Modeling the Correlation Relationship of Aqueous Battery Parameters Based on Regression Analysis

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Abstract. This study is a research on the new Aqueous battery. Based on the experimental data, the author selects the charge and discharge capacity, voltage and current of the battery during the charging and discharging process, establishing the correlation model between the parameters of the battery through regression analysis and other methods, and concluding the methods to optimise the performance and power supply capacity of the battery, which can explore a new high-efficiency battery that can replace the ordinary battery and provide new ideas and methods for the development of battery business.

Keywords: Aqueous battery; Correlation; Charging and discharging process.

1. Introduction

As an energy storage device, the performance of the battery becomes a key indicator. Numerous studies have shown that there is a pattern of battery performance changes during the design life ([1]). The performance and power supply capacity of the battery are mainly reflected in the charge capacity, discharge capacity, charge and discharge ratio and depth of discharge ([2]). In this paper, based on the measured values of different parameters of the battery under constant temperature and constant air pressure, we established the correlation relationship models of charge/discharge current and charge/discharge capacity, voltage and charge/discharge capacity, current and charge and discharge ratio to study the correlation of each parameter, grasp the impact of the small difference from the data, and improve the efficiency of the battery as much as possible while ensuring the battery life. The data used in this paper are derived from the author Bingnan Xiang's experiments on aqueous batteries.

2. Background

2.1. Brief Description of the Research Background

So far, resource-based fossil fuels are still the main source of electricity supply for human beings. Previously, fuel cells and lithium batteries were mostly used in the field of science and technology, and the carbon emissions caused by their massive use are the main reason of the current global greenhouse effect. In addition, fuel cells are costly with a relatively short life span, Lithium batteries have their own advantages rather than fuel cells, such as high-energy, long-life span and green. However, the disadvantages of Lithium batteries cannot be ignored, i.e., the production conditions of lithium batteries are harsh, the cost is high, and the safety of Lithium batteries is poor with the risk of explosion ([3]). As
one of the important solutions, the development and use of solar and wind power as the representative of renewable energy generation has become a top priority. However, these natural energy sources, including solar, wind and tidal energy, are intermittent, and the size of the electricity generated depends heavily on natural factors such as weather, season, time and location. Therefore, this paper studied the aqueous sodium ion battery. From the performance comparison of lead-acid battery, lithium-ion battery and sodium ion (Table 1 Comparison of the performance of lead-acid batteries, lithium-ion batteries and sodium-ion batteries), we can see that the performance of sodium ion battery is superior in all aspects compared to lead-acid battery; and compared to lithium ion battery, sodium ion battery is relatively weak in energy density and cycle life, but the low cost and high safety make sodium ion battery attract much attention([4]).

Table 1. Performance comparison of lead-acid batteries, Li-ion batteries, and Na-ion batteries

| Indicators                        | Lead-acid batteries | Lithium-ion batteries (lithium iron phosphate/graphite system) | Sodium ion batteries (Copper-based oxide/coal-based carbon system) |
|---------------------------------|---------------------|---------------------------------------------------------------|------------------------------------------------------------------|
| Mass energy density(1)          | 30-50 W-h/kg        | 120-180 W-h/kg                                                | 100–150 W-h/kg                                                   |
| Volumetric energy density(2)    | 60-100 W-h/L        | 200-350 W-h/L                                                 | 180–280 W-h/L                                                   |
| Cost per unit energy feedstock(3) | 0.40 Yuan/W-h       | 0.43 Yuan/W-h                                                 | 0.29 Yuan/(W-h                                                  |
| Cycle life(4)                   | 300-500 times       | 3000 times or more                                            | 2000 times or more                                              |
| Average operating voltage(5)    | 2.0V                | 3.2 V                                                         | 3.2 V                                                          |
| -20°C capacity retention rate   | Less than 60%       | Less than 70%                                                 | 88% or more                                                    |
| Over-discharge resistance       | Poor                | Poor                                                          | Can be discharged to 0V                                          |
| Safety                          | Excellent           | Excellent                                                     | Excellent                                                      |
| Environmental characteristics    | Poor                | Excellent                                                     | Excellent                                                      |

Note: (1) Corresponding values for single cells; (2) Only raw material costs are considered, raw materials include positive electrode, negative electrode, electrolyte, diaphragm and other assembly items; (3) If recycling is considered. The cost of raw materials for lead-acid batteries is about 0.2 Yuan/W-h; (4) $1=6.4604Yuan.$

2.2. Introduction to Battery Materials

Aqueous sodium ion batteries mostly use neutral sodium salt solution as electrolyte, which is safe and environmentally friendly, and abundant in resources. Compared with organic sodium ion batteries, aqueous sodium ion batteries can reduce the disadvantages caused by the strict operating conditions of organic electrolytes. Compared with lithium-ion batteries, sodium-ion batteries have the advantages of lower price, more abundant resources, and greener. Therefore, in large scale energy storage, aqueous sodium ion batteries have good practical prospects.

Compared with traditional secondary batteries, organic ion batteries are characterized by high energy density, high multiplication rate and long cycle life with the basic principle of ion embedding and discharge in the positive and negative electrodes and diffusion between the two electrodes. In terms of performance, it can meet the technical requirements of energy storage systems. The aqueous ion battery is one of the ideal systems to meet the technical requirements of large-scale energy storage systems because it uses neutral salt water solution as electrolyte, which avoids the flammability problem of organic electrolyte and overcomes the shortcomings of traditional aqueous battery with high pollution, short life (such as lead-acid battery) and high price (nickel-hydrogen battery) ([5]).

As one of the key technologies for the development and utilization of renewable energy (light and wind energy, etc.), the research and industrialization of aqueous ion batteries, which are characterized by high safety, non-pollution, low cost and long life, can meet the requirements of large-scale energy storage systems and are receiving increasing attention([6]).
3. Battery Parameter Correlation Relationship Modeling
The most important factor of mathematical modeling is to consider the selection of independent variables and dependent variables, which include four indicators, i.e. charge capacity, discharge capacity, charge and discharge ratio and depth of discharge where the performance and power supply capacity of the battery pack can be judged from.

In the work of the battery, there are two interrelated relationships, one is the change of battery charge capacity, discharge capacity, charge and discharge ratio and depth of discharge caused by voltage under the condition of constant current, and the other is the change of charge capacity, discharge capacity, charge and discharge ratio and depth of discharge caused by the change of current in the charging and discharging process. In this paper, we mainly focus on modeling and analyzing the correlation between charge and discharge capacity and voltage, charge and discharge capacity and current, charge and discharge ratio and voltage, and charge and discharge ratio and current of the battery. In the next part, we begin modeling by the correlation of measurement data during battery charge and discharge.

3.1. Modeling on the Relationship between Charge Current and Charge Capacity
In the 210-turn charge and discharge experiments, a total of 8 different currents were selected and the charging and discharging processes were carried out at constant currents at each of the 8 different currents. In this paper, the experimental data at 8 different currents are selected and the relationship between charge current and charge capacity is established.

3.1.1. Correlation analysis. As shown in the table 2, the correlation coefficient between the charge current and the charge capacity during a typical charging process is plotted, from which it can be seen that the Pearson coefficient between the charge current and the charge capacity during the charging process is -0.910, and the significance level \( P = 0.002 \), there is a significant negative correlation between the charge current and charge capacity.

| Charge current | Pearson Correlation | Charge capacity | Sig. (bobtail) | Number of cases |
|---------------|---------------------|-----------------|---------------|-----------------|
| Charge current | Pearson Correlation | -0.910          | .002          | 8               |
| Sig. (bobtail) |                     |                 |               | 8               |
| Number of cases |                   |                 |               | 8               |

3.1.2. Modeling. As shown in the figure 1, the correlation between the charge capacity and the charge current during a typical charging process is plotted, which are linearly related during the charging
process. The correlation relationship model between the charge current and the charge capacity can be established as follows.

\[ D_1 = -27.009 * I_1 + 7.998 \]

in which \( I_1 \) is the charge current, \( D_1 \) is the charge capacity.

3.2. Modeling the Relationship between Discharge Current and Discharge Capacity

3.2.1. Correlation analysis. As shown in the table 3, the correlation coefficient between the discharge current and the discharge capacity during a typical discharge is plotted, and the Pearson coefficient between the discharge current and the discharge capacity during the discharging process is -0.925, and the significance level \( P = 0.001 \), i.e., there is a significant positive correlation between the discharge current and discharge capacity.

|                  | Discharge current | Discharge capacity |
|------------------|-------------------|--------------------|
| Discharge current| Pearson Correlation | 1                  | .925               |
|                  | Sig. (bobtail)    | .001               |                    |
|                  | Number of cases   | 8                  | 8                  |
| Discharge capacity| Pearson Correlation | .925               | 1                  |
|                  | Sig. (bobtail)    | .001               |                    |
|                  | Number of cases   | 8                  | 8                  |

3.2.2. Modeling. The figure 2 shows the correlation between the discharge capacity and the battery discharge current during a typical discharging process. From the figure 2, it can be found that the discharge current and the discharge capacity are linearly related during the discharging process, and the correlation model between the discharge current and the discharge capacity can be established as follows.

\[ D_2 = 31.387 * I_2 - 9.004 \]

where \( I_2 \) is the discharge current, \( D_2 \) is the discharge capacity.

3.3. Modeling the Relationship between Voltage and Charge/Discharge Capacity

Drawing scatter plots between voltage and charge capacity, or voltage and discharge capacity at different currents as follows.
Figure 3. Scatter plot of voltage-charge and discharge capacity at constant current

From figure 3, it can be checked that the trend of the scatter plot of voltage and charge-discharge capacity is same under different currents, so we can consider that the relationship is consistent under different currents. We only need to analyze one case of the charge-discharge capacity and voltage at a certain current.

3.3.1. Correlation analysis of charging process. As shown in the table 4, the correlation coefficient between voltage and charge capacity during the charging process with a constant current is plotted, from which we find that the Pearson coefficient between voltage and charge capacity during the charging process is 0.945, and the significance level $p = 0.000$, there is a significant positive correlation between charge capacity and voltage.

| Table 4. Correlation analysis table |
|------------------------------------|
| Charge capacity | Pearson Correlation | Voltage |
| Charge capacity | Pearson Correlation | 1       | . 945 |
|                  | Sig. (bobtail)      | . 000   |
| Number of cases | 139                 | 139     |
| Voltage          | Pearson Correlation | . 945   | 1     |
|                  | Sig. (bobtail)      | . 000   |
| Number of cases | 139                 | 139     |
3.3.2. Modeling of the charging process. Figure 3.3-a) shows the correlation between the voltage and charge capacity during a typical charging process, which can be described by different functions at different voltages during the charging process. When $V_1 \in [0, 0.009]$, the relationship is linear, when $V_1 \in [0.009, 0.115]$, the relationship is linear, when $V_1 \in [0.115, 0.181]$, the relationship is linear, when $V_1 \in [0.181, 0.279]$, the relationship is quadratic. The correlation between voltage and charge capacity during the charging process is modeled as follows.

$$D_1 = \begin{cases} 63.89V_1 - 0.1249, & 0 \leq V_1 < 0.009, \\ 0.4727V_1 + 0.3705, & 0.009 \leq V_1 < 0.115, \\ 7.51V_1 - 0.4661, & 0.115 \leq V_1 < 0.181, \\ 37.17V_1^2 - 15.61V_1 + 0.181, & 0.181 \leq V_1 < 0.279. \\ \end{cases}$$

In this segmentation function, when $V_1 \in [0, 0.009]$, the goodness of fit $R^2 = 0.8748$, when $V_1 \in [0.009, 0.115]$, the goodness of fit $R^2 = 0.9642$, when $V_1 \in [0.115, 0.181]$, the goodness of fit $R^2 = 0.9870$ when $V_1 \in [0.181, 0.279]$, the goodness of fit $R^2 = 0.9533$, when $R^2$ greater than 0.7, the function is considered to be a good fit to the image. Where $V_1$ is the charge voltage, $D_1$ is the charge capacity.

3.3.3. Correlation analysis of the discharging process. As shown in the table 5, the correlation coefficient between the voltage and the discharge capacity during a discharge with a constant current is plotted, from which it can be found that the Pearson coefficient between the voltage and the discharge capacity is -0.913 during discharging process, and the significance level $P = 0.000$, i.e., there is a significant negative correlation between discharge capacity and voltage.

| Discharge capacity | Pearson Correlation  | Sig. (bobtail) | Number of cases |
|--------------------|----------------------|---------------|-----------------|
| Voltage            | -.913                | .000          | 134             |

Table 5. Correlation analysis table

3.3.4. Modeling of the discharging process. Figure 3.3-a) shows the correlation between the voltage and discharge capacity during a typical discharging process. The voltage and discharge capacity can be described by different functions at different voltages during the discharging process. When $V_2 \in [0, 0.009]$, the relationship is linear, when $V_2 \in [0.009, 0.418]$, the relationship is quadratic, when $V_2 \in [0.418, 0.256]$, the relationship is cubic, when $V_2 \in [0.256, 0.274]$, the relationship is cubic. The correlation between voltage and charge capacity during the discharging process the model is as follows.

$$D_2 = \begin{cases} -12.35V_2 + 0.9757, & 0 \leq V_2 < 0.009, \\ -37.14V_2^2 + 2.245V_2 + 0.8423, & 0.009 \leq V_2 < 0.418, \\ -180.5V_2^3 + 109.9V_2^2 - 22.35V_2 + 1.876, & 0.418 \leq V_2 < 0.256, \\ 2.782*10^5V_2^3 - 2.239*10^5V_2^2 + 5.999*10^4V_2 - 5351, & 0.256 \leq V_2 < 0.274. \\ \end{cases}$$

In this segmentation function, when $V_2 \in [0, 0.009]$, the goodness of fit $R^2 = 0.9469$, when
$V_2 \in [0.009, 0.418]$, the goodness of fit $R^2 = 0.9954$, when $V_2 \in [0.418, 0.256]$, the goodness of fit $R^2 = 0.9769$, when $V_2 \in [0.256, 0.274]$, the goodness of fit $R^2 = 0.9932$, when $R^2$ is greater than 0.7, the function is considered to be a good fit to the image. $V_1, D_2$ are discharge voltage and discharge capacity respectively.

### 3.4. Modeling of the Relationship between Current and Charge and Discharge Ratio

#### 3.4.1. Correlation analysis

As shown in the table 6, the correlation coefficient between the current and charge and discharge ratio during a typical charging and discharging process is plotted, from which we find that the Pearson coefficient between the current and charge/discharge ratio is -0.784, and the significance level $P=0.033$, there is a significant negative correlation between the charge current and Charge/discharge ratio.

| Charge current | Pearson Correlation | Sig. (bobtail) | Number of cases |
|----------------|---------------------|----------------|-----------------|
| Charge/discharge ratio | Pearson Correlation | Sig. (bobtail) | Number of cases |
| Charge current | 1                   | .033           | 8               |
| Sig. (bobtail) | -.748               |               |                 |
| Number of cases | 8                   |               | 8               |

#### 3.4.2. Modeling

Figure 4 shows the correlation change of current and charge/discharge ratio in a typical charging and discharging process. The current and charge/discharge ratio can be shown by different functions at different currents in the charging and discharging process. When $I_1 \in [0.246, 0.793]$, the relationship is linear, when $I_1 \in [0.793, 2.641]$ the relationship is linear, the correlation between current and charge/discharge ratio is modeled as follows.

$$D = \begin{cases} 
-0.05399I_1 + 1.051, & 0.246 \leq I_1 < 0.793, \\
-0.007579I_1 + 1.02, & 0.793 \leq I_1 < 2.641.
\end{cases}$$

where $I_1$ is the charge current, $D$ is the charge/discharge ratio.

This segmentation function, when $I_1 \in [0.246, 0.793]$, the goodness of fit $R^2 = 0.9511$, when $I_1 \in [0.793, 2.641]$, the goodness of fit $R^2 = 1$. 

Figure 4. Relationship between charge/discharge ratio and charge current
4. Summary
This study is a research on the new water-based battery which may be helpful to explore the alternative new energy batteries, and provide new ideas and methods for the development of the battery business. As a unit, all the parameters among the battery has a strong correlation. Through data analysis, we study the correlation of each parameter index, grasp the impact of the small difference from the data, and improve the efficiency of the battery as much as possible while ensuring the battery life.

The experimental data analysis shows that the charge capacity is negatively correlated with the charge current, the discharge capacity is positively correlated with the discharge current, the charge capacity is positively correlated with the charge voltage, the discharge capacity is negatively correlated with the discharge voltage, and the charge/discharge ratio is negatively correlated with the current. Since the current and voltage of the battery are positively correlated under the condition of constant resistance, in order to optimize the structure and the performance of the battery as soon as possible, we can increase the resistance and decrease the current, improve the battery charge-discharge capacity and charge-discharge ratio under the condition of constant voltage. It may optimize the battery structure by decreasing the resistance and increasing the voltage under the condition of constant current to increase the battery charge and discharge capacity.

By controlling the charge and discharge current, charge and discharge voltage to control the charge and discharge ratio as well as the charge and discharge capacity, it provides a new idea and method to optimize the performance of the battery and facilitate the provision of more efficient batteries.

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