ISSN 1330-3651 (Print), ISSN 1848-6339 (Online)
https://doi.org/10.17559/TV-20240522001645
Original scientific paper

Optimizing Lithium-Ion Battery Thermal Management using CFD and Nano-Cooling

Ramprabu JAYARAMAN*, Kandasamy VARATHARAJULU, Vairavel MADESHWAREN

Abstract: This study discusses the airflow for lithium-ion batteries during the charging process. The methodologies are designed for deployment on an inexpensive Battery Thermal Management System (BTMS). Hence, three separate phase model-based approaches for SOC estimation have been proposed and established, encompassing LIB modeling and identification techniques. This paper also examines the power intensity of a lithium-ion battery by combining and individual with the aforementioned methodologies to achieve better results. This research utilizes Computational Fluid Dynamics (CFD) to model and analyze fluid flow and heat transfer within lithium-ion batteries. It also explores the use of Phase Change Materials (PCMs) to enhance thermal management by regulating temperature through phase transitions. Together, CFD and PCMs aim to improve battery performance and safety. The best cooling efficiency was found to be achieved with a dielectric fluid, AL_2O_3 Nano fluid cooling system, and PCM nanofluid mixture. The battery reached 35 °C during the experimental cooling process and 34 °C during the simulation. The dielectric fluid with AL_2O_3 nano fluid cooling system and PCM reached a maximum temperature of 45 °C, while forced air and dielectric cooling reached maximums of 46 °C and 46 °C, respectively. The results are based on modern cooling efficiency techniques such as Phase Change Material (PCM) and Nano cooling fluids.

Keywords: battery thermal management system; lithium iron battery; nanofluids; PCM; state of charge; thermal management

1 INTRODUCTION

The primary impediments to the widespread use of lithium-ion battery-equipped public transportation systems are still safety, calendar life and cycle costs, and efficiency. However these difficulties are compounded by the impact of heat in the battery, such as low-temperature efficiency, runaway temperature, power or capacity decline, and electrical disequilibrium among several cells in a battery pack. Meanwhile most batteries should ideally run at their ideal average temperature within a relatively small differential range. In order to prevent the battery from ever reaching the thermal runaway temperature, the rate of temperature dissipation must be quick enough throughout the construction of a battery cell, pack, or system. The irreversible breakdown of the battery's composition-damage to the electrodes and electrolyte - begins when the temperature approaches the thermal runaway point. These breakdown processes are often exothermic, or heat-producing. It suggests that when the thermal runaway point is achieved, the temperature rises steadily. It starts an irreversible chain reaction that leads to the cell's eventual self-heating demise. The primary issues and disadvantages for various applications are temperature swings and the battery cell's non-uniform temperature. Lithium-ion cell thermodynamics are challenged by the inclusion of multiphase and single-phase solids, and also liquid electrolyte mixtures. The primary focus of this study is optimizing thermal management systems for lithium-ion batteries by evaluating the effectiveness of different cooling methods. It specifically investigates the performance of Computational Fluid Dynamics (CFD), Phase Change Materials (PCMs), and nano-cooling fluids. The goal is to enhance temperature regulation, improve battery efficiency, and extend operational lifespan. The study aims to identify the most effective cooling strategy to mitigate overheating and improve overall battery safety and performance.

In addition to the primary electrochemical processes, mixing and phase changes can also result in heat production. Precise estimation of the overall heat-generation rate is the first step towards predicting the temperature characteristics of individual cells and a battery system [1]. Thus, it is crucial to quantify the rise in temperature as well as the heat that battery cells absorb or dissipate. In general temperature has an impact on a number of battery characteristics, including how well the electrochemical system functions, power ability, charge acceptance, energy capability, round-trip efficiency, and dependability, longevity, and lifetime cost. As the working temperature rises, capacity increases, but so does the degree of capacity fading. However, low operating temperatures are associated with poor performance [2]. Furthermore, a system or pack's longevity is greatly shortened by an extreme or uneven temperature rise. Because of the elevated temperatures during discharge and charge, there is a chance that the temperature will raise over acceptable bounds, which will reduce battery performance.

The maximum lifetime of battery systems, cells, and packs can be impacted by localised degradation caused by uneven distribution of temperature in battery packs [3]. Depending on where each stack is located and the surrounding environment, the cooling and heating techniques may result in an unequal temperature distribution [4]. This may lead to an imbalanced system, which would limit its maximum potential and shorten the battery pack's lifespan [5]. This has an impact on the pack's operating lifetime, for example in electrical cars. Since the performance of each cell is dependent on its unique conditions and operating temperature, a Battery Thermal Management System (BTMS) is essential to keeping the pack's temperature within a certain range [6]. During both the discharge and charge processes, heat is produced and discharged from the cell. The temperature of the pack or cell and the entire battery system will rise if the heat produced therein is not effectively expelled. The amount of heat generated overall from a battery pack when it is under load determines the cooling system's dimensions and design [7]. The characteristic levels of Li-ion batteries vary depending on their kind; for example, the heat generated within the cell is represented by the battery heat flux measurement [8]. Accurate measurement of these data is necessary for the formulation of an appropriate BTMS in a thermal management plan [9]. According to [10] passive systems are basic and do not make extensive use of mechanical and electrical equipment, such as electric controllers and fans. Both air and liquid cooling methods are available for Phase Change Materials (PCM). Due to its superior cooling efficiency, liquid cooling dominates the market share [11]. In recent years, thermal management systems for batteries and thermal analysis of high-power lithium-ion battery cells and modules have been the subject of extensive research. The longevity, safety, and efficiency of the battery were entirely dependent on the heat management technology explained in this section [12]. Meanwhile this thermal management method was deemed cost effective, and several experiments were undertaken on dielectric and nanofluid coolants. However, in this study, the performance of the battery was evaluated using dielectric with nanofluid coolant, dielectric with PCM, and finally dielectric + nanofluid coolants + PCM to evaluate the efficiency of velocity, thermal distribution, conduction, convection, and radiation using the tool Computational Fluid Dynamics under the sections of design, pre-processing, and post-processing. Using the aforementioned approach, this research will deliver unique insights through the incorporation of PCM [13].

Finally, all the existing literature demonstrates the variety of cooling techniques to show how the temperature changes during fast charging. It was discovered that a dielectric fluid, AL_20_3 Nano fluid cooling system, and PCM nanofluid mixture produced the best cooling efficiency. The objectives of this study are to optimize thermal management in lithium-ion batteries by integrating Computational Fluid Dynamics (CFD), Phase Change Materials (PCMs), and nano-cooling fluids. The study aims to use CFD simulations to model and predict thermal behavior and heat distribution within the battery system. It evaluates the effectiveness of PCMs in regulating temperature through phase transitions and assesses the performance of nano-cooling fluids in enhancing thermal dissipation. The research compares these advanced cooling techniques with conventional methods to identify the most effective approach for improving battery performance and safety under varying operational conditions.

2 MATERIALS AND METHODS

The study investigates the cooling system component for maintaining a consistent temperature in lithium-ion batteries. Twelve-cell batteries were used to investigate charging and discharging conditions, and thermal behavior was determined using 2.7 V current. A 3D-printed battery cap was generated using the Fluid Deposition Method (FDM), and six distinct thermistors were found in the charging and discharging conditions. The Arduino board was used for analysis. Fig. 1 demonstrates the TMS setup and the components.

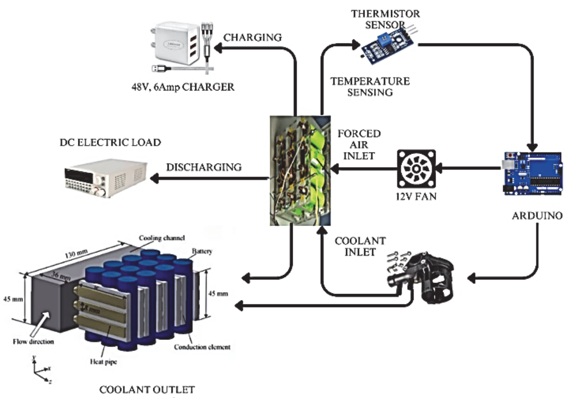


Figure 1 TMS experimental setup components diagram

2.1 Components

This research investigates the importance of a cooling system component in maintaining a consistent temperature in lithium-ion batteries. The experiment uses 12-cell lithium-ion batteries and 2.7 V current to study charging and discharging conditions. The outcomes of cell behavior were examined using PCM and dielectric fluid then using a combination of nano cooling fluids, PCM, CFD and dielectric fluid.

2.2 Al_2O_3 Nano Fluid Preparation

Ultrasonic sintering is a widely used method for fluid sintering, ensuring long-lasting durability. It uses magnetic pellets as magnets and can be adjusted in temperature or speed. For nano fluid sintering, a constant speed of 1000 revolutions per minute is used. A 1.5-liter glass beaker is filled with distilled water, 0.08% Ti, and 0.02% tergitol to create a stable mixture.

2.3 Phase Change Material

Phase Change Materials (PCMs) are used to store and release heat in batteries. They change their physical state to absorb heat from a battery, which melts at a specific temperature. When external cooling occurs, the phase returns to solid, releasing latent heat energy. With about 200 different PCMs, they are effective coolants due to their large heat storage capacity and low operating costs. This experiment uses a 60 V, 30 Ah battery container in a closed environment, connected to a charge controller/DC electronic load to maintain constant power, voltage, and current. Minute-by-minute readings are obtained during charging and discharging processes, ensuring consistent ampere rate. A thermistor sensor is used to monitor temperature, with six used in the experiment, and recorded on a screen. Moreover, integrating Phase Change Materials (PCMs) and nanocooling fluids posed challenges such as ensuring uniform distribution and preventing phase separation. These issues were addressed by optimizing PCM formulation for better thermal conductivity and incorporating advanced mixing techniques for nanocooling fluids. Additionally, robust containment strategies were developed to maintain stability and effectiveness under various operating conditions. These solutions ensured enhanced performance and reliability of the thermal management system.

2.4 Heat Pipe Cooling Method

Heat pipe cooling techniques are used to control battery temperature, using inexpensive, low-maintenance, passive devices with excellent heat conductivity. Flat heat pipes with a thermal conductivity of 8212 W/m.K. and 100 W cooling power were used to construct a heat pipe TMS for LiBs. Although they can lower temperature distribution by 17.7%, this reduction is insufficient for high power applications.

2.5 Computational Fluid Dynamics

A Computational Fluid Dynamics (CFD)-based periodic air-cooling technique is being used to improve the temperature distribution of lithium-ion batteries in large-capacity energy systems. The method improves heat dissipation, thermal homogeneity, and airflow disturbance. The directed airflow approach is more energy-efficient than periodic air-cooling as it lowers airflow temperature and increases airflow rate. The battery's shape can be determined by repeatedly repeating its constituent parts perpendicular to the flow. The CFD simulations were rigorously validated by comparing results with experimental data obtained from prototype testing under controlled conditions. Discrepancies were minimized through iterative adjustments to the simulation parameters and boundary conditions. Additionally, the simulations were cross-verified against industry standards to ensure accuracy and reliability, confirming that the models accurately reflect real-world performance.

The experimental setup for the proposed cooling system for LIB (Lithium-Ion Battery) pack dielectric fluid with Al_2O_3 (aluminum oxide) + PCM (Phase Change Material) involves the configuration and arrangement of various components and instruments to investigate the cooling performance of the system given in Fig. 2.

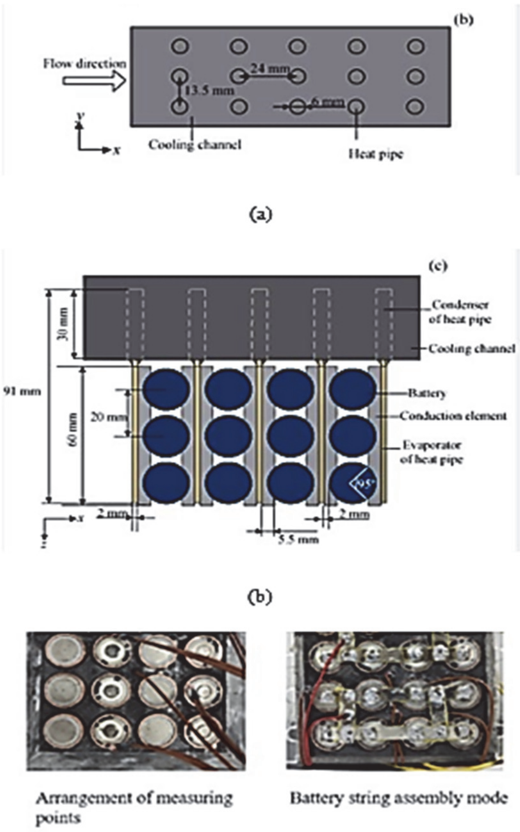


Figure 2 Experimental setup of proposed cooling system for LIB pac dielectric fluid with Al_2O_3 + PCM

By adapting to various battery sizes and configurations, from tiny electronic gadgets to massive electric vehicle batteries, the proven heat management system demonstrates significant scalability. Its excellent thermal regulation, which successfully controls heat under a range of working situations, demonstrates its practical application. The integration of Phase Change Materials (PCMs) with advanced Computational Fluid Dynamics (CFD) modeling in this system provides improved cooling performance when compared to current commercial alternatives. Improved thermal stability and a lower chance of overheating are two benefits of these characteristics. It is a competitive substitute for existing market solutions since it offers improvements in safety and battery lifespan in real terms. When it is used, thermal management in a variety of applications may become more dependable and effective.

3 METHODS

The method suggests an important cooling system component for maintaining the lithium-ion battery at a consistent temperature. The nominal voltage is 3.60, with a total capacity of 60 V and 30 Ah. Twelve-cell lithium-ion batteries were used to investigate charging and discharging conditions, and thermal behavior was determined using 2.7 V current. The temperature-analyzed cycle system was used to analyze maximum charging and minimum discharging levels. The cell behavior was examined using PCM and dielectric fluid, and a combination of nano cooling fluids, PCM, and dielectric fluid. The 12×17 configuration has a total capacity of 60 V and 30 Ah. The Fluid Deposition Method (FDM) was used to generate a 3D-printed battery cap, which can conduct heat up to 2600 °C. The battery is held in place by a 3.6 mm-diameter copper tube and a 400×200 mm glass cover. 12 V forced air passes through the enclosure, containing PCM-containing storage coolant oil. Six distinct thermistors were found in the charging and discharging conditions. The Arduino board was used for analysis, containing a lithium battery assembly system, water pumping system, cooling system, CFD and thermal energy waste sensor system are defined in Fig. 3.

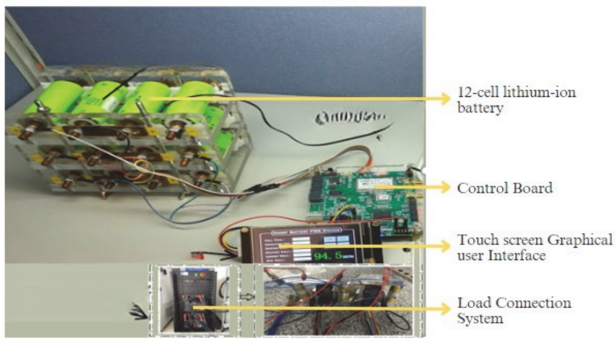


Figure 3 Experimental set up

A thorough 3D model of the lithium-ion battery, including its internal workings and cooling systems, was used in the CFD setup. In order to accurately capture heat transmission, factors included mesh resolution and a revised mesh around crucial locations. Boundary conditions with particular characteristics for Phase Change Materials (PCMs) and nanocooling fluids were employed in the simulations to represent realistic thermal loads and heat dissipation rates. Transient analysis was used in the solver parameters to take dynamic thermal effects into consideration. To verify model accuracy, validation involved comparing simulation results with experimental data.

4 RESULTS AND DISCUSSION

The results were obtained utilizing Computational Fluid Dynamics (CFD) to study air velocity, fluid temperature, and nanoparticle values in a Panasonic

18650P Lithium Ion Battery. SOLIDWORKS 2020 was used for modelling, and the IGES format was used for accurate estimation. The experiment simulated the battery's voltage, charging and discharging conditions, fluid flow value, battery material properties, and velocity flow rate. The main coolants used were dielectric fluid coolant system, AL_2O_3 nano fluid cooling system, and a combination of these coolants with PCM. Two methods were used to analyze the coolant process in lithium-ion batteries: simulation and experimentation. The efficiency of the LIB was validated using the temperature and time data from both simulations and experiments.

4.1 Effects of Simulated and Experimental Analysis of Forced Air Cooling during the Charging Conditions

This section examines the computational and experimental studies of forced air cooling under charging circumstances. Here, forced air cooling is critical for transporting heat and decreasing heat in batteries. Thermal cooling is maintained by the contact surface's temperature and time of battery. It is critical to analyse the flow route, fluid characteristics, and flow conditions.

For this experimental and simulation analysis of CFD in battery, the temperature and time were calculated in forced air-cooling during charging process. The temperature taken for this analysis for both experimental and simulation was from 0 °C to 40 °C and time interval was 0, 5, 10, 15, 20 and 25 mins. The performance was calculated in equal interval of 5 mins. During that interval time, the temperature varies to 1 or 2 C in both simulated and experimental analysis. The minimum value of temperature recorded in simulation analysis was 30 °C at 0 minutes and maximum value was 36 °C at 25 mins. The greatest value of temperature identified in experimental analysis was 32 °C at 0 minutes and maximum value attained was 37 °C at 25 mins. So therefore both experimental and simulation analysis of CFD in forced air-cooling during charging process achieved their maximum and minimum value at the same time.

4.2 Effects of Simulated Analysis of Forced Air Cooling during the Discharging Conditions

This section discussed forced air cooling during battery draining in both experimental and simulated analyses using CFD. When discharging a battery in this part, active air cooling can fulfil cooling requirements at a modest discharge rate, but it cannot keep the battery temperature below the safety limit. The temperature and time spent in forced air-cooling during the discharging process were calculated for this experimental and simulation investigation of CFD in batteries. The temperature range for this investigation, both experimental and simulated, was 0 °C to 40 °C, with time intervals of 0, 5, 10, 15, 20, and 25 minutes. The performance was calculated at five-minute intervals. During that timeframe, the temperature varies by 1 or 2 degrees Celsius in both simulated and experimental analyses. The lowest temperature measured in the simulation study was 30 °C at 0 minutes, while the highest was 36 °C at 25 minutes. The highest temperature value found in the experimental study was 32 °C at 0 minutes, while the highest value obtained was 37 °C after 25 minutes. As a result, both experimental and simulation analyses of CFD in forced air-cooling throughout the discharging process, attained their maximum and minimum values simultaneously.

4.3 Effects of Simulated and Experimental Analysis of Dielectric Cooling during the Charging Conditions

This section addresses experimental and simulated analysis of dielectric cooling systems when they are being charged. It emphasizes that high discharge and charge rates are made possible by optimizing the cooling surface area of the battery pack by soaking it in dielectric fluid. The experimental and simulation investigation of CFD in batteries involved calculating the temperature and time variation in dielectric cooling during the charging process. The temperature range for this study, both experimental and simulated, was 0 °C to 40 °C, with time intervals of 0 to 25 minutes. The performance was assessed at five-minute intervals. During that timeframe, both simulated and experimental assessments show temperature variations of 1 to 2 degrees Celsius. The lowest temperatures recorded in the simulation and experimental studies were 30 °C at 0 minutes and 32 °C at 0 minutes, respectively, while the highest were 36 °C and 37 °C at 25 minutes. As a consequence, both experimental and simulation evaluations of CFD in dielectric cooling throughout the charging process, reached their maximum and minimum values simultaneously.

4.4 Effects of Simulated Analysis of Dielectric Cooling during the Discharging Conditions

The consequences of experimental and simulated study of dielectric cooling under discharging situations were covered in this section. Until all thermal energy is gone from the battery and the discharge process is complete, it will continue. In this mode, the battery and the supplied temperature discharge are linked to the power outputs of both modules.

The simulation and experimental analyses for dielectric cooling method were plotted. In experimental cooling, the battery reached minimum temperature of 28 °C at 0 minutes and in simulation 30 °C temperature was reached by using the dielectric cooling method at discharge process. Likewise the maximum value was attained in 25 minutes in both experimental and simulation of CFD analysis and the temperature value was 36 °C and 37 °C. It is crucial to comprehend that a battery constantly discharges while it is not receiving direct power since it is dependent on temperature and time when integrating computational fluid dynamics.

4.5 Effects of Simulated Analysis of PCM Cooling during the Charging Conditions

The effects of experimental and simulated study of PCM cooling throughout the charging process were the main topic of this section. This section briefly discussed how PCM, particularly during the charging process, may absorb a significant amount of heat without experiencing extreme temperature swings during the solid-liquid phase shift. With CFD, it is possible to maintain consistent battery temperature regulation within the phase transition temperature without requiring additional energy consumption. In experimental cooling the battery reached 33 °C temperature and in simulation 33 °C temperature is reached by using the PCM cooling method during charging process. Finally temperature maintained in melting point for specific duration also increase in temperature takes time. PCM is use as conductor, buffer in hot battery handling unit.

4.6 Effects of Simulated Analysis of Forced PCM Cooling during the Discharging Conditions

This section focused on the effects of simulated and experimental analysis of PCM cooling system during the discharging condition. The simulation and experimental analyses for PCM during discharge were plotted. In experimental cooling, the battery reached 34 °C temperature and in simulation 33 °C temperature was reached by using the PCM cooling method during discharging process with the help of CFD analysis. At last both experimental and simulation evaluations of CFD in PCM cooling throughout the discharging process, reached their maximum and minimum values at the same time.

4.7 Effects of Simulated Analysis of Al_2O_3 Nanofluid Cooling during the Charging Process

In this part, the effects of experimental and simulated study of Al_2O_3 nanofluid cooling under charging circumstances were covered. According to this part, Al_20_3 nanofluid is anticipated to be a potential coolant option for the thermal management system of the next high temperature dissipation in battery. Both the experiment and the simulated analysis used Al_2O_3 Nanofluid at a 1:1 ratio. In the simulation, the battery reaches 34 ^{0}C during the charging process by utilizing Al_2O_3 nanofluid, whereas in the experiment, the battery reaches 35 ^{0}C. This is evaluated by CFD data. Therefore, the relative coolants of Al_2O_3 nanofluids are almost constant for both simulated and experimental analysis at 1:1 ratio level during the charging level.

4.8 Effects of Simulated Analysis of Al_2O_3 Nanofluid Cooling during the Discharging Conditions

This part provides a comprehensive description of the impacts of the experimental and simulated study of Al_2O_3 nanofluid cooling during the discharging conditions. Plots of simulational and experimental evaluations for the Al_2O_3 nanoparticle combination during discharge. The battery reached 35 °C during the experimental cooling process and 34 °C degrees during the simulation when the Al_2O_3 combination of nanofluid cooling technique was used during the discharging process. At last, the experimental analysis of AL_2O_3 nanoparticle during discharging using CFD attained high temperature cooling effect compared to simulation analysis.

4.9 Effects of Dielectric Fluid with Al_2O_3 Fluid Cooling System during Charging Process

This section investigates the effects of dielectric fluid with Al_2O_3 fluid cooling system during charging. The simulation and experimental analyses were plotted for Dielectric Fluid with Al_2O_3 Fluid with 1:1 mixture. In experimental cooling, the battery reached 35 °C temperature and in simulation, 34 °C temperature was reached by using Dielectric Fluid with Al_2O_3 nanofluid mixture for cooling method during charging process using CFD.

4.10 Effects of Dielectric Fluid with Al_2O_3 Fluid Cooling System during Discharging Process

This section focused on the effects of dielectric fluid with Al_2O_3 Fluid cooling system during discharging process using CFD. The simulation and experimental analyses were plotted for Dielectric Fluid with Al_2O_3 Fluid of mixture. In experimental cooling, the battery reached 36 °C temperature and in simulation 35 °C temperature was reached by using Dielectric Fluid with Al_2O_3 Fluid mixture of 1:1 nanofluid cooling method during discharging process.

5 EXPERIMENTAL RESULTS AND DISCUSSION

This section mainly investigated the PCM cooling system, Dielectric fluid + AL_2O_3 Nano fluid cooling system, and Dielectric fluid + with AL_2O_3 Nano fluid cooling system + PCM in both charging and discharging process with different voltage and time.

5.1 Impacts of Air Cooling

In this method, the experiment was carried out without any coolant, only by normal air cooling till the end. The experiment was started at the battery module voltage of 72 V and the initial temperature was noted as 30 °C, then the setup was undergone to discharge process up to 55 V of battery pack. The maximum temperature reached during this full discharge process was found to be 45 °C for 80 minutes of duration. In this analysis part, the battery module was kept in a closed environment without any cooling system. The experimental results of the different cooling systems will be compared with these readings to find the effectiveness of different cooling system, as shown in Tabs. 1 and 2. During the test cycle, after the discharge process gets completed, the setup remained undisturbed for a while to reach the normal room temperature then the charging process was carried out from the initial stage. The battery module has initial temperature of 34 °C and after completion of the charging process the maximum temperature rise reached up to 49 °C for a total time of 55 minutes without cooling system part.

Total twelve different cases were analyzed, such as using natural air cooling, forced air cooling, water cooling, PCM cooling system, Dielectric fluid + Al_2O_3 Nano fluid cooling system, and Dielectric fluid + with Al_2O_3 Nano fluid cooling system + PCM methods under both charging and discharging conditions. Thus from all the above cases, Dielectric fluid + with Al_2O_3 Nano fluid cooling system + PCM component dissipates heat well compared to all other techniques. In all the cases, first section of the chart shows temperature raise noted during discharging process and followed by charging process.

Table 1 Temperature during charging vs time in min

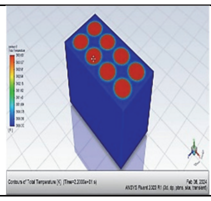
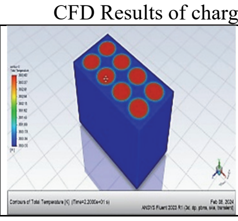
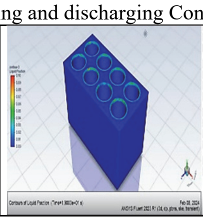
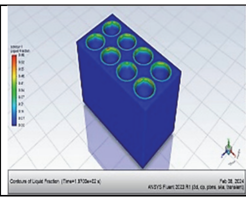
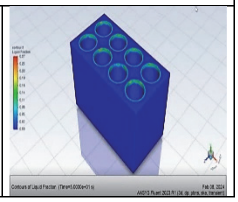
Time in Minutes	Forced air-cooling		Dielectric cooling		PCM		Al_2O_3 Nanoparticle		Dielectric Fluid with Al_2O_3 Fluid of nanoparticle	
	Sim link	Exp	Sim link	Exp	Sim link	Exp	Sim link	Exp	Sim link	Exp
0	30	32	30	33	28	29	28	30	28	29
5	32	33	31	33	29	30	29	31	29	31
10	33	34	32	34	30	31	30	31	30	31
15	34	35	33	35	31	32	32	32	32	32
20	35	36	35	35	32	32	33	34	33	33
25	36	37	36	37	33	33	34	35	34	35
CFD Results of charging and discharging Conditions										
										

Table 2 Temperature during discharging vs time in min

Time in Minutes	Forced air-cooling		Dielectric cooling		PCM		Al_20_3 Nanoparticle		Dielectric Fluid with Al_20_3 Fluid of nanoparticle	
	Sim link	Exp	Sim link	Exp	Sim link	Exp	Sim link	Exp	Sim link	Exp
0	30	32	28	30	28	29	28	29	28	29
5	33	33	29	30	28	29	29	31	29	30
10	33	33	32	33	29	30	30	31	30	31
15	34	35	34	35	29	31	32	32	32	32
20	35	36	35	36	31	32	33	34	33	34
25	36	37	36	37	33	34	34	35	34	36

5.2 Impacts Analysis of Dielectric Fluid Cooling System

In this section, the air was made to pass through the battery module at a speed of 1300 rpm using a cooling fan. This method was used in the initial stage of the battery cooling system in the EVs. As expected, the results of this method will be in good numbers as compared to the normal air-cooling method. This process was carried out without any coolants inside. The experiment was started at the battery module voltage of 80 V, and the initial temperature was found to be 36 °C. The test was made as discharge process until the battery voltage was reduced to 60 V and the temperature reached 45 °C after a period of 90 minutes.

After the discharge process was completed, the setup remained undisturbed for a while to reach the normal room temperature. Then the charging process is carried out. The battery module has a temperature of 45 °C, after the completion of the charging process up to 85 V the maximum temperature noise is found to be 45 °C for a total time of 65 minutes. The results of this method have shown that this cooling method is superior to the normal cooling method as results are provided in Tab. 3.

Table 3 Voltage and temperature during charging vs times in minutes

Time in Minutes	Forced air-cooling during discharging and Charging		Water-cooling during discharging and Charging		Al_2O_3 of Nanoparticle during discharging and Charging		AL_2O_3 nanofluids with PCM during discharging and Charging		Dielectric fluid + Al_2O_3 nanofluids [1:1] with PCM of Nanoparticle during discharging and Charging	
	Charging		Charging		Charging		Charging		Charging	
	Voltage in V	Temp in °C	Voltage in V	Temp in °C	Voltage in V	Temp in °C	Voltage in V	Temp in °C	Voltage in V	Temp in °C
0	56	32	54	32	54	28	54	28	55	28
10	58	34	55	33	56	28	56	28	56	29
20	59	34	56	33	59	30	59	30	58	30
30	60	36	58	36	60	31	60	31	60	31
40	61	37	59	38	62	32	62	32	62	32
50	64	38	60	40	63	33	64	33	65	33
60	66	39	61	41	64	34	68	34	68	34
70	69	40	62	42	66	36	70	36	71	35

5.3 Impacts Analysis of Dielectric with PCM Cooling Systems

In this part, water used as a coolant and made to cool down the battery, was found to be more effective as compared to air cooling. Here the water cooling will come under the active liquid cooling method. The liquid cooling method was the current employed method in EVs for their temperature uniformity and performance. The experiment was started at the battery module voltage of 80 V and the initial temperature was found to be 45 °C; then the setup was kept for discharge until the voltages got reduced to 60 V, and it reached the temperature of 55 °C after the period 75 minutes. After the completion of the charging process the body reaches 80 V, the maximum temperature raise is found to be 49 °C for a total time of 75 minutes. The results are given in Tab. 4 which is to be reached a good improvement in controlling the maximum temperature while compared to the air-cooling method, due to the lower performance when compared with the liquid cooling thus air-cooling method is found to be rarer in the recent year thus the upcoming new EVs are using only the liquid cooling methods.

Table 4 Voltage and temperature during discharging vs times in minutes

Time in Minutes	Forced air-cooling during discharging and Charging		Water-cooling during discharging and Charging		Al_2O_3 of Nanoparticle during discharging and Charging		AL_2O_3 nanofluids with PCM during discharging and Charging		Dielectric fluid + Al_2O_3 nanofluids [1:1] with PCM of Nanoparticle during discharging and Charging	
	Discharging		Discharging		Discharging		Discharging		Discharging	
	Voltage in V	Temp in °C	Voltage in V	Temp in °C	Voltage in V	Temp in °C	Voltage in V	Temp in °C	Voltage in V	Temp in °C
0	72	34	72	32	72	32	72	27	71	28
10	70	36	70	34	70	33	66	28	68	30
20	68	38	68	35	69	33	64	30	65	31
30	66	40	64	36	67	36	63	31	63	32
40	64	42	60	38	64	38	62	32	62	33
50	62	43	58	39	62	40	60	34	60	34
60	58	44	54	40	61	41	58	35	58	35
70	54	45	50	41	60	42	56	36	56	36

5.4 Impacts Analysis of Al_2O_3 Nanofluids

When it is under the active liquid cooling method there will be direct liquid cooling and indirect cooling. The proposed process will be labelled as indirect cooling method, as the liquid will not be in direct contact with the batteries. In this section, the coolant used was called to be nanofluid, 8 grams of nanoparticles mixed up with the distilled water. The experiment was started at the battery module voltage of 80 V and the initial temperature was found to be 45 °C. Then the setup was taken for discharge until battery voltages got reduced to 60 V. Here the temperature reaches 40 °C after the period of 80 minutes. After the discharge process got completed, the setup remained undisturbed for a while to reach the normal room temperature. The charging process was carried out at the initial stage the battery module has a temperature of 30 °C after the completion of the charging process until it reaches 75V, the maximum temperature raise is found to be 40 °C for a total time of 60 minutes. The charging process produces similar maximum temperature to the discharging process of the battery module. During charging a maximum temperature of 45 °C is reached likewise discharging also reached a maximum temperature of 35 °C.

Nanofluids are the recent trend in liquid cooling and have higher thermal conductivity than normal water. The results show that the maximum temperature reached in this method was the lowest one among the other methods which implies that nanofluid as coolant was effective while compared to the water as coolant and provides good results than any other methods.

5.5 Impacts Analysis of Al_2O_3 Nanofluids with PCM

In this section, the coolant used was called to be nanofluid with Al_2O_3 nanofluids with PCM of mixture, 15 grams of nanoparticles mixed up with the distilled water. The experiment was started at the battery module voltage of 80 V and the initial temperature was found to be 39 °C then the setup was runs to the voltages get reduced to 65V, and the temperature reaches 43 °C after the period of 90 minutes. After the discharge process gets completed, the setup was remained undisturbed for a while to reach the normal room temperature. Then the charging process was carried out at the initial stage the battery module has a temperature of 34 °C after the completion of the charging process until it reaches 80 V, the maximum temperature is found to be 40 °C for a total time of 70 minutes.

5.6 Impacts Analysis of Dielectric Fluid + AL_20_3 Nanofluids [1:1] with PCM

In this section, the coolant used was called to be nanofluid with AL_2O_3 mixture with PCM mixed up with the distilled water. The experiment was started at the battery module voltage of 80 V and the initial temperature was found to be 35 °C, then the setup was kept as it is after the voltages get reduced to 60 V the discharge unit is turned off and the temperature reaches 40 °C after the period 78 minutes. After the discharge process gets completed, the setup was remained undisturbed for a while to reach the normal room temperature then the charging process was carried out at the initial stage the battery module has a temperature of 35 °C after the completion of the charging process until it reaches 76 V, the maximum temperature is found to be 40 °C for a total time of 65 minutes.

Nanofluids are the recent trend in liquid cooling and have higher thermal conductivity than the normal water. Also among different combinations of Nanofluids, this Al_2O_3 with PCM plays the optimum role. To boost the cooling performance and temperature uniformity in a battery module under the proposed fast charging system, optimization research for better colling system was conducted in this proposed system.

5.7 Effects of Comparison Analysis Different Coolant Materials at Fast Charging Process

The PCM cooling system, the dielectric fluid + Al_2O_3 nano fluid cooling system, and the dielectric fluid + with Al_2O_3 nano fluid cooling system + PCM during rapid charging process with varied temperature are all compared in this part. The experimental results for the battery thermal management was shown in Tab. 5.

System with air cooling and liquid cooling were matched well with the simulation results. During the development of an optimization scenario cooling methods and also for different mixtures of nano-fluids, the temperature of the battery module during charging and discharging was considered for air, water, and nanofluid cooling. Similarly, the simulation results are closely mirrored the experimental outcomes, with only few minor differences. The dielectric fluid + with Al_2O_3 nano fluid cooling system + PCM has reached only a maximum temperature of 45 °C compared to forced air and dielectric cooling, which they have reached the maximum temperatures of and 46 °C respectively, during the fast charge process.

Table 5 Comparison between different coolant methods

	Air cooling system temp	Dielectric fluid Cooling system Setup	PCM cooling system Temp	Dielectric + AL_2O_3 Nano fluid [1:1] Cooling system temp	Dielectric fluid + with AL_2O_3 Nano Fluid cooling system + PCM temp
100	28	28	28	28	28
90	30	29	29	29	29
80	31	30	29	29	29
70	33	32	30	30	30
60	35	33	31	30	30
50	37	34	32	31	31
40	40	35	33	31	32
30	41	36	34	32	33
20	42	37	35	32	34
10	44	38	36	33	34

In both the cases dielectric fluid + with Al_2O_3 nano fluid cooling system + PCM system performs well and results proved the superiority of this mixture coolant material. During the discharging process nanofluid has reached a maximum temperature raise of 45 °C whereas the maximum temperatures for forced air and water cooling are 40 °C and 46 °C, respectively. Due to its higher thermal conductivity than any other coolant, it may be stated that the nanofluid with PCM was the one that produces good cooling performance.

6 CONCLUSION

The above experiment shows temperature variation during fast charging with different cooling methods, showing that Dielectric fluid + with AL_2O_3 Nano fluid cooling system + PCM nanofluid mixture performs best.

1. The maximum and minimum temperature percentage (42% to 36%) for cooling efficiency was described in both simulated and experimental evaluation of CFD.
2. The battery reached 35 °C during the experimental cooling process and 34 °C degrees during the simulation when the dielectric+ Al_2O_3 combination of nanofluid cooling technique was used during the discharging process at that time of finding temperature.
3. The dielectric fluid + with AL_2O_3 nano fluid cooling system + PCM has reached only a maximum temperature of 45 °C compared to forced air and dielectric cooling, which they have reached the maximum temperatures of and 46 °C respectively, during both the charging and discharging process.
4. The maximum temperatures recorded for the Dielectric fluid + Al_2O_3 nanofluids with PCM cooling system were 71 °C during charging. This is higher compared to the forced air-cooling system, which reached 69 °C, and the dielectric fluid alone with Al_2O_3 nanofluids, which reached 68 °C. The water-cooling system and Al_2O_3 nanoparticle cooling system recorded lower maximum temperatures of 62 °C and 66 °C, respectively.
5. The Dielectric fluid + Al_2O_3 nanofluids with PCM cooling method demonstrated the best performance, maintaining the lowest maximum temperatures of 68 °C during charging and 71 °C during discharging. This indicates superior thermal management compared to other cooling methods tested.
6. The nanofluid with Dielectric fluid + with AL_2O_3 Nano fluid cooling system + PCM showed good cooling performance due to its higher thermal conductivity.

The study's limitations include the idealized boundary conditions and the use of simplified thermal models, which might not accurately represent battery operating circumstances in the actual world. Future studies ought to examine increasingly intricate and diverse climatic conditions as well as the impact of aging on PCM and nanocooling fluids in the real world. Thermal management may be further optimized by looking into the combination of cutting-edge materials and hybrid cooling methods. Validating the efficacy and resilience of the suggested solutions also requires field testing and long-term performance evaluations.

Abbreviation

EV - Electric vehicle
BTMS - Battery Thermal Management System
SOC - State of Charge
PCM - Phase Change Material
FDM - Fluid Deposition Method
PLA - Polylactic Acid
CFD - Computational Fluid Dynamics

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Contact information:

Ramprabu JAYARAMAN
(Corresponding author)
Department of Electrical & Electronics Engineering,
Kumaraguru College of Technology,
Coimbatore, Tamil Nadu, India
E-mail: ramprabu.j.eee@kct.ac.in

Kandasamy VARATHARAJULU
Department of Electrical & Electronics Engineering,
Kumaraguru College of Technology,
Coimbatore, Tamil Nadu, India
E-mail: kandasamy.v.eee@kct.ac.in

Vairavel MADESHWAREN
Department of Mechanical Engineering,
Dhanalakshmi Srinivasan College of Engineering,
Coimbatore, Tamil Nadu, India
E-mail: phdannauniv2020@gmail.com