Research on high energy density portable power supply based on metal-air battery

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Abstract. Because of the increasing number of personal electronic devices, there is an urgent demand for portable power supplies with high energy density. Metal-air batteries have the advantages of high energy density, high safety, good infrared concealment, no vibration and noise, low self-discharge rate. They can effectively meet the needs of users. In this paper, we studied the influence of electrode distance, single cell structure and battery module of magnesium-air battery on battery discharge performance, and designed a battery module structure to meet the requirements of high energy density. The results show that, the mass energy density of the module assembled with cells consisting of two positive electrodes and one negative electrodes cell is higher than other modules, and the discharge performance is best when the electrode distance is in the range of 2 mm to 3.5 mm.

1. Introduction
With more and more electronic equipment used, portable power supply must have higher energy density. Metal air battery is a power generation device that uses oxygen in the air as the positive active material and metal (aluminum, zinc, magnesium, lithium, etc.) as the negative active material to convert chemical energy into electrical energy, have the advantages of high energy density, high safety, good infrared concealment, no vibration and noise, low self-discharge rate. [1] Therefore, metal air batteries used as a portable power supply, can significantly reduce the weight and volume of the battery, easy to carry a single soldier, in the field of portable electronic devices has a broad application prospect.

Magnesium metal has the characteristics of abundant resources, low price, at the same time is a non-toxic, environmentally friendly materials, and easy to process, compared to metal aluminum, zinc, using neutral electrolyte, thermal effect and electrolyte acidification are not serious, magnesium alloy density is small and electronegativity is high [2], in many fields such as military battery materials as sacrificial anode material, primary battery anode material, secondary battery anode material, etc. to a very widely used. [3-5] 2017, Wei Yuan proposed a design scheme of magnesium air battery with multiple cavities in series and circumferential distribution, and the battery discharge performance test results showed that the total open circuit voltage of the battery was maintained at about 8±6%. [6] 2019, Chunhui Liu et al. made three composites, Mn3O4/rGO, Ag/rGO, Ag-Mn3O4/rGO, respectively, and the battery performance and stability were monitored for a long time. The final results showed that the catalytic performance of the composites co-doped with Ag-Mn3O4 and rGO was greatly improved, the oxygen reduction peak was shifted to 0.15 V and the polarization current was significantly increased, the cell stability was better, the open-circuit voltage could reach 1.57 V and the stable...
working time could reach 500 h. [7] So we need to develop high energy density magnesium-air battery from air electrode, metal cathode, electrolyte, battery structure design, etc.

This paper is mainly oriented to the demand of portable power supply. First, the influence of electrode distance, single cell structure and battery module on the battery discharge performance of magnesium-air batteries are studied. Second, different structures of battery modules are designed. Third, the discharge performance of battery modules is tested. Finally, it provides the correct guidance and scientific basis for the technical research and product development of a new generation of high energy density portable power supply based on metal-air batteries.

2. Electrode distance design

The distance between the positive and negative materials of the battery has a certain influence on the reaction degree of the battery. Too large a cell distance will lead to an increase in the internal resistance of the battery and a relatively low reaction voltage of the battery, and too small a cell distance will make the space between the two electrodes smaller, and the corrosion products will be more likely to accumulate between the positive and negative electrodes, thus blocking and affecting the normal discharge of the battery. Figure 1(a) shows the distance testing device between positive and negative electrodes of the homemade air battery, and Figure 1(b) is the schematic diagram of the device.

Using the device in Figure 1(a), control the distance between the negative magnesium plate and the positive air electrode, apply 2.5 mA/cm² current density after 5 h of discharge, find out the average discharge voltage, you can get the graph of the relationship between the average voltage and the distance in Figure 2.

**Figure 1.** Diagram of test setup (a) and test schematic (b) of positive and negative distance in magnesium-air batteries.

Using the device in Figure 1(a), control the distance between the negative magnesium plate and the positive air electrode, apply 2.5 mA/cm² current density after 5 h of discharge, find out the average discharge voltage, you can get the graph of the relationship between the average voltage and the distance in Figure 2.

**Figure 2.** Average discharge voltage of magnesium-air battery versus positive and negative distance.
It can be seen from Figure 2 that when the distance is very close, the average value of the discharge voltage is not high. When the distance increases from 0.5mm to 3mm, the average voltage gradually increases; then as the distance increases further, the average value of the discharge voltage gradually decreases; when the distance increases to about 8mm, the average value of the discharge voltage drops to 0.2 V. This shows that the distance between the positive and negative electrodes in the discharge process exists an optimal value range, when the distance of the battery device falls within this range, the battery discharge can achieve the best discharge effect. When the distance between the positive and negative electrodes is too close, the main reason for the voltage not being high is that the closer distance causes the concentration difference polarization on the electrode surface. The electrochemical reaction in the electrolyte is too fast, and the diffusion of substances between the positive and negative electrodes cannot keep up with the reaction speed. After the negative reaction of magnesium negative electrode, a large number of magnesium ions will first gather in the electrolyte layer on the surface of magnesium negative electrode, and then the magnesium ions will enter the electrolyte by diffusion.

3. Single cell structure design

The single cell is a unit cell system formed by the positive and negative materials according to a reasonable design, and it is the basis of the overall cell preparation. Different forms of structure design have been carried out for the single cell, and various structures such as cells consisting of two positive electrodes and one negative electrode, or consisting of two positive electrodes and one negative electrode have been designed successively, and the advantages and disadvantages between different structures have been analyzed through corresponding test comparisons.

3.1. A cell consisting of two positive and one negative electrode design

According to the relationship between positive and negative electrode distance of magnesium air battery, the air battery device with double-sided positive electrode is assembled, and the negative electrode plate can be inserted in the middle of the device, i.e., the single cell is designed with two positive electrodes and one negative electrode assembly, and the discharge reaction is realized simultaneously on both sides of the plate. From the schematic diagram of the structure of the single cell in Figure 3, the advantage of this design is to reduce the current density carried by the positive material, thus extending the service life of the positive material, and at the same time, the discharge voltage of the single cell can be increased.

![Figure 3. Structure design.](image)

As seen from the discharge performance curve of the single cell in Figure 4, the discharge test was performed at a constant current of 1.8A. It can be seen that the maximum battery voltage reaches 1.271V; with 1.0V as the effective cut-off voltage, the discharge time accumulates 27h, the discharge power is between 1.8W and 2.286W, the discharge capacity is 48.5Ah, the discharge energy is 58.1Wh, and the discharge mass energy density is 314.05Wh/Kg.
3.2. A cell consisting of two positive and two negative electrodes design

According to the problem of large space for cells consisting of two positive electrodes and one negative electrode, the cell consisting of two positive electrodes and two negative electrodes was designed. This structure is two one-positive and one-negative cell batteries connected in series in the same cell box, and the two cell batteries are separated using a spacer to avoid short-circuit phenomenon. From the structure schematic of the single cell in Figure 5, the advantage of this design is that the voltage of the single cell will be the sum of the voltages of the two cell batteries, which can appropriately reduce the design space of the battery.

![Figure 5](image)

**Figure 5.** Schematic diagram of the structure of a cell consisting of two positive and two negative electrodes.

![Figure 6](image)

**Figure 6.** A cell consisting of two positive and two negative electrodes one (a) and repeated (b) injection of electrolyte discharge performance test.

As seen from the discharge performance curve of the single cell in Figure 6, the single cell tests were all discharged at constant current at 1.8 A. According to Figure 6(a), when the electrolyte was added at once, the discharge voltage at the beginning reached 2.5V and the discharge was relatively smooth, and the continuous discharge was 6.36h at the cut-off voltage of 2.0V, at which time the discharge power was between 3.6W and 4.5W, the discharge capacity was 11.443Ah, the discharge energy was 27.354Wh, and the discharge mass energy density was 146.178Wh/Kg. Considering that the electrolyte will decrease significantly during the reaction process after adding electrolyte at one time, the electrolyte was added several times. According to Figure 6(b), the discharge voltage reached 2.5V at the beginning, and the discharge was smooth. This shows that the amount of electrolyte will directly affect the usage time of the battery when it is discharged. The continuous discharge can reach 10.7h, the discharge power is between 3.6W and 4.5W, the discharge capacity is 19.205Ah, the discharge energy is 44.688Wh, and the discharge mass energy density is 237.45Wh/Kg.

3.3. Comparison of different designs of battery

According to the design and testing of several electrode structures, several structures have their own characteristics. Table 1 is a comparison table of the advantages and disadvantages of several different structures.
As can be seen from Table 1, with the compression of the overall battery space, there is a significant increase in voltage with the design of more cell cells within a single cell, but the reduction in space and the increase in current density carried by the corresponding cathode material will result in a significant reduction in the service time of the single cell. Therefore, when considering battery design, there is still a mutual balance between space and performance, with targeted design of cells with different performance requirements. In addition, the more cells are designed within a single cell, the easier it is to short circuit inside the whole single cell, which seriously affects the use of the single cell. Combined with the relevant performance requirements of this project, cells consisting of two positive electrodes and one negative electrode are more suitable, but considering the space problem the cell consisting of two positive and two negative electrodes can also be used for the overall battery design experiments.

Table 1. Comparison table of several different structures.

| Structure                              | Advantages                                                                 | Disadvantages                                                                 |
|----------------------------------------|-----------------------------------------------------------------------------|-------------------------------------------------------------------------------|
| Cells consisting of two positive electrodes and one negative electrode | The ability to effectively reduce the current density carried by the positive electrode. Increasing the discharge voltage of the cell. Extending the service life of the unit cell. | The internal space of the single cell is relatively large, and the overall volume is difficult to reduce. |
| Cells consisting of two positive electrodes and two negative electrodes | An appropriate reduction in overall volume. Higher voltage of the battery. | Higher current density carried by the positive electrode. Affects the duration of use of the single cell. |

4. Battery module prototyping and performance testing

4.1. Performance test of a battery module consisting of two positive electrodes and one negative electrode

A magnesium air battery module was assembled using cells consisting of two positive electrodes and one negative electrode as shown in Figure 7. To meet the performance requirements of the project design, the battery was assembled using 12 single cells and split into two groups of 6 cells, which can be used individually or combined through connecting wires.

Figure 7. Magnesium air battery prototype.  
Figure 8. Magnesium air battery performance test curve.

The discharge performance curve test was performed on a electrodes magnesium metal air battery assembled with cells consisting of two positive electrodes and one negative electrode. The discharge
test was performed at 2A constant current. As can be seen from Figure 8, at the beginning of the battery discharge 1-2 hours, the voltage slowly increases to the highest battery voltage of about 15.45V, and then decreases smoothly and slowly, after the electrolyte is consumed for a period of time, continue to fill the battery with salt solution until it is not over the magnesium plate, after the salt solution is filled, the battery voltage will increase briefly, and then continue to decline. With 10 V as the effective cut-off voltage, the total discharge time is 25.155 h, the discharge power is between 20 W and 30 W, the discharge capacity is 50.31Ah, the discharge energy is 666.84Wh, and the discharge mass energy density is 172.85Wh/kg. The energy density is lower than that calculated for the single cell because the whole battery is designed with the shell part as protection, thus increasing the overall weight and causing the energy density to decrease.

4.2. Performance test of a battery module consisting of two positive electrodes and two negative electrodes

A magnesium air battery module was assembled using cells consisting of two positive electrodes and two negative electrodes as shown in Figure 9. In order to meet the performance requirements of the project design, the battery was assembled with six electrodes cells.

The results of the discharge test conducted at a constant current of 2A as shown in Figure 10. At the beginning of the battery discharge 1-2 hours, the voltage slowly increases to the highest battery voltage of about 14.8V, after which it decreases smoothly and slowly. After the electrolyte is consumed for a period of time, the battery continues to be filled with salt solution until it is not over the magnesium plate, and after the salt solution is filled, the battery voltage increases briefly and then continues to decrease. With 10V as the effective cut-off voltage, the total discharge time is 5.535h, the discharge power is between 20W and 26W, the discharge capacity is 11.07Ah, the discharge energy is 149.64Wh, and the discharge mass energy density is 91.47Wh/kg. The energy density is lower than that calculated by the single battery because the whole battery is designed with the shell part as protection. Therefore, the overall weight is increased, resulting in a decrease in energy density.

4.3. Comparison of performance test of two battery modules

For the two different types of modules, the discharge test was carried out at a current of 2A until the voltage was reduced to 10V, and the test results are shown in Table 2.

As can be seen from Table 2, the module consisting of two positive and two negative poles is significantly lower than the module consisting of two positive and one negative poles in terms of maximum discharge voltage and discharge energy density. This is consistent with the discharge test results for the single cell in Section 3.
Table 2. Comparison table of performance test of two battery modules.

| Structure                                                | Maximum discharge voltage (V) | Mass-energy density (Wh/kg) |
|----------------------------------------------------------|-------------------------------|----------------------------|
| Module consisting of a single cell with two positive and one negative poles | 15.45                         | 172.85                     |
| Module consisting of a single cell with two positive and two negative poles | 14.50                         | 91.47                      |

5. Conclusions

In this paper, the effects of electrode distance, single-cell cell structure and cell module on the discharge performance of magnesium-air batteries are investigated, and a cell module structure that meets the requirements of high energy density is designed. The conclusions are as follows.

1. The electrode distance of magnesium-air battery when the distance increases from 0.5mm to 3mm, the average voltage gradually increases; then as the distance further increases, the average discharge voltage gradually decreases, when the electrode distance is within 2mm to 3.5mm, the battery discharge can reach the best discharge effect.

2. About single cell structure, considering the mutual balance between space and performance, the cell consisting of two positive and one negative electrode is more in line with the requirements.

3. The battery module performance test results show that the mass energy density of the module assembled with cells consisting of two positive and one negative electrode is higher than others.

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