Experimental investigation on the impact of evaporative cooling based battery thermal management system on charging process of valve regulated lead acid batteries in E-bike

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Abstract. The thermal behaviour of valve regulated lead acid batteries with an evaporative cooling-based thermal management system is experimentally examined during the charging process of an E-bike. The thermal behaviour of valve regulated lead acid batteries is investigated during charging process with three different cooling strategies: evaporative cooling-based battery thermal management system, pre-cooling + battery thermal management system, and natural convection. The valve regulated lead acid batteries from the OREVA ALISH E-bike were used for testing. A portable evaporative cooling system was built for investigation based on available space on the E-bike. The results show that the developed evaporative cooling-based battery thermal management system kept temperatures between 1.5°C and 2.2°C below ambient during the charging process. The temperature of the battery during the charging process is increased slightly, by 1.6°C during the pre-cooling + battery thermal management system cooling mode. The temperature uniformity among valve regulated lead acid batteries was improved during the charging process with pre-cooling + thermal management system cooling mode.

1. Introduction

In the midst of increased oil prices and global climate disasters due to greenhouse gas emissions, electric vehicles (EV) and hybrid electric vehicles (HEV) are considered eco-friendly modes of transportation. E-bikes have also become more popular as a single-user mobility vehicle in urban areas around the globe. As power sources, a variety of battery technologies such as Valve Regulated Lead Acid (VRLA), Ni-MH, Li-ion, and others are employed. Among all the battery technologies, VRLA batteries are the most reliable for E-bikes in India due to its merits such as safety, low cost, and recyclable nature.
However, for optimal performance and battery life, the VRLA battery must be precisely maintained (electrically and thermally). VRLA battery-powered E-bikes have critical issues with unsatisfactory charging performance [1][2]. The charging process then begins, forcing the charge in the reverse direction directly into the battery. The chemical reaction that occurs while charging is the reverse of that which occurs during discharging. At the negative electrode, the charging reaction transforms the lead sulphate to lead. The reaction transforms lead to lead oxide at the positive terminal. Hydrogen is produced as a by-product of this process. Sulphuric acid reverts to its original chemical state at the completion of the charging process [3].

The ambient temperature and rate of input current have a direct effect on the rate of a chemical reaction between positive and negative plates.

The battery reaction rises exponentially with battery cell temperature, according to the Arrhenius equation of battery electrochemistry. As a result, cells which are hotter degrade more rapidly than cells that are colder. These few hot cells reduce an entire battery pack's lifetime. Thus, proper thermal management of batteries is essential to keep the temperature within the manufacturer's recommended range (25°C to 30°C) for optimal performance and long battery life. Battery thermal management system (BTMS) based on air or liquid cooling are commonly utilised in EVs. The energy consumption of various components used in air or liquid cooling, such as pumps, blowers, and so on, has a direct effect on the range of E-bikes. To enhance the overall characteristics of BTMSs, extensive research into the thermal and energy performance of battery packs during charging operations is essential.

Several studies on the temperature behaviour of the battery pack during the charging process have been conducted using this experimental method. Maheshwari et al.[4] examined into the various thermal characteristics of cells while they were charged and discharged at different rates of 2, 5 and 10°C. Tong et al.[5] choose a coupled thermal electrochemical approach to investigate the thermal behaviour of a bipolar battery pack and the impact of active BTMS design factors. To analyze the physical characteristics of a composite board with a sandwich construction in a BTMS. Yan et al.[6] devised a three-dimensional battery thermal model. Experiments with air cooling BTMS were employed to understand the thermal performance of fast-charging battery packs at different charge rates.

Wu et al. [7] carried out experiments and calculations and determined that natural air circulation through the Li-ion battery pack is inadequate. The battery temperature can be controlled to a certain extent through the use of a forced-air system. However, the variation in surface temperatures among battery cells makes thermal management problematic. Sabbah et al. [8] observed that air cooling in stressful and harsh conditions is not appropriate when employing the air cooling system, exceptionally high release rates and higher operating or atmospheric temperature (>40°C). Furthermore, non-uniform temperature distribution on the battery's surface becomes unavoidable.

The heat transfer medium in thermal management systems might be water, ethylene glycol or oil. The liquid comes into direct contact with the battery module and operates in a similar manner to air cooling; however, the liquid has a higher thermal conductivity than air. Pendergast et al. [9] used Panasonic batteries and submerged them. Their experiment could be seen as a simple thermal management of water-cooling batteries.

The ideal thermal management system would be small, light, and inexpensive. Because of the fans, pumps, tubing and other equipment, forced air and liquid cooling systems are massive, complicated, and costly. Also, manufacturers avoid using liquid-based thermal management systems due to the leakage [10]. Also, an air or liquid-cooled thermal management system cannot keep the battery temperature below ambient. Evaporative cooling can keep battery temperatures below ambient[11]. So we developed an evaporative cooling based thermal management system and investigated its effect on charging of VRLA batteries for E-bikes.
This study investigated the temperature variation of E-bike batteries while charging with BTMS, pre-cooling + BTMS, and natural convection cooling modes. The OREVA ALISH E-bike's VRLA battery pack was used for testing. The portable evaporative cooling system-based BTMS is built to fit in the E-bike for this experiment.

2. Experimental Setup

The experimental setup is divided into two sections: E-bike and evaporative cooling BTMS. The OREVA ALISH E-bike is powered by a 500W BLDC hub motor and four 12V 24Ah batteries as a power source. VRLA batteries are used. Batteries are enclosed in compartments below the evaporative cooling system to prevent climatic conditions (shown in Figure 1). The evaporative cooling system is designed to accommodate in the available space in the E-bike. It is positioned in the leg space of the E-bike, as illustrated in Figure 1. The evaporative cooling system is comprised of two units: the control unit and the cooling unit. A 20 W air blower, a 2.25 lit. water tank, a 3W water pump and a cooling pad make the cooling unit. The air blower and water pump are powered by a 12V, 7 Ah VRLA battery housed in a separate control unit. A data logger, temperature control unit and speed control unit for the air blower and pump are included inside the control system. As a data management system, the Khoat KH208 paperless data recorder is used. The data logger monitors and records the battery's surface temperature and the current delivered to the battery during the charging process.

2.1 Location of measuring elements

The battery pack contains four 12V, 24 Ah VRLA batteries. As illustrated in Figure 2, all batteries are connected in series. Four J-type thermocouples (T1, T2, T3, and T4) are affixed to the surface of the batteries. Thermocouples T5 and T6 were used to measure the air temperature at the battery pack's entrance and exit. The measurement elements for voltage (V) and current (A) are linked in parallel between battery chargers and battery packs.

| Sr. No. | Device Name | Parameter                        | Symbol | Unit    | Range  | Accuracy |
|---------|-------------|----------------------------------|--------|---------|--------|----------|
| 1.      | J – type thermocouple | Battery temperature              | T1 to T5 | Celsius | 0 – 750 | 1.1      |
| 2.      | J – type thermocouple | Inlet & outlet air temperature   | T6     | Celsius | 0 – 750 | 1.1      |
| 3.      | Voltage measuring probe (conFigure. through 1K Ω) | Battery voltage                  | V      | Volts   | 0 to 5V | 0.5      |
3. Experimentation

Three different sets of experiments were conducted using three distinct cooling mechanisms, namely BTMS, pre-cooling + BTMS, and natural convection. The evaporative cooling system was activated at the start of the charging process in BTMS cooling mode. The evaporative cooling system pre-cooled E-bike batteries two hours before starting a charge in pre-cooling + BTMS mode. Batteries are positioned in their regular place in the E-bike and allowed to cool by natural convection in natural convection mode. Figure 3 illustrates the experimental analysis methodology in detail using a flowchart.

The VRLA batteries are initially installed within the battery box. After discharging the batteries, they are maintained in a no-load condition for two hours to restore them to a steady-state condition. Now, correctly connect the battery to the battery charger and any other equipment. Keep records of the battery's initial temperature, the ambient temperature, the wet bulb temperature and initial battery voltage, and the experiment's start time. Configure a data logger to record the battery voltage, charging current, and temperature of the battery at ten-minute intervals until the battery voltage reaches 54.6 V. Switch off the charging unit; when the voltage indicator displays 54.6 V.

![Figure 3. Flow chart for the procedure of experimental analysis](image-url)
The first battery is discharged up to 80% in a charging test. The charging process is carried out in various of operating modes, including BTMS, pre-cooling + BTMS and natural convection. There are three main charging methods: (1) constant voltage charging, (2) constant current charging and (3) trickle charging. The tested vehicle's manufacturer provided a trickle charging-based 48V, 2.5A DC battery charger. The trickle charging approach eliminates the risk of the battery overcharging. A trickle charging method charges the battery with a 20% current supply and progressively reduces the charging current by raising the state of charge (SOC). Figure 4 illustrates the charging curve of the VRLA battery.

Figure 4. Charging curve of 48V, 24 Ah. VRLA battery pack in E-bike

4. Results and Discussion

This section initially presents the variation of battery temperature in different cooling modes, then a comparison of the summary temperature difference data are followed.

4.1 Battery temperature variation with different cooling modes

The variation in battery temperature, ambient temperature, and inlet and outlet air temperature for the battery box during the charging process with BTMS cooling mode is shown in Figure 5. The typical initial conditions of the experiment are as follows: ambient temperature 34°C, battery temperature 30.5°C, relative humidity 60%, and battery voltage 47.3V. The batteries were fully charged during the experiment in 4 hours and 9 minutes. The Figure 5 shows that battery temperatures are kept at an average of 2.5°C below ambient temperature during the charging process. During the experiment, the battery temperature rose from 30.5°C to 33.2°C. The temperatures of the air inlet and output steadily increased at nearly the same rate up to 2400 seconds, and then remain close to constant until the charging is completed.
Figure 5. Battery temperature profiles during charging process with BTMS cooling mode

Figure 6 shows the battery temperature profiles for pre-cooling + BTMS mode. The charging of the batteries begins at 47.5V and takes four hours to fully charge them. The batteries were pre-cooled for two hours before charging started in this experiment. The following are the typical values for initial pre-cooling conditions: ambient temperature 33°C, battery temperature 34°C, and relative humidity 58%. At the end of the pre-cooling period, the battery temperatures dropped to 32.4°C. Moreover, throughout the first 2.5 hours of charging, battery temperatures continually decreased up to 30.7°C. Following that, a sudden 3.5°C temperature rise was observed in the previous 1.3 hours. At the end of charging, the rate of a chemical reaction between active materials is higher, which results in a larger rate of heat generation from the battery than at the beginning.

Figure 6. Battery temperature profiles during charging process with precooling+ BTMS cooling mode

Figure 7 illustrates the temperature profiles of the battery when cooling with natural convection is employed. When the experiment is carried out, the following average values for the initial conditions are observed: ambient temperature of 35°C, battery temperature of 35°C, relative humidity of 47 percent, and battery voltage of 47.2V. During the experiment, the batteries were completely charged in 3 hours and 55 minutes. As part of this experiment, the batteries were installed in a standard location on the E-bike, below the seat compartment and allowing them to cool naturally by convection. As illustrated in Figure. 7, the temperature of battery – 3 has been increasing steadily since the start of charging, whilst the temperatures of the remaining three batteries have stayed nearly constant for up to
2 hours and 40 minutes. Battery-3 has a maximum surface temperature of 39.1°C. The reason for such a high rate of temperature in battery – 3 is that this battery is kept in the middle of the battery pack, where air circulation and cooling rates are low. The temperature of the remaining three batteries is rose to approximately 37.5°C.

![Figure 7. Battery temperature profiles during charging process with natural convection](image)

### 4.2 Comparison of individual battery temperature ranges

The temperature range for individual batteries with various cooling modes is shown in Figure 8. It can be seen that the battery temperature stayed between 30.8°C and 32.4°C, 30.4°C and 33.2°C, and 35.1°C and 37.9°C during pre-cooling + BTMS, with BTMS, and natural convection cooling mode. The temperature range of all batteries used in pre-cooling + BTMS and With BTMS cooling modes is approximately 4°C lower than the temperature range observed in natural convection cooling mode. The pre-cooling + BTMS cooling mode has the smallest temperature variation of 1.6°C, which is 55.17 % and 53.33 % less than the BTMS and natural convection cooling modes. It has been demonstrated that during the charging process, pre-cooling + BTMS cooling mode delivers a superior cooling effect and temperature uniformity than BTMS and natural convection.

![Figure 8. Comparison of temperature ranges for individual batteries during charging with different cooling modes](image)
4.3 Comparison of individual battery temperature difference from ambient condition

Figure 9 shows the average value of temperature difference from ambient for individual batteries with various cooling modes. It is observed that the average temperature of the batteries stayed 2.16°C and 1.45°C below the ambient temperature, respectively, during the charging process with BTMS and pre-cooled + BTMS cooling mode. While the average temperature of batteries remained 1.45°C above the ambient temperature during natural convection. Thus, it has been established that natural convection alone is insufficient for battery cooling; evaporative cooling-based BTMS provides appropriate cooling and keeps the battery temperature below ambient levels throughout the charging process.

![Figure 9. Comparison of average temperature difference from ambient condition during charging process with different cooling modes](image)

5. Conclusions

Experiments to study the thermal performance of the charging process for VRLA battery pack were performed with three different cooling modes viz., with BMTS, pre-cooling + BTMS and natural convection. Summarized experimental results of charging process with different cooling modes are compared and analyzed. The main conclusions can be summarized as follows,

- Natural convection alone is insufficient to keep the batteries cool during the charging process in an E-bike during hot seasons. Some additional battery thermal management system is required to maintain the temperature within its optimum temperature range.
- The battery thermal management system based on evaporative cooling is found to be very effective in cooling down the batteries and maintaining uniform temperature distribution between batteries throughout the charging process.
- While charging the battery using the pre-cooling + BTMS cooling mode, significantly lower temperatures and temperature differences were observed. Experiments revealed that combining pre-cooling with the BTMS cooling mode resulted in an average temperature drop of 1.4°C compared to the ambient temperature. Pre-cooling + BTMS cooling mode can also keep the temperature distribution uniform during the charging process. In charging with pre-cooling + BTMS cooling mode, a minimum temperature fluctuation of 1.6°C was found, followed by 2.8°C and 3.0°C in BTMS and natural convection cooling.

Thus, in the current work it is found that pre-cooling + BTMS cooling mode is the best strategy for cooling of VRLA battery bank, helping to enhance the life and prolonged efficient performance of the battery bank.
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