Review on Heat Pipe Assisted Battery Thermal Management System For EVs and HEVs

Sounak Chatterjee[1] , Sateesh Patil[1]

[1] Mechanical Engineering Department, MIT School of Engineering, MIT ADT University, Pune 412201

Abstract: *Prioritizing battery safety and thermal management of battery packs of electric vehicle because of their direct involvement in the durability, safety and performance of electric vehicles. Prior study of battery thermal management has been done by using various techniques of Natural convection, forced convection, phase change materials, di-electric oils etc. Battery Thermal Management(BTMS) By use of heat pipes is under research over the last few years but very limited study has been done over this topic.This paper aims to give us a review and gist of Battery Thermal Management of electric vehicles(EVs) using heat pipes And discusses the various arrangements possible for doing the same. It will also give us an idea about the workingof a heat pipe in the above case and benefits and loses of the same. Thus we can conclude that Cooling of Battery packs of EVs by using heat pipes is a viable solution to battery heating problems and also a budding topic of extensive study in the upcoming years.*

Keywords: Electric Vehicles (EV), Heat pipe, Battery Thermal Management System (BTMS), Cooling and heating, convection

1. Introduction

As per the current scenario of the automobile market, we know that gasoline powered vehicles are slowly being replaced by electric and hybrid vehicles which are a suitable alternative for the same.

Li-ion powered rechargeable batteries are mostly used as the power source for electric and hybrid vehicles
due to their high energy density, low self-discharge, stability. Li-ion batteries also have a high no of cycle life which make it an ideal choice for EVs and HEVs specifically.

High operating temperatures will cause rapid discharging of the battery cells, decrease in the life span and also safety issues. Thus the operating conditions of the battery cells must be maintained between 20 to 40 degrees for efficient functioning of the battery cells. On study and investigation about the thermal characteristics and behavior of batteries, we would be able to relate that the relationship between the rate of discharge rate and the heat generated and released by a battery pack is nonlinear. This implies that the higher the rate of discharge, the higher will be the heat generated.

Now the discharge rate of a battery may mutate due to a number of factors like acceleration, braking, the type of motion the vehicle is following etc. Thus we can say that the value of total discharge of heat in these cases has a very high instantaneous value and a proper and efficient battery thermal management system is required, battery conditions within an appropriate range.

The battery thermal management of an li-ion battery pack is basically an efficient way to maintain
Appropriate battery cell temperature by various heat transfer techniques. Some commonly used techniques
Is air cooled, liquid cooled, by the use of phase change materials and cooling by use of heat pipes.

Heat pipes are an innovative and modern day solution for the Battery Thermal Management of li-ion battery packs in EVs. This type of battery thermal management systems have been under intensive research and experimentation in the recent years.

If we consider the use of phase change materials for the cooling of battery cells, one of the major problem is the low thermal conductivity of phase change materials. To resolve this issue various approaches have been made for enhancing the thermal conductivity of phase change material probably by introduction of a second component with a higher thermal conductivity.

Heat pipes use a combination of phase change materials along with metallic pipes that help in efficient thermal management of the battery cells and also is a suitable approach to serve the criteria's of compact and well-designed vehicles for the future.

Various setups and arrangements can be made for efficient cooling of the battery cells which have been discussed as we proceed further.

Efficient methods of cooling using heat pipes have been developed in various fields like electron cooling, solar heater and energy recovering. Heat pipes expose us to a flexibility of shape and structure which enables us to transfer and circulate coolant between the cells of battery packs thus maintaining battery packs under working conditions and suitable temperatures[11][12].
Cooling using heat pipes have been under study by various authors and have turned out to be a very promising method of maintaining battery thermal conditions[4][5][8].

2. Description and working of heat pipes

A simple structure of a heat pipe is shown in **Fig 1.**
A heat pipe may be stated as a very basic type of heat exchanger that uses a working fluid which is a phase change material and under goes a phase change when passed via the condensing and evaporating sections which are cold and hot respectively.
Firstly the fluid rises to the tubular section where it can flow between the heating and cooling regions. The two portions of the heat pipe are separated by a film which allows capillary motion this allowing the liquid from the cooler region and the vapor from the hotter region to flow.
Heat pipes are usually copper sintered. Aluminum/ammonia heat pipes are used in aircrafts. Usually copper/R134a or steel/R134a heat pipes are used in HVAC applications as in this case [12**].** In case the working temperatures are estimated to be very high, super alloy/alkali metal heat pipes may be used. Heat pipes being light weight are suitable for use in EVs.
The Phase Change Material used in most cases is water which is better stated as copper water sintered heat pipe [12] [13] [14]. Certain applications have also shown use of copper methanol sintered heat pipes. Depending upon the working range of temperature the working fluid may be selected [9] [16**].**
The heat pipes can also be bent according to the setup requirement by repeated heating and preheating and also are used in various shapes like flat heat pipes [15].
Heat pipes have a very high thermal conductivity to weight ratio and the large contact area with battery surfaces make it a viable solution for the thermal management of batteries in EVs.

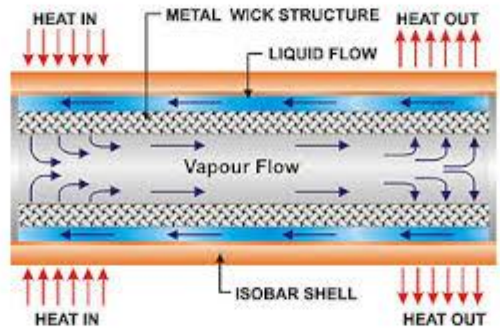

Fig.1. - Heat pipe

3. Heat generation inside a battery

As we proceed further into the concept of battery thermal management, it is very vital for us to understand how heat is actually generated inside a battery pack or more precisely a battery cell.
Heat is generated in batteries from two sources; electrochemical operation and Joule heating[1].In a simplified manner as shown in reference [1][2][3] using a thermodynamic energy balance equation we can write[3] total heat generated as a sum of heat generated by Joule heating minus the heat generated due to entropy changes.

$$q = I(U - V) - J[J(dU/dT)] \quad (1)$$

On a more clear break down of the heat generated in a battery cell [3] we can further break down the above equation in three parts which are generation of heat due to internal resistance, change of entropy of cell during discharge and heat transferred by convection under ambient conditions. Cell temperature is assumed uniform in this case of heat dissipation.

$$\mathrm{m.}\frac{C_{cell}\mathrm{dT}}{\mathrm{dt}} = \mathrm{I}^{2\mathrm{R}} + \frac{\mathrm{T(cell)SL}}{\mathrm{nF}} + \mathrm{Ah}(\mathrm{T}_{cell}\mathrm{l} - \mathrm{T}_{\mathrm{ambient}}) \quad (2)$$

in some cases[14][15] the total heat generated by charge and discharge is the sum of resistive heat as mentioned in the earlier equation and the entropic heat. Thus the total heat generated can be estimated by[3] **:**

$$\phi = \mathrm{I}(U_i - \mathrm{U}) - \mathrm{IT}[\mathrm{dU/dT}]\,] \quad (3)$$

During all calculation related to heat dissipated by a battery module, equal and homogeneous discharge rates of all the cells is considered.

4. Arrangements of heat pipe assisted BTMS in EVs

As mentioned earlier, the thermal management of battery packs by using heat pipes is still a understudy topic but there are various experimentally proven suitable setups for the same.

4.1. Heat pipe assisted PCM based BTMS

An experimented compact and generic design of a battery thermal management system which constitutes of modules and sub-modules in series and parallel arrangements with PCM surrounded by an arrangement of battery monomers is shown in **Fig. 2**[12] . The evaporator section of the Heat pipe is combined with phase change materials and the condenser section of the heat pipe is extended outside the battery box. In reference [15] the author presents an idea of an air flow channel on the side of the battery pack. This channel acts as an heat exchanger. Air convection can be carried out via these using fans to take away heat from the condenser section of the heat pipe. A finned setup may also be used for the condenser section to further increase heat dissipation. In the setup module, a total of 6 phase change materials with an average thickness of 6mm and five batteries were compactly packed in a sandwich structure .Now each long side of the heat pipe is kept in contact with two such modules as shown in **Fig.2** [12]. A total of three such modules have been used.
The heat pipes used in this case is a copper water sintered heat pipe which has been flattened for further compactness of the BTMS to a width and thickness of 8mm and 3mm respectively. The evaporator section is 175mm while the condenser section is 45mm [12].
Now as the temperature of the battery pack increases, the heat transfer process starts as shown in **Fig. 3**[12] the PCM absorbs the heat and utilizes it for change of phase. The heat pipe now assists in increasing the overall heat dissipation capacity from the module to the surrounding environment. Forced convection by the channel setup mentioned earlier is further used for cooling of this condenser section.

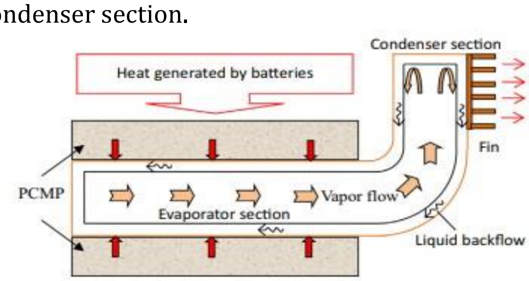

Fig. 3. - Schematic of heat transfer in heat pipe

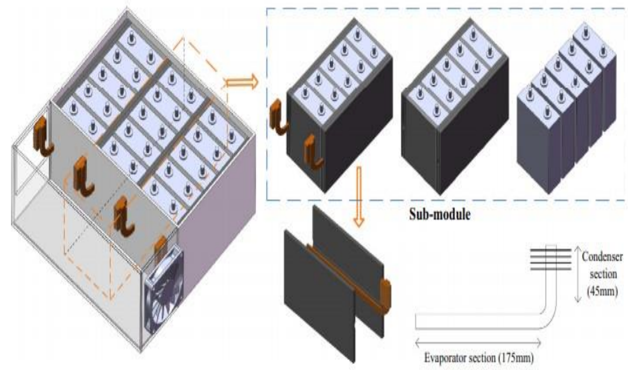

Fig.2. - Schematic of battery modules and sub modules.

Dynamic load testing has been performed on the battery packs from initial temperatures of 20.0, 36.8, 41.1, and 42.2 in the first to the fourth cycle respectively to temperatures of 53.2, 60.7, 63.3, 63.7 in the first to fourth cycle respectively. The overall temperature was maintained less than 60 degrees.
The phase change material used is composite paraffin with a thermal conductivity of 7.654 W\m\K which is thirty times higher than the thermal conductivity of paraffin which is 0.268 W\m\K.

Key points for Heat pipe assisted PCM based BTMS

1. The battery thermal management of EVs and HEVs using HP assisted PCM based BTM system is well designed, compact and practical.
2 .Significant reductions in temperature has been observed by this method as compared to other cooling methods. Use of PCM also increases temperature uniformity.
3. Even under conditions of rapid discharge the temperature was well maintained and efficiently controlled less than 60 degree centigrade.

4.2. Forced Convection assisted Heat pipe based BTMS for EVs and HEVs

In reference [15] the author has carried out experimental study of battery thermal management in heat pipes by using convection techniques along with heat pipes.
The author has used a flat heat pipe and a 14 cell battery structure which has been outlined for use in a hybrid electric vehicle. The cells have a capacity of 7Ah and dimensions of 38mm diameter and 142mm height. A resin matrix shown in **Fig. 4**[15] was designed to give the cells a support and sturdy

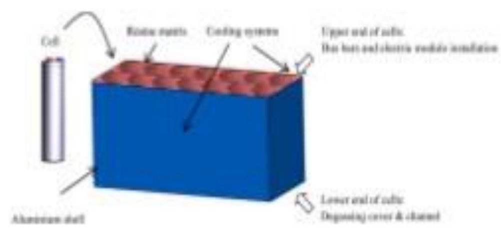

Fig. 4.-Resin matrix structure

structure. The resin structure has been used in both references [14][15]. This resin matrix acts as an insulation between the cells and also enhances thermal conductivity between the cells.

Now as discussed earlier the heat dissipated during charging and discharging conditions of the battery pack can be given by equation 3 which is a sum of resistive heat and entropic heat[1][3][14].

The author used a flat heater to produce heat in an experimental investigation [15] instead of the battery module directly. Induction heater was used to generate transient heat flux.

A setup as shown in **Fig. 5**[15] is used in this experiment [15].Heat pipes are copper powered water sintered and have a flat geometry. Water is used as a working fluid in this case. Referring to **Fig. 5**[15]**,** under application of forced convection assisted by a fan, air was passed via the channel towards the fins. Convection was carried out with the fins kept in both vertical and horizontal positions. Three air velocities of 0.2m/s,0.5m/s and 1.5m/s were experimented. Testing under variable heat generation was also carried out during which the power of the heater was varied between 10% and 90% [15].

Referring to reference [14] the author has mentioned a similar setup with the battery cells of the same dimensions but 6.5Ah.Here each cooling module has been assisted by seven heat pipes with an outer diameter of 7mm.The working fluid used was demineralized water. Aluminum blocks and fins were attached to the condenser and evaporator sections respectively. Heat pipe cooling was experimented for the modules under 3 power levels of 38, 54, 84 watts with heat generations of 76, 108, 168 watts respectively [14].

Various rapid discharge conditions of uphill, downhill and also abusive discharge was carried out for the experimental setups mentioned in references [14][15]. The temperatures were maintained below 60 degree centigrade in both cases. It was also noticed that the cells present at the center of the modules had a subsequently higher temperature than the cells present at the outer peripheries of the battery modules [15][14]. Forced air cooling strategies

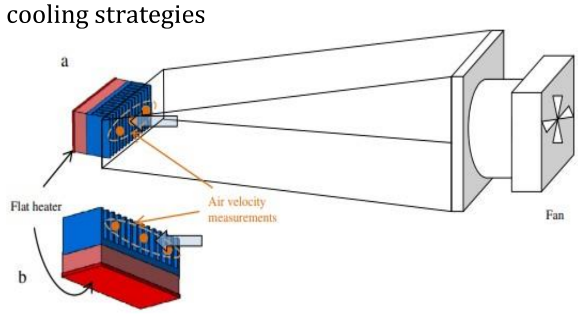

Fig. 5.- Schematic of air channel cooling setup assisted by heat pipe

Coupled with heat pipe assisted cooling can thus be an effective way for battery thermal management system for HEVs and EVs.

Key points for Forced Convection assisted Heat pipe based BTMS for EVs and HEVs

1. Flat heat pipes are an efficient and maintenance free solution for BTM in EVs and HEVs. The thermal resistance of heat sink based cooling is reduced by almost 20% in case of natural convection and almost 30% in case of forced convection [15]

2.On considering the space available for the BTMS in electric vehicles, flat heat pipes give us a promising flexibility of geometry and also provides efficient cooling in cases of vertical and horizontal placements.[13][14]

3. When coupled with forced convection, the setup was able to handle rapid fluctuations of heat dissipation and abusive discharge in a more stable and developed way as compared to heat sink cooling [15].

4.3 Coolant Based Heat pipe assisted BTMS for EVs and HEVs.

In reference [16] the author uses an arrangement as shown in **Fig. 6**[16]. The heat pipes are inserted into the battery voids and either the evaporator or condenser section are kept in contact with the aluminum plate at the bottom of the setup to maintain steady circulation temperatures. A liquid channel is also provided in the aluminum setup provided at the bottom. This channel enables the circulation of the coolant for maintaining proper temperatures of the heat pipes and ultimately the battery module. The coolant used in this case is glycol water which enables efficient heat dissipation from the heat pipes to the surrounding atmosphere. It can also be noted that the setup can also be used for battery preheating in cases of low temperatures.

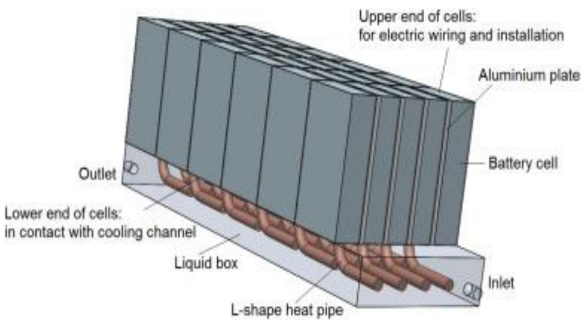

Fig. 6. – Heat pipe BTMS demonstration

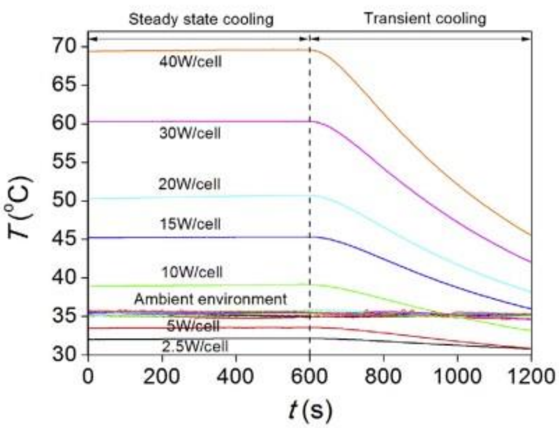

Fig. 7.- Battery surface temperature variation according to conditions

For the experimental setup in [16] the author uses a setup of two stimulated battery containers filled with atonal 324.This setup gives an overall thermal heat capacity which is nearly equal to that of a li-ion battery. A L-shaped copper water sintered heat pipe with dimensions of 120*13.16*4.5mm and diameter of 10mm on the flattened part with be placed in between the battery cells. The evaporator section of the heat pipes are kept in contact with the aluminum liquid box with glycol-water as shown in **Fig. 6**[16].Cartidge heaters are used to produce heat equivalent to a range of 2.5-40 watt/cell [16].
Fig. 7[16]. shows a number of conditions under which the setup has been tested.
Now it was observed [16] that the proposed heat pipe BTMS was able to maintain a battery temperature of below 40 degree centigrade for watt/cell conditions which is usually the case used in electric vehicles. For cases involving battery cell of 20 watt/cell the temperature was maintained below 50 degree centigrade. A rare case of abusive discharge of 20 to 40 watt/cell was also investigated and it was observed that the BTMS under investigation was able to maintain to maintain temperatures below 70 degree centigrade and any case of thermal runway was avoided. The whole system was able to maintain a peak temperature of 63 degree centigrade [16] under extreme conditions and also was able to maintain stable temperatures of 35 to 41 degree centigrade under normal battery discharge.

Key points for Coolant Based Heat pipe assisted BTMS for EVs and HEVs

1. Heat pipe assisted coolant based BTMS is able to handle all normal rates of discharge and off normal rates of discharge very efficiently.
2. In the experimented setup[16][17] in case of cylindrical cells such an arrangement can also be used.

5. Conclusions

The assisted heat pipe techniques are an efficient and compatible technique for BTMS of EVs and HEVs. Heat pipes serve the purpose of heat exchangers for BTMS. The main conclusions that could thus be drawn are

1. Heat pipe assisted battery thermal management is a practical and feasible technique of BTMS which also fulfills the criteria of compactness and low cost maintenance. It also has no moving parts thus making it better than other complex cooling strategies.

2. Heat pipes can be coupled with other forms of cooling strategies like forced convection, natural convection and also coolant based ways for efficient BTMS as we have seen in the paper.

3. We can also conclude from the paper that among the discussed methods and strategies of battery thermal management system for electric vehicles and hybrid electric vehicles, heat pipe assisted coolant based method was the most successful and efficient BTM setup investigated. It was able to handle normal and off normal conditions very efficiently. This method is although costlier than the others proposed.

4. Convection based cooling strategies coupled with Heat pipes are also productive BTMS ideas that have been discussed in this paper. Forced and natural cooling strategies assisted by heat pipes are cost effective and have been investigated to be practical solutions for the BTMS of EVs and HEVs over a range of conditions like uphill, downhill etc.

5. The structure and rigidity of the battery cells can be maintained while using heat pipe assisted cooling

mechanisms by using resin matrix which provides thermal conductivity and electrical insulation to the BTMS which has been discussed in detail in the paper.

6. The research results thus concludes that the heat pipe assisted cooling mechanisms and also the ideas of heat pipe heat exchangers can be a budding , cost effective and intelligent way for BTMS and can be further researched by using numerical analysis.

References

[1]. NurHazimaFaezaa Ismail, *Simplified Heat Generation Model for Lithium ion Battery used in Electric Vehicles*, Material science and engineering, IOP conference series, 2013.

[2]. Xuan Tong, *Calculation methods of heat produced by a lithium-ion battery under charging discharging condition*, Fire and Materials, Wiley, 2018.

[3]. Wei-dong Fu, *Heat generation breakdown of lithium ion batteries,* CATL, COSMOL Conference, 2017.

[4]. BoucarDiouf, *Potential of lithium ion batteries in renewable energy,* Renewable Energy, Elsevier, 2014.

[5]. Zachary P. Cano, *Batteries and fuel cells for emerging India,* nature Energy, Macmillan, 2018.

[6]. Benjamin Frieske, *Trends in Vehicle Concept and Key Technology Development For Hybrid And Battery Electric Vehicles,* International battery, hybrid and fuel cell electric vehicle Symposium, EVS27, 2013.

[7]. Kaushik Rajashekara, *Present Status and Future Trends in Electric Vehicle Propulsion Technologies,* Power Electronics, IEEE, 2013.

[8]. G.J.Offer,*Comparative analysis of battery electric, hydrogen fuel cell and hybrid vehicles in a future sustainable road transport system,* Energy Policy, Elsevier, 2009.

[9]. Ziye Ling, *Review on thermal management systems using phase change materials for electronic components, Li-ion batteries and photovoltaic modules,* Renewable and Sustainable Energy Reviews, Elsevier, 2014.

[10]. X.Duan, *Heat transfer in phase change material for thermal management of electric vehicle battery modules,* International Journal Of heat and mass transfer, Elsevier, 2010.

[11]. Z.Lu, *Thermal Management of Densely-packed EV battery with Forced Air Cooling Strategies,* Energy Procedia, Elsevier, 2015.

[12]. Kai Chen, *Experimental investigation for the thermal performance of heat pipe assisted phase change material bases battery thermal managementsystem,* Energy conversion management, Elsevier, 2017.

[13]. Huiming Zou, *Experimental investigation on an integrated thermal management system with heat pipe heat exchanger for electric vehicle*, Energy conversion and management, Elsevier, 2016.

[14]. Thanh-Ha Tran, *Experimental investigation on Heat pipe cooling for Hybrid Electric Vehicle and Electric Vehicle Li-ion battery,* Journal of power sources, Elsevier, 2014.

[15]. Bernard Desmet, *Experimental investigation on the feasibility of heat pipe cooling foe HEV/EV lithium-ion batteries,* Applied Thermal Engineering, Elsevier, 2013.

[16]. Q. Wang, B. Jiang, *Experimental investigation on EV battery cooling and heating by heat pipes,*Applied Thermal Engineering, Elsevier, 2014.

[17]. Jianqin Wang, *Sensitivity analysis of factors influencing a heat pipe based thermal management system for a battery module with cylindrical cells,* Applied thermal engineering, Elsevier, 2019.