EXPERIMENTAL ANALYSIS OF TEMPERATURE CONTROL OF LITHIUM-ION BATTERY BY UTILIZE HEAT PIPE

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ABSTRACT

In “electric vehicles’ and “lithium-ion batteries” are widely utilizedfortheir long cycle life and strong energy density. Heat generates at charging or discharging which causes increasing heat in the battery. Due to high temperature the battery cells are damaged which cause the battery to explode and burn. Temperature management is essential for Li-ion batteries because it impacts on its performance and life. The prime aim of this research is experimental evaluation and function of the battery in the temperature control system by utilizing “loop heat pipe (LHP)”.LHP is expected to be applied to BTMS for secure function of strong performance and long-lasting serviceable life. The LHP is applied with different temperature gain and fluids working. Water, nanofluid and hybrid nanofluid were used with 60 % filling ratio and with heat loads of “20 W, 30 W and 40 W” experiment was conducted. Result of this research shows that hybrid nanofluid (Water-Al2O3 _5%. TiO2_1%) provides the best result with successfully reducing the temperature by 46°C.

Keywords: *Loop heat pipe, “Li-Ion battery”, “Battery thermal management (BTM)”, Hybrid Nano fluid*

I. Introduction

Battery is the most effective device that helps to strengthen energy and also helps to release the energy as the electrical power. Moreover, the battery has played the most significant role in the functioning of electric cars. The battery has worked as a major source of energy. It is needed to perform like fossil fuels to control the temperature [1]. This aspect has increased the quality of the battery and developed the lifespan and distribution of energy in a certain period. In the other words, the performance of the battery depends on the thermal as well. In thermal management system, the range of temperature permit of battery to be below ‘50°C’ [2]’.

The lithium-ion battery has occurred through the chemical reaction. In a lithium-ion battery the heat is mainly generated for charging or discharging [3]. Moreover, generated heat has increased heat [4]. Temperature runaway is high temperature activities of the battery. Thermal control of the battery is the most significant approach that can reduce the blast and burn the battery. In the battery the temperature has dreaded one cell to another neighbor cell that causes the imbalance temperature controlled in the battery. This spreading temperature by one cell to another cell has caused a blast and burn of the battery [5].

Likewise, excessively high temperature activities can reduce capacity and compress battery life [6].

The main reason of energy reduction and saving are to operate electric vehicles with proper manners for controlling heat range [7]. Moreover, an effective heat control system is one of the most essential things that help to operate electric cars successfully.

In the heat management system, the heat exchanger has played the most effective role to reduce the temperature. The “heat pipes” are significant heat exchangers that can manage the heat of the battery. The heat pipes are the most suitable subsidy that is applied in the temperature control system of the “Central Processing Unit (CPU)” the batteries of electric vehicles [8]. Moreover, it helps to maintain the lightweight, compact size of the vehicles and also it does not need any external supply of energy.

Fig. 1. “Loop heat pipe’

In temperature transfer, the loop temperature pies are one of the most significant devices that can control thermal changes of battery. The loop heat pipe is a well-organized device of heat transfer that is employed in spacecraft for thermal control. Moreover, this heat transfer device has helped to reduce the temperature from electronic devices with high heat flux [9]. The LHP’s can control the heat better than the heat pipes. This heat transfer device sets up a link between evaporator and condenser through the liquid line and vapour line. This thermal control device has provided a suitable arrange ment for evaporator and condenser. Moreover, in a thermal controlling system evaporator management can reduce the resistance of temperature management of the battery. In thermal management systems, capillary force has provided facilities to transfer interference in the evaporator; moreover, it has encouraged the work of fluid in the vehicles. This aspect drives the work from the fluid to evaporation interface. It also helps to create a bound in the development of the vapour layer and it helps to decrease thermal resistance of the battery [10].

The activities of the heat pipes depended on structure and design of this device, structure of capillary wick, and working with fluid [11]. The LPHs have the power to reduce the temperature of the battery compared to straight pipes [12]. Moreover, increased inclusion of the nanoparticles can increase the concern of heat pipes in thermal control management [13]. Capillary wick has originated corals united with nanofluid that can develop functions of LHP [14]. Temperature control system, the smooth and pore structure of coral delivers high mass flow rates and high capillary pressure [15]. The main limits of coral use are environmental consideration. In the creation of “Lotus Type Porous (LTP)”, copper by sintering methods, slip casting in caricaturist structure of coral pore [16].

Nandy Putra et al. used different nanofluids with different volume fraction 1% to 5% to determine the thermal resistance of nano fluids with “Screen mesh” like wick and found out that “Al2O3-water 5%” shows the lower thermal resistance compare to other nano fluids [17].RosariSaleh et al. developed a biomaterial wick and used nanofluid Al2O3-water 5% for experiment and found out that biomaterial wick is more efficient than sintered powder wick [18]. P. Gunnasegaran et al. use water-based silicon dioxide nano fluid in LHP of heat range of “20 W to 100 W” and found out that Nano fluid provides better result than base fluid (distil water) and has lower thermal resistance than water [19]. M. Zufar et al. used different hybrid nano fluids in PHP with 10-100 W heat load and 50-60% filling ratio and found the best result for Sio_2.Cuo at 60% FR [20]. Bambang Ariantara et al. carried out the experiment with water as a fluid working of 50% filling ratio moreover, different heat gain of ‘20 W, 30W’ and ‘40W’ and results shows that heat pipe was successfully able to manage the surface heat of the battery simulator less than ‘50°C’ [21].

The main objective of this research, to experiment the evaluation of the battery performance in temperature control system (BTMS) by utilizing loop heat pipe ‘LHP’ and to evaluate the performance enhancement by using hybrid nanofluid at different heat loads.

II. Methodology

The heat pipe design is adopted from the model developed by B. Ariantara[16] to transfer the heat load up to 100 W. ‘Battery simulator’ is made of aluminium alloy. As the source of heat,a heat plate with the capacity of ‘10-110 W’ will be put under ‘the battery simulator’. The size of BS is “105 mm x 40 mm x 15 mm” (According to dimensions of Lithium-Ion battery used in Mahindra e2o plus P2 model).

Table I. Loop heat pipe configuration

Loop heat pipe configuration		
Component	***Diameter***	***Length***
Evaporator	10 mm	240 mm
Condenser	25 mm	100 mm
Vapor line	10 mm	135 mm
Liquid line	10 mm	80 mm
wick	0.5 mm	110 mm

A. *Numerical calculations*

"Steady state mathematical model" of a "loop heat pipe":
Based on energy and thermodynamic equilibrium between each component, a "steady state mathematical model" of "LHP" has increased. In order to make things easier the model with the subsequent assumptions are made [22]:

(1) Flows of vapor and liquid are incompressible and one dimensional
(2) Fluid working flow is split in "LHP".
(3) Condensation process of vapor is an isobaric process
(4) Fluid thermophysical properties have changed with temperature.
(5) Energy reduction by vapor line is omitted.

Therefore, the "LHP" is distributed in five types which are: "evaporator", "single phase zone in condenser (subcooled zone)", "two phase zone in condenser", "liquid line wick" and "liquid line".
"Energy conservation" in these sections are registered below. In this regard, the pressure drop of LHP, "single phase pressure drops", "two phase pressure drop', and "wick pressure drop' is considered.

Energy conversion each component:
Evaporator

$$Q_{in} = Q_{ev} + Q_{ev\ amb} + G_{hl}(T_{ev} - T_{wi})Q_{in} = Q_{ev} + Q_{ev\ amb} + G_{hl}(T_{ev} - T_{wi}) \quad (1)$$

$$Q_{ev} = G_{ev}(T_{ev} - T_v)Q_{ev} = G_{ev}(T_{ev} - T_v) \quad (2)$$

$$G_{ev}(T_{ev} - T_v) = m\Delta h_v + mC_p(T_v - T_{wi}) + G_{w\ ll}(T_v - T_{wi})$$
$$G_{ev}(T_{ev} - T_v) = m\Delta h_v + mC_p(T_v - T_{wi}) + G_{w\ ll}(T_v - T_{wi})$$
(3)

"Two-phase zone" in condenser

$$m\Delta h_v = G_c(T_v - T_{sink})m\Delta h_v = G_c(T_v - T_{sink}) \quad (4)$$

"Single-phase zone" in condenser

$$mC_p(T_v - T_{co}) = G_{sub}(T_v - T_{co})/\ln\left(\frac{T_v - T_{sink}}{T_{co} - T_{sink}}\right)mC_p(T_v - T_{co}) = G_{sub}(T_v - T_{co})/\ln\left(\frac{T_v - T_{sink}}{T_{co} - T_{sink}}\right) \quad (5)$$

"Liquid line"

$$mC_p(T_{co} - T_{wi}) = G_{ll}(T_{co} - T_{wi})/\ln\left(\frac{T_{co} - T_{amb}}{T_{wi} - T_{amb}}\right)mC_p(T_{co} - T_{wi}) = G_{ll}(T_{co} - T_{wi})/\ln\left(\frac{T_{co} - T_{amb}}{T_{wi} - T_{amb}}\right) \quad (6)$$

"Liquid line wick"

$$mC_p(T_v - T_{wi}) + Q_{llw\ amb} = G_{ev\ llw}(T_v - T_{wi})mC_p(T_v - T_{wi}) + Q_{llw\ amb} = G_{ev\ llw}(T_v - T_{wi}) \quad (7)$$

Pressure drop in each component:

'Vapor groove", "liquid line'', "vapor line", and "single-phase zone" in condenser:

$$\Delta P = f\left(\frac{l}{d}\right)\left(\frac{\rho v^2}{2}\right)\Delta P = f\left(\frac{l}{d}\right)\left(\frac{\rho v^2}{2}\right) \quad (8)$$

'Two-phase zone" in condenser "Annular flow":

$$\Delta P_{2\varnothing} = \int_{x_{in}}^{x_{out}} \left[-\varnothing_L \frac{2f}{d} \frac{(1-x)^2}{2\rho} \left(\frac{m}{A}\right)^2 \left(\frac{dz}{dx}\right) \right] dx \Delta P_{2\varnothing} = \int_{x_{in}}^{x_{out}} \left[-\varnothing_L \frac{2f}{d} \frac{(1-x)^2}{2\rho} \left(\frac{m}{A}\right)^2 \left(\frac{dz}{dx}\right) \right] dx \quad (9)$$

Wick:

$$\Delta P_{wick} = \frac{m\mu L_w}{K_w \rho A_w} \Delta P_{wick} = \frac{m\mu L_w}{K_w \rho A_w} \quad (10)$$

The thermodynamic equation is as follows:

$$T_v - T_c = (\frac{\partial T}{\partial P})(\Delta P_{vg} + \Delta P_w + \Delta P_v) T_v - T_c = (\frac{\partial T}{\partial P})(\Delta P_{vg} + \Delta P_w + \Delta P_v) \quad (11)$$

$$T_v - T_c = (\frac{\partial T}{\partial P}) \Delta P_u T_v - T_c = (\frac{\partial T}{\partial P}) \Delta P_u \quad (12)$$

$\partial T / \partial P \, \partial T / \partial P$ is the "slope of the saturation temperature" and "pressure curve", that represents through the relation of 'Clausius-Clapeyron':

$$\frac{\partial T}{\partial P} = \frac{T(\frac{1}{\rho_v} - \frac{1}{\rho_l})}{\Delta h_v} \frac{\partial T}{\partial P} = \frac{T(\frac{1}{\rho_v} - \frac{1}{\rho_l})}{\Delta h_v} \quad (13)$$

B. *Experimental procedure*

An LHP with heat loads 20w,30w and 40w with different working fluids Distil water, Water-Al_2O_3 _5% nanofluid and Water-Al_2O_3 _5%. TiO_2_1% hybrid nanofluids are tested for a time interval of 9 hrs. Total 36 observations are taken at 1 hr interval for three different working fluids and battery simulator without LHP. The filling ratio remains constant at 60%. "Volumetric flow rate" of cooling water remained at "180 ml/min". The experiment is conducted at room temperature. Nanoparticles were purchased from a standard supplier which is *Qualikems Fine Chem Pvt. Ltd* [23].

Temperature at different positions of LHP were measured using digital thermometers. Liquid line pressure drop was measured using a pressure gauge.

C. *Experimental calculations*

With overlooking the reduction of temperature from the surrounding environment, transfer heat by "LHP" is gained by utilizing heat balance in the condenser with the equation and fraction of transfer heat. This equation has divided the heat transfer by heath generation with "LHP" [24].

$$Q = \rho V c_p (T_{co} - T_{ci}) Q = \rho V c_p (T_{co} - T_{ci}) \quad (14)$$

Fig. 2. Experimental setup

The "LHP" temperature resistance can be achieved from the scientific calculation.

$$R = \frac{(T_e - T_c)}{Q} R = \frac{(T_e - T_c)}{Q} \quad (15)$$

III. Results and Discussion

The results show that LHP with hybrid nano fluid provides better thermal management compared to nano fluid and base fluid. Hybrid nanofluid provide about 15.8°C more temperature drop at 40 W heat generation. The 'LHP' is able to reduce the heat of battery simulator to 47°C which is under the working limits of li-ion battery by using hybrid nano fluid.

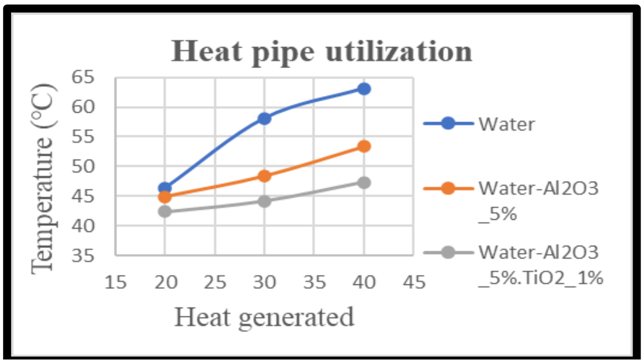


Fig. 3 Heat pipe utilization

The LHP performance increases up to 7% and 10% by using nanofluid and hybrid nano fluid respectively.

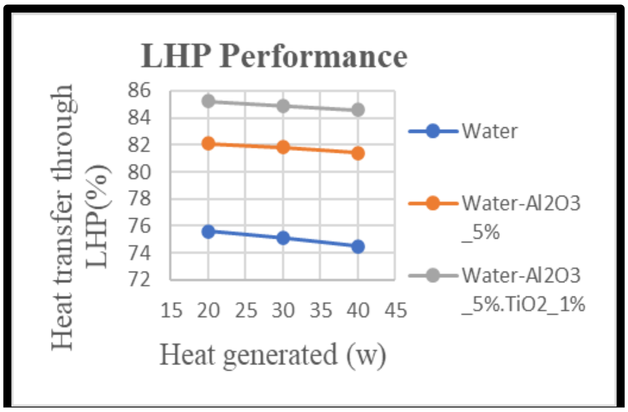


Fig. 4 Loop heat pipe performance

The experimental results graph is identical to numerical results graphs which validates the results obtained by the experiment. However, the deviation in the experiment and numerical results is due to the more heat losses to the surroundings, uncertainty in instruments and uncertainty in measurements.

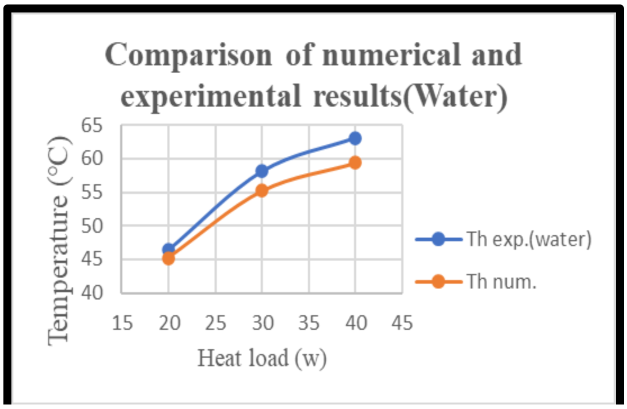


Fig. 5 "Comparison between numerical and experimental results" (Water)

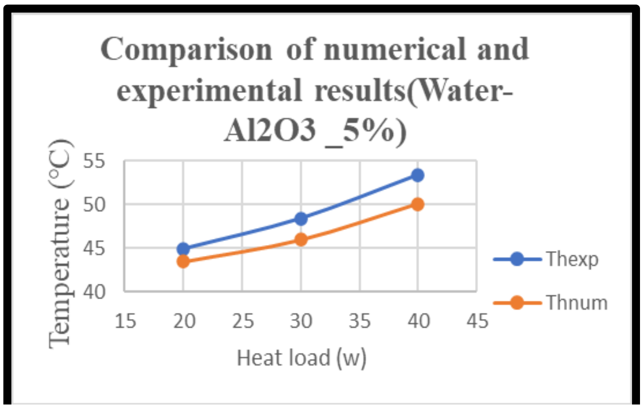


Fig. 6 "Comparison between numerical and experimental results" (Water-Al2O3_5%)

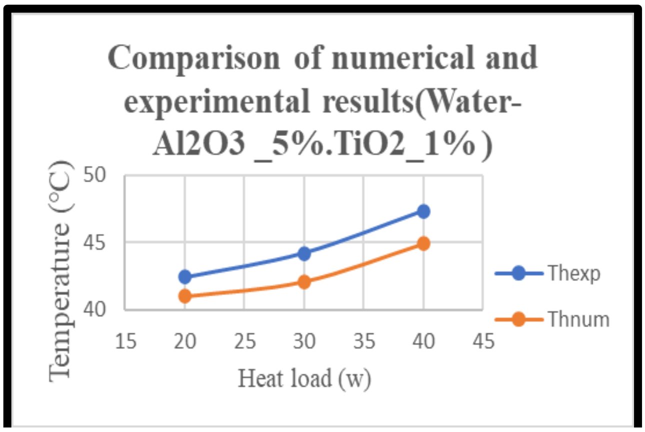


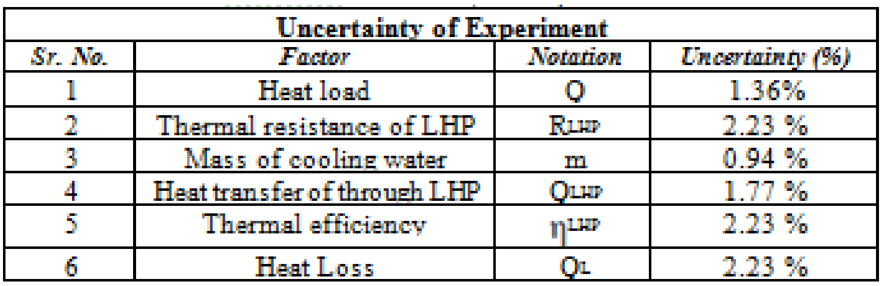
Fig. 7 "comparison between numerical and experimental results" (Water-Al2O3_5%. TiO2_1%)

IV. Uncertainty Analysis

In this analysis, several aspects have been represented that created deviation of the data. Parameters of deviation data have changed the outcomes of this analysis. The most significant part of this analysis is to find the actual reason for deviation. This analysis has investigated reasons like carelessness and environmental factors. This experimental analysis has represented possible errors with numerical value. This analysis has conducted random sampling to get authentic results of this experimentation. Uncertainty analysis shows the expected accuracy not exact accuracy; This analysis has represented the estimated expected accuracy of the equipment and systems. Kline and McClintock have suggested the uncertainty experiment method to find the accurate result. This analysis gets the accurate result through certain measured quantities and measurement of error 'y' (parameter) is given as follows [25].

$$\frac{\delta y}{y}=\sqrt{\left(\frac{\delta y}{\delta x_1}\delta x_1\right)^2+\left(\frac{\delta y}{\delta x_2}\delta x_2\right)^2+\left(\frac{\delta y}{\delta x_3}\delta x_3\right)^2+\cdots}\frac{\delta y}{y}=\sqrt{\left(\frac{\delta y}{\delta x_1}\delta x_1\right)^2+\left(\frac{\delta y}{\delta x_2}\delta x_2\right)^2+\left(\frac{\delta y}{\delta x_3}\delta x_3\right)^2+\cdots} \quad (16)$$

Table II. **“Uncertainty of Experiment”**



Uncertainty of Experiment			
Sr. No.	*Factor*	*Notation*	*Uncertainty (%)*
1	Heat load	Q	1.36%
2	Thermal resistance of LHP	R_{LHP}	2.23 %
3	Mass of cooling water	m	0.94 %
4	Heat transfer of through LHP	Q_{LHP}	1.77 %
5	Thermal efficiency	η^{LHP}	2.23 %
6	Heat Loss	Q_L	2.23 %

The performance of LHP by considering the uncertainty is shown in the graph. Which shows the minimum performance of LHP at maximum uncertainty. The LHP performance decreases up to 1.15% if maximum uncertainty is considered.

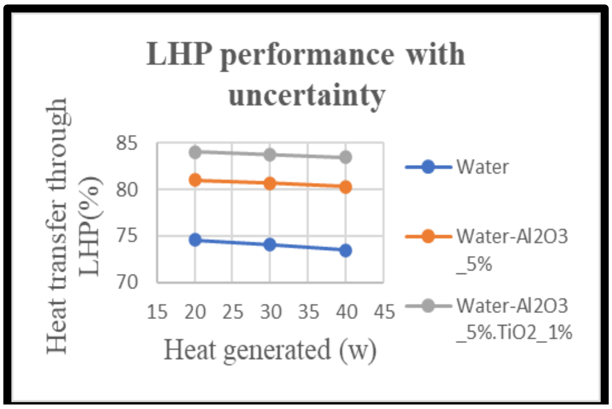


Fig. 8 LHP performance with uncertainty

V. Conclusions

After all these discussion, it can be conclude that in thermal management system, to control performance of battery has used ‘loop heat pipe’ with different working fluids with 60% filling ratio has performed successfully. The “loop heat pipe” by Hybrid Nanofluid as a fluid working that can reduce the simulator temperature of the battery successfully.

In heat generation of “40 W”, the “battery simulator temperature” can be reduced from “93 °C” to “47 °C”, also decreased by 46 °C by using hybrid nano fluid (Water-Al2O3 _5%. TiO2_1%). LHP with water and nano fluid (Water-Al2O3 _5%) were able to handle heat loads of ‘20 W’ and ‘30 W’ respectively. The ‘loop heat pipe’ with Water-Al2O3 _5%. TiO2_1% as a working fluid is capable of reducing the temperature from the batter simulator effectively as 88% of heat originated from the heater.
Temperature management issues of “LHP” have decreased through increased heat load which shows that LHP can handle more heat load. The heat pipe performance increases up to 12% by using hybrid nano fluid.

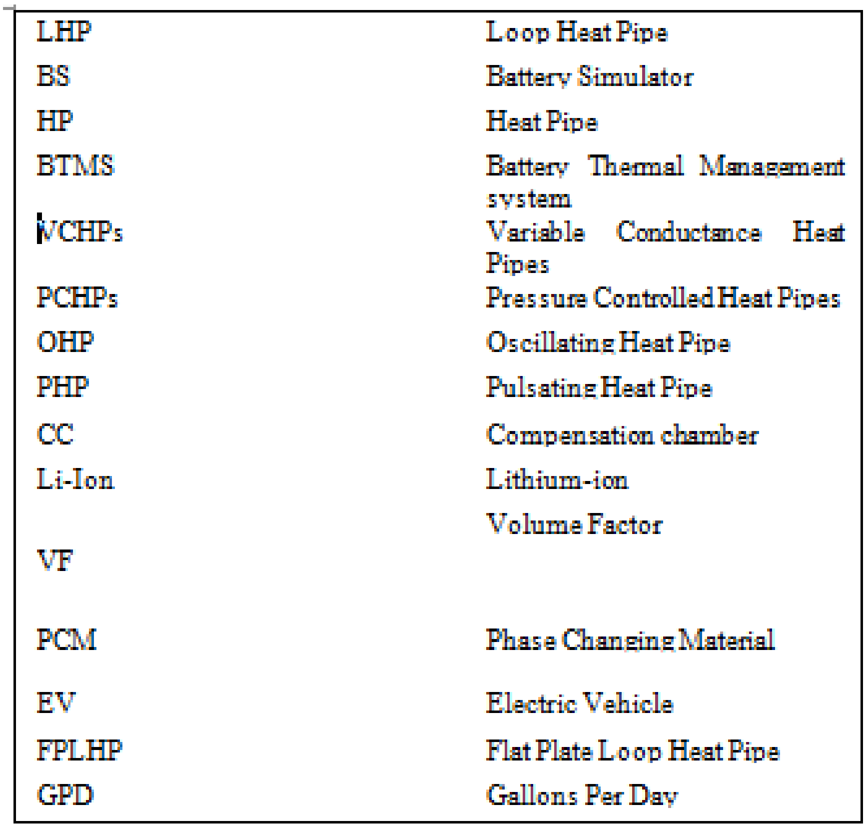
References

1. M. WADA, (2009). Research and development of electric vehicles for clean transportation, J. Environ. Sci., vol. 21, no. 6, pp. 745–749
2. J. Zhao, Z. Rao, C. Liu, and Y. Li, (2016). Experimental investigation on thermal performance of phase change material coupled with closed-loop oscillating heat pipe (PCM/CLOHP) used in thermal management, Appl. Therm. Eng., vol. 93, pp. 90–100
3. L. Lu, X. Han, J. Li, J. Hua, M. Ouyang, (2013). A review on the key issues for lithium-ion battery management in electric vehicles, Journal of power sources, 226, 272-288.
4. Ramadass P, Haran B, White R and Popov B N (2002). Capacity fade of Sony 18650 cells cycled at elevated temperatures: Part II, Capacity fade analysis Journal of Power Sources. 112(2):614-20
5. Ross PE.(2013) Boeing's battery blues [News] Spectrum, IEEE 50(3) 11-2
6. J. Liu, H. Li, W. Li, J. Shi, H. Wang, and J. Chen, (2020). Thermal characteristics of power battery pack with liquid-based

thermal management," Appl. Therm. Eng., vol. 164, pp. 114421

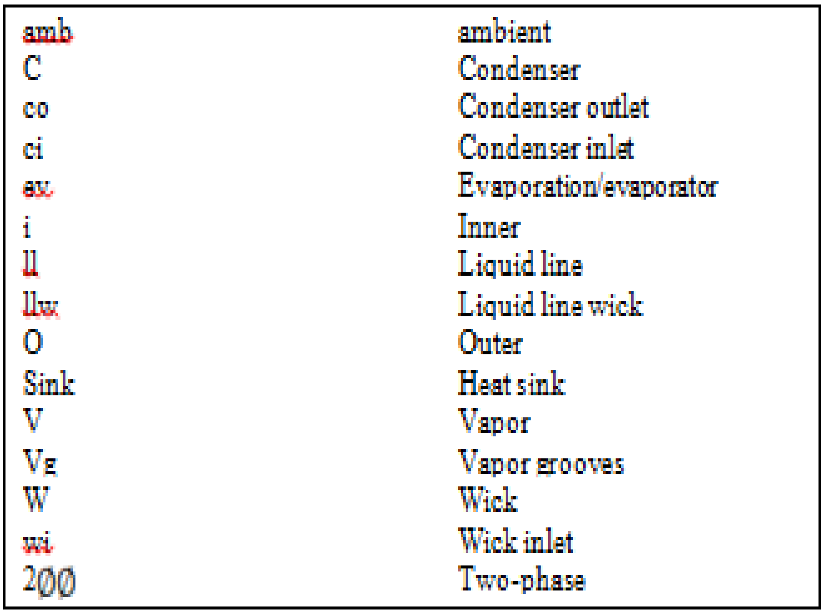
7. Z. Rao, S. Wang, M. Wu, Z. Lin, F. Li, (2013), Experimental investigation on thermal management of electric vehicle battery with heat pipe, Energy Conversion and Management, 65 92-97.
8. N. Putra, W.N. Septiadi, R. Sahmura, C.T. Anggara, (2013). Application of Al2O3 Nanofluid on Sintered Copper-Powder Vapor Chamber for Electronic Cooling," Advanced Materials Research, 789, 423-428.
9. S. Al Hallaj and J. R. Selman, (2000). A Novel Thermal Management System for Electric Vehicle Batteries Using Phase-Change Material," J. Electrochem. Soc., vol. 147, no. 9, p. 3231
10. J. Zhao, P. Lv, and Z. Rao, (2017). Experimental study on the thermal management performance of phase change material coupled with heat pipe for cylindrical power battery pack," Exp. Therm. Fluid Sci., vol. 82, pp. 182–188
11. W. Yuan, Z. Yan, Z. Tan, W. Chen, and Y. Tang (2016). Heat-pipe-based thermal management and temperature characteristics of Li-ion batteries," Can. J. Chem. Eng., vol. 94, no. 10, pp. 1901–1908
12. Reay D, McGlen R and Kew P (2013). Heat pipes: theory, design and applications: Butterworth-Heinemann
13. Putra N, Yanuar and Iskandar F N (2011). Application of nanofluids to a heat pipe liquid-block and the thermoelectric cooling of electronic equipment," Experimental Thermal and Fluid Science 35(7)1274-81
14. N. Putra, B. Ariantara, and R. A. Pamungkas (2016). Experimental investigation on performance of lithium-ion battery thermal management system using flat plate loop heat pipe for electric vehicle application," Appl. Therm. Eng., vol. 99, pp. 784–789
15. Putra N, Saleh R, Septiadi W N, Okta A and Hamid Z (2014). Thermal performance of biomaterial wick LHPs with water-base Al2O3 nanofluids. International Journal of Thermal Sciences. 76(0)128-36
16. B. Ariantara, N. Putra, and S. Supriadi, (2018). Battery thermal management system using with LTP copper capillary wick.
17. N. Putra, W. N. Septiadi, H. Rahman, and R. Irwansyah (2012). Thermal performance of screen mesh wick heat pipes with nanofluids," Exp. Therm. Fluid Sci., vol. 40, pp. 10–17.
18. N. Putra, R. Saleh, W. N. Septiadi, A. Okta, and Z. Hamid (2014). Thermal performance of biomaterial wick loop heat pipes with water-base Al2O3 nanofluids, Int. J. Therm. Sci., vol. 76, pp. 128–136,
19. P. Gunnasegaran, M. Z. Abdullah, and N. H. Shuaib, (2013). Influence of nanofluid on heat transfer in a loop heat pipe," Int. Commun. Heat Mass Transf., vol. 47, pp. 82–91
20. M. Zufar, P. Gunnasegaran, H. M. Kumar, and K. C. Ng, (2020). Numerical and experimental investigations of hybrid nanofluids on pulsating heat pipe performance," Int. J. Heat Mass Transf., vol. 146.
21. M. Amin, B. Ariantara, N. Putra, A. F. Sandi, and N. A. Abdullah,(2018). Thermal management of electric vehicle batteries using heat pipe and phase change materials, E3S Web Conf., vol. 67, pp. 1–5
22. M. Fanxi, Q. Zhang, S. Du, C. Yue, and X. Ma, (2020). One-dimensional steady-state mathematical model of a novel loop heat pipe with liquid line capillary wick, Energy Explor. Exploit., vol. 38, no. 1, pp. 253-273.
23. D. Sheng, Z. Quan, H. Peilin, Y. Chang, and Z. Sikai, (2019). Experimental study and steady-state model of a novel plate loop heat pipe without compensation chamber" Sustainable Cities and Society.
24. Q. Su, S. Chang, M. Song, Y. Zhao, and C. Dang, (2019). An experimental study on the heat transfer performance of a loop heat pipe system with ethanol-water mixture as working fluid for aircraft anti-icing," Int. J. Heat Mass Transf., vol. 139, pp. 280–292

Abbreviations



LHP	Loop Heat Pipe
BS	Battery Simulator
HP	Heat Pipe
BTMS	Battery Thermal Management system
VCHPs	Variable Conductance Heat Pipes
PCHPs	Pressure Controlled Heat Pipes
OHP	Oscillating Heat Pipe
PHP	Pulsating Heat Pipe
CC	Compensation chamber
Li-Ion	Lithium-ion
VF	Volume Factor
PCM	Phase Changing Material
EV	Electric Vehicle
FPLHP	Flat Plate Loop Heat Pipe
GPD	Gallons Per Day

Subscripts



amb	ambient
C	Condenser
co	Condenser outlet
ci	Condenser inlet
ev.	Evaporation/evaporator
i	Inner
ll	Liquid line
llw	Liquid line wick
O	Outer
Sink	Heat sink
V	Vapor
Vg	Vapor grooves
W	Wick
wi	Wick inlet
2ØØ	Two-phase