Experimental Research on Micro-nozzle Applied on Micro-propulsion Systems based on MEMS

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Abstract. In order to study the influence of the structural parameters of micro thruster applied in micro satellite attitude adjustment and orbital maneuver on its propulsion performance, this paper considers the factors influencing the performance of the thruster, and utilizes the orthogonal test design to obtain nine groups of micro-nozzles with different structural parameters. We processed this series of micro nozzles through MEMS (Micro-Electro-Mechanical Systems) technology. The micro-nozzles are made of single crystal silicon and glass through the anode bonding, and the electric heating wire is creatively processed through MEMS in the thrust chamber to improve the performance of the micro thruster. Experiments were carried out in a vacuum chamber. Finally, we analyse the experimental results by analysis of variance and analysis of range. The experimental results show that the performance of the micro nozzle is optimal when the semi-shrinking angle is 30 degrees, the semi-expansion angle is 15 degrees and the area ratio is 6.22. Meantime, the experiment verifies that it is feasible to improve the propulsive performance of micro-propulsion system through electronic heater strip.

1. Introduction

With the launch of various satellites, the sustainable development of aerospace technology has not only promoted the continuous improvement of modern science and technology, but also brought earth-shaking changes for people’s lives. Small satellite technology emerging in 1980s has attracted increasing attention from major aerospace countries by virtue of its small size, light weight, low cost, short development cycle, and excellent performance as well as the functions of rapid launch and spatial network and to achieve the functions of large satellites[1-4]. In order to realize the attitude control, gravitational compensation, formation flying and other functions of microsatellite, the demands for propulsion system are continuously enhanced[5, 6]. The existing propulsion systems and thrusters cannot meet the demands of micro-satellites because of their size, mass, and thruster requirements, etc. [7]. Therefore, it is necessary to develop a new type of thruster suitable for micro-satellites, which has light mass, small size, precise thrust and low power consumption.

Traditional manufacturing methods cannot produce the appropriate micro-propulsion system, thus the micro-propulsion system based on MEMS (Micro-Electro-Mechanical-Systems) emerged cater to the demands and was developed subsequently [8-11]. The existing micro-thrusters applied in the spacecraft include: high pressure cool gas micro-thruster, chemical micro-thruster, electric micro-
thruster, and so on. High pressure cool gas micro-thruster is relatively mature and the mostly widely utilized at present [12-15].

In this paper, we use MEMS technology to design and process a series of micro-thrusters with different aspect ratios and shrinkage ratios. The detailed processing flow is given. In addition, a special form of heating wire is processed in the micro-thruster chamber. The micro-thruster uses nitrogen as propellant and the designed thrust is 10mN. Based on the principle of torsion pendulum measurement [16], the thrust force is measured indirectly. Finally, we analyze the experimental results and put forward some suggestions for the improvement.

2. Design of cool gas micro-thruster

The cool gas micro-thruster utilizes a classic Laval nozzle configuration (as shown in Figure 1). Under the condition of high Reynolds number and low Knudsen number, the following design hypotheses about the ideal engine are satisfied:

1. Propellant is homogeneous (mainly gaseous, the amount of any aggregate phase can be ignored);
2. Propulsive working medium obeys the ideal-gas law;
3. The entire flow process is adiabatic, and there is no heat transfer through the engine wall;
4. In the whole gas flow process, there is no obvious friction, and all of the boundary layer effects are ignored;
5. No shock waves or discontinuity occurs in the nozzle flow;
6. The flow of the propellant is a steady state. The expansion of the working medium is uniform and stable. The transient effect time is short and can be ignored.

![Figure 1. Typical configuration of Laval nozzle](image)
2.2. Specific impulse and thrust calculation of thruster based on adiabatic process

The gas flow process of the micro-thruster can be calculated by the nozzle flow equation (1),

\[ v_s = \left( \frac{2\gamma RT_0}{\gamma-1} \right)^{\frac{1}{2}} \left[ 1 - \left( \frac{p_a}{p_0} \right)^{\frac{\gamma-1}{\gamma}} \right] \]

Where \( v_s \) is the nozzle outlet velocity, \( p_0 \) is the total inlet pressure. \( T_0 \) is the total inlet temperature. \( A_t \) is the cross-sectional area of the nozzle throat, \( R = R_g/M \) is a gas constant. \( M \) is the molecular weight of the gas, and \( \gamma \) is the specific heat ratio of the gas.

We can obtain the specific impulse of the micro-thruster by equation (2) [19],

\[ I_w = c' C_f / g_0 \]  (2)

where \( c' = \sqrt{\gamma R U_0 \gamma^{-1}} \left( \frac{2}{\gamma+1} \right)^{\frac{\gamma+1}{(\gamma+1)}} \), \( C_f = \left[ 2\gamma^2 \left( \frac{2}{\gamma+1} \right)^{\frac{\gamma+1}{(\gamma+1)}} \left[ 1 - \left( \frac{p_a}{p_0} \right)^{\frac{\gamma-1}{\gamma}} \right] \right]^{\frac{1}{2}} + \delta \frac{p_e - p_a}{p_e} \)

The thrust of the micro-thruster can be obtained through the following equation,

\[ F = C_f p_a A_t \]  (3)

Where \( I_w \) is a gas specific impulse. \( F \) is the thrust. \( \delta \) is the area ratio of the nozzle, \( p_e \) and \( p_a \) are the nozzle outlet pressure and the ambient pressure, respectively.

In space, since the external environment of the thruster is vacuum microgravity, the ambient pressure \( p_a = 0 \). Assuming that the expansion ratio of the nozzle is infinite, \( p_e = p_a = 0 \). We can get the expression of ideal specific impulse of the cool gas thruster in equation (4),

\[ I_e = \left( \frac{2\gamma RT_0 g_0}{\gamma-1} \right)^{\frac{1}{2}} \]

Equation (4) shows that the ideal specific impulse of the cool gas thruster is only related to the molecular weight of the gas \( M \), the total inlet temperature \( T_0 \), and the specific heat ratio \( \gamma \).

For the cool gas micro-propulsion system, the whole process of gas flow from the cylinder into the micro-thruster is adiabatic. There is no loss of heat during the gas flow process. Therefore, the inlet temperature of the thruster is equal to the gas temperature in the cylinder, namely, \( T = T_0 \).

Then, the calculation formula of ideal thrust of the micro-thruster is equation (5),

\[ F = C_f p_e A_t = p_e A_t \left[ 2\gamma^2 \left( \frac{2}{\gamma-1} \right)^{\frac{\gamma+1}{(\gamma+1)}} \right]^{\frac{1}{2}} \]

For the selected propellant, it can be observed that the ideal thrust depends mainly on the inlet pressure \( p_0 \) and the nozzle throat area. Therefore, we shall adjust the inlet pressure and nozzle throat area to achieve the ideal thrust.

### Table 1. The structural parameters of nozzles chips

| Number | Semi-shrinkage angle \( \alpha \) | Semi-expansion angle \( \beta \) | Area ratio |
|--------|-------------------------------|--------------------------------|------------|
| 1      | 30                            | 20                             | 10         |
| 2      | 45                            | 30                             | 10         |
| 3      | 30                            | 15                             | 6.22       |
| 4      | 45                            | 15                             | 4          |
| 5      | 60                            | 15                             | 10         |
| 6      | 60                            | 30                             | 6.22       |
| 7      | 30                            | 30                             | 4          |
| 8      | 60                            | 20                             | 4          |
| 9      | 45                            | 20                             | 6.22       |
During the actual operation of the micro-thruster, since the nozzle expansion ratio is not infinite, the nozzle outlet pressure of the thruster is not zero, i.e. $p_e \neq 0$. As we can see from equation (3), the thrust of the thruster will be slightly smaller than the ideal case.

The mass flow of the micro-thruster can be calculated through equation (6):

$$
\dot{m} = \frac{F}{I_g s_0} \frac{A_o p_0 \gamma}{\sqrt{\gamma RT_0}} \left[ \left( \frac{2}{\gamma + 1} \right)^{\frac{\gamma + 1}{\gamma - 1}} \right]^{1/2}
$$

According to equation (6), if the theoretical thruster $F$, micro-nozzle expansion ratio $\varepsilon$ and total inlet pressure are known, we can calculate the specific impulse and mass flow of the micro-thruster.

3. Manufacturing process of cool gas micro-thruster

The cool gas micro-thruster is manufactured through the standard MEMS technology. As a micro-electro-mechanical system, MEMS is the miniaturized revolutionary technology developed and expanded from microelectronic technology [20, 21]. It integrates physical, chemical and biological sensors, information processing and storage units as a micro-integrated systems, which refers to the micro-devices and system manufactured in large batch through micro-machining technology [22].

The micro-fabrication technology of micro-electro mechanical system is an important part of MEMS, which is the technological extension and relevant application in three aspects of theoretical basis, technical basis and application research. Modern micro-fabrication technology can be divided into four categories: first, the separation process, such as evaporation, sputtering, cutting, etc.; second, bonding processing, such as deposition, evaporation, etc.; third, deformation processing of materials, such as moulding deformation processing, and fluid deformation processing, etc.; fourth, the material processing and surface modification processing, such as diffusion, mixing and reaction incentives[23].

3.1. Processing of the micro-nozzle

At present, MEMS micro-processing technologies mainly include: lithography masking, high-energy beam etching (laser etching) and LIGA process [24]. In this paper, the processing mode utilized to process the micro-nozzle is lithography masking and high-energy beam etching (laser etching). The specific processes include oxidation of silicon wafer, deep reactive ion etching, laser drilling, removal of surface oxide layer, corrosion of Al material, etc. [25].

After the above-described processing flow, the micro nozzle with the thrust chamber and the heating function has been manufactured. The specific form of each component is as shown in Figure 2.

![Figure 2. Micro-thruster with heating filaments](image)

3.2. The connection of the heating wire and the fixing of the micro-nozzle

After the fabrication of the micro-nozzles, the copper wire is bonded to the Al electrodes through the conductive adhesive, as shown in Figure 3. The conductive adhesive can withstand temperature as high as 350 degrees which meets the heating requirements.
In order to verify the conductive properties and bond strength of conductive adhesive, we measured the resistance of each experimental part. The experimental results in Table 2 show that the properties of the conductive adhesive are good and the resistance of the heating wire is not greatly changed, which can guarantee the stability of the heating power. However, the heating power is too large during the heating process, which leads to burnout of heating wire, which is as shown in Table 2.

| Number | The resistance before bonding wire | The resistance after bonding wire |
|--------|-----------------------------------|----------------------------------|
| 1      | 329 Ω                             | \                              |
| 2      | 325 Ω                             | 296.4 Ω                         |
| 3      | 276 Ω                             | \                              |
| 4      | 264 Ω                             | 266.1 Ω                         |
| 5      | 273 Ω                             | 281.2 Ω                         |
| 6      | 271 Ω                             | 262.9 Ω                         |
| 7      | 323 Ω                             | 290.6 Ω                         |
| 8      | 316 Ω                             | 339.3 Ω                         |
| 9      | 312 Ω                             | \                              |

Figure 4 shows the components used to connect the air supply tube to the micro-nozzle, and figure 5 shows the cool gas micro-thruster manufactured after above steps.

4. Experimental devices and thrust measurement

4.1. Thrust test gas path
Micro thrust test gas path is composed of cylinders, the corresponding valves, pressure sensors, flow sensors and control system. Figure 6 shows the schematic diagram of the gas path.
The physical map of micro test gas path is shown in Figure 7. Before placing the experimental system into the vacuum chamber, close the manual valve and charge 2 L of nitrogen gas into the cylinder through the filter relief-pressure valve. Close the stop valve after the inflation and remove the filter relief-pressure valve. Finally, open the control system, close the magnetic valve, open the manual valve, and the entire gas path equipment can be placed in the vacuum chamber together with the thrust test bench.

**Figure 6.** The schematic diagram of the gas path

4.2. **Thrust test bench**

The micro thrust test is carried out based on the steady-state thrust measurement principle. Figure 8 shows the thrust test bench. The micro-thruster is attached to one end of the torsion bar and connected with the gas path through the silicone hose. First, thrust is exerted on the plane of the torsion bar, and converts into the torsion angle. Second, with the increase of the torsion angle, the thrust and the restoring force tend to balance. Finally, we can measure the steady-state voltage through the photoelectric sensor, and then calculate the thrust by the functional relationship between the voltage and the torsion angle.

**Figure 7.** The physical map of micro test gas path

**Figure 8.** Thrust test bench in vacuum chamber

In order to reduce the influence of environmental and human factors on the thrust test process and the thrust calibration process, we have taken the following measures. Firstly, both the thrust test and the thrust calibration are carried out in the vacuum chamber, ensuring that the thrust test bench will not move throughout the testing process. Secondly, the gas supply pipe is fixed to the torsion bar to prevent the test result from being affected by the swing of the pipe during the thrust test.
4.3. Thrust test process

4.3.1 Calibration of thrust test system. In order to guarantee the accuracy of the thrust test and calibration, the entire thrust test bench, especially the torsion bar, shall be in the horizontal state. Both thrust test and calibration are carried out in the vacuum chamber.

Several weights with different masses are selected, and the weights are equal to the tested thrust. Tie a filament to the torsion bar which fixes the nozzle, and hang the weight on the filament. Pull up the filament so that the weight is hung from the torsion bar plane, and the angle between the filaments on both sides of the weight is maintained at 135 degrees. According to the decomposition of the force, it can be known that the simulated thrust is equal to the mass of the weight, namely, $F = G$.

Figure 9. Calibration force diagram

The mass of the weight utilized to simulate micro-thrust is close to the measured thrust so as avoid the inconformity between the calibration value and the range of actual measured thrust. Change the weights with different masses, and record the sensor charge signal. The two signals on the display card are gradient. The difference between two stairstep signals is the mass of the weight, namely the simulated continuous thrust.

Each weight is calibrated for twelve times in different position of the filament. Assume that the calibration data at each point are randomly distributed, and we can obtain the precision of the measurement by calculating the variance of the data distribution at each point.

$$
\tilde{x} = \frac{1}{12} \sum_{i=1}^{12} x_i,
\nu_i = x_i - \tilde{x},
\sigma = \sqrt{\frac{\sum_{i=1}^{12} \nu_i^2}{n-1}}
$$

(7)

Where $x_i$ is the measurement value of each time, $\nu_i$ is the measurement residual, $\tilde{x}$ is the average measurement value, $\sigma$ is the standard deviation of the measurement, and $n$ is the times of measurements.

According to Figure 10, the calibration curve approximates a straight line. There is a high degree of linearization between the output voltage signal (horizontal axis) and the simulated thrust (vertical axis) of the calibration system. The fitting curve can be set as $y = a + b \times x$, where $a$ and $b$ are the fitting curve coefficient.

Figure 10. The calibration curve
4.3.2 Measurement of micro thrust. Before measuring the micro thrust, stabilize the test system and evacuate the vacuum chamber to 10 Pa. Select the measurement range on the digital charge meter, and reset the meter to carry out the experiment for data acquisition. Open the valve to jet, and start to collect the signal when it comes to stable, after a period of time to close the valve; continue to gather the signal for a period of time. The measured stairstep signal is shown in Figure 11. The magnitude of the thrust is expressed as the height difference between the two steps in the signal data.

The measured voltage has a lot of ambient noise. After the signal is filtered, the signal-to-noise ratio is obviously improved, and the measurement accuracy is increased.

![Original signal](image1.png) ![Processed signal](image2.png)

Figure 11. Original and processed signals of thrust

4.4. Error in measurement
There are three main sources of error in this experiment. One is the influence of the environment, the other is the design defect of the experimental system and processing error and the third is the error of the signal acquisition system.

5. Experimental results and discussion

5.1. Orthogonal test analysis of thrust measurement results
The range and variance of the experimental results of the nine groups of micro-thrusters at the inlet pressure of 1.29 bars are analysed. The optimized parameters are initially screened through the significant level order of the factors obtained from the range analysis. Afterwards the significance level of each factor is evaluated by the F test of variance analysis to get the influence of each factor on the thrust.

The range analysis results indicate that semi-shrinkage angle is the main factor affecting the test index, that is, the change of semi-shrinkage angle has the greatest influence on the thrust value.

In order to the influence of various factors on the test index trends and laws more intuitively reflect, the factor level is taken as the abscissa, and the average of the test indicators as the vertical axis to draw factors and index change trend chart as shown in figure 12.

![Graph A](image3.png)
![Graph B](image4.png)
![Graph C](image5.png)

Figure 12. Factors and index change trend
As shown in Figure 12, we can see that in the case of inlet pressure of 1.29 bars, the optimal structure parameters of the micro-nozzles can be determined as semi-expansion angle of 30 degrees, semi-expansion angle of 20 degrees and area ratio of 6.22.

Due to the poor precision of range analysis, we perform a variance analysis on the experimental results so as to get a quantitative standard to judge the influence of various factors on the thrust, and the results are shown in Table 3.

| Factor | DevSq | DOF | F    | F_{0.05}(2,2) | Significance level |
|--------|-------|-----|------|--------------|-------------------|
| A^a    | 17.944| 2   | 36.251| 19.000       | *                 |
| B^b    | 1.178 | 2   | 2.380 | 19.000       |                   |
| C^c    | 0.562 | 2   | 1.135 | 19.000       |                   |
| Error  | 0.49  | 2   | 0.49  | 19.000       |                   |

^a Semi-shrinkage angle.
^b Semi-expansion angle.
^c Area ratio.

F_{0.05} (2, 2) = 19.000, we can see in table 3 that F_A > F_{0.05} (2, 2). Therefore, factor A is significant, that is semi-shrinkage angle has a greater impact on micro thrust, which is consistent with the previous range analysis.

5.2. Thrust and Mass flow rate at different heating power

Figure 13 shows the change in micro thrust at different heating powers. At the same inlet pressure, the thrust increases with the heating wire heating power. Moreover, and the effect of heating on the thrust is relatively large. This is because the gas in the thrust chamber absorbs heat, and the temperature gradually rises, which leads to expansion, and increases the gas inlet pressure. According to equation (1), the outlet gas flow rate is increasing. Formula (5) indicates that thrust is also increasing.

In addition, as shown in Figure 13, with the changes of inlet pressure changes, thrust also increases accordingly, which has been verified by formula (5).

![Figure 13. Thrust change under different heating power](image1)

![Figure 14. Mass flow rate change under different heating power](image2)

According to Figure 14, as the heating power of the heating wire increases, the mass flow rate of the gas enhances. This is for that the gas is heated to accelerate its flow velocity, thereby taking more gas in the same time. However, larger inlet pressure does not necessarily result in the greater mass flow rate. As can be seen from Figure 14, when the inlet pressure is 1.29bar, the mass flow rate of the gas is the largest. This may be for that the air flow cannot be fully expanded due to the large inlet pressure, which aggravates the friction loss.

6. Conclusion

Nine groups of thrusters with different structure parameters designed by the orthogonal experimental design method were tested in a vacuum chamber. Through the experimental results, range analysis and variance analysis were utilized to get a better set of structural parameters, i.e., the semi-shrinkage...
angle is 30 degrees, the semi-expansion angle is 20 degrees, and the area ratio is 6.22. For whether the result is the optimal, it remains to be further explored in the late test. In addition, we utilized the heating wire in thrust chamber to heat the gas. The results show that the thrust of the propeller increases with the heating power, and the change of the thrust is obvious. This indicates that the heating wire set in the thrust chamber of the micro propeller is conductive to improving the thrust.

7. References
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