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Temperature and Aging Effects on Lead-Acid Battery Performance: Insights from Constant Current Charging Simulations

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Abstract

Lead-acid batteries are vital in industries for their reliability and cost-effectiveness. Here's a revised version of your line to better align with the conference themes of "Clean & Renewable Energy Technology" and "Energy Conversion and Management. Understanding the charging and discharging behaviors of lead-acid batteries across various temperatures and over their lifespan is critical for optimizing energy storage performance, enhancing system efficiency, and ensuring reliability in clean and renewable energy applications. This study employs MATLAB simulations of the Copetti et al. (1993) battery model to investigate the effects of temperature (5°C to 45°C) and aging on lead-acid battery performance during constant current charging, focusing on gassing and final charge voltages. The findings emphasize the need for temperature control and aging management to ensure safe and efficient operation. Further research could examine ambient temperature impacts and explore how aging leads to capacity loss. Additionally, plotting voltage curves would offer more insight into the aging process and its influence on charging and discharging behavior.

Keywords: Lead-acid batteries, charging-discharging characteristics, temperature effect, aging effect, industrial safety.

1. Introduction

Lead-acid batteries, the first type of rechargeable battery, are still widely used today in mobile and stationary applications like emergency power systems, solar PV setups, and vehicle starter batteries. They are cost-effective, use mature technology, and are easily recyclable. Despite their low energy density, they provide high surge currents, offering a favorable power-to-weight ratio. There are two main types: flooded and valve-regulated lead-acid (VRLA) batteries. However, their capacity decreases under high-power discharge, and they contain hazardous materials like lead [1].

Operation of Lead-Acid Batteries

A lead-acid battery has a positive lead oxide (PbO_2) electrode and a negative porous lead (Pb) electrode, both submerged in a sulfuric acid (H_2SO_4) solution. The battery operates through reversible chemical reactions:

Charging: Lead sulfate ($PbSO_4$) on both electrodes converts back to lead (Pb) and lead oxide (PbO_2), releasing sulfuric acid (H_2SO_4) into the electrolyte.

Positive electrode: $PbSO_4 + 2(OH)^- \rightarrow PbO_2 + H_2SO_4 + 2e^-$

Negative electrode: $PbSO_4 + 2H^+ + 2e^- \rightarrow Pb + H_2SO_4$

Discharging: During discharge, sulfuric acid splits into H_2 and SO_4, which react with lead to form lead sulfate ($PbSO_4$) and water (H_2O).

Positive electrode: $PbO_2 + 4H^+ + SO_4^{2-} + 2e^- \rightarrow PbSO_4 + 2H_2O$

Negative electrode: $Pb + SO_4^{2-} \rightarrow PbSO_4 + 2e^-$

Effect of Temperature on Lead-Acid Battery Operations

Temperature affects lead-acid batteries by increasing the rate of chemical reactions and thermal energy, but it also raises internal resistance, with the latter often having a more significant impact on overall battery performance.

Effect of Aging on Lead-Acid Battery Operations

Aging in batteries leads to irreversible capacity loss over time due to factors such as corrosion, acid stratification, gassing, sulfation, and the degradation of active materials.

2. Literature Review

Battery Charging and Discharging Characteristics Analysis

Lead-acid (LA) batteries, commonly used in uninterruptible power supply systems, require a thorough understanding of their charging and discharging behaviors for optimal performance. Studies have analyzed deep discharge behavior and voltage curve changes across cycles [2], as well as charging behaviors at different rates. Fast chargers only achieve 97.3% of full capacity compared to slower chargers [3]. Performance comparisons between LA and NiMH batteries, based on discharge curves and state of charge (SOC), were also conducted [4]. Experiments in New Delhi and on a scooter battery evaluated LA battery characteristics under various conditions [5].

Battery Characteristics at Different Temperatures

Several authors have modeled battery operation during charge and discharge, incorporating internal temperature in some models ([6]; [7]; [8]; [9]). Experiments were conducted at various temperatures (5°C, 25°C, 45°C) to observe corresponding charging-discharging characteristics, but final charge and gassing voltages were often omitted ([7]). [10] investigated temperature impacts on SLA cell cycle life. [11] introduced a new battery model incorporating temperature, verified by statistical tests and simulation. However, few studies focused on temperature's impact on charging and discharging voltage curves. This research addresses this gap by showing final charge and gassing voltage curves across temperatures, considering Bangladesh's average temperature range (5°C - 35°C).

Battery Characteristics due to aging

A study by [12] proposed a method to estimate Li-ion battery health using a vector machine algorithm, showing discharge voltage and current curves over various cycles. [3] suggested using a neural network to analyze charging voltage curves, comparing it with other methods and applying it to Li-ion batteries. Research on lead-acid batteries, however, is limited in this area. [13] introduced an "aging factor" to predict energy loss in lead-acid batteries, showing a method with less than 9% estimation error. [14] enhanced aging models with stress factors, while [15] presented a model for battery lifespan estimation. [16] discussed physicochemical processes behind battery aging, and [17] explored state-of-health evaluations for lead-acid batteries.

Previous research focused mainly on Li-ion batteries, neglecting aging effects on lead-acid batteries. This work highlights these effects, including a unique graph showing temperature and aging impact on gassing voltage.

3. Methodology

Battery Model for Charging and Discharging

[7] provided equations to model the charging and discharging characteristics of batteries, incorporating factors like capacity (C) and temperature variation (ΔT). These equations are essential for predicting battery behavior under various conditions.

1. Charge voltage equation: $Vc = \left(2 + 0.16\frac{Q}{C}\right) + \frac{I}{C1}\left(\frac{6}{1+I^{0.6}} + \frac{0.48}{\left(1-\frac{Q}{Ct}\right)^{1.2}} + 0.036\right)(1 - 0.025\Delta T)$
2. Discharge voltage equation: $Vd = \left(2.085 - 0.12\frac{Q}{C}\right) - \frac{I}{C10}\left(\frac{4}{1+I^{\frac{1}{3}}} + \frac{0.27}{\left(1-\frac{Q}{Ct}\right)^{1.5}} + 0.02\right)(1 - 0.007\Delta T)$
3. Final charge voltage equation: $Vec = [2.45 + 2.011\ln(1 + \frac{I}{C10})](1 - 0.002\Delta T)$
4. Gassing voltage equation: $Vg = [2.24 + 1.97\ln(1 + \frac{I}{C10})](1 - 0.002\Delta T)$

Here, Vc = Charge voltage, Vd = Discharge voltage, Vec = Final charge voltage, Vg = Gassing voltage, ΔT = Temperature variation, Where, $\Delta T = T - Tref$, Tref = 25°C

$C10$ = Capacity at 10 hours of rated capacity

I10= Battery current at $C10$, I = Battery current, C = Capacity at battery current

Where, $C = \frac{1.67C1\ \ (1+0.005\Delta T)}{1+0.67(\frac{I}{I10})^{0.9}}$, Ct = Maximum capacity

Where, $Ct = 1.67C10(1 + 0.005\Delta T)$, Q = Charge delivered/supplied at ttime of interest

Where, $Q = It$

These equations are used to accurately model battery performance under varying conditions.

For observing the aging effect, the rated capacity ($C10$) reduces as the battery ages.

A standard situation has been considered where a battery is replaced when its actual capacity drops to 80% of its rated capacity[18]. So, at the end of service life an LA battery has only 80% of its initial capacity assuming 100% of it's rated capacity at the initial stage. An LA battery loses 20% of its capacity during lifetime.

Average LA batteries are designed to last for 5 years. So every year an LA battery loses 4% of its capacity on average.

If $C10$ is the initial capacity of the battery in the above equations, after one year the capacity $C10_1$ would be

$C10_1 = C10 - 0.04C10$

For $n = 1,2, \ldots..5$

$C10_n = C10_{n-1} - 0.04C10_{n-1}$

Here n = No. of years of battery's lifetime.

The reduced capacity $C10_n$ is used in the discharge and charge equations to observe the aging effect each year.

MATLAB 2018 was used to obtain charging and discharging voltage curves over time. It is a mathematical tool with built-in toolboxes for specific tasks, enabling the implementation and analysis of complex algorithms through graphs and data.

4. Result

Temperature Effect on Charging

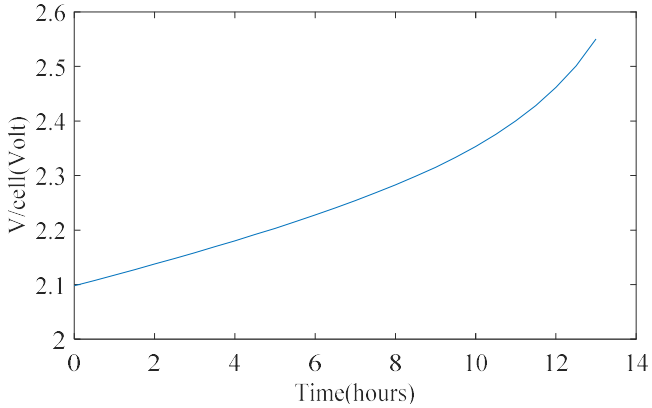


Fig. 1. Charge curve of battery at standard situation (T = 25 °C)

Fig. 1. shows the charge voltage curve with respect to time at a standard condition where battery temperature is **25 °C**. It shows the charging voltage behavior while charging for a certain period time. The battery cell is charged at constant current (CC) method each time while charging in this thesis.

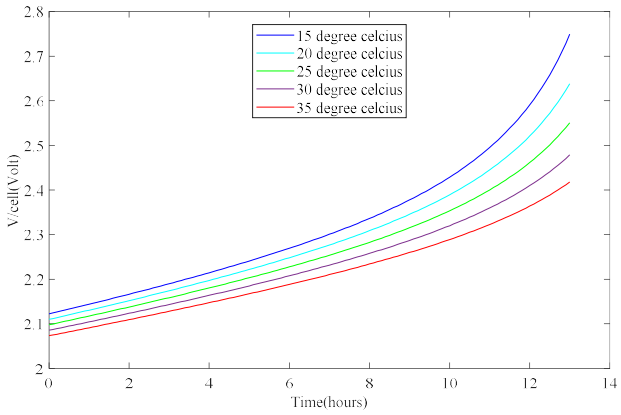


Fig. 2. Charge curve of battery at different temperature

Fig. 2. shows that at the same battery current, lower temperatures lead to faster charging, as reaching a specific voltage takes less time; however, this frequent fast charging can create internal pressure and degrade battery life.

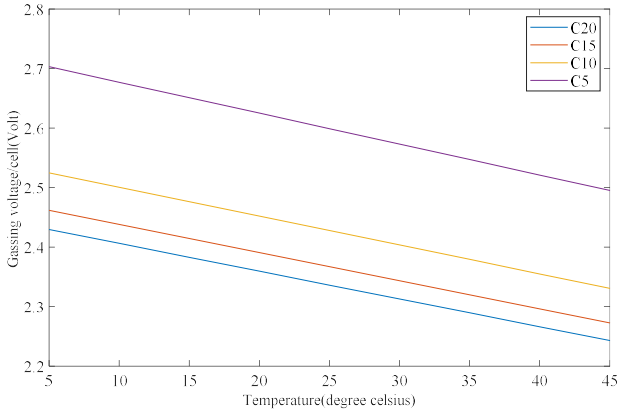


Fig. 3. Gassing voltage change with respect to battery temperature at different current rates

Fig. 3. illustrates that gassing voltage during charging decreases with increasing temperature, leading to earlier gassing at elevated temperatures, as hydrogen and oxygen form at the negative and positive electrodes, respectively, at lower voltages; this variation in gassing voltage across different temperatures and current rates is shown in the figure.

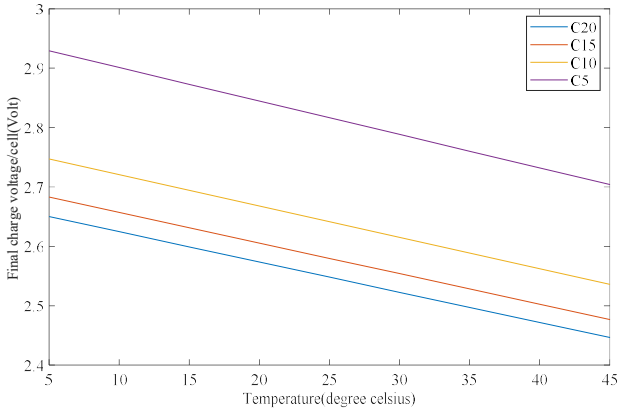


Fig. 4. Final charge voltage change with respect to battery temperature at different current rates

Fig. 4. The final charge voltage decreases with increasing temperature, as elevated temperatures raise the battery's internal resistance despite accelerating the chemical reactions, with variations observed at different current rates.

Temperature Effect on Discharging

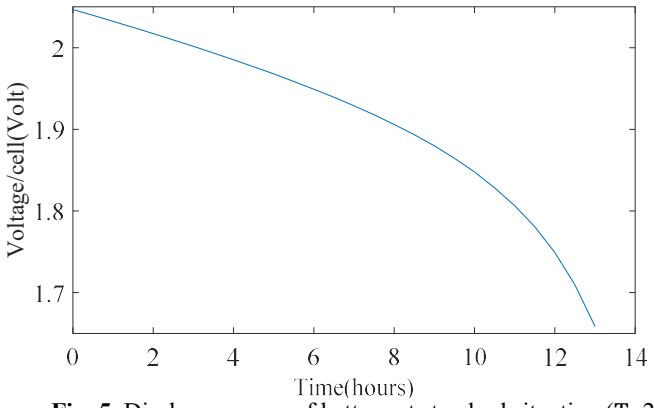


Fig. 5. Discharge curve of battery at standard situation (T=25 °C)

Fig. 5. The discharge voltage curve over time at a standard temperature of 25°C is plotted for a battery with a rated capacity of C10 = 180Ah, using a current equal to I10 for each graph of discharging and charging voltage.

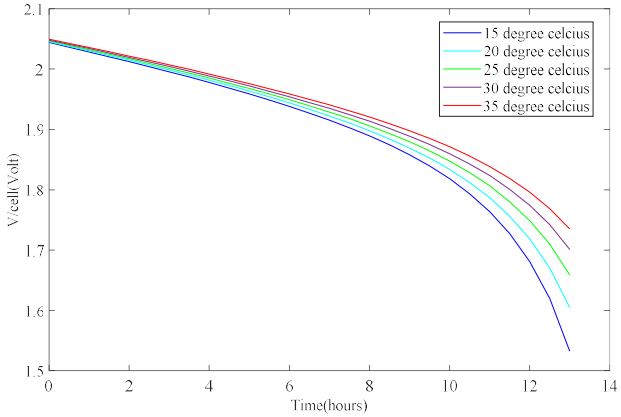


Fig. 6. Discharge curve of battery at different temperature

Fig. 6. shows that the discharge voltage curves over time at different temperatures reveal that, although the battery current remains constant, the battery discharges less at higher temperatures, while deeper discharges occur at certain lower temperatures, which can be detrimental to battery health despite the same discharge duration.

Aging Effect on Charging

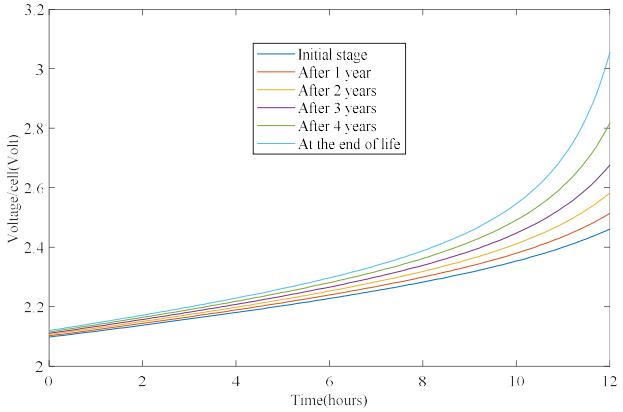


Fig. 7. Charge curve of battery at different times of lifespan

Fig. 7. shows the charge voltage with respect to time at different times at the same temperature and current. We see from the graph that the battery cell is charging faster as it ages and fast charging adversely effects the cell[19]. The internal pressure caused by fast charging inside the cell damages the cell gradually.

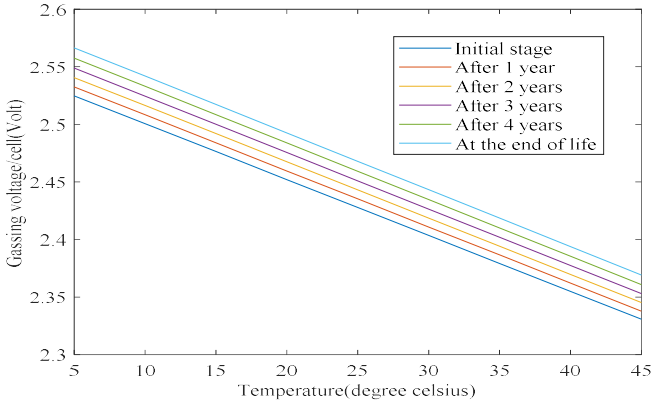


Fig. 8. Gassing voltage change with respect to battery temperature at different times

Fig. 8. shows that the gassing voltage during charging decreases with temperature, while older cells experience gassing at higher voltages.

Aging Effect on Discharging

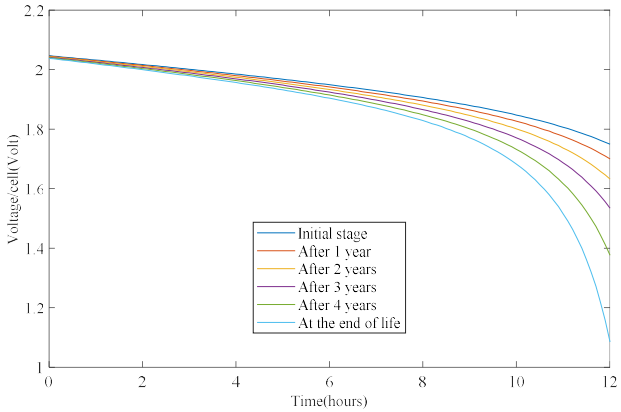


Fig. 9. Discharge curve of battery at different times of lifespan

Fig. 9. The discharge voltage over time at constant temperature and current demonstrates that the time to reach a certain voltage limit decreases as the battery ages, indicating faster discharging with age.

5. Discussion

Temperature Effect

As observed, battery cells discharge and charge more rapidly at lower temperatures within the 15°C to 35°C range. Specifically, gassing voltage during charging decreases as temperature increases, and the final charge voltage also declines with higher temperatures. Similar findings were reported by [7], who noted that at 5°C, 25°C, and 45°C, batteries exhibited faster discharge and charge rates at lower temperatures.

Aging Effect

As seen in **Fig. 7.** and **Fig. 8.** aging increases battery voltage and gassing voltage during charging. An aged cell charges faster and reaches higher voltages compared to a new one. Similarly, [3] observed higher charging voltages over time in Li-ion cells. **Fig. 9.** shows reduced discharge time with aging, a trend also noted by [12], although they studied Li-ion batteries and considered cycle life, unlike this thesis which focuses on the calendar life of lead-acid batteries.

6. Conclusion

In this research, the impact of temperature and aging on lead-acid (LA) battery charging and discharging voltage curves was analyzed using the model by [6]. The findings indicate that temperature significantly influences battery performance. While charging, the graphs show us that the battery cell is charging faster at lower temperature than it charges at elevated temperature. In case of discharging, the battery cell discharges less at higher temperature than it does at lower temperature for a certain period of time. An aged LA cell discharges faster than a new LA cell does. As temperature increases, both gassing and final charge voltage decrease, leading to less efficient charging.

Aging effects show that older batteries discharge and charge more quickly, though fast charging negatively impacts battery longevity.

7. References

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