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ABSTRACT

We propose a prototype design of a propulsion thruster that utilizes air plasma induced by microwave ionization. Such a jet engine simply uses only air and electricity to produce high temperature and pressurized plasma for jet propulsion. We used a home-made device to measure the lifting force and jet pressure at various settings of microwave power and the air flow rate. We demonstrated that, given the same power consumption, its propulsion pressure is comparable to that of conventional airplane jet engines using fossil fuels. Therefore, such a carbon-emission free thruster could potentially be used as a jet thruster in the atmosphere.

Similar to solids, liquids, and gases, plasma is a normal state of matter. Plasma naturally arises due to the ionization of molecules at high temperatures (such as in the sun) or in high electric fields (such as in lightning). In the laboratory, plasma can be generated using an electric arc, microwave cavity, laser, fire flame, or discharging high-voltage needle. Plasma has wide applications in many areas, including metal processing, crystal growth, medical treatment, food processing, energy, and environmental industries. Plasma jet thrusters have also been used in aerospace applications for many years. The jet thruster using xenon plasma in a spacecraft exerts only a tiny propulsion force and can only be used in outer space in the absence of air friction. Even though such a plasma engine has a very small propulsion force, after months and years of constant acceleration, the spacecraft can ultimately reach a high speed. However, this type of an engine, like that of the NASA Dawn space probe, is not useful in the atmosphere environment. Recently, a research team from MIT demonstrated a plasma-powered glider that can operate in air by using a needle-discharge array to generate air plasma to power the flight. This team demonstrated a continuous flight time of 12 s and a flight distance of 55 m. However, this Tesla type of plasma thruster has a lifting force and jet pressure of only 6 N/kW and 3 N/m², respectively. It is very challenging for this approach to become feasible for use as a powerful engine for actual air transportation. In this report, we consider a microwave air plasma jet thruster using high-temperature and high-pressure plasma generated by a 2.45 GHz microwave ionization chamber for injected pressurized air. We propose a simple prototype plasma jet thruster that can generate approximately 10 N of thrust at 400 W using 0.5 l/s for the airflow, corresponding to the lifting force of 28 N/kW and a jet pressure of $2.4 \times 10^4$ N/m². At a higher microwave power or greater airflow, propulsion forces and jet pressures comparable to those of commercial airplane jet engines can be achieved.

Our experimental setup is shown in Fig. 1 and includes a magnetron with the power of 1 kW at 2.45 GHz, a circulator, a flattened waveguide, an igniter, and a quartz tube. The magnetron is the microwave source, the circulator is used to absorb reflected microwaves, and a three-stub tuner is used to optimize the power inside the air ionization chamber. The length, width, and height of the waveguide are 600 mm, 90 mm, and 50 mm, respectively. The flattened part of the waveguide has a height of 25 mm. The flat area of the waveguide is designed to increase the electric field strength. The microwave generated by the magnetron passes through the circulator and the three-stub tuner and reaches the flattened waveguide. The igniter is used to ignite and generate a plasma jet.
An industrial cooler is used to cool the circulator and the magnetron. We use an air compressor and an airflow meter to generate and condition the high-pressure air into the quartz tube. Air enters the quartz tube from the side, forming a vortex that keeps the plasma jet stable in the tube. As shown in Fig. 2, variation in the microwave power affects the length of the air microwave plasma jet. Our observation indicates that the length of the flame increased with increasing power. In addition, changes in the injected airflow also affect the flame length.

The flame temperature can reach higher than 1000 °C; a general-purpose barometer will not withstand such a high temperature and could not be used. Therefore, in this experiment, we devised a simple tool to measure the jet pressure of the hot plasma. We placed a hollow steel ball (117 g, outer diameter 75.5 mm) on top of the quartz tube, as shown in Figs. 3(a) and 3(b) (Multimedia view). A small hole was drilled on the top of the ball with an opening for the insertion of much smaller steel beads to change the overall ball weight. If the plasma jet is sufficiently strong, it can cause the hollow steel ball to vibrate. In order to keep the steel ball stationary, small steel beads need to be added. We define the threshold weight as the minimum total weight (including the steel ball and small steel beads) that can make the steel ball keep still. We can calculate the threshold propulsion force from this critical weight. Then, based on the known area for the quartz tube cross section, the jet pressure can be determined. The jet propulsion force \( F \) is equal to the critical total weight \( M \) times the gravitational acceleration \( g \), which is 9.8 N/kg. In the experiments, we used 400 W, 600 W, and 800 W for...
the microwave power, and $0.7 \text{ m}^3/\text{h}$, $0.85 \text{ m}^3/\text{h}$, $1 \text{ m}^3/\text{h}$, $1.15 \text{ m}^3/\text{h}$, $1.3 \text{ m}^3/\text{h}$, and $1.45 \text{ m}^3/\text{h}$ for the airflow rate. Even in the absence of microwave power, the injected compressed air can provide some propulsion to the steel ball. Therefore, when calculating the net propulsion $F_{\text{net}}$ generated purely by the plasma jet, it is necessary to subtract the $F_0$ propulsion contribution that is present in the absence of microwave irradiation. Thus, the net propulsion force is given by

$$F_{\text{net}} = F - F_0 = (M - M_0)g.$$  \hspace{1cm} (1)

$M_0$ is the critical steel ball weight obtained in the absence of the microwave irradiation. The overall pressure $P$ generated by the air plasma jet is equal to $F/\pi R^2$, where $R$ is the inner diameter of the quartz tube. Subtracting the contribution to the pressure generated purely by air injection, the net jet propulsion pressure is obtained as

$$P_{\text{net}} = (F - F_0)/\pi R^2.$$  \hspace{1cm} (2)

We measured the threshold weight at which the steel ball started to rattle to measure the corresponding jet propulsion force of the plasma jet under different microwave powers and airflow rates. Figures 4(a) and 4(b) show the overall jet propulsion force including the contribution from the injected air with no microwave power, where the x-axis represents the power and flow rate. These data were linearly fitted with a slope $m$ and an intercept $c$, indicating a linear increase with increasing power or airflow. Figure 5 shows the net pressure generated by the plasma jet at various microwave power and airflow settings based on the area of the inner quartz tube. For example, at the power and airflow rate of 600 W and 1.15 m$^3$/h, respectively, the net jet pressure reaches $1.6 \times 10^4$ N/m$^2$ after the subtraction of the airflow component.

The above experimental results proved that the microwave power and airflow have a significant influence on the plasma jet propulsion. At a constant airflow, higher microwave power makes the electric field inside the ionization chamber much stronger, leading to a more efficient ionization of the gas molecules. At higher microwave power and airflow, the temperature and density of the plasma increase, resulting in increased jet propulsion force and pressure.

In summary, we propose a prototype device that utilizes microwave air plasma for jet propulsion as a viable engine. To measure the propulsion pressure of very hot plasma (easily over $1000^\circ$C) at temperatures where a conventional pressure meter can be damaged, we devised a technique based on the use of a hollow steel ball with adjustable weight. The pressure was determined according to the threshold weight at which the ball started to rattle. Based on the threshold weight data, we have determined the plasma propulsion force and pressure as a function of microwave power and the airflow rate. For example, at the microwave power and airflow rate of 400 W and 1.45 m$^3$/h, respectively, the overall jet propulsion force was approximately 11 N or 28 N/kW. Based on the area of the quartz tube opening, we estimated the total propulsion pressure to be $2.4 \times 10^4$ N/m$^2$. These values are comparable to those of a conventional jet engine of an airplane and are much higher than the values obtained for the airplane powered byionic wind. The battery pack of a Tesla Model S electric car has 416 horsepower, or 310 kW equivalent. Assuming linear extrapolation, using such a power, our jet thruster can generate a force of approximately 8500 N.

Therefore, using a high-power microwave source or an array of multiple microwave sources in parallel operation, with materials resistant to high temperature and pressure, it is possible to construct a high-performance microwave air plasma jet thruster in the future to avoid carbon emissions and global warming that arise due to fossil fuel combustion. When high-power microwave is generated using microwave sources arranged in parallel, higher heat is also generated. At this time, the method of measuring the propulsive force with a steel ball is no longer applicable. How to deal with the impact of high temperature on equipment and how to evaluate the driving force are challenges that require further research.
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**AUTHORS’ CONTRIBUTIONS**

D.Y. and J.L. contributed equally to this work.

**DATA AVAILABILITY**

The data that support the findings of this study are available within the article.

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