Effect of Low Temperatures on Battery Recharge and Discharge Voltage

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Abstract. At a low temperature, due to its use of an organic electrolyte system, and its active substances having a poor electric conductivity as well, a lithium-ion battery will deliver a relatively poor performance at a low temperature, usually showing the symptoms of the common problem that individual batteries are consistent with each other better at a normal temperature, but showing a big difference in electric performance at a low temperature. Moreover, because of the effect of processing and fabricating techniques, the inconsistency among individual batteries in internal resistance also arises at a low temperature, which cannot be effectively detected at a normal temperature. Therefore, this article has studied the effect of low temperatures on battery recharge and discharge voltages. The results indicate that, with the decrease in temperature, batteries deliver a poor performance on discharge, the discharge curve shows an obviously downward trend, both average discharge voltage and discharge capacity fall somewhat, discharge capacity decreases remarkably, therefore the performance of batteries as a whole decreases faster, and batteries are noticeably less active.

1. Introduction
Among all the environmental factors, temperature has the strongest effect on the discharge performance of lithium batteries, and the electrochemical reaction on the interface between electrodes and electrolyte is also related to ambient temperatures, with the interface between electrodes and electrolyte deemed as the heart of a lithium battery. If temperature goes down, electrodes will also become slow in reaction. Assuming that battery voltage keeps the same, if discharge current decreases, battery power output will also decrease. It will be the opposite if temperature goes up, that is, battery power output will increase. Temperature also affects the transport speed in electrolyte, which will increase if temperature goes up, and become slow if temperature goes down, and a battery’s performance on recharge and discharge will also be affected [1-2]. Therefore, in order to more clearly understand the performance of lithium batteries at low temperatures, this article has studied the effect of low temperatures on battery recharge and discharge voltages at 20℃, -10℃, -20℃, and -30℃.
2. Experiment
At 20℃, -10℃, -20℃, and -30℃, 4 batteries that are consistent with each other in capacity, internal resistance, and initial open circuit are chosen to combine into two battery packs, respectively, and are recharged and discharged at 0.2C, with the voltage and temperature of each battery being monitored in real time.

3. Results

3.1. Effect of low temperatures on battery recharge and discharge voltage
Figure 1 is the discharge curve of a set of lithium-ion batteries at different temperatures (20℃, -10℃, -20℃, and -30℃), where the cutoff voltage for discharge is 5.4V.

![Discharge Curve of Lithium-Ion Batteries](image)

It can be seen from Figure1, at 20~30℃, the discharge capacities of the lithium-ion batteries in the set are, in turn, 12.81 Ah, 11.27Ah, 9.92 Ah, and 4.20Ah, equivalent to 100%, 88.0%, 77.44%, and 32.79% of their discharge capacities at a room temperature, respectively. Average discharge voltages (average discharge voltage = integral area of discharge curve / discharge capacity) are, in turn, 7.55V, 7.16V, 6.34V, and 6.15V, and at a low temperature, they are 0.39V, 1.21V, and 1.4V, respectively, lower than those at a room temperature. It can be learnt from the analysis above that, with the decrease in temperature, both the average discharge voltages and discharge capacities of the lithium-ion batteries in the set decrease somewhat, and especially when the temperature is lower than -30℃, the discharge capacities and average discharge voltages of the batteries in the set decrease faster. This is because that, with the decrease in temperature, the ionic conductivity of electrolyte will decrease accordingly, and the electric resistance in SEI and electrochemical reaction will increase correspondingly, resulting in enhanced ohm polarization, enhanced concentration polarization, and enhanced electrochemical polarization, and this is reflected in the battery discharge curve where both average voltage and discharge capacity decrease with the decrease in temperature.

The results from the experiment indicate that, at the same C-rate, battery discharge voltage drops with the decrease in temperature. Taking a constant current of 2.4A for example, by comparison of -30℃ with 20℃, battery discharge voltage decreases by 1.4A on average, accounting for 11.67% of nominal voltage.

3.2. Effect of low temperatures on battery recharge voltage
Figure 2 is the recharge curve of a set of lithium-ion batteries at different temperatures, and Table 1 gives the constant-current and constant-voltage recharge capacity and total recharge capacity of the batteries set at different temperatures.

![Recharge Curve](image)

**Figure 2.** The recharge curve of a set of lithium-ion batteries at different temperatures

**Table 1.** The recharge capacity of a set of lithium-ion batteries at different temperatures

| Temperature/℃ | Constant-current recharge capacity/Ah | Constant-voltage recharge capacity/Ah | Total recharge capacity/Ah |
|---------------|---------------------------------------|---------------------------------------|---------------------------|
| 20℃           | 12.56                                 | 0.27                                  | 12.83                     |
| -10℃          | 6.83                                  | 4.46                                  | 11.29                     |
| -20℃          | 3.41                                  | 6.49                                  | 9.90                      |
| -30℃          | 0.19                                  | 3.76                                  | 3.95                      |

In the light of Figure 2 and Table 1, it can be learned that, similarly to the process of discharge at a low temperature, with the decrease in temperature, the low-temperature recharge performances of the batteries decrease, while the constant-current recharge capacities and total recharge capacities fall. At a room temperature, the ratio between a battery’s constant-current recharge capacity and its total recharge capacity (CC/CV) is 97.90%. When the temperature decreases to -10℃, CC/CV changes to 60.50%. When the temperature decreases to -20℃, CC/CV changes to 52.54%, and at -30℃, CC/CV changes to 4.81%. With the decrease in temperature, the average recharge voltages of the batteries go up gradually. At 20 to -30℃, the average recharge voltages of the lithium-ion batteries are 7.68V, 8.18V, 8.31V, and 8.39V respectively. At a low temperature (-10℃, -20℃, or -30℃), the average recharge voltages increase by 0.5V, 0.63V, and 0.71V, respectively, as compared with the average recharge voltages at a room temperature. When the temperature decreases to -30℃, the voltages of the batteries are so fast polarized as to reach their upper limits, and the process of constant-voltage recharge follows, with CC/CV decreasing to 4.81%.

3.3. Microanalysis

Table 2 and Figures 3 and 4 show the data on the recharge and discharge of a set of batteries at -20℃.

**Table 2.** Data on the recharge and discharge of a set of batteries at 20℃

| Serial number of specimen | Highest recharge voltage/V | Lowest discharge voltage/V | Remark |
|---------------------------|---------------------------|----------------------------|--------|
| -20℃                      | T-1-3                     | 4.198                      | 2.699  | The time of constant-current discharge is relatively short, while the time of constant-current and constant-voltage recharge is |
| -20℃                      | T-1-4                     | 4.065                      | 2.632  |                                    |
When the ambient temperature is at -20℃, after Specimen T-1-3 in Batteries Set T-1 is discharged at a constant current, its voltage goes up again to a relatively high degree when it is put on standby, relatively long.

| Temperature | Specimen | Maximal difference in recharge voltage | Minimal difference in discharge voltage |
|-------------|----------|----------------------------------------|---------------------------------------|
| -20℃        | T-2-5    | 4.196                                   | 2.699                                 |
| -20℃        | T-2-6    | 4.126                                   | 2.652                                 |

See Tables 3, 4, and 5 for T-1-3 as an example.

Figure 3. Change of voltage in the 4th cycle of recharge and discharge of the 1st set of batteries at 20℃ (T-1-3)

Figure 4. Change of voltage in the 4th cycle of recharge and discharge of the 2nd set of batteries at 20℃ (T-2-5)

Table 3. Organized experimental data

| Serial number of specimen | Maximal difference in recharge voltage | Minimal difference in discharge voltage |
|---------------------------|---------------------------------------|---------------------------------------|
| T-1-3                     | 0.133                                 | 0.067                                 |
| T-1-4                     | 0.133                                 | 0.067                                 |
| T-2-5                     | 0.137                                 | 0.047                                 |
| T-2-6                     | 0.137                                 | 0.047                                 |
reaching 0.54V. At the time of recharge at a constant current, the voltage reaches 4.2V rapidly in 260s. After 56817s, the process of recharge with a constant current comes, with the current reaching only 350 mA.

Table 4. Organized experimental data on Specimen T-1-3

|                          | Initial voltage /V | Final voltage /V | Voltage difference /V | Time          | Time difference/s |
|--------------------------|-------------------|------------------|-----------------------|---------------|------------------|
| Constant-current discharge | 3.80              | 2.70             | -1.1                  | 303388-295233 | 8155             |
| On standby               | 3.02              | 3.56             | 0.54                  | 306989-303389 | 3600             |
| Constant-current recharge| 3.95              | 4.20             | 0.25                  | 307250-306990 | 260              |
| Constant-voltage recharge| 4.20              | 4.20             | 0                     | 364077-307260 | 56817            |
| On standby               | 4.17              | 4.13             | -0.04                 | 367678-364078 | 3600             |

When the ambient temperature is at -20℃, after Specimen T-2-5 in Batteries Set T-2 is discharged at a constant current, its voltage goes up again to a relatively high degree when it is put on standby, reaching 0.58V. At the time of recharge at a constant current, the voltage reaches 4.2V rapidly in 200s. After 58167s, the process of recharge with a constant current comes, with the current reaching only 350 mA.

Table 5. Organized experimental data on Specimen T-2-5

|                          | Initial voltage /V | Final voltage /V | Voltage difference /V | Time          | Time difference/s |
|--------------------------|-------------------|------------------|-----------------------|---------------|------------------|
| Constant-current discharge | 3.78              | 2.70             | -1.08                 | 315085-307553 | 7532             |
| On standby               | 3.04              | 3.62             | 0.58                  | 318686-315095 | 3591             |
| Constant-current recharge| 3.02              | 4.20             | 1.18                  | 318887-318687 | 200              |
| Constant-voltage recharge| 4.20              | 4.20             | 0                     | 377064-318897 | 58167            |
| On standby               | 4.17              | 4.13             | -0.04                 | 380667-377075 | 3592             |

At a low temperature, the performance of the batteries set as a whole decreases relatively fast, with the batteries obviously less active, both the internal resistance in the batteries and polarization voltage increasing, the ability of discharge failing, and the utilization rate being low, that is, the phenomenon emerges where the time of discharging the batteries set at a constant current is relatively short, while the time of recharge at constant current and voltage is relatively long. And the inconsistency decreases among the batteries in the set.

During the process of recharging and discharging lithium-ion batteries, lithium ions are transported across the interfaces between the three substances of graphite anode, electrolyte, and cathode [3-4]. The transportation of lithium ions between anode and cathode is the main factor in restricting the electrochemical performance of a battery [4-5]. With the gradual decrease in ambient temperature, salt is separated gradually from solvent and builds up on electrode interface, causing the inner and outer layers of the particles in anode and cathode to more polarized during the process of discharge, i.e. the resistance to the transportation of lithium ions increases across the solid particles in cathode and anode, causing battery voltage to reach final discharge voltage too early during the process of discharge, and the discharge capacity to decrease accordingly.

4. Conclusion
With the decrease in temperature, batteries perform badly in discharge, the discharge curve takes on an obviously downward trend, both average discharge voltages and discharge capacities decrease
somewhat, and discharge capacities decrease remarkably. Especially when the temperature is lower than -30℃, the discharge capacity and average discharge voltage of the batteries set decrease faster. This is because that, with the decrease in temperature, the ionic conductivity of electrolyte will decrease accordingly, and the electric resistance in SEI and electrochemical reaction will increase correspondingly, resulting in enhanced ohm polarization, enhanced concentration polarization, and enhanced electrochemical polarization, and this is reflected in the battery discharge curve where both average voltage and discharge capacity decrease with the decrease in temperature.

With the decrease in temperature, batteries become weak fast in the performance of recharge and discharge, and the time of recharge at a constant current becomes short, while the time of recharge at a constant voltage become long. As compared with the performance of discharge, batteries become more obviously weak in the performance of recharge.

In summary, at a low temperature, a set of batteries as a whole become weak relatively fast in performance, with the batteries obviously less active, both the internal resistance in the batteries and polarization voltage increasing, the ability of discharge failing, and the utilization rate being low, that is, the time to discharge the battery is relatively short, and the time to charge with constant current and constant voltage is relatively long. And the inconsistency among the batteries in the set decreases. This is mainly because, during the process of recharge and discharge, lithium ions are transported across the interfaces between the three substances of graphite anode, electrolyte, and cathode. The transportation of lithium ions between anode and cathode is the main factor in restricting the electrochemical performance of batteries. With the gradual decrease in ambient temperature, salt is separated gradually from solvent and builds up on electrode interface, causing the inner and outer layers of the particles in anode and cathode to more polarized during the process of discharge, i.e. the resistance to the transportation of lithium ions across the solid particles in cathode and anode increases, causing battery voltage to reach final discharge voltage too early during the process of discharge, and the discharge capacity to decrease accordingly.

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