Study of airbreathing electric thruster for nearspace propulsion

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Abstract: The electric propulsion is regarded as a potential alternative propulsion system to the propeller system for near-space vehicles. The goal of this paper is to study the performance of an air-breathing electric thruster based on the single dielectric barrier discharge (SDBD) technology. Experiments were conducted and the thrust was measured under various ambient pressures corresponding to different altitudes to evaluate the in-suit propulsion ability. The applied voltage was also varied under each pressure condition to explore its influence. The present results show that the voltage has a great effect on the thrust, but the effect of the pressure on the thrust is not so obvious because the voltage is relatively low. The thruster is capable to produce a normalized thrust of 0.84 mN/m at 60kPa with a voltage of 4.5kV. The thrust-to-power ratio of the tested thruster in all these experiments is mainly at the level of tens of mN/kW.

I. Introduction

THe near-space vehicles have been a research focus for its merits such as its higher load capacity, higher efficiency and faster deployment than spacecrafts, as well as longer flight endurance and better survivability than aircrafts. However, the development of the near-space vehicles faces many difficulties because of the complex near-space environment, making the near-space still undeveloped.

The propulsion system is one of these limitations. The electric propeller system is the most widely used one in current low-speed near-space vehicle designs, because it is lighter and simpler than chemical propulsion systems and has a high efficiency in low-speed flight. But it has been demonstrated that the electric propeller system behaves well when the flight altitude is lower than 30km,[1,2] and at a high altitude, the propeller system also has some technical problems.[2]

Thus, developing the alternative propulsion systems is meaningful to the development of the near-space vehicles, and the electric propulsion is regarded as a potential choice for those long-endurance near-space vehicle concepts.[3,5] Compared with the propeller system, the electric propulsion is thought to increase the flight endurance, the range of flight altitude and also the payload of the near-space vehicles. Besides, most of the long-endurance near-space vehicle designs apply the solar arrays together with the batteries to supply energy partially or fully, providing conditions for the use of electric propulsion systems.

Up to now, some researches concerned with the atmospheric electric propulsion have been done, but few of them focus on the near-space applications. Electrohydrodunamic (EHD) propulsion, which uses the corona discharge driven by a high-voltage dc to induce a ionic wind to produce the thrust, has been studied experimentally and numerically by many research groups, and their researches shows the EHD propulsion system is capable to have a thrust-to-power ratio of tens of N/kW or even as high as approximately 100 N/kW, whereas the energy conversion efficiency is relatively low (approximately 1%).[3-10] A concept of air-breathing coaxial Pulsed Plasma Thruster (PPT)

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has been proposed and tested at the pressure ranging from 10 to 40Torr by the Advanced Propulsion Laboratory at the University of Washington, and the results shows a thrust-to-power ratio of tens of mN/kW.[11]

We've proposed an air-breathing electric thruster based on the Single Dielectric Barrier Discharge (SDBD). Using the SDBD technology, this kind of thruster can ionize the air to form the plasma within a wide range of pressure (from several Pa to 1tam) without consuming too much power, so from this point of view, it is suitable for near-space vehicles. Such a device has been demonstrated to be able to generate a thrust in the researches related to the flow control technology and a normalized thrust (the thrust per spanwise length) of several mN/m is obtained in certain conditions even at a pressure less than 20kPa.[12-15] As a kind of air-breathing propulsion, its propulsion performance is directly affected by the environment parameters if without any auxiliary equipments. So it is important to look into the force production mechanisms and investigate the influence of various parameters. In the present work, a simple thruster was designed and fabricated. Experiments were conducted under various sub-atmospheric pressures to preliminarily study the propulsion performance as well as the influence of the ambient pressure, and the effect of applied voltage on the generated thrust at different pressures was also investigated.

II. Experimental Apparatus

A. Thruster Description

The typical configuration of this kind of thruster is shown in Fig.1, mainly consisting of a dielectric layer with two electrodes attached to each side. One electrode (the upper one in Fig.1) is exposed to the air (so-called the exposed electrode) and connected to the power supply, while the other one (the lower one in Fig.1) is encapsulated by the insulant (so-called encased electrode) and grounded.

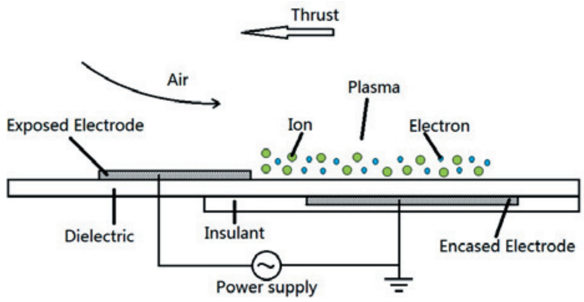

Figure 1. Schematic of the typical thruster configuration.

The working principle is that when an ac voltage or a nanosecond pulse voltage is applied to the exposed electrode and the consequent electric field in the area between two electrodes exceeds the breakdown electric field of the air, the air ionizes and the plasma is formed. Driven by the electric field, the ions accelerate and impact the neutral particles around them, so that the energy is converted to the air to speed up it and finally the thrust is produced.

In the present study, the quartz glass with a thickness of 3.5mm is used as the dielectric. Both of the two electrodes are made of copper and are 0.06mm thick. The width of the exposed electrode is 15mm while the encased electrode is 20mm wide. The streamwise gap between two electrodes is 5mm. The insulant we used is the Kapton tap.

B. Test Facilities

The experimental setup shown in Fig.2(a) mainly consists of the vacuum chamber, the power supply, the thruster and the measuring instruments. During the experiments, the thruster is mounted on the top of the thrust stand and both of them are placed inside the vacuum chamber, while the power supply and all those measuring instruments are placed outside the vacuum chamber.

The cylindrical vacuum chamber (Fig.2(b)) is made of steel and it has a inner diameter of 1.8m as well as a length of 3m. The pressure inside the vacuum chamber is monitored using a vacuum gauge.

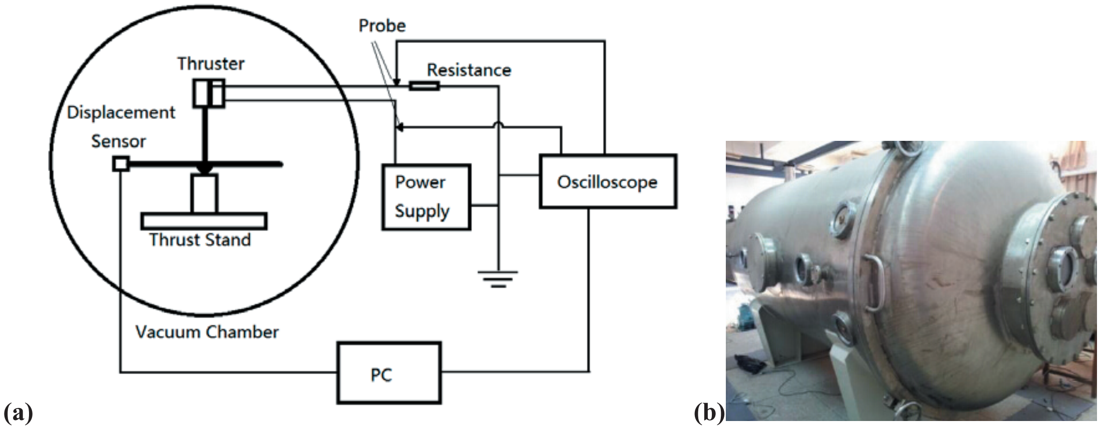

Figure 2. Schematics of the experimental system: (a) the experimental setup, (b) the vacuum chamber.

The power supply can output a sinusoidal ac waveform. The frequency of the sinusoidal waveform is chosen to be 20kHz. Because of the power supply's properties, the regulating range of the output voltage is determined by the output load, which is related to the pressure condition inside the vacuum chamber, the geometry parameters of the thruster and so on. And this results in difficulties in voltage control in the present works.

The instant output voltage and the current are detected using high voltage probes and the data were recorded by the oscilloscope. The power dissipation was then obtained by integrating voltage and current using Eq.(1).

$$P = \frac{1}{T}\int_0^T U_t I_t dt \tag{1}$$

Where P is the power dissipation. T is the period of the voltage. U_t is the instant voltage and I_t is the current.

The thrust stand uses a displacement sensor mounted at one end of the balance arm to detect the displacement (i.e., the angular deflection) caused by an external force, and this displacement sensor will also transfer the detected displacement to the electric signal, which is then recorded by a data acquisition card and a PC. The thrust stand will be calibrated to determine the relationship between the electric signal and the external force before each time a series of experiments begin.

C. Experimental Approach

In this paper, the pressure inside the vacuum chamber and the applied voltage were chosen to be the variables. Using the equipped vacuum pumps, the pressure was changed discretely from 90kPa to the present limit to conduct the measurements. Under each pressure condition, firstly the breakdown voltage was "measured" using the detected current waveform to determine when the plasma appeared. Then the applied voltage was increased step by step from the breakdown voltage to the limit at that pressure and the thrust was measured at each voltage. Also the voltage and the current waveform data were recorded to calculate the power dissipation.

III. Results and Discussion

Corona discharge around the wires as well as the insulator (which were placed between wires and metals to prevent direct contact) surface flashover were observed when the pressure was low while the applied voltage was relatively high in order to obtain a measurable thrust, so up to now, threshold was measured within the pressure range of 5-90kPa, while for thrust measurements, the range was 60-90kPa.

Figure 3 shows the variation of the threshold (i.e., the breakdown voltage) with the pressure. The threshold increases with the higher pressure within 5-90kPa, which is similar to the results of Ref.16. It also shows that the threshold decreases rapidly when the pressure is high and it changes more and more slowly at lower pressure.

Figure 4 shows the thrust as a function of the applied voltage at different pressures. To specify the basic performance of the thruster, the measured thrust data were all divided by the spanwise length converted to the normalized thrust. It was found that for the tested thruster, the threshold at 90kPa is bigger than the maximum voltage the power supply could output at 80kPa, so the data of 90kPa are not presented here for comparison. At 90kPa, the thruster can produce a thrust of 15mN/m when the voltage amplitude is 9kV.

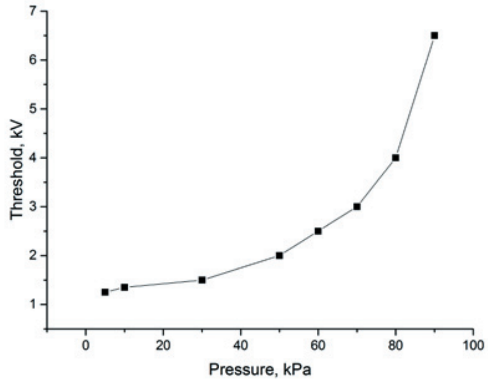

Figure 3. Curve of threshold change with pressure from 5kPa to 90kPa

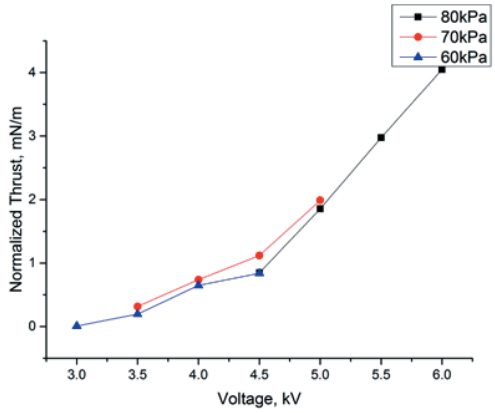

Figure 4. Curve of normalized thrust change with applied voltage

It can be seen from the Fig.4 that with the same applied voltage, the measured thrust does not change obviously as the pressure changes. We think this is because the applied voltage is relatively low, and this is similar to the low-voltage result of an unpublished work mentioned in Ref.16.

Figure 5 shows at a given voltage, the power dissipation decreases with the increasing pressure. This relationship is also noticed and mentioned in Ref.14. It has been found that at a lower pressure, the plasma volume became larger with the same voltage, and we think this may be one fact that increases the power dissipation. Besides, the threshold decreases with lower pressure, which means at a given voltage, the discharge intensity at lower pressure is higher than that at higher pressure, leading to a higher power dissipation. So the power dissipation as a function of the delta-voltage (the difference between the applied voltage and the threshold) is presented in Fig.6, and it can be seen that with a same delta-voltage, the difference of the power dissipation at different pressure is not so obvious as in Fig.5.

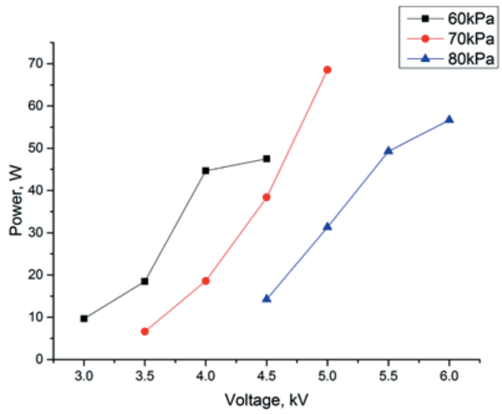

Figure 5. Curve of power dissipation change with applied voltage

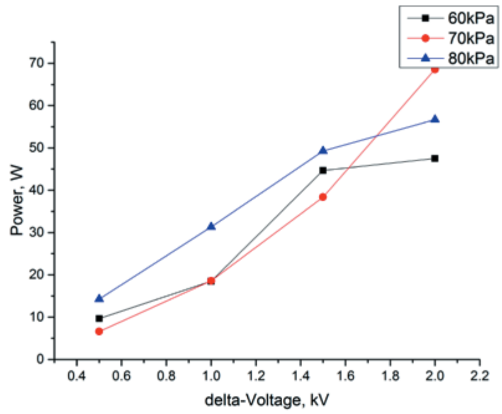

Figure 6. Curve of power dissipation change with delta-voltage

Figure 7 shows the normalized thrust as a function of the power dissipation and it indicates that under the experiment conditions, the efficiency at a higher pressure is higher than that at a lower pressure.

According to all these experimental results, the thrust-to-power ratio of the tested thruster is mainly within a range of 20-60 mN/kW in the present study.

IV. Conclusion

An air-breathing electric propulsion system based on the SDBD technology was proposed for long-endurance near-space vehicles. A simple thruster consists of basic components only was made and a series of experiments at sub-atmospheric pressures were conducted to investigate the effects of pressure and applied voltage on the propulsion performance. In the present work, the thrust was measured at a lowest pressure of 60kPa, and the results show that a normalized thrust of approximately 1mN/m can be obtained and the thrust-to-power ratio is tens of mN/kW.

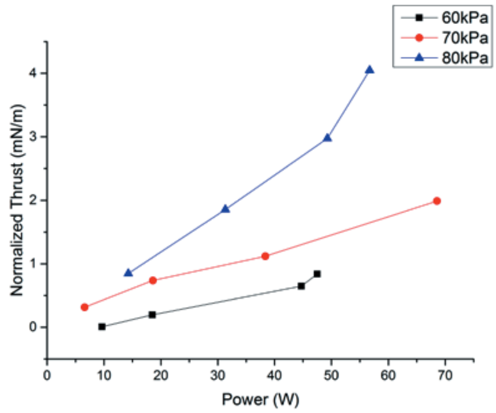

Figure 7. Curve of normalized thrust change with power dissipation

Some problems need to be solved in the following works. The experiment system has to be optimized so as to conduct experiments at the much lower pressure as well as to make the thrust more measurable at those quite low pressures corresponding to the pressure conditions in near-space. Besides, because it is difficult to detect some parameters related to the plasma and the electric field, numerical simulation shall be used to help understand the mechanisms.

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