

Experimental Investigation of Novel Thin Aluminium Flat Heat Pipe Assisted Battery Thermal Management System for Cylindrical Lithium-ion Batteries of Electrical Vehicles

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Abstract- A novel thin aluminium flat heat pipe-assisted hybrid battery thermal management system is presented in this paper. A battery thermal management system is a crucial component of an electric vehicle as it is required to maintain the cell temperature within optimum operating range. Usually, conventional thermal management systems are based on air cooling and liquid cooling, and they have their own limitations. The presented hybrid cooling system is fabricated, and its performance is investigated as compared to conventional free convection and forced convection cooling in terms of temperature uniformity (ΔT), peak temperature ($T_{\max}$), and average temperature (T_{avg}) of battery pack. The heat pipes selected are 2 mm thick and aluminium made with acetone as working fluid. The battery pack consisted of twelve Lithium Iron Phosphate batteries of 32650 type and six heat pipes were inserted through the core of the battery pack for heat extraction. The condenser section of the heat pipes was forced air-cooled while evaporator section remains in contact with cylindrical battery. The limitation of perfect contact of flat heat pipe with cylindrical battery surface was overcome by using fine silicon carbide powder which was compressed filled in the empty space between battery and heat pipe. The experimental facility mainly consists of a battery pack, battery charger/discharger (tester), heat pipes insertions, air cooling arrangements, 16 channel data logger and K-type thermocouples. The battery pack was discharged at three discharge rates: 1C, 2C and 3C, combined with three different air flow rates: 3.6 m/s, 4.6 m/s and 5.5 m/s. Results indicated that hybrid thermal management system with heat pipe insertions is better at maintaining temperature uniformity and peak temperature within optimum limits.

Keywords Battery charger/discharger, Li-ion batteries, Lithium Iron Phosphate, Ultra-thin flat heat pipe, C-rate.

1. Introduction

Electrical Vehicles (EVs) is one of key areas research area which has got a lot of attention due to its ability to utilize cleaner sources of energy as compared to fossil fuels [1], [2]. Transportation sector is major contributor to greenhouse gases emission and utilization of EVs can play a critical role in reducing air pollution [3]. As compared to Internal Combustion Engines (ICEs), EVs produce 20% less greenhouse gases during operation phase [4]. The source of power and energy storage for the majority of EVs developed nowadays are Lithium-ion type batteries. These batteries have many advantages: high energy density, better life cycle, low self-discharge rate and no memory effects [5]. Li-ion batteries are available in various material configurations such as Lithium magnetite, Lithium cobaltate and Lithium Iron Phosphate (LFP). LFP batteries are higher energy capacity

batteries with a safe operative cycle [6]. Still to minimize safety risk and ensure effective functioning of batteries, real time monitoring and control of battery parameters such as voltage, state of charge (SOC), and temperature is required. EVs require a highly efficient battery thermal management system (BTMS) for proper functioning of batteries as they generate heat during charging and discharging cycle. Joule heating due to cell internal resistance is one of the major sources of heat generation inside batteries [7]. When battery pack is discharged at high C-rates, chances of overheating increases which results in premature degradation of batteries, cell imbalance inside battery pack or unequal ageing of cells, fire, and explosion hazards [8].

The most common issues of Li-ion batteries are capacity fading, self-discharge, electrical imbalance in battery pack, cold and high temperature performance degradation, and

thermal runaway at high temperatures [9], [10]. To counter limitations of Li-ion batteries, peak temperature and temperature uniformity of pack should be within optimum operating range [11]. The electrical imbalance caused by non-uniformity of temperature within battery module affect state of charge (SOC) of cells thereby reducing the performance of batteries [12]. There is 30% and 50% degradation of battery module with temperature variations of 10°C and 15°C respectively [13]. The most prominent factor which affect performance of batteries is temperature which must be controlled in a narrow range of 20-40°C [14], [15]. Temperature difference across battery module can occur under stressful operating conditions but must be maintained below 5°C [13], [16]. Charging at high C-rates is needed in EVs to shorten charging time [17]. High rate charging pose challenge as lithium plating can occur at low temperatures which cause safety concerns and shortens battery life [18].

A reasonable BTMS is a necessity to maintain battery temperature within safe limits and improve the performance of batteries [19]. BTMS are usually divided into two types based on cooling methods: Passive and Active thermal management systems. Active BTMS need energy from external sources as they are equipped with fans, pumps, and other power consuming devices [20]. Air-cooling, liquid cooling and refrigerant cooling are three traditional methods used in thermal management of EVs. Air cooling BTMS are simpler in constructive and less costly as compared to liquid cooling arrangements. However, air cooling is not reliable under stressful conditions of high charge/discharge rates and high ambient temperature [21]. Liquid cooling systems are more promising methods of battery cooling, but they are bulky and complex in construction. Moreover, there are chances of leakage, and they require proper seal layer and packaging [22]. Air cooled BTMS can be applied to lower power density vehicles with short operating durations. To enhance the performance of air-cooled systems, several research studies have been conducted numerically and experimentally on parameters that affect performance of air cooled BTMS such as cell arrangement, air flow pattern and inlet air velocity [23], [24]. The research by Fan et al. [25] showed that the best cooling performance is achieved in neatly arranged battery cells where power consumption for air cooling was 23% lower as compared to staggered and cross arrangement. When comprehensive cost is considered, a 5×5 cubic arrangement of cells has best cooling capacity [26]. By optimizing width of air inlet and outlet channels, the power consumption can be reduced by 32% in forced air-cooling system [27]. Even after various optimizations, the air-cooling system lacks the performance offered by liquid cooling systems. The main drawbacks of air-cooling systems are the low heat dissipation at high discharge rates, uneven temperature, low thermal conductivity of air and low temperature drop [28]. On the other hand, liquid cooling systems are expensive, complex, difficult to maintain and require leak proof design.

The drawbacks of various cooling methods and specific operating requirements of manufacturers and consumers are pushing towards development of hybrid cooling systems. High heat transfer passive devices such as heat pipes and phase change materials (PCM) can effectively improve

performance of traditional air-cooling systems [29]. Heat pipes and PCM assisted cooling methods have gained more attention in recent years. Heat pipes are high conductivity devices which can control temperature rise in pouch and prismatic li-ion batteries. However, the effective use of heat pipes for cylindrical is still a challenge as these cells present low effective contact area for heat transfer [30]. Heat pipes when inserted through core of cylindrical cells and through critical zone of cylindrical cells-based battery module can effectively control temperature rise of cells and prevent overheating [31]. But still to effectively use heat pipes for battery thermal management, a new contact design is required. A thermal management system embedded with heat pipes designed by Gan et al. [32] was effective at enhancing cooling performance of traditional cooling system. In their experimentally designed system, a conduction element was used to increase contact area. Behi et al. [33] developed a hybrid thermal management system based on air cooling and heat pipe. They developed a heat pipe copper sheet design (HPCS) where copper sheets provided better contact between flat heat pipe and curved surface of cylindrical batteries. Dan et al. [21] presented a micro heat pipe array based thermal management system. Their numerically designed thermal management system was able to provide quick response under varying charge/discharge conditions. The heat pipes assisted BTMS can significantly reduce peak temperatures and at the same time maintain temperature uniformity inside battery module of EV. Various types of heat pipe configurations such as loop type, L-type, circular and flat type have been investigated experimentally and numerically in various research studied [34], [35]. Ultra-thin vapor chambers have potential to significantly reduce maximum temperature and non-uniformity of temperature in battery pack [36]. A particular area of interest is flat and ultra-thin heat pipe designs which are flexible and suitable for various practical applications.

In present research, a thin aluminium flat heat pipe of thickness of 2 mm and width 40 mm is embedded in the battery pack for heat extraction. These thin flat heat pipes are usually used in electronic cooling but their application in EVs is still not explored. These ultra-thin heat pipes could bend at odd angles and are made of aluminium which make them lighter than conventional copper heat pipes. To overcome the limitation of non-perfect contact between flat heat pipes and the curved surface of cylindrical batteries, a unique method is tried whereby purified fine silicon carbide (SiC) is filled and compressed in the empty spaces of battery pack between batteries and heat pipe. The design is like immersion of cells in a dielectric fluid but here instead of fluid, fine SiC powder is used for immersion. This reduces chances of leakage and at the same time provide perfect contact between cylindrical batteries and heat pipe. In this paper, the cooling performance of hybrid heat pipe assisted thermal management is compared with conventional forced air-cooled and free convection based thermal management.

2. Experimental Facility and Procedure

2.1 Description of Battery Pack

EVs battery module/pack consists of several battery cells usually Li-ion connected in either series or parallel connection or combination of both configurations. The present work is based on Lithium Iron Phosphate (LFP) batteries connected in series to form battery pack of twelve cells. The cells are arranged in rectangular configuration. The selected Li-ion cells in the present work are 32650 type LFP cells. The cathode material of these cells is LiFePO_4 while anode material is carbon. The diameter and height of these cells are 32 mm and 65 mm respectively. The specifications and thermophysical properties of LFP cells are given in Table 1. The process of charging/discharging a cell is exothermic and the heat generated (q) inside battery can be calculated from simplified Eq. (1) [37] where first and second term represents joule heating and entropy heat generation respectively.

$$q = I(U-V) - I(T \, dU/dT) \quad (1)$$

The present research is focussed on three different battery packs layouts: Battery pack for free convection (Fig. 1), Battery pack for forced convection (Fig. 1) and Battery pack with heat pipe insertions (hybrid) (Fig. 2). The total capacity and nominal voltage of fabricated battery pack were 6 Ah and 38.4 V respectively. The LFP cells were placed in acrylic case and the interspacing between cells was kept at 2 mm. The acrylic case was left open from all sides for free convection based BTMS, so every side of cells was exposed to free convection except bottom side of cells. In forced convection based BTMS, a variable speed fan was installed at inlet section of acrylic casing. The cells were neatly arranged in rectangular layout with 2 mm interspacing. In hybrid BTMS, the heat pipes as shown in Fig. 3 were installed between interspacing of cells such that evaporator section of heat pipe was inserted inside the battery pack while condenser section was air cooled by forced convection. Specifications of flat heat selected for present research are given in Table 2. The width and thickness of heat pipes are 40 mm and 2 mm respectively. The width is selected such that the critical section of cell remains directly in contact with heat pipe. Due to geometry of cell, the upper and lower section of cylindrical cell can reject heat at much higher rate as compared to middle part of cell. The heat accumulation is much higher in middle part of cell and thus it become a critical region of cell [38]. The heat pipe of 40 mm width can cover critical region of the cell thereby providing better cooling to the core region of cell. A perfect surface contact is desired between cells and heat pipe for efficient heat transfer, but it is difficult to achieve due to cylindrical shape of cells. To overcome this difficulty, fine silicon carbide powder was used to fill gap between cells and heat pipes. Silicon carbide was used to facilitate the transfer of heat from cylindrical surface of cells to flat surface of heat pipe. SiC in purified form act as an electrical insulator with electrical conductivity varying from 10^{-6} at 300 K to 10^{-2} at 1000 K [39]. To further ensure safety, cells were wrapped in insulation and non-conductive thermal gel was applied between SiC. The electrical connection were insulated by spacers.

Table 1. Battery Specifications

Parameter	Specification
Battery Type	32650 LFP
Capacity	6 Ah

Nominal Voltage	3.2 V
Charge cut-off voltage	3.7 V
Discharge cut-off Voltage	1.8 V
Depth of discharge	70%

Table 2. Heat pipe specifications

Item	Description
Material of container	Aluminium 1070
Wick Structure	Groove type
Working Fluid	Acetone
Thickness, Width, Length	2 mm, 40 mm, 250 mm
Maximum heat transfer rate—horizontal and vertical	45 W; 175 W at 50°C
Typical thermal resistance	<0.3°C/W (average)

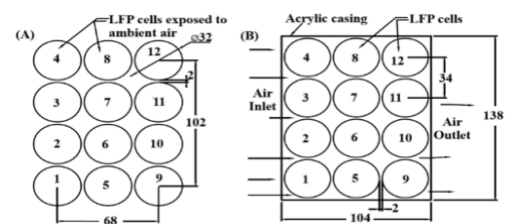


Fig. 1. BTMS (a) free convection and (b) forced convection.

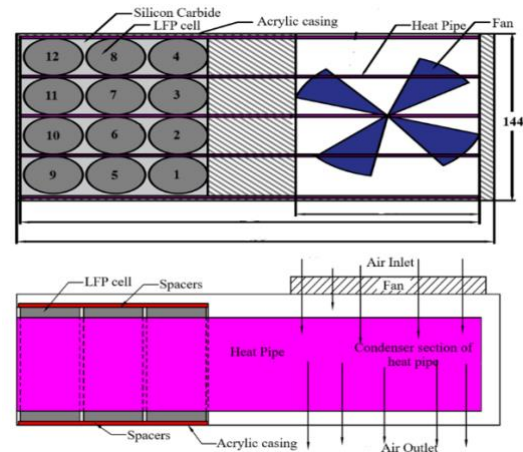


Fig. 2. Battery pack with heat pipe insertions- hybrid BTMS

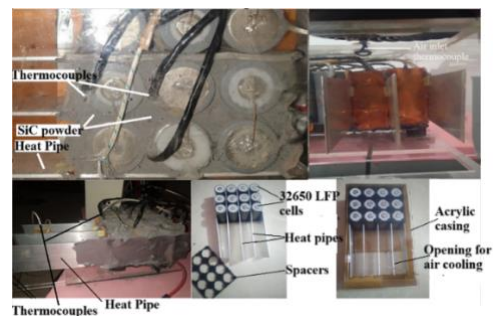


Fig. 3. Fabricated battery pack with heat pipe insertion

2.2 Description of Test Facility

Experimental facility has been developed based on our previous work as shown in Fig. 4 [40]. Apart from the battery pack, it consists of three main components: Temperature measurement and data acquisition system (data logger),

Battery tester (charger/discharger), and Battery cooling system. The surface temperature of cells was measured by K-type thermocouples fixed at middle critical region of each cell. The selected thermocouples have upper and lower temperature limits as 200°C and 0°C respectively. A thermal paste and adhesive tapes were applied to sensor of thermocouple to ensure proper cell-sensor contact. The temperature measured during testing were recorded by a 16-channel data logger having resolution of 1°C. The data logger selected can measure temperature at various variable time intervals, minimum being 5 seconds. Three cooling systems were tested experimentally: free convection, forced convection (air cooled) and hybrid cooling based on heat pipe and forced air cooling. A vane type anemometer was used to measure air inlet and outlet velocity in forced and hybrid cooling systems. The rise in temperature of air is an indication of heat carried away by air while cooling the battery cells. The air inlet and outlet temperature were measured by K-type thermocouples installed at inlet and outlet section of battery pack. The battery tester selected in the present study can charge and discharge batteries at various C-rates by adjusting the value of current and capacity to be discharged. The discharging and charging methods of battery tester and other specifications are given in Table 3. Three different discharge rates are selected for testing: 1C, 2C and 3C, and respective current, capacity discharged, and discharge time are given Table 4. As a safety precaution and operating limitation of cells, the cut-voltage where the discharge process will stop irrespective of capacity discharged was predefined in the battery tester as 22 V. So, in each case, the discharge process was stopped when battery pack voltage reached or fall below this value of 22 V.

2.3 Design of Experiments

The cooling performance of heat pipe-assisted cooling systems was investigated, and comparative analysis was conducted to compare performance with conventional forced and free convection-based cooling systems. To simulate real application scenarios, a test process was conducted at room temperature. The room temperature was controlled during experimentation and $\pm 2^\circ\text{C}$ variation was allowed. "Full factorial" method of design of experiments was considered to study the discharge rate and air flow velocity effects on battery pack. All the possible levels and factor combinations considered in "full factorial design" are given in Table 5. Total number of experiments conducted were 27 where values obtained with similar combinations were averaged.

2.4 Experimental Procedure

Table 5. Design of experiment process

Factors	Levels
Discharge rate (C)	1 C [1] , 2 C [2], 3 C [3]
Air flow rates (m/sec)	V1 = 3.6 m/s [A], V2 = 4.6 m/s [B], V3 = 5.5 m/s [C]
Full factorial: [3 levels of discharge rate, 3 levels of air inlet velocity]	
DOE = 1 A, 1 B, 1 C, 2 A, 2 B, 2 C, 3 A, 3 B, 3 C	
Levels	1 C 2C 3C

The battery pack was discharged from maximum nominal voltage to cut-off voltage of 22 V at constant current. The current rate and time of discharge were selected as per desired discharge rate (1C, 2C and 3C) as given in Table 4. Typical discharge curves at 1C, 2C and 3C rates can be seen in Fig. 5. After each discharge process, the battery pack was charged again to maximum nominal voltage by Galvanostatic method. The cells were allowed to rest after every charge process to ensure cells reach electrochemical stability and battery pack cools down to room temperature (initial values). After each charge process, the nominal voltage of each cell and battery pack were checked. If any cell was found to deviate from nominal voltage range that cell was replaced. Surface temperature of cells during discharge process were recorded at intervals of 10 seconds and values were extracted from data logger at time intervals of 120 seconds. The inlet and outlet air velocity in forced and hybrid systems were measured by a vane type anemometer. The air readings were taken at four locations (A, B, C and D) around the cross-section of fan as indicated in Fig. 6, and average velocity values were used to find mass flow rates required to measure heat carried away by cooling systems. The air density values were taken at temperature of inlet air as recorded by K-type thermocouple.

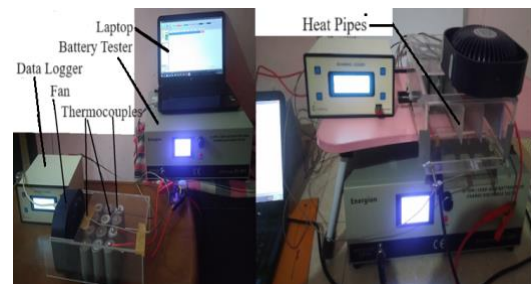


Fig. 4. Experimental testing facility

Table 3. Battery tester specifications

Parameter	Specification
Input Voltage	AC-220V $\pm$ 10%
Maximum Power	900W
Charging Method	Constant current & constant voltage charge
Discharging Method	Constant current discharge
Current	0.5-20A adjustable
Voltage	9V-99V adjustable

Table 4. Current and Capacity settings for C-rates

Discharge rate (C-rate)	Current	Capacity discharged	Discharge time
1C	6 A	6 Ah	60 min.
2C	12 A	6 Ah	30 min.
3C	18 A	6 Ah	20 min.

	V1	V2	V3	V1	V2	V3	V1	V2	V3
1	Discharge	Discharge	Discharge	Discharge	Discharge	Discharge	Discharge	Discharge	Discharge
2	Discharge	Discharge	Discharge	Discharge	Discharge	Discharge	Discharge	Discharge	Discharge
3	Discharge	Discharge	Discharge	Discharge	Discharge	Discharge	Discharge	Discharge	Discharge

2.5 Investigated Objective Functions

The surface temperature profiles of twelve (12) cells of battery pack were monitored and recorded by K-type thermocouple during discharge process. The time taken to discharge battery pack at various selected discharge rate was less as compared to ideal discharge rate as battery pack reached the cut-off voltage. For analysis of performance of BTMS, three major parameters were obtained from recorded data: Peak Temperature, Temperature uniformity and Average temperature.

2.5.1 Peak temperature (T_{max})

The performance of cells is strongly affected by peak temperature generated during operating cycle. The internal temperature of a cell is higher than the surface temperature measured. Ideally peak temperature should not exceed 40°C [41]. The threshold of ideal temperature can be further increased owing to improvement in cell technology. A more relaxed acceptable threshold may be set at 50°C [42]. Peak temperature recorded in case free convection based BTMS, forced convection based BTMS and heat pipe-based hybrid BTMS are indicative of the overall performance of cooling systems.

2.5.2 Temperature uniformity (ΔT)

Temperature uniformity is a measure of difference between temperature of cells in a battery pack/module. Ideally, the temperature difference between cells should not be allowed to increase beyond 5°C [13], [43], however in present research, a more relaxed acceptable value of ΔT at 8°C was used. Overall better temperature uniformity in a battery pack promotes cell balancing and uniformity in charge/discharge cycle of Li-ion batteries.

2.5.3 Average temperature of battery pack (T_{avg})

Increase in average temperature of battery during operating cycle is indicative of performance of BTMS. It takes into consideration the overall temperature of the battery pack. If the difference between peak temperature and average temperature is large, this indicates that some cells are under thermal stress. Average temperature should not exceed safe limit of battery cells i.e. 50°C. The average temperature measured values were used to compare the performance of battery thermal management systems under various discharge rates and air inlet velocities.

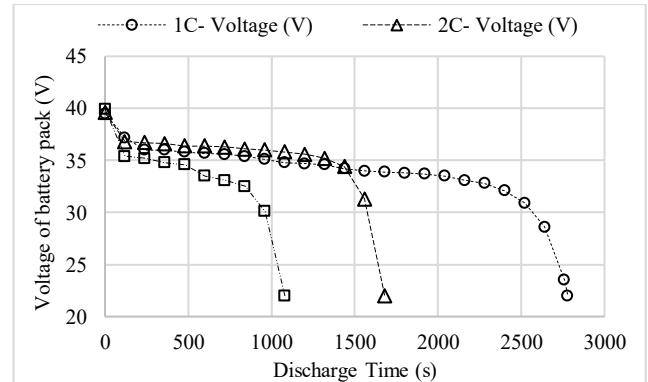


Fig. 5. Discharge curves at 1C, 2C and 3C.

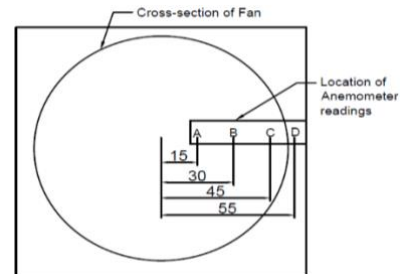


Fig. 6. Location of anemometer readings on fan

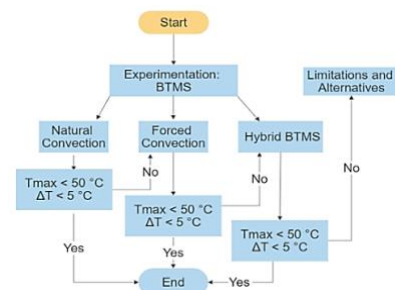


Fig. 7. Process flow of experimentation

2.6 Thermal Analysis and Validation of Results

Experimental results obtained were initially compared with available correlations for free and forced convection. The forced convection cooling of battery pack was considered a case of in-line arrangement of cylindrical tubes (cells). A comparative study was conducted to establish that heat transfer rate achieved by experimental forced convection based BTMS agrees with empirical correlation proposed by A. Zukauskas [44] (Eq.2) for flow over in-line bank of tubes. After determination heat transfer coefficient (h), the heat transfer rate was calculated by using Newton's law of cooling (Eq.3). The actual heat transferred to air by experimental forced convection based BTMS was calculated by applying energy balance to battery pack (Eq.4). The mass flow rate (m_f) is calculated based on average air velocity at inlet, and

inlet/outlet temperature (T_i , T_e) of air were measured by K-type thermocouples

$$h = 0.86(k_f/D) 0.27(Re_D)^{0.63} Pr^{0.36} (Pr/P_s)^{0.25} \quad (2)$$

$$Q_{\text{(correlation-forced)}} = NhA_s (\Delta T_{lm}) \quad (3)$$

$$Q_{\text{(experimental-forced)}} = m_f c_p (T_e - T_i) \quad (4)$$

Where in Eq. (2), k_f is thermal conductivity of air, D is the diameter of cells (32 mm), Pr is Prandtl number (air), Re_D is Reynolds number, P_s is Prandtl number (air) at surface temperature of cells. All the properties of air except P_s were taken at arithmetic mean temperature of air, $(T_i + T_e)/2$. In Eq. (3) and Eq. (4), N is total number of cells, A_s is curved surface area of each cell, m_f is mass flow rate of air, c_p is specific heat of air and ΔT_{lm} is logarithmic mean temperature difference as calculated in Eq. (5).

$$\Delta T_{lm} = [(T_{as} - T_e) - (T_{as} - T_i)] / \ln[(T_{as} - T_e) / (T_{as} - T_i)] \quad (5)$$

Where T_{as} is average surface temperature of all cells. The agreement between empirical correlation (emp) by A. Zukauskas [44] and experimental (Exp) heat transfer rates at 1C and 2C discharge and air inlet velocities of 3.6 m/s and 4.6 m/s are shown in Fig. 8, Fig. 9, Fig. 10 and Fig. 11. The data logger has a resolution of 1°C with K-type thermocouples and therefore in validation results seems to remain constant for certain period. But when experimental results were converted to polynomial function, the polynomial function line closely follow empirical results given by A. Zukauskas for in-line arrangement of cylinders in forced convection. The value of coefficient of determination (R^2) value for each polynomial fit is indicated in the figures and its value in all cases is above 0.9 which indicates a good fit. The percentage difference between empirical and experimental results was under 10 percent. As discharge rate is increased from 1C to 2C, the clustered values of heat transfer rate disappear as temperature rise at much faster rate at higher discharge rates as can be seen in Fig. 10 and Fig. 11.

A simplified approach was followed in free convection cooling for validation of results. In free convection, heat transfer coefficient based on temperature values of experimental data were compared with standard established range of heat transfer coefficient in free convection (air). Heat transfer coefficients were calculated from empirical relations (Eq.6) suggested for entire range of Rayleigh number (Ra_L) by Churchill and Chu [45].

$$h = k/L_c \{0.825 + [0.387 (Ra_L)^{1/6}] / [1 + (0.492/Pr)^{9/16}]^{8/27}\} \quad (6)$$

Where L_c is the characteristic length of cell (i.e., height of cell). All the properties of air were taken at film temperature (T_f). The heat transfer coefficient values as can be seen in Figure 12, were within established range of h i.e., 2.5 to 25 W/m^2K in free convection(air) [46].

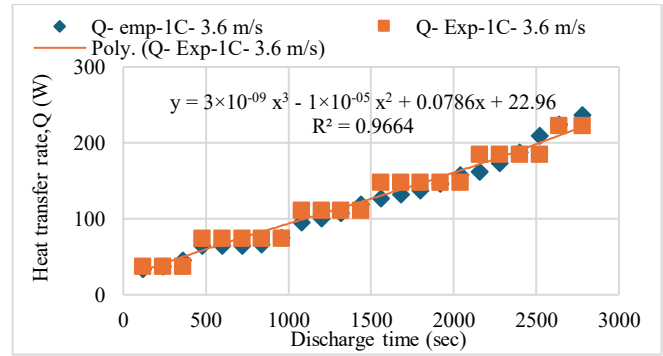


Fig. 8. Validation of results at 1C discharge rate and 3.6 m/s air inlet velocity

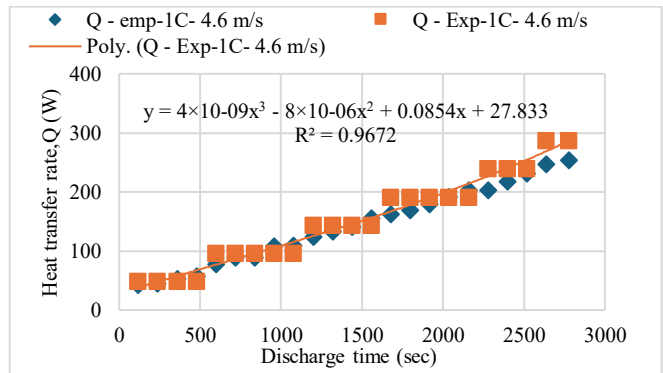


Fig. 9. Validation of results at 1C discharge rate and 4.6 m/s air inlet velocity

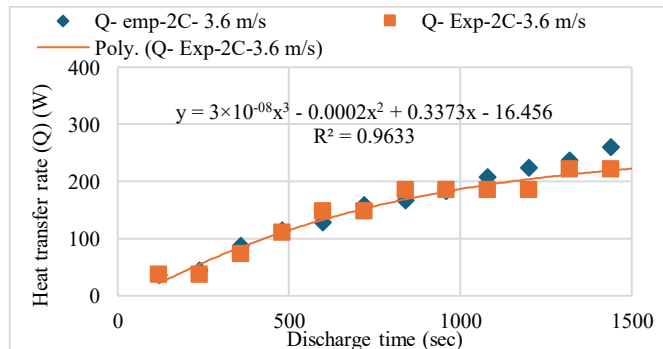


Fig. 10. Validation of results at 2C discharge rate and 3.6 m/s air inlet velocity

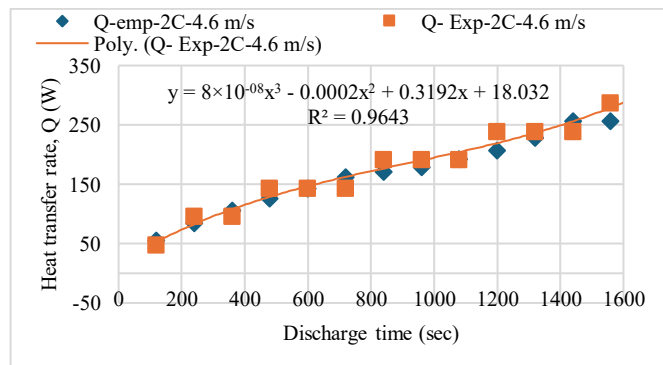


Fig. 11. Validation of results at 2C discharge rate and 4.6 m/s air inlet velocity

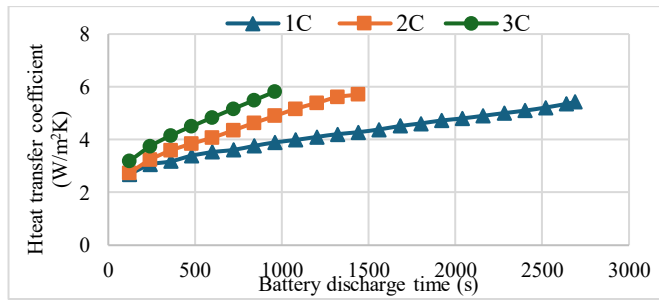


Fig. 12. Validation of results in free convection at 1C, 2C and 3C discharge rate

3. Results

The performance of three different types of BTMS i.e. free convection based, forced convection based and heat pipe assisted hybrid BTMS, were investigated experimentally at three discharge rates 1C, 2C and 3C and three air inlet velocities: 3.6 m/s, 4.6 m/s and 5.5 m/s (see Table 5).

3.1 Free Convection Based BTMS

The variation of average temperature of battery pack under free convection cooling can be seen in Fig. 14. At discharge rates of 2C and 3C, the free convection is not able to maintain temperature within acceptable limit of 50°C. The voltage of battery pack in discharge processes at 1C, 2C and 3C reached the cut-off voltage at 2690, 1440 and 960 seconds respectively. The temperature uniformity as indicated by ΔT in Fig. 15, was better at 1C rates but increase in C-rate has adverse effect on ΔT . Higher values of ΔT indicate lower temperature uniformity in the battery pack. The peak temperature (T_{max}) of each cell at the end of discharge process at 1C, 2C and 3C rates can be seen in Fig. 13. Cell numbers 6 and 7 were identified as critical cells in free convection as the peak temperature of these cells was higher as compared to other cells of the battery pack. The reason for this high temperature readings is due to the rectangular layout of battery pack where the inner most cells (6&7) were not able to freely reject generated heat to the surrounding air by convection. The results indicated that there is crucial need of forced convection or other alternatives to maintain ΔT and T_{max} values within acceptable limits of 8°C and 50°C respectively.

3.2 Forced Convection Based BTMS.

In forced convection, results were evaluated at six combinations of three different discharge rates (1C, 2C and 3C) and three different air inlet velocities ($V1 = 3.6$ m/s, $V2 = 4.6$ m/s, and $V3 = 5.5$ m/s). As can be seen in Fig. 16, Fig. 17 and Fig. 18, forced convection was successful in maintaining average temperature below 50°C but non-uniformity in temperature was much higher as compared to free convection. The peak temperature of cells in row 3 (cell number 9,10,11,12) was higher as compared first two rows. Increase in air inlet velocity reduces average and peak temperature of cells but it has adverse effect on temperature uniformity as ΔT values increases with increasing value of air inlet velocity. Forced convection based BTMS failed to maintain temperature uniformity and peak temperature within

acceptable limits at higher discharge rates. The adverse effect of increase in air velocity on temperature uniformity limit in the battery pack under forced convection demands a new alternative and approach to maintain both T_{max} and ΔT within acceptable limits.

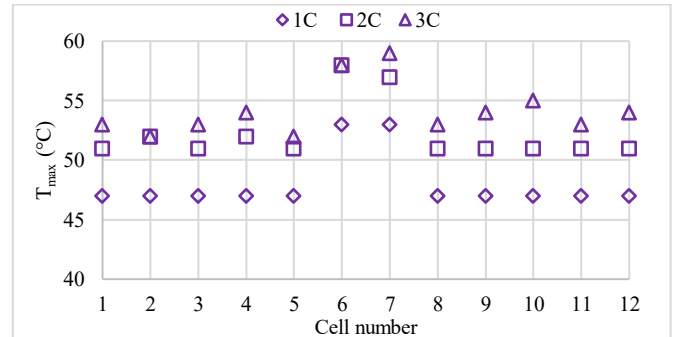


Fig. 13. Peak temperature of battery pack under free convection BTMS at 1C, 2C and 3C discharge rates

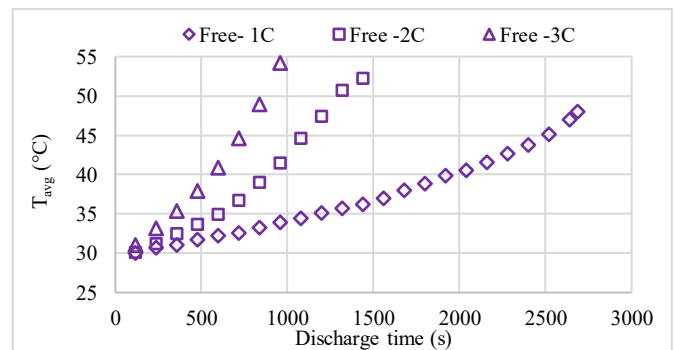


Fig. 14. Average temperature of battery pack under free convection at 1C, 2C and 3C discharge rates

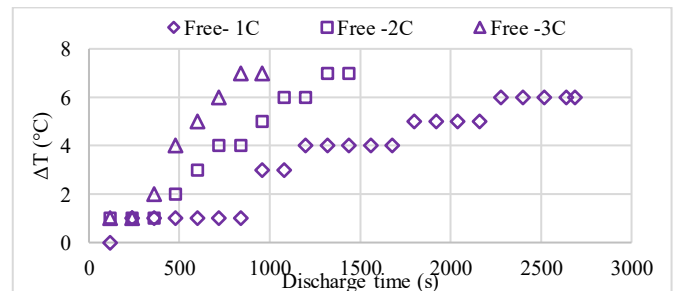


Fig. 15. Temperature uniformity of battery pack under free convection BTMS at 1C, 2C and 3C discharge rates

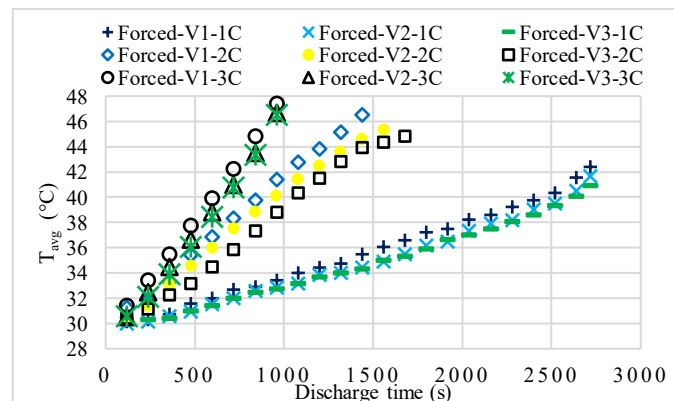


Fig. 16. Average temperature of battery pack under forced

convection BTMS at 1C, 2C and 3C discharge

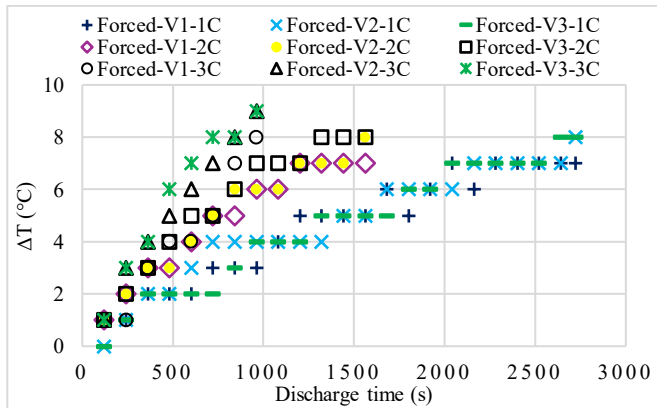


Fig. 17. Temperature uniformity in battery pack under forced convection BTMS at 1C, 2C and 3C discharge rates

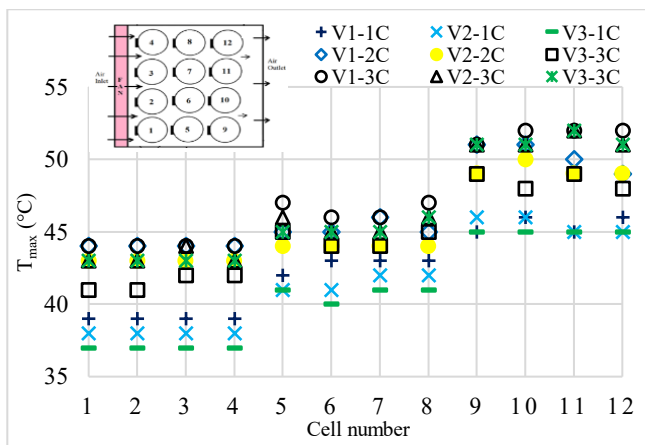


Fig. 18. Peak temperature of battery pack under forced convection BTMS at 1C, 2C and 3C discharge rates

3.3 Hybrid Heat Pipe Based BTMS.

The addition of flat heat pipe to convectional forced convection based BTMS improved the temperature uniformity of battery pack. The ΔT values of battery pack in all cases except at 3C and V3 combination, were within ideal limit of 5°C. In all nine test cases, the ΔT and T_{max} were within acceptable limits of 8°C and 50°C respectively. Increasing air velocity has adverse effect on temperature uniformity in hybrid system however increase in the value of ΔT was lower as compared to convection forced convection BTMS. The variation of average temperature, temperature uniformity and peak temperature can be seen in Fig. 19, Fig. 20 and Fig. 21 respectively. Although peak temperature is slightly lower in hybrid case, but still the last row cells i.e. 9, 10, 11 and 12 are critical cells in hybrid system as was the case with forced convection. The voltage of battery pack in discharge processes at 1C, 2C and 3C with air inlet velocity of V3 (5.5 m/sec) reached cut-off voltage at about 2810, 1560 and 960 seconds respectively. The time to discharge battery pack was improved in hybrid case as compared to free and forced convection. The

increase in discharge time indicates improvement in discharge cycle of battery cells.

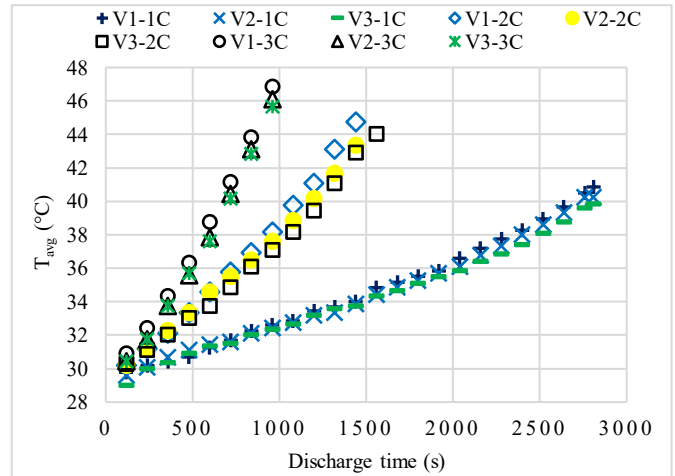


Fig. 19. Average temperature of battery pack under hybrid heat pipe assisted BTMS at 1C, 2C and 3C discharge rates

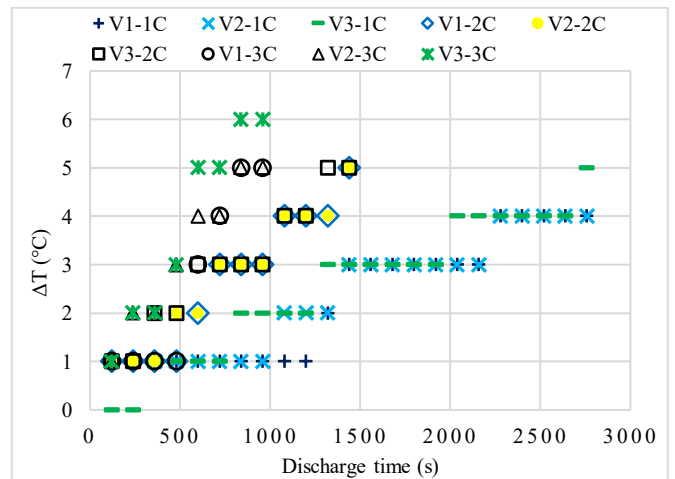


Fig. 20. Temperature uniformity in battery pack under heat pipe assisted BTMS at 1C, 2C and 3C discharge rates

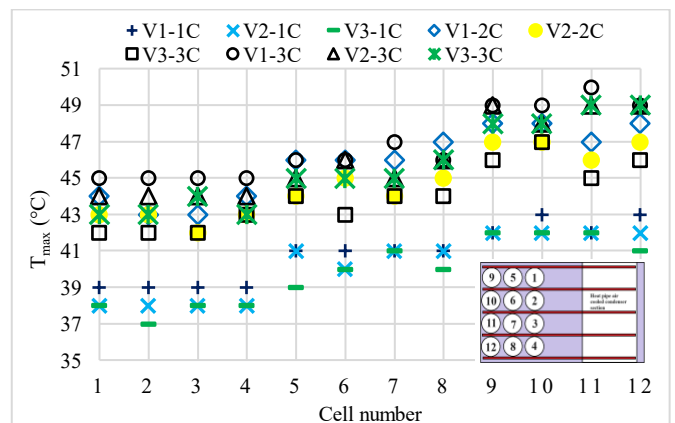


Fig. 21. Peak temperature of battery pack under hybrid heat pipe assisted BTMS at 1C, 2C and 3C discharge rates

3.4 Comparison Results

The cooling performance of free, forced and hybrid BTMS in terms of average temperature, peak temperature and

temperature uniformity have been investigated. As can be seen in Fig. 22, there was a slight reduction in average temperature at (T_{avg}). The highest average temperature was 54°C for free convection at 3C, 47°C for forced convection at 3C and V1 (3.6 m/s) air inlet velocity and 47°C for hybrid heat-pipe based system at 3C and V1 air inlet velocity. Higher average temperature values were observed at lower air velocities and higher discharge rates. The peak temperature (T_{max}) measured at end of discharge process in hybrid systems as compared to forced convection and free convection can be seen in Fig. 23. There was reduction of about 2°C to 3°C in hybrid case as compared to forced convection. This reduction may seem small, but it is very significant as for every 1°C increase in operating range, Li-ion battery life reduced by two months [47]. The highest peak temperature was 59°C for free convection at 3C, 52°C for forced convection at 3C and V1 (3.6 m/s) air inlet velocity and 50°C for hybrid heat-pipe assisted system at 3C and V1 air inlet velocity. When performance of cooling systems was analyzed based on temperature uniformity, the hybrid system provided a way better control as compared to forced and free convection. The reduction in ΔT in hybrid cooling was about 2°C to 4°C as compared to free and forced convection. The hybrid system was able to maintain both peak temperature and temperature uniformity within acceptable operating limits of 50° C and 8° C respectively. Moreover, in majority test cases, the temperature uniformity in hybrid system was under ideal limit of 5° C. Summary results under various discharge rates and air inlet velocities for free, forced and hybrid cooling systems are shown in Table 6. Tests were divided into four thresholds, two ideal (I) and two acceptable (A), one each for peak temperature and temperature uniformity. The combinations of ideal (I) and acceptable threshold (A) were made to evaluate failure and success of systems under various operating conditions. At acceptable threshold, the free convection failed in all three cases of testing while forced convection failed in eight tests out of nine tests. The heat pipe-assisted hybrid system for acceptable limits was successful in all nine tests and thus outperformed the other two in terms of both peak temperature and temperature uniformity control. The significant improvement in performance was observed at all levels and tests for heat pipe-based hybrid battery cooling system as compared to other two convectional cooling systems i.e. free convection and forced convection.

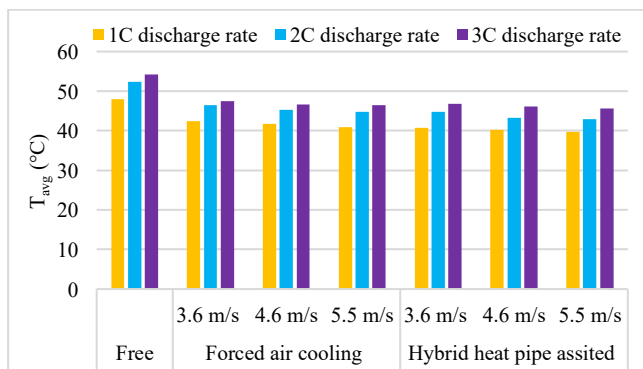


Fig. 22. Average temperature at end of discharge process in Table 6. Summarized results indicating ability of battery thermal management systems to keep peak temperature and

free, forced and hybrid heat pipe assisted BTMS

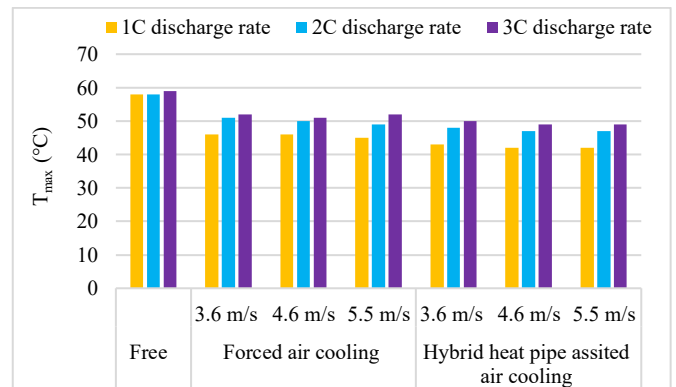


Fig. 23. Peak temperature in free, forced and hybrid heat-pipe assisted BTMS

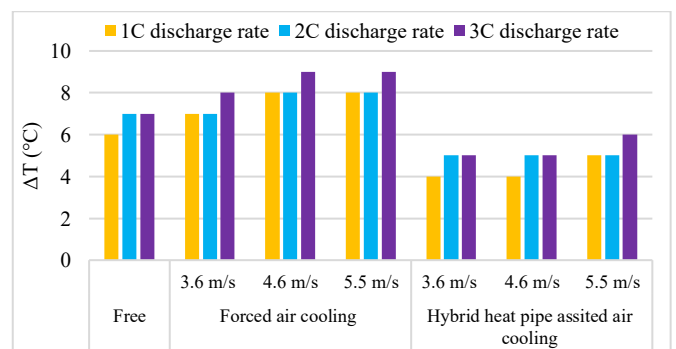


Fig. 24. Temperature uniformity in free, forced and hybrid heat-pipe assisted BTM

3.5 Uncertainty Analysis

The testing procedure was controlled, and equipment were calibrated before experimentation to ensure that errors do not exceed baseline, but during experimentation certain uncertainties are always present. Mainly uncertainty in present work were due to variations in thermal joint resistance, thermal conductivity, thermocouple response and environmental heating or cooling. The overall uncertainty was controlled within $\pm 10\%$. The overall uncertainty R of experimental work was predicted with method by Moffat [48], where each measurement is $X_i \pm \delta X_i$, and δX_i represent uncertainty. R is described as $R(X_1, X_2, \dots, X_n)$, and overall uncertainty was predicted using Eq. 7.

$$\delta R = \left\{ \sum_{i=1}^n \left(\frac{\delta R}{\delta X_i} \delta X_i \right)^2 \right\}^{1/2} \quad (7)$$

Although error cannot be reduced to zero, but steps were taken during experimentation to isolate and reduce random errors, and repeatability of testing ensured that errors are minimized.

temperature uniformity within ideal and acceptable threshold limits

BTMS	(PT) Threshold limits of Peak temperature		(TU) Threshold limits of Temperature uniformity		BTMS performance (PT) $\cap$ (TU)		
	Ideal (I)	Acceptable (A)	Ideal (I)	Acceptable (A)	PT-I $\cap$ TU-I	PT-A $\cap$ TU-I	PT-A $\cap$ TU-A
	(T $\leq 40^{\circ}\text{C}$)	(T $\leq 50^{\circ}\text{C}$)	($\Delta T \leq 5^{\circ}\text{C}$)	($\Delta T \leq 8^{\circ}\text{C}$)			
Free- 1C	fail	fail	fail	success	fail	fail	fail
Free- 2C	fail	fail	fail	success	fail	fail	fail
Free- 3C	fail	fail	fail	success	fail	fail	fail
Forced-V1-1C	fail	success	fail	success	fail	fail	success
Forced-V2-1C	fail	success	fail	success	fail	fail	success
Forced-V3-1C	fail	success	fail	success	fail	fail	success
Forced-V1-2C	fail	fail	fail	success	fail	fail	fail
Forced-V2-2C	fail	success	fail	success	fail	fail	success
Forced-V3-2C	fail	success	fail	fail	fail	fail	fail
Forced-V1-3C	fail	fail	fail	success	fail	fail	fail
Forced-V2-3C	fail	fail	fail	success	fail	fail	fail
Forced-V3-3C	fail	fail	fail	fail	fail	fail	fail
Hybrid-V1-1C	fail	success	success	success	fail	success	success
Hybrid-V2-1C	fail	success	success	success	fail	success	success
Hybrid-V3-1C	fail	success	success	success	fail	success	success
Hybrid-V1-2C	fail	success	success	success	fail	success	success
Hybrid-V2-2C	fail	success	success	success	fail	success	success
Hybrid-V3-2C	fail	success	success	success	fail	success	success
Hybrid-V1-3C	fail	success	success	success	fail	success	success
Hybrid-V2-3C	fail	success	success	success	fail	success	success
Hybrid-V3-3C	fail	success	fail	success	fail	fail	success
* $\cap$ -Intersection of results							

4. Conclusion

The experimental investigations were carried out to analyse the enhancement in the performance of conventional forced air-cooling system by insertion of heat pipes. The comparative results in terms of peak temperature, temperature uniformity and average temperature were presented. As can be seen in Table 6, out of the nine cases of convectional forced air cooling, eight failed in keeping parameters within acceptable limits. The failures were mainly at higher air inlet velocities as at higher velocities front cells are cooled at higher rate thereby increasing non-uniformity of temperature within battery pack. This non-uniformity of temperature within battery pack was reduced when heat pipes were inserted, and results improvement was also observed in peak temperature. The following conclusions can be drawn from the results:

- Conventional forced convection cooling was successful in maintaining peak temperature and temperature uniformity within acceptable limits in about 45 percent of test cases. The control of peak temperature was better at higher air velocity, but temperature was more uniform at lower air velocity and discharge rate.
- With flat heat pipe insertion (hybrid system), the system was able to control peak temperature and temperature uniformity within acceptable limits. The success rate in maintaining peak, average and temperature uniformity within

acceptable limits in hybrid heat pipe assisted battery thermal system was 100 percent.

- The peak temperature of temperature of battery cells is reduced by addition of heat pipe. The reduction in peak temperature ranges from 2°C to 4°C and 10°C to 16°C as compared to forced and free convection respectively. This reduction may not seem much but even a 1°C drop in temperature effect battery life significantly.
- The main benefit of heat pipe addition was in terms of temperature uniformity. The heat pipe assisted cooling was able to restrict maximum temperature difference within battery pipe to optimum level of 5°C in majority of cases. This was not possible with conventional forced convection and values were as high as 9°C . Higher values promote early degradation of a few cells which reduce overall battery pack life.

Heat pipes are utilized in various electronic components but their use in electrical vehicles is still a challenge. This passive system of heat extraction when combined with active cooling systems can overcome certain inherent limitations of active systems and enhance their performance. The hybrid system presented was mainly designed to compare convectional and heat pipe-assisted hybrid system of cooling in simplest way possible. Their practical utilization in EVs is still under research. The future work would be to modify and use present heat pipe assisted system with liquid cooling which may

further enhance performance of heat pipe assisted thermal management system.

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N/A

Author Contributions

All authors were responsible for the conceptualization, validation, resources, data curation, software development, and project administration. They jointly contributed to the methodology, formal analysis, investigation, original draft preparation, review and editing, visualization, supervision, and funding acquisition. All authors have read and agreed to the published version of the manuscript.

Conflict of Interest

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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