by Bernardi's equation:

$$Q = I(E - Va) - I\left[T\left(\frac{dE}{dT}\right)\right]$$

E = open circuit voltage (V), Va = Cell Voltage (V), T= Temperature (°C), I = current (A), dE/dT = temperature coefficient (V/°C). Where, Q is the heat generated in Watt I(E-Va) is known as the Ohmic or Joule's heating and I[T(dE/dT)] is known as the reversible heat resulting from changes in open circuit voltage with respect to temperature at two electrodes. For EV application for large discharge second term can be neglected.

Heat generation increases non-linearly as battery discharges at constant current as shown in Fig. 1. By Behi *et al*.[4] battery is converted into nine multi zones to simulate the constant battery heat generation distribution close to a real battery. In actuality, as shown by the paper[5] heat generation varies with the state of charge of the battery and operating temperature of the battery.

Every cooling method has its own advantages and disadvantages. Coolant in liquid cooling has a higher specific heat capacity than air to remove excess heat generated in the battery but it has a higher setup cost and maintenance cost. Air cooling is economic and sufficient enough when the battery produces <10 W per cell. Air cooling is done either by using the vehicle's speed or using a fan to produce forced convection. In electric mopeds because of space constraints and low load air cooling method is used. Natural air cooling has a very low convective heat transfer coefficient hence forced air cooling is always preferred. With an increase in velocity heat transfer coefficient also increases.

Forced air cooling of the battery can be done in two ways, direct cooling[6] and indirect cooling[7]. Indirect cooling, air directly comes in contact with the battery surface where in Indirect air cooling, high thermal conductivity material is attached to the battery surface and an extended part of that material is cooled by air with or without fins. Air cooling is also combined with thermoelectric-cooling[8] or heat pipe[4] to improve thermal performance depending upon application.

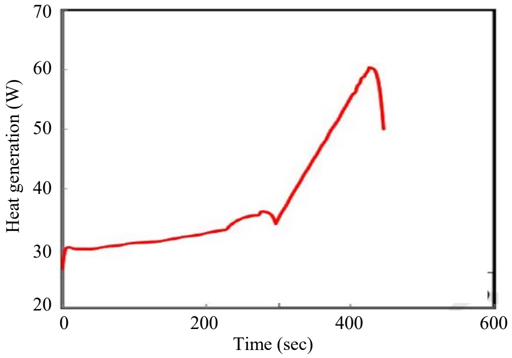

Fig. 1: The heat generation of the LTO cell in 8C discharging rate[4]

Heat pipe: Heat pipe were first invented in 1963 by Wyatt and reinvented in 1964 by George Grove for space programs for moving heat from the reactor core to a radiating system[9]. Heat pipes are being used in simple heat exchanger, space applications, oil lines, nuclear reactor and other power electronics. Researchers have been using heat pipes for battery cooling.

A heat pipe is a heat exchanger device that can operate without extra pump power and transfer large amounts of heat energy even at small temperature differences. It has properties such as flexible geometry, compact size, high durability and low maintenance. Therefore, it has been used in many industries for efficient thermal management[10] (Fig. 2).

Construction and working of heat pipe: The structure of the heat pipe consists of only a vacuum container and a working fluid. It is composed of an evaporator section, an adiabatic section and a condenser section. The evaporator section is attached to a heat source from where heat has to be extracted. The working fluid in a heat pipe evaporates by absorbing heat from the heat source even at a small temperature rise because of low vapor pressure and then moved to the condenser section through the adiabatic section due to the difference in pressure difference in the container. In the condenser section, the working fluid condenses. After that, it becomes liquid and moves back to the evaporator section by the capillary force of the wick[11]. The micro heat pipe doesn't have powder sintered wick region. It has grooves along the inner side of the heat pipe. Capillary action is produced by

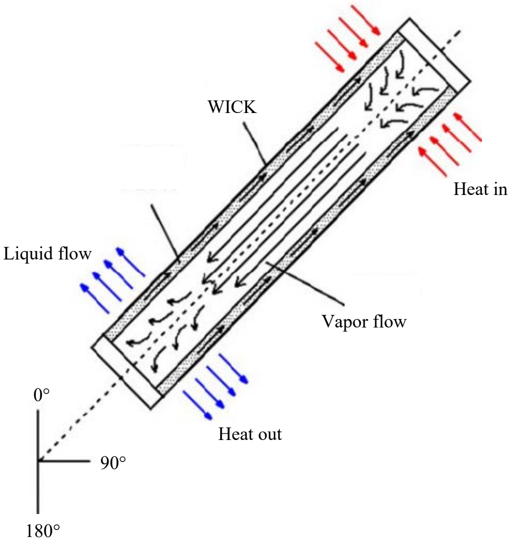

Fig. 2: Schema of the wick heat pipe

the sharp edges of the grooves. Conductivity of a heat pipe can vary from 500-18000 W/mK[12] and can go beyond that depending upon thediameter and length of the pipe, fluid and material properties. Water as a fluid has operating range from 30°C-200°C Which is suitable for research in battery cooling. Hence, most researchers use battery water-copper sintered heat pipe.

Air cooling of battery using heat pipe: Battery thermal management system using Air cooling technique is being used from the start and is being still used because of its simple implementation, economic and lightweight of the system. Though it is the most convenient system, electric vehicle at high load, air cooling is not sufficient enough to maintain the battery at desired temperature. For electric mopeds or battery producing heat <10 W per cell, air cooling can control the battery temperature[13]. Researchers are now using heat pipes with air cooling for faster dissipation of heat. In space-constrained battery pack heat pipes are very effective to transfer the heat from the source to open atmosphere to release heat.

Zhao *et al*.[14] did analysis of battery using heat pipes with air cooling and compared it with liquid cooling with heat pipe. Heat pipes were placed between lithium batteries as shown in Fig. 3.

Figure 4 shows the maximum temperature of the battery for different cooling methods with heat pipe. For 3C discharge rate, forced air cooling with heat pipe managed to maintain the battery temperature between 25°C-32°C.

Liquid cooling of battery using heat pipe: At a high load and rate of heat generation >10 W per cell, air cooling is not enough to maintain the battery temperature. Liquid cooling performs best in such conditions because of its coolant having high specific heat capacity. Liquid cooling systems are costlier and heavier than air cooling but modern cars need such cooling systems for high acceleration and high speed.

Fig. 3: The 8 Ah (top) and 3 Ah (bottom) battery packs with heat pipes

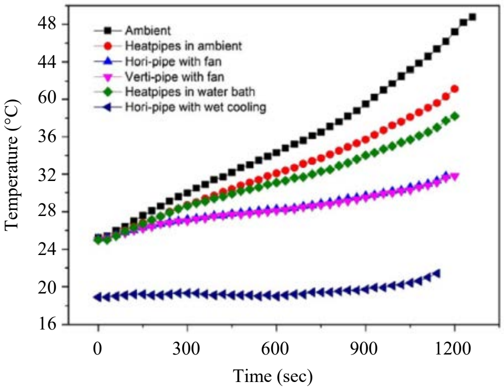

Fig. 4: Maximum temperature curves of 3 Ah battery pack equipped with different BTM systems at the discharge rate of 3C

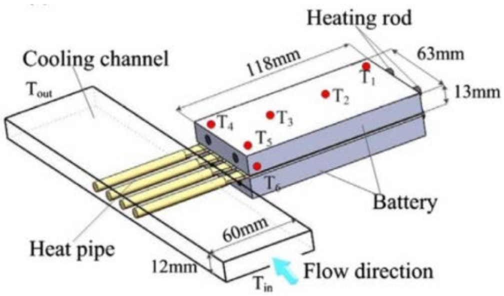

Fig. 5: Test section and measuring points

Liang *et al*.[15] performed an experimental analysis of liquid cooling of a lithium-based prismatic battery using heat pipe for different coolant inlet temperature, coolant flow rate and ambient temperature and setup model is shown in Fig. 5. Figure 6 shows that maximum temperature of the battery reduces as ambient temperature

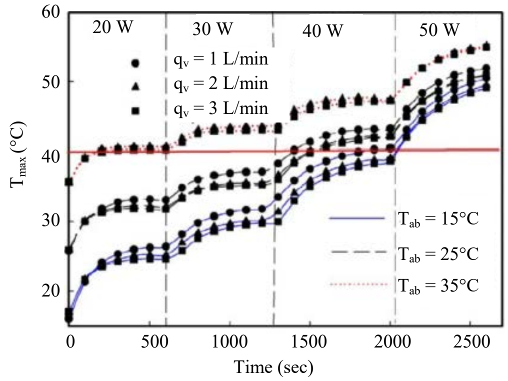

Fig. 6: T_{max} with different coolant flow rates under different ambient temperatures

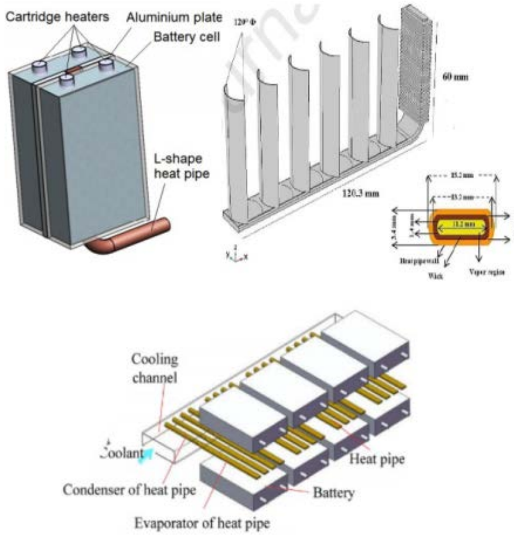

Fig. 7(a-c): (a) Model[13] (left) (b) heat pipe model with fins[16] (right) and (c) Sandwich pattern[17] (bottom)

reduces and coolant's flow rate increases. Some of the setups from research works are shown in Fig. 7 for cylindrical as well as prismatic cells.

PCM cooling of battery using heat pipe: Putra *et al.*[18] constructed passive cooling system with Phase Change Material (PCM) and heat pipe and studied effectiveness of the cooling system. Figure 8 shows the setup of passive cooling system.

PCM absorbs the heat from battery and converts into liquid form. That heat is then transferred by heat pipe to the surrounding using fins with air cooling. Heat pipe with passive cooling system reduces maximum battery temperature by 26.62°C with beeswax and 33.42°C with RT44 as PCMAs shown in Fig. 9. The use of heat pipes resulted in a quicker release of batterysystem heat to the ambient environment. Thus, the risk of overheating was lowered.

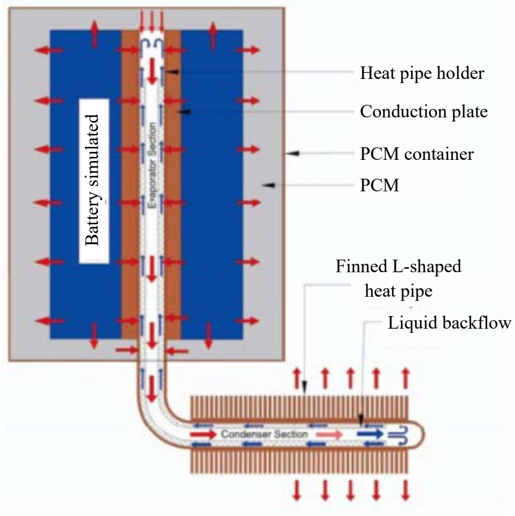

Fig. 8: Heat transfer and exchange process in heat pipe and PCM

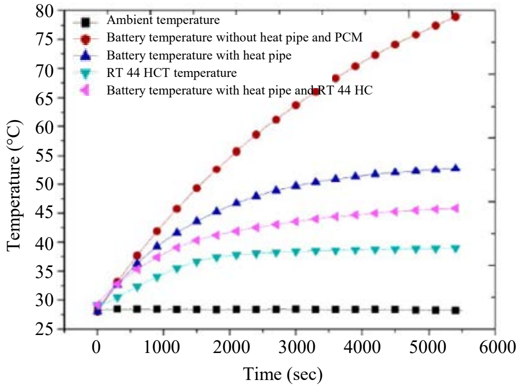

Fig. 9: Battery simulator surface temperature with and without heat pipes

Literature review: The cooling of Lithium-based batteries have been done by many researchers by various cooling techniques. Temperature distribution in the battery is non-uniform and it is crucial while designing a battery thermal management system. Panchal *et al.*[19] showed lithium-ion prismatic battery temperature contour at 1C,2C, 3C and 4C discharge rate at ambient temperatures of 5°C, 15°C, 25°C and 35°C. In recent years, researchers have been working on battery cooling using all the methods mentioned above with heat pipe. Behi *et al.*[4] conducted experimental work and CFD simulation on the battery thermal management system of Lithium-Titanate prismatic cell using heat pipe with air cooling and liquid cooling and compared the reduction in maximum temperature for both cases. Same authors[3] researchedabout heat pipes sandwiched between two prismatic cells and analysed the temperature distribution by CFD analysis in COMSOL Multiphysics and validated experimentally. The effectiveness of heat pipe with air cooling and liquid cooling is compared by Zhao *et al*.[14]. Cooling of extended heat pipes from the 3*3 AH pouch lithium-ion battery pack is done by air cooling, water Bath and wet cooling (liquid spray). Wang *et al*.[13] did experimental work on the liquid cooling of Lithium-ion prismatic battery using heat pipe with heat pipe sandwiched between two batteries. The analysis is done for 1C, 2C, 3C and 4C current discharge. Liang *et al*.[15] conducted a similar sandwich pattern and did an analysis of liquid cooling with heat pipe for different cooling temperatures and compared the maximum differential temperature of an individual battery. Behi *et al*.[20] did a numerical analysis of Lithium-ion cylindrical battery by natural and forced air cooling using heat pipes. It compared the effect of cell spacing, air velocity on battery cooling. Kumar *et al*.[21] carried out an experimental and theoretical study of the heat pipe, compared change in heat transfer coefficient by varying tilting angle of the heat pipe and fluid inlet temperature. Loh *et al*.[22] concluded that gravity and heat source orientation have less effect on sintered powder metal heat pipes as it has strong capillary action. They analysed the thermal performance of heat pipe for inclination angle between -120 degrees to 120 degrees for different ambient temperatures. Won[23] analysed the temperature distribution of lithium-ion battery considering factors such as the coolant flow rate, the coolant inlet temperature and the input power. Heat pipes come in various shapes and sizes. Rectangular heat pipes are more effective for the prismatic battery than cylindrical heat pipes because of a larger area of contact. Lin and Wong[24] compared the thermal performance of powder sintered and grooved heat pipes. Maximum heat transfer capacity is compared for circular and flattened heat pipes. Kumarsen *et al*.[25] conducted experimental to find the effect of different wick structures at various inclination angles on the thermal performance of the heat pipe. Dan *et al*.[26] did an analysis of a battery pack using micro heat pipe and air cooling. At 1C discharge rate, this system was able to maintain the battery temperature below 40°C for air velocity of 3 m $\sec^{-1}$.

Kim *et al*.[27] proposed an analytical method called a modified shah method to get maximum heat transfer through micro heat pipe by considering the effect of liquid-vapour interfacial shear stress and validated experimentally. Nemec *et al*.[3] proposed a mathematical model to calculate the heat transport limitations of the heat pipe by considering various wick structures and working fluid properties. The capillary limit is the primary maximum heat transport limitation of a heat pipe. The thermal conductivity of a heat pipe depends on different material and fluid used in the heat pipe and its analytical expression is proposed by Solomon *et al*.[28] based on the heat transport limit equation. Do *et al*.[29] developed a mathematical model to find the effect of the amount of liquid charge, liquid-vapor interfacial shear stress and contact angle on the heat pipe with rectangular grooved wick structure using a novel method called modified shah method. For micro trapezoidal grooved heat pipe[30] presented a mathematical model to find the effect of contact angle on meniscus radius and heat flux distribution.

DISCUSSION

A heat pipe as it is a heat exchanger device, it can be used with any type of cooling technique. Depending on the application, material and inner fluid of heat pipe can be selected for the best operating range. Parameters like orientation, flattening, fluid properties and material properties of heat pipe plays important role in deciding heat transfer capacity of a heat pipe. Most of the researchers had shown interest in lithium prismatic batteries and use of flattened heat pipes. Researchers have done both experimental and numerical analysis of battery cooling with heat pipe and showed the effectiveness of heat pipe for battery thermal management. Mostly for research, water and copper sintered heat pipe is used. Heat pipe can be used for cooling as well as for warming of the batteries in cold weather conditions. As per the literature review, heat pipe assisted air cooling reduces the maximum battery temperature within the battery operating range and does not exceed maximum differential temperature beyond 4°C when cell generates heat <10 W per cell. Whereat high load liquid cooling and PCM is suitable option.

CONCLUSION

The purpose of this study is to get an overview of different cooling methods with heat pipe used for battery thermal management system. heat pipes are effective in heat transfer and reducing maximum battery temperature. Proper heat pipe assisted battery setup can also reduce the maximum differential temperature of the battery. Heat pipes are more effective with liquid cooling than air cooling. In space constrained application heat pipes are viable option for battery thermal management.

RECOMMENDATIONS

Heat pipes are proven to be effective in transferring heat but still for battery cooling in electric vehicle space constraint is the major criteria and this condition has to be satisfied for better range and safety for EVs by designing different configurations of heat pipe and battery. There is a scope of doing research in cooling cylindrical cells using a heat pipe. Different heat pipe materials can be also used to manage a wide range of battery temperatures and can be validated analytically and by numerical analysis.

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