Experimental research of arc heater with three electrodes

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Abstract: As a heat source capable of producing extremely high temperature, the arc heater developed with the development of ballistic missiles and other spacecraft. With the development of hypersonic vehicles, the requirement of thermal protection performance test on ground simulation equipment is higher and higher, the current and power of arc heater are increasing. The traditional single-electrode arc heater can’t run stably for a long time under large current. In order to improve the operation stability of the arc heater under large current, a multi-electrode technique was developed. In this paper, the effects of parameters such as arc current, gas flow rate and resistance on the current distribution of each sub-electrode of the three-electrode arc heater are studied. The results show that when the arc current is constant, increasing the resistance difference of each sub-electrode is beneficial to the average distribution of current. With the increasing of arc current, the current distribution of each sub-electrode is more uniform. The setting of parameters such as arc current, gas flow rate and resistance has great influence on the distribution of cathode current of multi-electrode arc heater, but little influence on the anode.

1. Introduction

As a heat source device capable of producing extremely high temperature, arc heater has been developed closely with the development of space vehicles such as ballistic missiles (see FIG 1).¹⁻⁵ In the 1970s, NASA AMES built a 60MW arc heater. By the end of the 20th century, two more 70MW arc heaters had been built.¹⁻¹⁰ According to relevant knowledge and data calculation, when the power of the arc heater reaches 70MW, the arc current will reach 4500A. If the single electrode is still used, it will cause severe ablation on the electrode surface, and it is unable to maintain the stable operation of the heater for a long time.¹¹ To this end, Heinemann¹² developed a multi-electrode operation technique, in which the original cylindrical electrode was horizontally divided into several segments, each segment being an electrode ring separated by an insulating material. An energizing coil is installed on the ring, and the arc root is rotated by the electromagnetic field of the coil. Each electrode ring is connected with a resistor in series, and the current on each electrode ring is approximately equal by adjusting the resistance value (see FIG. 2)². This technology has been already quite mature in foreign countries, the domestic is still in its infancy stage, the China Aerodynamics Research and Development Center carried out a double/single anode and double/dual anode cathode arc heater running debugging, found that the resistance matching method, gas flow parameters and arc current will affect the heater running stability.

On the basis of the previous work, this paper carried out the commissioning of the three-cathode/three-anode arc heater. Explore the influence of the resistance matching mode, gas flow...
parameters and arc current parameters on the current distribution of each sub-electrode under the above electrode configuration, and compared with the operation data of the two-electrode arc heater.

Fig.1 The development history of world arc plasma equipment

Fig.2 Schematic diagram of multi-electrode

2. Test Equipment and Methods
The structure diagram of the arc heater used in the test is shown in figure 3. The heater is composed of a front electrode, a rear electrode, a compression section and a nozzle. The front and rear electrodes are respectively composed of three sub-electrodes surrounded by an excitation coil. The middle compression section of the heater is composed of a number of mutually insulated water-cooled restraint sheets. A high speed rotating airflow is introduced between the restraint plates so that the arc is restrained near the center position. Under the action of electric field and rotating airflow, the arc is stretched for several meters. Under the action of the magnetic field of the electrode excitation coil, the arc root rotates around the inner wall at high speed. According to the preliminary test results of China aerodynamics research and development center, the matching mode of gas flow, arc current and shunt resistance will affect the current distribution of each sub-electrode. In the experiment, the influence of the above three factors on the current distribution was studied respectively. The current distribution was observed by changing the gas flow rate, the total arc current and the shunt resistance value of water-cooled structure, and the factors affecting the stable operation of the three-electrode arc heater were explored.

Fig.3 Three-electrode arc heater

3. Results Analysis
The maximum arc current was set at 2600A and the maximum gas flow was 450g/s. For the convenience of subsequent explanation, each sub-electrode of the cathode was numbered CA1 to CA3 along the airflow direction, and each sub-electrode of the anode was numbered AN1 to AN3 along the airflow direction. A total of 18 groups of data were obtained, as shown in table 1.
The cathode charges obviously, while the anode charges little. This phenomenon is related to the position charge of the plasma core area and the distribution ratio of the outer sub-electrode. Current distribution of each sub-electrode under different arc currents and parameters is studied by analyzing current distribution diagram and calculating variance value of distribution current of sub-electrodes with different parameters.

3.1 Influence of arc current on distribution current of each sub-electrode

Figure 4 is the current distribution diagram of each sub-electrode under different arc currents under the same matching parameters of gas flow rate and stabilization resistance. 4(a) is the current distribution diagram of each sub-electrode when the gas flow is 162g/s, and the arc current is 800A and 1200A, respectively (corresponding to S1 and S2 in table 1); 4(b) is the current distribution diagram of each sub-electrode when the gas flow is 240g/s, and the arc current is 1000A, 1300A, 1600A and 2000A, respectively (corresponding to S3-S6 in table 1); 4(c) is the gas flow 310g/s, respectively. When the arc current is 1000A, 1400A, 1800A, 2200A and 2600A respectively (corresponding to S7-S11 in table 1), the current distribution diagram of each sub-electrode. Average current represents the ideal distribution of each sub-electrode under different parameter settings of the sub-electrode arc heater. The current distribution value of each sub-electrode under different arc currents under the same matching parameters is given.

Table 1 Current distribution table of three-electrode arc heater

| No | \( \eta_{\text{f}} \) (g/s) | \( I \) (A) | Cathode | | | Anode |
|---|---|---|---|---|---|---|
| 1 | 162 | 800 | 0.13 | 239 | 0.16 | 332 | 0.18 | 224 | 0.13 | 147 | 0.15 | 139 | 0.16 | 512 |
| 2 | 162 | 1200 | 0.13 | 340 | 0.16 | 391 | 0.18 | 461 | 0.13 | 356 | 0.15 | 317 | 0.16 | 538 |
| 3 | 240 | 1000 | 0.13 | 369 | 0.16 | 420 | 0.18 | 266 | 0.13 | 311 | 0.15 | 295 | 0.16 | 587 |
| 4 | 240 | 1500 | 0.13 | 418 | 0.16 | 454 | 0.18 | 418 | 0.13 | 402 | 0.15 | 380 | 0.16 | 606 |
| 5 | 240 | 1600 | 0.13 | 468 | 0.16 | 516 | 0.18 | 606 | 0.13 | 504 | 0.15 | 476 | 0.16 | 609 |
| 6 | 240 | 2000 | 0.13 | 620 | 0.16 | 636 | 0.18 | 753 | 0.13 | 644 | 0.15 | 609 | 0.16 | 732 |
| 7 | 310 | 1000 | 0.13 | 535 | 0.16 | 511 | 0.20 | 149 | 0.13 | 317 | 0.15 | 283 | 0.17 | 392 |
| 8 | 310 | 1400 | 0.13 | 500 | 0.16 | 545 | 0.20 | 350 | 0.13 | 473 | 0.15 | 424 | 0.17 | 495 |
| 9 | 310 | 1800 | 0.13 | 561 | 0.16 | 597 | 0.20 | 634 | 0.13 | 631 | 0.15 | 565 | 0.17 | 594 |
| 10 | 310 | 2200 | 0.13 | 704 | 0.16 | 714 | 0.20 | 766 | 0.13 | 773 | 0.15 | 692 | 0.17 | 717 |
| 11 | 310 | 2600 | 0.13 | 852 | 0.16 | 844 | 0.20 | 887 | 0.13 | 978 | 0.15 | 875 | 0.17 | 727 |
| 12 | 240 | 1000 | 0.13 | 333 | 0.16 | 401 | 0.20 | 259 | 0.13 | 327 | 0.15 | 292 | 0.17 | 370 |
| 13 | 240 | 1400 | 0.13 | 441 | 0.16 | 478 | 0.20 | 473 | 0.13 | 483 | 0.15 | 432 | 0.17 | 475 |
| 14 | 240 | 1800 | 0.13 | 575 | 0.16 | 574 | 0.20 | 640 | 0.13 | 613 | 0.15 | 549 | 0.17 | 624 |
| 15 | 240 | 2200 | 0.13 | 717 | 0.16 | 709 | 0.20 | 759 | 0.13 | 798 | 0.15 | 715 | 0.17 | 667 |
| 16 | 310 | 2200 | 0.13 | 701 | 0.16 | 718 | 0.20 | 767 | 0.13 | 781 | 0.15 | 700 | 0.17 | 700 |
| 17 | 380 | 2200 | 0.13 | 688 | 0.16 | 721 | 0.20 | 779 | 0.13 | 781 | 0.15 | 700 | 0.17 | 700 |
| 18 | 450 | 2200 | 0.13 | 677 | 0.16 | 725 | 0.20 | 785 | 0.13 | 781 | 0.15 | 700 | 0.17 | 700 |

Analyze the data in table 1. Set the other two parameters unchanged, the deviation of current distribution point and average current of each sub-electrode under different parameter Settings is given. The influence of matching mode of arc current, gas flow and shunt resistance on current distribution of each sub-electrode was studied by analyzing current distribution diagram and calculating variance value of distribution current of sub-electrodes with different parameters.
3.2 The influence of gas flow on the distribution current of each sub-electrode

In the arc current and shunt resistance matching parameters is the same case, figure 5 (a) as the arc current 1000 A, gas flow rate is respectively 240 g/g/s and 310 s (S3 and S7) in the table case each electrode current distribution diagram, figure 5 (b) as the arc current 1400 A, gas flow rate is respectively 310 g/g/s and 240 s when the S8 and S13 in (table 1) each electrode current distribution diagram, figure 5 (c) as the arc current 2200 A, The gas flow was 240 g/g/s, 310 g/g/s, 380 g/g/s and 450 g/g/s (corresponding to S15, S10, S17 and S18 in table 1).

It can be clearly seen from figure 5 (a) and (b) that when the matching parameters of arc current and shunt resistance are constant, when the gas flow is increased, the distribution current of each sub-electrode of the anode changes significantly, which is not conducive to the average distribution of current. With the increase of gas flow, the general trend of the current Shared by the inner sub-electrode and the outer sub-electrode of the anode gradually increases. Among them, when the arc current is small (arc current 1000A and 1400A), the increment is large, but at the large arc current (2200A), the increment is small. In addition, the gas flow has more influence on the current distribution of the cathode than the anode, and almost no influence on the current distribution of the sub-electrodes of the anode.

3.3 Influence of stabilization resistance matching mode on current distribution of each sub-electrode

Figure 6 is the current distribution diagram of each sub-electrode under the condition that the arc current and gas flow are the same, and different stabilization resistance matching methods are adopted. At this time, the arc current is 1000A, and in an ideal situation, the average current obtained by each sub-electrode is 333.3A. It can be seen from the figure that there is little difference in the current distribution of each sub-electrode under the two parameter Settings. After calculating the variance of each sub-electrode current, it can be seen that the variance of each sub-electrode current in the case of S3 resistance matching is less than that in the case of S12 resistance matching. Due to the large difference in the stabilization resistance of S12, it can be seen that under a certain arc current and gas flow, when the stabilization resistance difference is large, the average current distribution of each

Fig. 4 Current distribution diagram of each sub-electrode under different arc currents

Fig. 5 Current distribution of each sub-electrode under different gas flow rate
sub-electrode is better. Therefore, when the arc current is constant, the equalization resistance matching method is better than the gas flow. In addition, by comparing the changes in the proportion of current distribution and combining the data of the two electrodes, it can be found that the resistance plays a decisive role in current distribution. Within a certain range of gas flow and current changes, it is easier to achieve the uniform allocation of current distribution by changing the resistance value.

Fig.6 Current distribution diagram of each sub-electrode under different resistance matching modes

4. Conclusion
The main conclusions are as follows:

1) Under a certain arc current, increasing the difference of stabilizing resistance of each sub-electrode is conducive to the average distribution of current in each sub-electrode, while increasing the gas flow is not conducive to the current distribution.

2) With the increase of current, to achieve even distribution of current, the larger the resistance difference of shunt resistance is, the better the average distribution of current of each sub-electrode will be with the increase of arc current. The larger the current is, the more even the distribution of current of each sub-electrode will be.

3) The setting of parameters such as arc current, gas flow and stabilization resistance has a great influence on the distribution of cathode current of the multi-electrode arc heater, but a small influence on the distribution of anode current.

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