Development of Battery Thermal Management System for Valve Regulated Lead Acid Battery

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Abstract

The VRLA battery is an improved Lead-Acid battery. The VRLA battery uses the same base materials and chemical reaction as a traditional battery; the main difference is that the electrolytes are immobilised. Typically, VRLA batteries are preferred as a power source in electric motorcycles (E-bikes) because to of advantages such as robustness, maintenance-free operation, lower costs, full recycling, and mature and reliable battery technology. However, for greater better performance and battery life, VRLA batteries must be precisely regulated (electrically and thermally). VRLA battery-powered E-bikes have serious concerns with short battery life and poor performance. The Battery Thermal Management System (BTMS) in a battery pack is required to reject heat generated by the battery to the surrounding environment in order to avoid overheating during operation and to keep the temperature nearly constant among the batteries in the pack.

A systematic approach to developing a BTMS is established on the basis of a review of the relevant literature. The first step towards developing BTMS is to conduct experiments to determine how temperature of battery affects various performance parameters metrics of VRLA batteries. Experimental data indicate that higher temperatures improve capacity and discharge recovery, however battery operation at a higher temperature for an extended duration leads in acid evaporation from the Adsorbent Glass Mat (AGM) separator, reducing battery life. On the other hand, internal resistance increases with decreasing temperature, and a high internal resistance results in a start-up problem with the VRLA battery. As a result, either too low or too high temperatures are detrimental to VRLA batteries.

The following phase in the development of BTMS is to determine the real temperature obtained by VRLA batteries on an E-bike, when running in summer settings (most adverse conditions). Thus, field testing using several routes were conducted in accordance with the geography and climatic conditions circumstances of the region. According to the results of the field testing, ambient temperature plays an important effect in increasing the battery temperature. During afternoon field tests, the battery temperature rapidly rises, reaching up to 45.4^{o}C when the ambient temperature is 39.7^{o}C. An evaporative cooling-based BTMS is designed and constructed based on the peak temperature obtained by VRLA batteries of the E-bike during field testing. Finally, in a field test, the performance of the battery pack integrated with the newly created BTMS is compared to that of a regular battery pack. The

thermal behaviour of valve-regulated lead-acid batteries during field testing and charging is investigated using three alternative cooling strategies: evaporative cooling-based BTMS, pre-cooling + BTMS, and without BTMS. The results show that using the pre-cooling + BTMS cooling mode on a VRLA battery resulted in much lower temperatures and temperature variations. During the road testing with pre-cooled + BTMS cooling mode, the average temperature of the batteries remained 5°C below ambient. In addition to that, a minimal temperature fluctuation of 1.6°C was observed during field testing and charging with pre-cooling + BTMS cooling mode. As a result of this study, it is shown that a battery thermal management system based on evaporative cooling is very effective in cooling down the batteries and maintaining uniform temperature distribution amongst batteries.

2. A brief description of the state of the art of the research topic

A battery is an electrochemical device, so its performance is highly dependent on the temperature at which it operates. Because of the higher internal resistance at low temperatures, starting problems arise. A higher temperature causes evaporation of the battery acid, which eventually kills the battery cell. Heat is produced in the batteries during the charging and discharging processes. If heat is not dissipated efficiently, battery life is reduced and its performance suffers. Many other factors, such as E-bike operators' driving and charging habits, road conditions, climatic conditions, operating temperature, and so on, affect the performance and life of the VRLA battery in the E-bike. Operating temperature is a critical factor that influences the performance and lifespan of VRLA batteries in E-bikes. Ronda Hutchinson [1] investigates the effects of temperature on the cycle time of a VRLA battery in an experiment. Sigma Systems C4 temperature chamber was used for the experiments. Experiments demonstrate that the ideal operating temperature for a VRLA battery is 25°C (77°F). According to various testing, it was proven that each 8°C (15°F) increase in temperature will halve the battery life. Pavlov et al. [2] investigated the effect of temperature on oxygen cycle efficiency. The kinetics of the oxygen recombination process was studied at different temperatures ranging from 15°C to 60°C. It was observed that at higher temperatures, hydrogen production is increased, reducing the oxygen cycle efficiency in the VRLA battery. This demonstrates that temperature is a crucial factor affecting the life and performance of VRLA batteries. Thus, an effective thermal management system is necessary in a battery pack to disperse the heat generated by the battery to the environment, preventing the battery from overheating during operation and ensuring a consistent temperature across the pack's batteries.

For quite some time, researchers have studied various thermal management strategies and techniques to reduce the impact of temperature on batteries. Cosley et al. [3] developed a BTMS for VRLA batteries used in telecommunication applications. The cold plate-based BTMS was designed, with the battery resting perfectly on the cold plate and a warming pad put below the cold plate. It also uses Fourier's law of conduction to measure thermal conductivity for VRLA battery in all three directions. Finally, it is checked whether the VRLA battery is temperature-sensitive. The difference in ambient temperature and the heat generated as a result of the chemical reaction rate have a significant impact on battery life. In an outdoor environment, the life of a VRLA battery has been found to range from 1.5 to 7 years, depending on location, temperature, charging, and maintenance. As a result, hotter cells degrade more rapidly decayed than colder cells. 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 optimum temperature range (25°C to 30°C) for optimal performance and long battery life.

The Thermal Management System can use different kinds of cooling technologies, such as air cooling, liquid cooling, evaporative cooling, PCM, and heat pipe. Yu et al. [4] compared the charging/discharging process of Li-ion batteries used in electric vehicles (EVs) using two different cooling systems, natural cooling and forced air cooling. Forced air cooling at a flow rate of 0.8 m/s improves the transient thermal properties of a battery pack at a high discharging rate (1°C) and the battery pack's life cycle. Bao et al. [5] examined and compared the energy performance of active air cooling BTMSs with exterior and internal air circulation. The findings indicated that interior air circulation was more effective. Zhen et al. [6] examined the performance of a Li-ion battery with a liquid-cooled cold plate equipped with a variable number of mini-channels. It was discovered that more the number of channels, better the cooling. Zhang et al. [7] developed an efficient BTMS on ultra-thin flat heat pipes combined with liquid cooling. The highest temperature reached with ultrathin flat heat pipe-liquid cooling was found to be 73.7 percent lower than with natural convection and aluminium plates. Rahman et al. [8] proposed a BTMS based on evaporative cooling for $LiFePO_4$ battery packs used in electric vehicles (EV). The EV performance of an evaporative cooling-based BTMS was compared to an air cooling-based BTMS. BTMS based on evaporative cooling can save 17.69% more energy than air cooling. Behi et al. [9] also presented BTMS based on evaporative cooling for a Li-ion battery. The temperature of the cell and module is evaluated experimentally and numerically by the natural convection, forced convection, and evaporative cooling. The evaporative cooling approach was found to reduce the maximum temperature of the cell and module by up to 35.8% and 23.8% respectively.

The reported literature shows that temperature is a significant parameter that has a negative impact on the performance and life of VRLA and Li-ion batteries. Major research was conducted on Li-ion batteries, which are extensively used in electric vehicles. In most cases, air or liquid-based temperature management systems are employed in electric car battery packs, but it has been noticed that high amount of power is consumed by the air blower or pump during operation. Additionally, many researchers reject liquid-based thermal management systems due to the problem of leakage and corrosion. While the PCM-based thermal management technology is more effective compared to air or liquid-based thermal control, it has the problem of overheating during periods of excessive heat generation from a battery. Thus, it is insufficient at high discharge rates. Additionally, a thermal management system that is air-cooled, liquid-cooled, or based on a PCM cannot keep the battery temperature below ambient. Refrigeration or evaporative cooling are the only methods for lowering battery temperatures below ambient [10]. Evaporative cooling is simpler and less expensive than refrigeration systems. Thus, in this research study, an evaporative cooling-based thermal management system was developed and its effect on the performance of VRLA batteries for E-bikes was investigated.

3. Problem definition

According to the literature review, operational temperature has a significant impact on the life and performance of VLRA batteries. Every 15°F (8.3°C) above 77°F (25°C) reduces battery life by half. Thus, a more effective Battery Thermal Management System (BTMS) is necessary to control the temperature of the batteries within their optimal range while also protecting them from the impacts of seasonal climate variations. Enough investigations are not available regarding effect of temperature on performance of VRLA batteries and use of BTMS using evaporative cooling.

4. Research objectives

Prime objective of the present research work is,

"To develop a battery thermal management system for valve-regulated lead-acid battery, which can maintain the battery temperature within the preferred temperature range, resulting in enhanced battery life and improvement in the battery performance"

Sub-objectives

1. Experimentally understanding the effect of temperature on performance of VRLA battery.
2. To identify the highest temperature reached in VRLA batteries during the adverse operating condition of E-bike.
3. To design & fabricate an evaporative cooling based battery thermal management system for the VRLA battery pack used in E-bike.
4. Experimentally evaluate the performance of VRLA battery with BTMS and compare it with a conventional battery pack.

5. Scope of work

This study focuses on the development of a battery temperature management system for VRLA batteries used in E-bikes. The BTMS is a system and method for maintaining optimal battery temperature while also shielding them from the impacts of seasonal climate variations, resulting in increased battery life and improved battery performance.

In developing nations like India, VRLA batteries are preferred for E-bikes because of their resilience, low cost, and improved safety. The largest market sector in India was found to be VRLA batteries for E-bikes [11][12]. Indian subcontinent is located in a tropical and sub-tropical zone, where the atmospheric temperature remain in the range from 30°C to 45°C for large part of the year [13]. Such high temperatures have a substantial negative impact on the performance and life of the VRLA battery used in E-bikes. BTMS provides the solution for keeping the battery near its ideal operating temperature.

6. Original contribution by the thesis

The initial step in developing a Battery Thermal Management System (BTMS) for VRLA batteries was to undertake an exhaustive literature review. After doing a literature review, an approach to developing BTMS for VRLA batteries was established.

The thesis of this research includes a brief review of VRLA batteries, basic VRLA battery terminologies and a brief description of BTMS under the heading "Introduction". The section on "literature review" contains an extensive review of the literature on the effect of temperature on battery life and thermal management systems in electric vehicles, as well as statistical analysis, the motivation for the research, the scope of the research, and the research objectives. Prior to initiating to create a battery thermal management system, it is necessary to understand the thermal behavior of a VRLA battery under various working situations. Therefore, the section under "Thermal analysis of VRLA batteries" provides a full description of the thermal analysis of heat generation from VRLA batteries and heat dispersion from the battery surface. The following chapters are organized chronologically in accordance with the stages of development of the battery thermal management system. The initial step towards the development of BTMS is discussed under the heading "Experimental Study– 1: effect of temperature on VRLA battery." In this chapter, details of numerous tests to investigate the effect of temperature on various performance characteristics of VRLA batteries are presented. Also, results are graphically presented and discussed in detail. The second step in developing BTMS is discussed under the heading "Experimental study – 2: Performance assessment of VRLA battery of E-bike in field test”. The details of field experiments conducted to ascertain the actual temperature obtained by E-bike VRLA batteries are discussed in depth in this chapter. Also, all of the performance characteristics, such as battery temperature and energy usage, are graphically illustrated and discussed. Finally, the "Evaporative cooling based battery thermal management system" section discusses the conceptual design and fabrication aspects of the evaporative cooling-based BTMS. The discussion under the heading "Experimental study – 3: comparison of the performance of BTMS-based battery pack and conventional battery pack in field test" is about evaluating the thermal behavior of VRLA batteries in a field test with an evaporative cooling-based BTMS and an E-bike charging test.

7. Methodology of Research, Results / Comparisons

Research methodology

The purpose of this research is to develop a thermal management system for valve-regulated lead-acid batteries. Numerous techniques to designing a battery temperature management system are possible, depending on the sophistication and accessible data. Based on the knowledge gained from the literature study, the following systematic approach to developing BTMS is proposed,

1. **Experimentally understanding the effect of temperature on VRLA battery.**
    - Development and experimentation of test setups to determine the effect of temperature on various performance parameters of a VRLA battery, including the charging - discharging process, battery capacity, internal resistance, self discharge rate, and gassing rate.

2. **To Measure the actual operating temperature of VRLA battery in summer condition (most adverse condition) for E-bike during the working condition.**
    - To conduct a field test to determine the effect of real-world road and climatic conditions on the thermal behaviour of VRLA batteries in an e-bike.
    - To develop a transportable experiment setup that fits within the available space of the E- bike.
3. **Design & fabrication of Evaporative cooling based battery thermal management system**
    - To determine the rate of heat generation by VRLA batteries in an E-bike based on the actual temperature reached during field testing.
    - To determine the volumetric flow rate required to reject the heat. Additionally, choose the type of fan, cooling pad, and other evaporative cooling-based BTMS equipment.
4. **Experimentally compare the performance of battery pack integrated with new BTMS & conventional battery pack**
    - To conduct field tests to evaluate the performance of a VRLA battery pack integrated with a novel BTMS.
    - Using the full factorial method, create sets of experimental trials with different assessment criteria. Using Analysis of Variance (ANOVA), you can also analyse and validate the experimental data.

According to the steps outlined above, the first step toward developing BTMS is to gain a better understanding of the effect of temperature on VRLA batteries. To understand the impact of temperature on VRLA batteries, the performance parameters i.e. charging-discharging process, battery capacity, internal resistance, self-discharge rate and gassing rate of VRLA battery are all assessed at five different temperatures (10°C, 20°C, 30°C, 40°C, and 45°C). To analyze the effect of temperature on various parameters, VRLA batteries undergo five performance tests: capacity test, charging test, measurement of gassing rate, internal resistance test, and self-discharging test. All performance testing are conducted in accordance with the acceptance tests specified in IS – 15549: 2005 (Indian standard for stationary valve-regulated lead-acid battery – specification).

The experimental setup for the capacity test is illustrated schematically below in fig. 1. 7Ah, 12V VRLA battery was placed in the water bath. Inside the water bath are other components such as a water heater, a motorised stirrer, and temperature sensors. The temperature inside the water bath is controlled by the temperature controller. A temperature controller is a device that regulates the temperature of a water heater by turning it on and off. To maintain the temperature homogeneity of the battery, the motorized stirrer continuously swirled the water inside the water bath. The battery eliminator provides the necessary DC power source to drive the stirrer. The stirrer's spinning speed can be adjusted by varying the supplied voltage of the battery eliminator.

As a Data Acquisition System (DAS), a KH-208 paperless data recorder is provided which measures the value and logs it with a computer using DAQ software. Sensors, a measurement device, and a DAQ software computer make up a DAS. The data recorder comes with eight channels. Temperature sensors, voltage measurement pins and current measurement pins are all connected to the data recorder's various channels. All of the channels take different measurements. The data recorder captures the information and sends it to the computer via an ATC – 820 RS – 485 Interface Converter. As demonstrated, a 12V DC load board is attached for battery discharge at a fixed current. The load board is made up of eight 12V DC bulbs of various capacities.

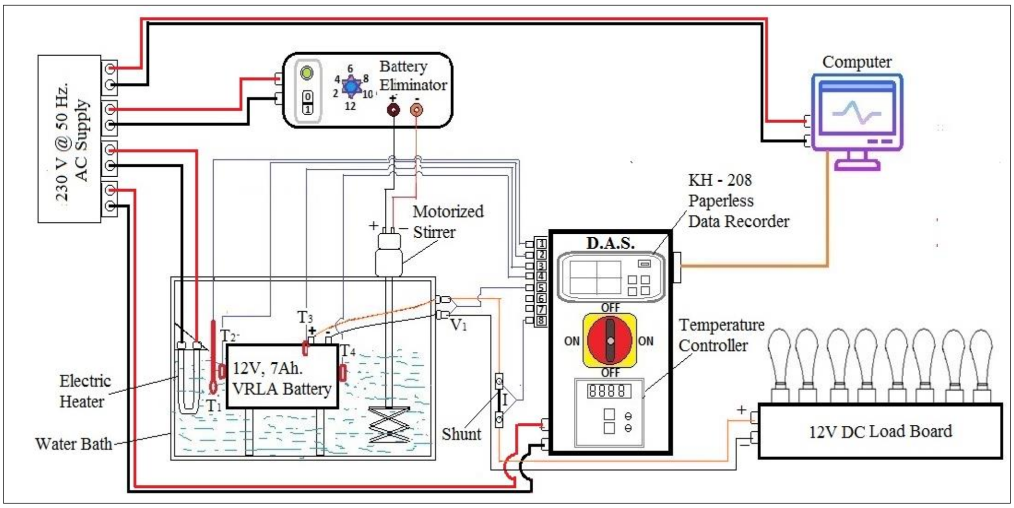


Fig. 1. Schematic diagram of experimental setup

The test results for each performance parameter are shown in table as given below.

	10°C	20°C	30°C	40°C	45°C
Battery Capacity (Ah.)	2.45	3.4	3.64	4.01	4.86
Discharging Time (min.)	21:00	29:22	31:29	34:40	41:53
Charging Time(Hrs.)	2:24	3:56	4:50	5:16	5:20
Gas generation (ml.)	1.4	5	12.5	15.2	29
Self Discharge rate (%)	-	6.7	10.2	11.22	-
Internal Resistance (mΩ)	23.54	20.45	19.16	17.21	16.12

The following are the findings from above experiments,

- Higher temperatures improve capacity and discharging backup, but battery operation at higher temperatures for a longer period causes acid evaporation from the AGM separator, reducing battery life. Internal resistance increases at low temperatures, and a high internal resistance in the VRLA battery causes a start-up difficulty.
- It was concluded that the VRLA battery should not be operated at either a higher or lower temperature. For optimal performance and battery life, VRLA batteries should be operated at temperatures ranging from 20 to 30 degrees Celsius.

The next stage in creating BTMS for VRLA batteries is to determine the battery's actual maximum operating temperature for use in the most unfavourable temperature circumstances. The current research work is focused on VRLA batteries used in "E-bikes." Thus, field experiments are conducted to ascertain the real temperature reached by VRLA batteries in E-bikes operating in summer conditions (most adverse conditions). Experiments are conducted on a variety of road types (Urban, Gradient, Highway, and Rural route), climatic circumstances (Morning, Afternoon, and Evening), and two different states of health (SOH) of VRLA batteries (Old battery pack and New battery pack). Twenty-four driving cycles have been developed based on the aforementioned requirements. The experimental analysis is used the OREVA ALISH E-bike as the test vehicle.

Fig. 2 illustrates the comparison of the maximum surface temperature of batteries to the ambient temperature along various routes with a new battery set in the morning, afternoon and evening testing. When the ambient temperature was 39.7°C in the afternoon test with gradient route, the highest temperature recorded was 44.0°C. The lowest temperature rises (ΔT) were found in the evenings for all routes, although the lowest battery temperatures were observed in the morning tests. According to the Arrhenius equation, the rate of chemical reaction increases as the temperature increases and vice versa [14]. Thus, when the ambient temperature is high (as it is during afternoon tests) and the battery is used, the temperature rapidly climbs above the ambient temperature due to the increased rate of heat generation at a higher temperature.

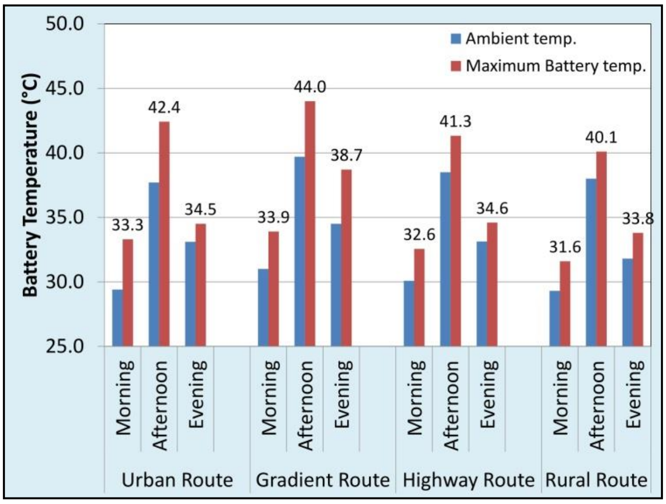


Fig. 2. Comparison of battery surface temperature of new batteries during different routes

Fig. 3 shows a comparison of the battery's minimum and maximum surface temperatures during various routes with the old VRLA battery pack in E-bike. The highest battery temperature of 45.4°C was observed in the afternoon test of the urban route while the ambient temperature was 39.7°C during these field testing. In addition, the lowest temperature rise (ΔT) has been seen on all routes in the evening, although battery temperatures are lower in early field tests.

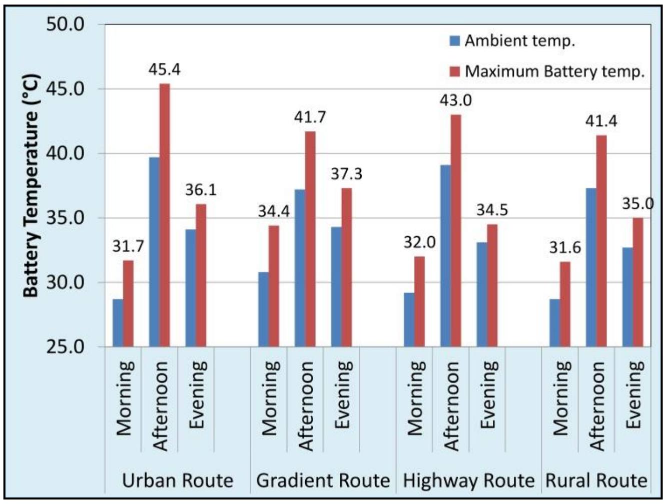


Fig. 3. Comparison of battery surface temperature of old batteries during different routes

Fig. 4 illustrates the effect of ambient temperature on energy consumption per km along various routes. A linear regression analysis is used to determine the relationship between the corresponding path and energy consumption. It demonstrates that the ambient temperature and the route's characteristics have a significant effect on energy consumption.

The gradient route consumes the most energy (15.05 Wh/km), and the rise due to the higher ambient temperature is also steeper. On the other hand, the highway route's energy consumption of 11.20 Wh/km is the lowest. The effect of ambient temperature seems to be highest on highway route, the specific energy consumption being in the range of 11.20 to 12.29 Wh/km.

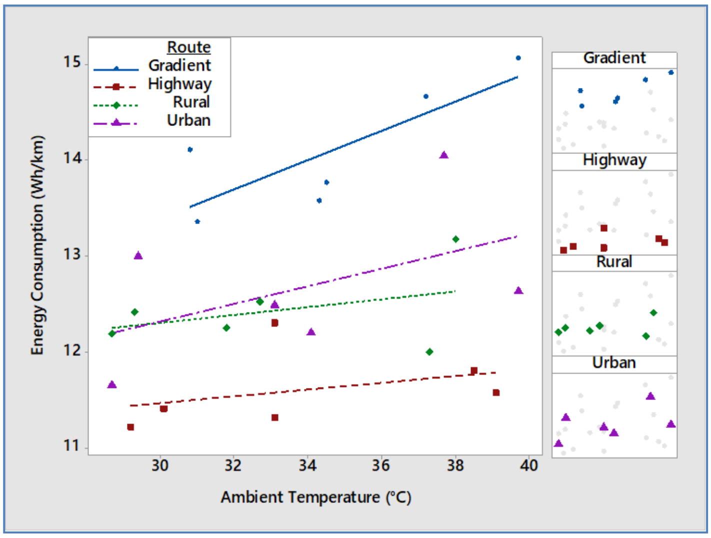


Fig. 4 The effect of temperature on total energy consumption during a field test. Each point represents a different driving cycle, and the shape and colours indicate the type of route**.** (gradient, highway, rural or urban).

The following are the findings from experiments,

- Field testing have revealed that ambient temperature has a critical influence in increasing battery temperature. During afternoon field tests, the battery temperature rapidly rise, reaching 45.4˚C when the ambient temperature is 39.7˚C.
- A comparison of battery temperatures reveals that the highest and lowest temperature rises of batteries over ambient temperatures are up to 5.7˚C and 1.4˚C, respectively, as measured during field tests in the afternoon and evening. Thus, air ventilation is an effective cooling method in the morning and evening but becomes ineffective in the afternoon.
- The recommended operating temperature is 20°C to 30°C, while the old battery operated at a much higher temperature in the afternoon. This is bad for the battery's health and shortens its life.
- An external battery cooling system is strongly recommended to keep battery pack temperatures within acceptable operating ranges.

The following step in constructing VRLA battery BTMS is to choose a suitable thermal control technique for the E-bike VRLA battery pack. The ideal thermal management system would be compact, lightweight, and low-cost. Thermal Management System makes use of a variety of cooling technologies, such as air cooling, liquid cooling, PCM, heat pipe, evaporative cooling, and so on. Only evaporative cooling or refrigeration, however, can achieve temperatures lower than the ambient. Furthermore, evaporative cooling is less complicated and less expensive than other cooling systems. Thus, an evaporative cooling-based thermal management method is selected and constructed based on the highest temperature reached by the VRLA batteries of the E-bike during the field test. The BTMS with evaporative cooling was designed based on the heat generated at the highest battery temperature in previous field tests.

Calculation for heat generation rate

VRLA battery is an electrochemical system. Electrochemical reaction between electrodes in battery is always connected with heat effect. There are two sources of heat generation in VRLA battery[15][16],

(1) Heat generation due to reactions between active materials[16][17].

(2) The joule effect causes by current flow through the battery[16][17].

Summation of heat generation due to reaction and the Joule effect gives the total heat generated by battery cell.

$$Q_{total} = Q_{Rec.} + Q_{Joule}$$

$$(Q_{total})_{cell} = I\left[T\frac{dE}{dT}\right] + I\,(\mathrm{E} - \mathrm{V}) \quad \text{\_\_\_\_\_\_ (1)}$$

The heat generation rate in a cell can be calculated from eq. (1) [18][19][20].

The heat generation rate should be calculated according to highest battery temperature observed during field test. According to previous experimental data, highest temperature of 45.4^{o}C was observed during afternoon time period of urban route field test. The following parameters was recorded during field test,

Average power consumption : 257 W

Battery Temperature(T_b) : 45.4^{o}C

Ambient temperature (T_a) : 39.7^{o}C

Now, the total heat generated by battery cell,

$$(Q_{total})_{cell} = I\left[T\frac{dE}{dT}\right] + I\,(\mathrm{E} - \mathrm{V})$$

Where,

Average Current (I)	= 5.35 A
Battery Temperature(T)	= 45.4+273.15 = 318.55 K
Entropy Coefficient (dE/dT)	= 0.4337 mV/K = 0.0004337 V/K [21]
Open circuit voltage (V)	= 54V @4 nos. of batteries= 13.50 V for 1 no. of battery
	= 2.25 V/cell (6 cells/battery)
Cell voltage (V)	= 48.0 V@4 nos. of batteries= 12 V for 1 no. of battery
	= 2 V/cell

$$Q = 5.35\ [318.55 \text{ x } 0.0004337] + 5.35\ (2.25 - 2.0)$$

$$Q = 2.077\ W/cell$$

$$\boxed{Q_{battery} = 12.46\ W}$$

There are 4 nos. of batteries in a battery pack. Thus, total heat generated from battery pack is 49.84W. When batteries are discharged with average power of 257W during field test, total 49.84W heat generated from battery pack.

Calculate required volumetric flow rate of air

The amount of forced air require to remove the heat from battery chamber is depends on the heat generated by VRLA battery and required temperature of battery surface. Proper selection of fan for the evaporative cooling system is depends on the required volumetric flow rate. Volumetric flow rate is calculated from mass flow rate of air.

The mass flow rate of air in forced air cooling can be expressed as,

$$m_a = \frac{Q}{c_p(T_1 - T_2)}$$

Where,

Heat dissipate by battery (Q)	= 49.84 W
Specific heat of air (C_p)	= 1007 J/kgK
Inlet air temperature (T_1)	= 27 + 273.15 = 300.15 K
Outlet air temperature (T_2)	= 29 + 273.15 = 302.15 K
Density of air @ 27°C	= 1.174 kg/m^3

Here, the inlet air temperature is assumed based on the ambient conditions (wet bulb temperature) of the tested region (Junagadh, Gujarat, India) during the summer. In the summer, the average wet bulb temperature in Junagadh is 27°C. Outlet air temperature is assumed according to battery temperature required to be maintained during operating condition. According to the manufacturer's recommended temperature range, the VRLA battery temperature should not be higher than 30°C during operating condition. The outlet temperature should be slightly lower than the battery temperature. Thus, the outlet air temperature is assumed to be 29°C for evaporative cooling-based BTMS.

Put all the values in above equation

$$m_a = \frac{49.84}{1007(302.15 - 300.15)}$$

$$m_a = 24.75 \times 10^{-3}\ kg./\sec$$

$$Volumatric\ flow\ rate\ (q) = \frac{mass\ flow\ rate\ of\ air}{Density\ of\ air\ @27}$$

$$Volumatric\ flow\ rate\ (q) = \frac{24.75 \times 10^{-3}}{1.174}$$

$$\boxed{Volumatric\ flow\ rate\ (q) = 21.08 \times 10^{-3}\ m^3/s = 44.66\ cfm \approx 45\ \text{CFM}}$$

A volumetric flow rate of 45 CFM is required for rejecting the 49.84W heat from the E-bike battery pack.

Design criteria

The evaporative cooling based BTMS should be fulfil the following requirement,

1. The evaporative cooling-based BTMS should be compact and transportable.
2. The evaporative cooling-based BTMS should be easily implemented in E- bike.
3. The effect of climatic changes should be minimum on batteries in E- bike.
4. The power consumption of evaporative cooling-based BTMS should be minimum.
5. The BTMS based on evaporative cooling should have a modular design that allowing for easy assembly and disassembly of all components.
6. The evaporative cooling-based BTMS should be automatically controlled in accordance with battery temperature.

According to above design criteria, a novel evaporative cooling based BTMS for VRLA battery pack was developed and implemented in E-bike. The schematic diagram in Fig. 5 depicts the developed evaporative cooling-based Battery Thermal Management System (BTMS). In the current BTMS, cooling is performed through the use of evaporative cooling.

The current unique technology employs a cooling module to extract heat from warmer ambient air that is then blown into the enclosed chamber to efficiently cool it.

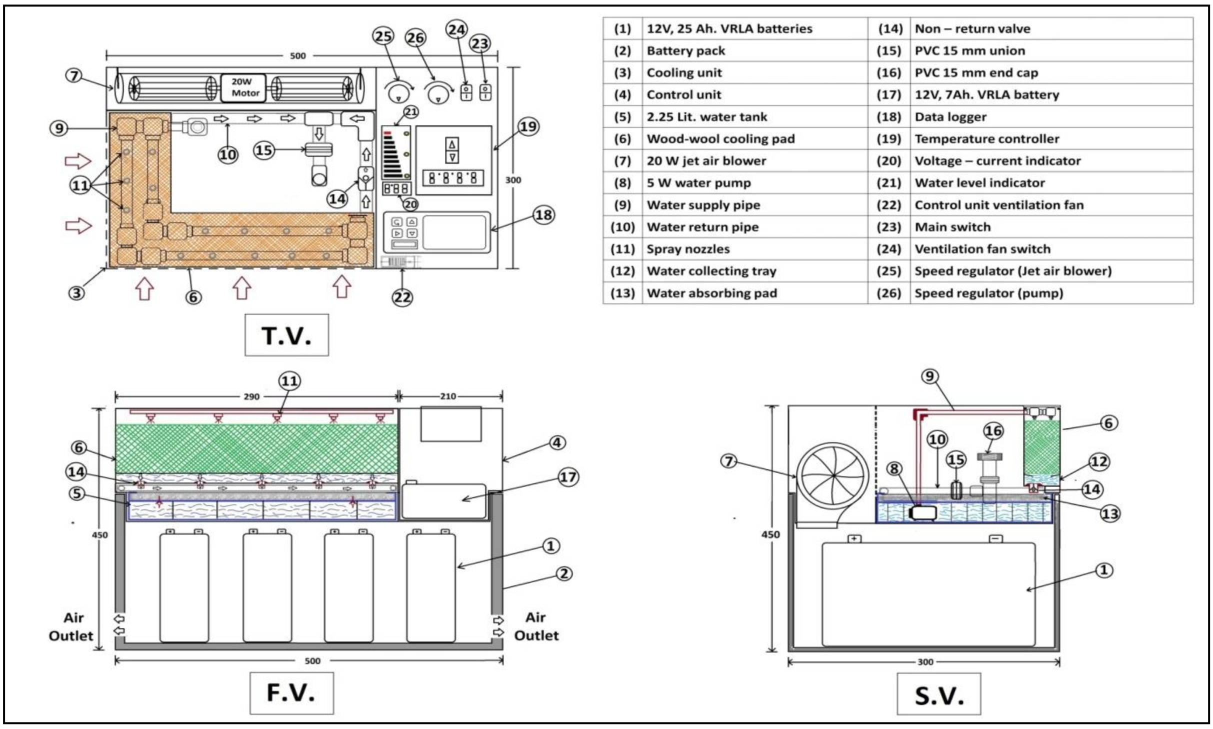


Fig. 5. Schematic diagram of the developed evaporative cooling based Battery Thermal Management System (BTMS)

A jet air blower, a water tank, a wood-wool cooling pad, and a water pump comprise the Cooling module. A battery that powers the Jet air blower and Water pump is housed in a separate Control module. A data recorder, temperature controller, speed regulator (jet air blower), and speed regulators are all part of the control module (pump). The water level indicator displays the amount of water in the Water tank. The data logger continuously monitors and records the surface temperature of the batteries included within the battery pack. The cooling module was created to be totally leak-proof. The cooling module is made up of several major components, including a water tank, water collecting tray, an L-shaped iron grill, and a water return pipe that is held together with temporary fasteners. As a result, the cooling module's components may all be easily assembled and dismantled. A Wood–wool cooling pad is included with the Cooling module. The metallic perforated L-shaped metallic grill is wrapped over the wood–wool cooling pad. The metallic grille in the shape of a L allows air to enter from both sides. The modern revolutionary BTMS's cooling system is completely automated.

Finally, the battery thermal management system prototype is produced in accordance with the component designs as shown in fig. 6. Using evaporative cooling, this battery thermal management system can keep the E-bike battery temperature closer to the recommended temperature range for VRLA batteries (20°C to 30°C). During normal operation, the battery heat management system runs automatically. The components are assembled to create a fully functional system. As illustrated in Fig. 6, the battery thermal management system's functional design and manufacturing have been completed to meet the design criteria. The above design and method have been applied for an Indian patent and published in the Patent Journal 02/2022 with the title "Evaporative Cooling Based Battery Thermal Management System" (No. 202221000095A).

Fig. 6. Complete prototype of evaporative cooling based BTMS

Experimentation

The final stage of BTMS development is to conduct an experimental comparison of the VRLA-powered E-bike battery pack combined with the new BTMS to a traditional battery pack. Thus, using a field test and a charging test, the thermal behaviour of Valve Regulated Lead Acid (VRLA) batteries equipped with an evaporative cooling-based battery thermal management system (BTMS) is investigated experimentally.

The experimental system is separated into two components: an e-bike and a BTMS with evaporative cooling. The 500W BLDC hub motor and four 12V 24Ah VRLA batteries power the OREVA ALISH E-bike. To avoid climatic extremes, batteries are encased in a battery pack located beneath the evaporative cooling system. The evaporative cooling system is adapted to meet the available area on the E-bike. It is mounted in the E-bike's leg-space, as seen in Fig. 7.

As a data management system, the Khoat KH208 paperless data recorder is employed. The data logger continuously monitors and records the surface temperature of the battery and the current fed to the battery during operation. On the surface of the batteries, four J-type thermocouples (T1, T2, T3, and T4) are attached. The air temperature at the battery pack's entrance and exit was measured using thermocouples T5 and T6. Voltage (V) and current (A) monitoring devices are connected in parallel between battery chargers and battery packs.

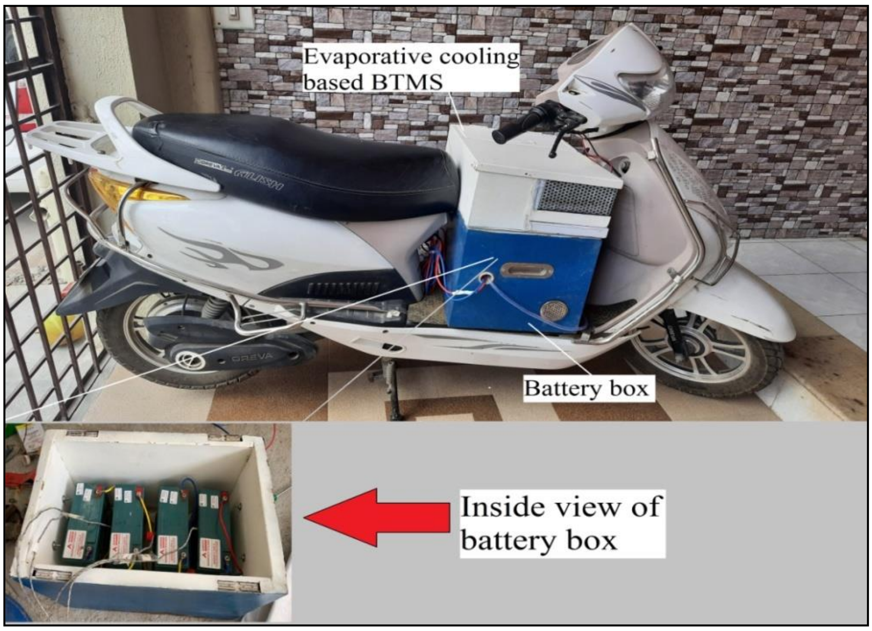


Fig.7: Experimental setup

Twelve field test-based studies were carried out in accordance with three separate assessment criteria; including vehicle speed, load condition, and battery pack condition. All of the assessment criteria are listed below in detail,

Vehicle Speed Mode	
Eco mode	15 km/h to 20 km/h
Power mode	30 km/h to 35 km/h
Load condition	
Without additional load	70 kg (Person) + 15 kg. (BTMS) = 85 kg.
With additional load	70 kg (Person) + 15 kg. (BTMS) + 30 kg. (Dead weight) = 115 kg.
Battery Pack condition	
With BTMS	Evaporative cooling system will be started at beginning of trip.

Precooling+ With BTMS	E-bike batteries will be precooled by evaporative cooling system two hours before starting a trip.
Natural Convection	Batteries are allowed to cool by natural convection.

The experiments are designed using the full factorial technique in MINITAB 18 (Statistical data analysis software). The factorial design allows for the investigation of all distinct combinations of factor levels during each trial of an experiment.

Design summary

Factors:	3	Replicates:	1
Base runs:	12	Total runs:	12
Base blocks:	1	Total blocks:	1

Factors	Level - 1	Level - 2	Level - 3
Battery pack condition	With BTMS	Precooling + with BTMS	Natural convection
Vehicle Speed Mode	Eco mode	Power mode	--
Load condition	Without Load	With Load	--

Total 15 trials are performed with different sets of experimental parameters during the road and charging tests.

Exp. No.	Battery pack condition	Load condition	Vehicle Speed Mode
1	With BTMS	Without load	Eco mode
2	With BTMS	Without load	Power mode
3	With BTMS	With load	Eco mode
4	With BTMS	With load	Power mode
5	Precooling + with BTMS	Without load	Eco mode
6	Precooling + with BTMS	Without load	Power mode
7	Precooling + with BTMS	With load	Eco mode
8	Precooling + with BTMS	With load	Power mode
9	Natural Convection	Without load	Eco mode
10	Natural Convection	Without load	Power mode
11	Natural Convection	With load	Eco mode
12	Natural Convection	With load	Power mode
Charging test			

13	With BTMS	Charging	-
14	Precooling + with BTMS	Charging	-
15	Natural Convection	Charging	-

Details of road tests

Road tests are performed in the city of Junagadh (Gujarat), India. The trip is approximately 24 kilometres long in total. The field test route (as shown in fig.8) is distinguished by substantial traffic conditions, such as extra-urban (A-B), urban (B-C), and highway (C-D) driving conditions. Extra-urban driving circumstances are chosen, with high traffic density and local streets. The urban driving condition route is chosen with medium traffic density and arterial streets, whereas the highway driving condition route is picked with low traffic density and flat road.

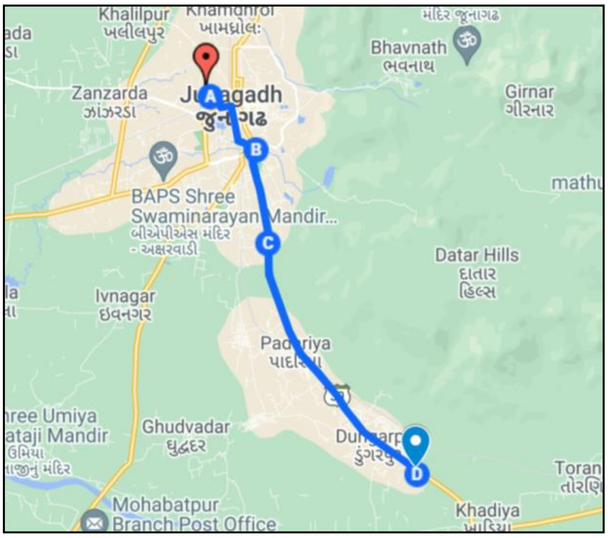
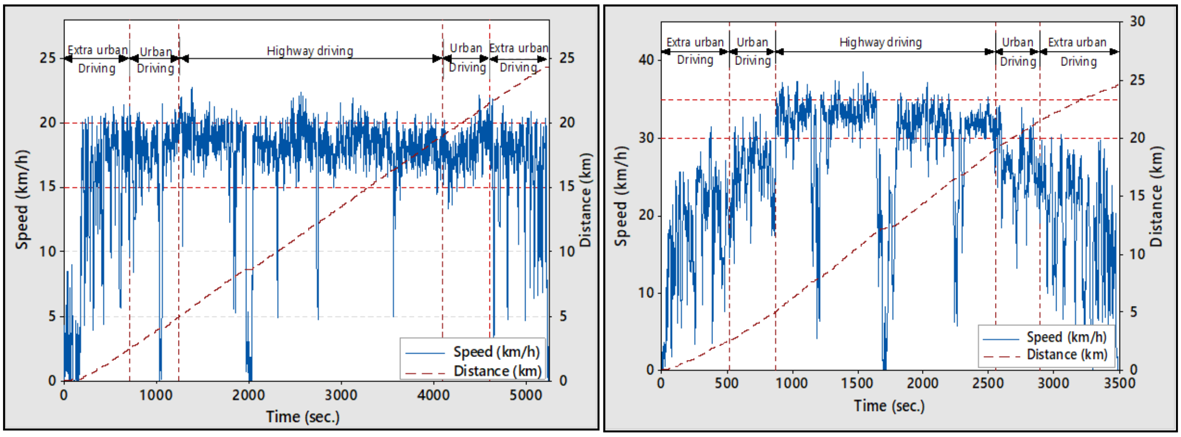


Fig. 8: Typical route of the travelled area for road test with GPS data, (Image provided by Google map data ©2021)

Vehicle speed

Fig. 9 illustrates the speed-time variation for E-bikes acquired from GPS tracking data in Eco and Power modes. Throughout the field test, an average speed of 15 to 20 km/h is maintained in eco mode. During power mode, the e-bike can reach a top speed of 35 km/h. During the urban trip in power mode, the E-bike's average speed varied between 10 and 15 km/h. Due to the high traffic density, the speed profile of the urban route indicates frequent stops. The E-bike was driven at an average speed of 15 to 20 km/h in extra-urban and urban areas due to high traffic density. The highway route allows an E-bike to travel at a faster pace for a longer distance. As a result, during a field test, an average speed of 30 to 35 km/h was observed along the highway route.



(a) (b)

Fig.9. Speed Profile for (a) Eco mode & (b) Power mode

Results and discussion

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

Battery temperature variation with different cooling modes

The variation in battery temperature, ambient temperature, and inlet and outlet air temperature for the battery pack during the field test with BTMS cooling mode is shown in Fig. 10. The typical initial conditions of the experiment are as follows: ambient temperature 41°C, initial battery temperature 35.4°C, relative humidity 40% and battery voltage 53.1V. This experiment performed in eco mode of speed with 80 kg load condition. The E-bike is driven for 24 km. in 1 hour and 25 minutes during field test. It observed that battery temperatures are remained at an average of 5.2°C below ambient temperature during the entire field test. It is observed that initially battery temperature reduces from 35.4°C to 34.6°C up to 40 minutes than temperature of batteries remains nearly constant for next 25 minutes. After that, continuous rise of temperature up to 36.6°C in last 20 minutes of trip. This rise is observed due to higher rate of chemical reaction. The temperatures of the air inlet and outlet steadily increased at nearly the same rate up to 50 minutes, and then remain close to constant up to end of trip.

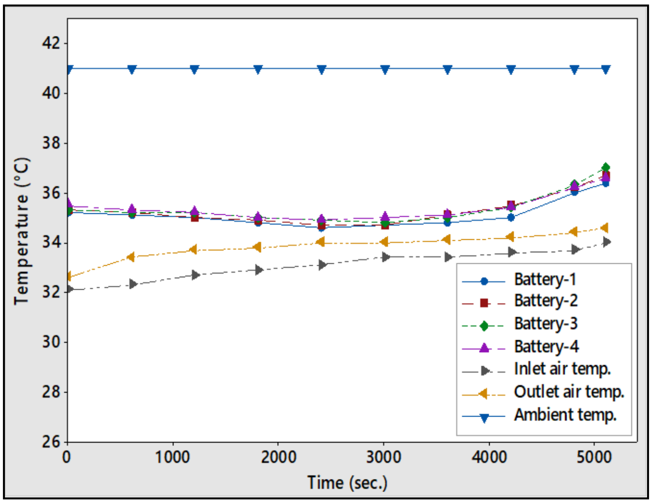


Fig. 10. Battery temperature profiles during field test with BTMS cooling mode

Fig. 11 shows the battery temperature profiles for pre-cooling + BTMS mode. This experiment performed in power mode of speed with 120 kg load condition. The E-bike is driven for 24 km. in 1 hour and 20 minutes during field test. In this experiment, the batteries were pre-cooled for two hours before the trip. The following are the typical values for initial pre-cooling conditions: ambient temperature 35°C, battery temperature 32.2°C, and relative humidity 38%. At the end of the pre-cooling period, the battery temperatures dropped to 31.8°C. Moreover, battery temperatures continually increased up to 33.4°C during the trip. This experiment was performed with higher load condition, more power consumed from batteries during operating condition of E-bike. That is leads the rate of a chemical reaction between active materials is which results in a larger rate of heat generation from the battery.

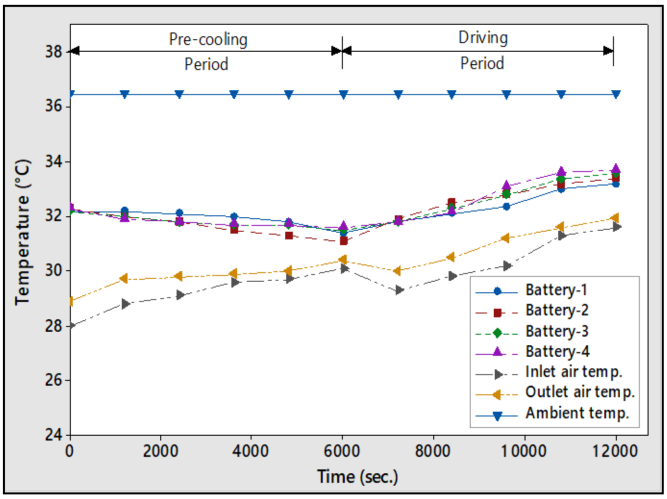


Fig. 11. Battery temperature profiles during field test with precooling+BTMS cooling mode

Fig. 12 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 37°C, battery temperature of 37°C, relative humidity of 51%, and battery voltage of 51.5V. . The E-bike is driven for 24 km. in 1 hour and 25 minutes during field test. 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 Fig.12, the temperature of battery – 3 has been increasing with higher rate compare to other batteries. Battery-3 has a maximum surface temperature of 42.3°C at end of trip. The reason for such a high rate of temperature in battery – 3 is that it is kept in the middle of the battery pack, where air circulation is low.

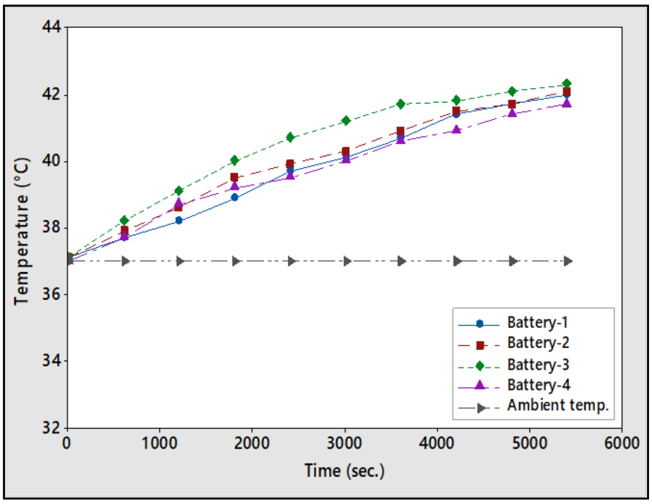


Fig. 12. Battery temperature profiles during field test with natural convection

Comparison of individual battery temperature ranges

Fig. 13 illustrates the temperature range for separate batteries with varied cooling mechanisms. The average battery temperature remained between 31.4°C and 33.5°C, 32.7°C and 36.7°C, and 36.1°C and 42.1°C, respectively, throughout pre-cooling + BTMS, with BTMS, and natural convection cooling modes. All batteries used in the pre-cooling + BTMS and With BTMS cooling modes have a temperature range roughly 6°C smaller than the temperature range observed in natural convection cooling mode. The temperature variation is the smallest in the pre-cooling + BTMS cooling mode, at 1.6°C. It demonstrates that pre-cooling combined with BTMS cooling mode provides a more effective cooling effect and temperature uniformity than BTMS alone or natural convection alone.

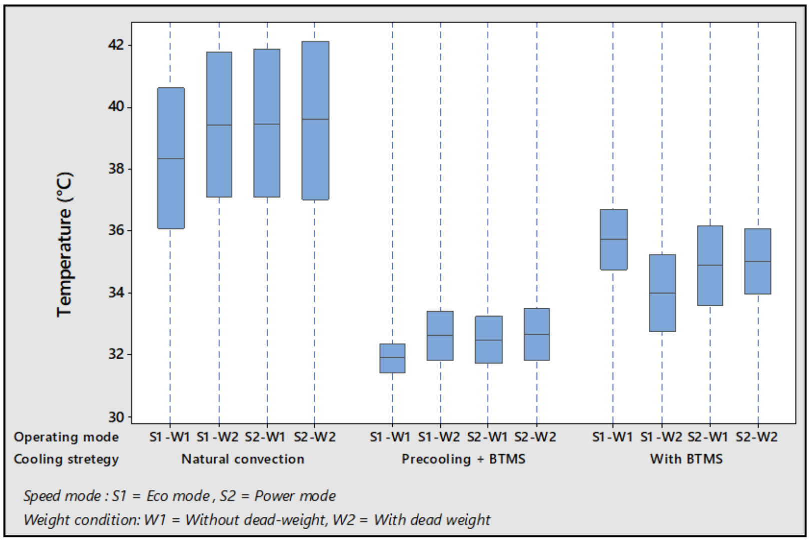


Fig. 13. Comparison of temperature ranges for individual batteries during field tests with different cooling modes

Comparison of individual battery temperature difference from ambient condition

Fig.14 illustrates the average temperature difference from ambient for individual batteries using various cooling strategies. During the road tests with BTMS and pre-cooled + BTMS cooling mode, the average temperature of the batteries remained 5°C and 6°C below the ambient temperature, respectively. During natural convection, the average temperature of the batteries remained 2.5 °C above the ambient temperature. Thus, it has been demonstrated that natural convection alone is insufficient for battery cooling; evaporative cooling-based BTMS provides adequate cooling and keeps the battery temperature below ambient levels during the operating condition.

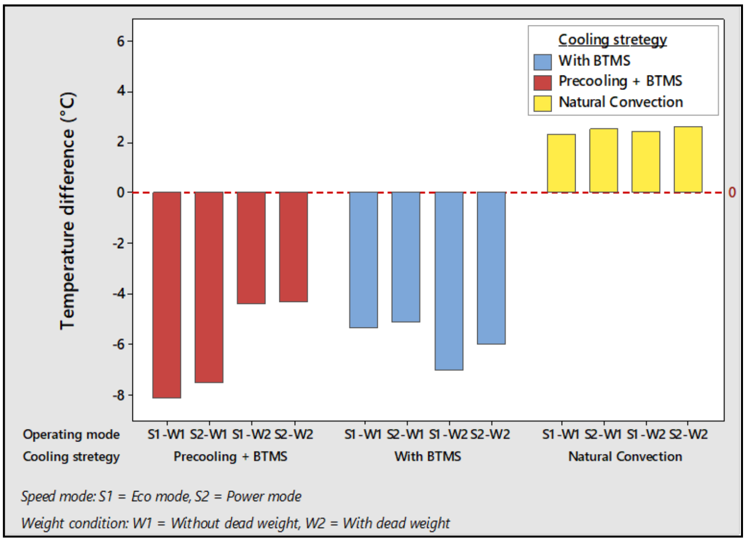


Fig. 14. Comparison of average temperature difference from ambient condition during charging process with different cooling modes

8. Achievements with respect to objectives

Prime objective	Achievement
To develop a BTMS using experimental approach, which can maintain the battery temperature within preferred temperature range, resulting in enhanced battery life and improvement in the battery performance.	The evaporative cooling based battery thermal management system was developed and successfully implemented in E-bike.
Sub-objectives	**Achievement**
Experimentally understanding the effect of temperature on VRLA battery.	• Experimentally evaluate the behavior of VRLA battery at five different operating temperatures (10°C, 20°C, 30°C, 40°C, 45°C). • Following performance parameters were evaluated at different temperatures during the experiment i.e., Battery capacity, Charging time, Discharging time, gassing rate of battery, Internal resistance and Self discharging rate. • The capacity, amount of gas released, charging time and discharging back up is higher at higher temperature and on other side internal resistance is higher at low temperature.
To identify the highest temperature reached in VRLA batteries during the adverse operating condition of E-bike.	• Initially, measure the highest temperature attained by battery during the operating condition of E-bike under four different road conditions (i.e. gradient, highway, urban and rural route), three different time of day (morning, afternoon and evening) and two different state of health of battery (old and new battery set).The OREVA ALSIH E-bike is used as a test vehicle. • It is found from the field tests that the battery temperature raises rapidly in afternoon field

	tests. The highest temperature attained by VRLA battery in E-bike is 45.4˚C when the ambient temperature was 39.7˚C.
To design an evaporative cooling based battery thermal management system for VRLA battery pack used in E-bike.	• The evaporative cooling technique is selected for BTMS due to its benefits like lower cost and low complexity. • The Evaporative cooling based BTMS was designed according to highest temp. attained by VRLA batteries in E-bike during the field test.
Experimentally evaluate the performance of VRLA battery with BTMS and compared it with conventional battery pack.	• Evaporative cooling-based battery thermal management systems (BTMS) for VRLA batteries are compared to conventional battery packs in road and charging tests on an E-bike. • 12 no. of road tests have been designed according to three different assessment criteria i.e. Vehicle speed, Load condition and Cooling mode. • The results show that Evaporative based BTMS can maintain approximately 6˚C below the ambient temperature.

9. Conclusion

In the present research, a Battery Thermal Management System (BTMS) for VRLA batteries used in E-bike is developed step by step using a systematic approach. Initially, an experimental study of the behaviour of VRLA batteries at various operating temperatures was conducted. According to the experimental results, capacity and discharge back up are seen to be greater at higher temperatures, whereas internal resistance is higher at low temperatures. Afterwards, the highest temperature reached by the VRLA batteries was determined when the E - bike is operating under the adverse conditions. The Field tests are performed to assess the performance of valve-regulated lead acid batteries in E-bikes under a variety of road and weather situations. All sets of field tests are classified by route (urban route, gradient route, highway route, and rural route) and time of day (morning, afternoon, and evening). All experiments are carried out with both old and new battery sets in order to conduct a full examination of the performance of batteries in various states of health. According to the results of the field tests.

- The battery temperature rises rapidly in the afternoon. The VRLA battery in the E-bike reached the highest temperature of 45.4°C when the ambient temperature was 39.7°C.
- It was also discovered that the route pattern has a significant impact on the energy consumption of the E-bike. The gradient route has the highest energy consumption of 15.05 Wh/km.

Thus, during warmer seasons, the available cooling scheme in E-bikes is insufficient to keep the VRLA batteries cool. To keep the temperature within the optimal temperature range, an additional battery thermal management device is necessary.

In the following phase, the BTMS was then designed using evaporative cooling based on the heat generated at highest temperature reached by the VRLA batteries in the E-bike during the field test. Finally, experiments were conducted to determine the thermal performance of a VRLA battery pack using three types of operating condition: With BMTS, pre-cooling + BTMS, and without BTMS in field tests. The experimental findings of field tests with various operating condition are compared and analysed. The major conclusions are as follows:

- Significantly lower temperatures and temperature differences were recorded in the VRLA battery when employing the pre-cooling + BTMS cooling mode. During the field tests with pre-cooled + BTMS cooling mode, the average temperature of the batteries remained 5°C below the ambient condition (37°C).
- Temperature rise could be kept limited to 1.6°C during a road test and charging with pre-cooling + BTMS cooling mode.

Thus, it is shown in the current work that pre-cooling + BTMS cooling mode is the most effective technique for cooling of VRLA battery pack and helps to keep battery temperature closer to its optimum temperature range.

Future scope

Due to limitation and time and resources, the field tests with evaporative cooling system were conducted by keeping the system in foot-rest area. Efforts should be done to design the E-bike and the cooling system such that all components can be integrated inside. Further research may lead to the creation of a battery thermal management system based on evaporative cooling that can be easily implemented in electric cars.

10. List of publication

(1) Jaydeep M. Bhatt, P.V. Ramana, Jignesh R. Mehta, "Performance assessment of valve regulated lead acid battery for E–bike in field test" Materials Today: Proceedings,Volume 49, Part 5, 2022, Pages 2058-2065, ISSN 2214-7853, DOI: https://doi.org/10.1016/j.matpr.2021.08.305. **(SCOPUS).**

(2) **Jaydeep M Bhatt,** P V Ramana, and Jignesh R Mehta, "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", Journal of Physics: Conference Series, Volume 2070, November 2021, DOI: https://doi.org/10.1088/1742-6596/2070/1/012087 **(SCOPUS).**

11. Patent

Jaydeep Manojkumar bhatt, Dr. Paladugula Venkataramana, Dr. Jignesh Rajnikant Mehta, "Evaporative Cooling Based Battery Thermal Management System", Patent journal: 02/2022, Dated: 14/01/2022, No. 202221000095 A

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