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Experimental study on the laser plasma jet propulsion - plasma jet generation and thrust measurement

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Abstract

The generation of air plasma, measurement of thrust, and evaluation of I_{SP}, specific impulse were conducted as basic research for the development of an electric aircraft engine using heat generated by plasma. In the experiment, various effect such as input power and air flow rate on thrust and I_{SP} were evaluated. The experimental results showed that an increase in I_{SP} is greater when the flow rate was reduced. This indicates that engine performance can be drastically increased by more efficient heat transfer between plasma and air.

Keywords: plasma jet propulsion, air plasma, electric aircraft, thrust

1. Introduction

Environmental standards for aircraft, especially passenger planes, are becoming stricter these years, including CO2. Therefore, it is expected that future aircraft engines will be more environmentally compatible. Currently, research institutes in the world are developing electric aircraft, and various ideas are being proposed. Some of these ideas are 100% electric and some are hybrid, but most of them use electric motors to drive the aircraft. Battery not only add to the weight of the aircraft, but also take up a lot of space. This is where aircraft that use plasma to generate thrust can be considered. This propulsion system uses lasers, microwaves, and electrical discharges to generate plasma, and the heat from the plasma provides the thrust. This propulsion system is supposed to generate plasma by use of remote high-power laser or microwave, as shown in Figure 1.

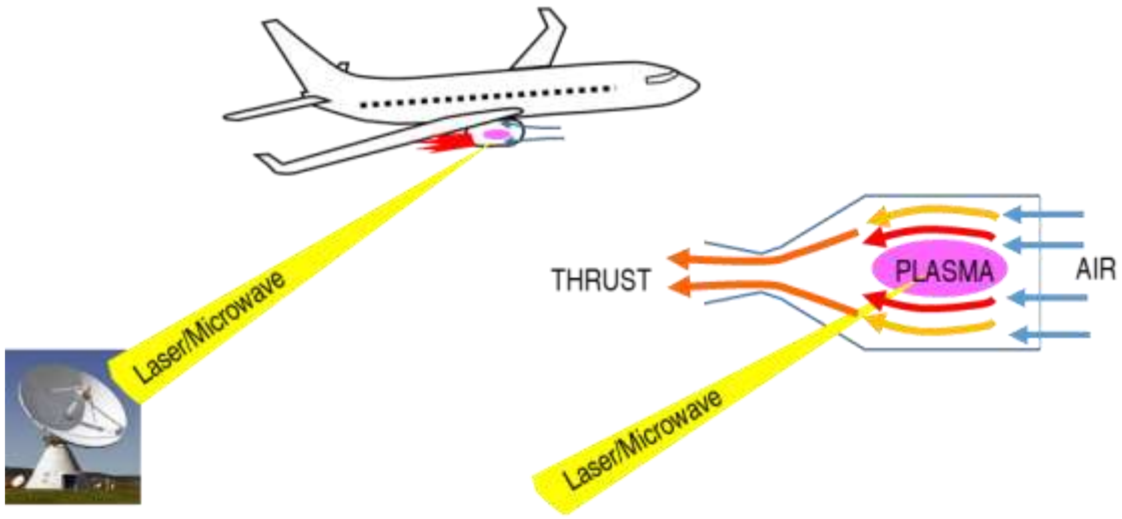


Figure 1 – Concept of air-breathing plasma jet propulsion
(no fuel, no batteries, no motors)

To study the new propulsion system shown in the Figure 1, research on air-breathing electric propulsion systems was used as a reference. Research on using air plasma to generate thrust has been conducted for space propulsion [1][2][3]. However, few studies on air-breathing electric propulsion for aircraft have been reported. In this study, plasma is generated by electrodes as shown in the Figure 2. Then the effects of the generated plasma heat on the thrust are evaluated. Thus, this paper reports the results of a fundamental and experimental study to realize laser-plasma propulsion.

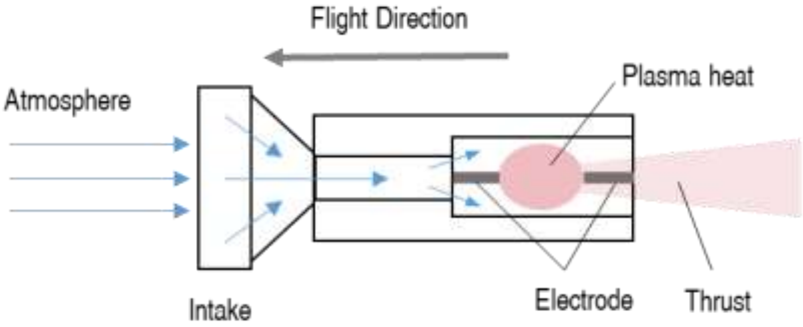


Figure 2 – Air-breathing electric propulsion

2. Method

2.1 Air plasma generation

In this study, we generate plasma jet at atmospheric pressure and at close to vacuum pressure condition using AC high voltage. Figure 3 shows an overview of the plasma jet generation system. The plasma is generated by boosting the input voltage from 100 [V] to 12 [kV] using a voltage booster and discharging it in a quartz tube. As shown in Figure 3, plasma is visualized through the quartz tube.

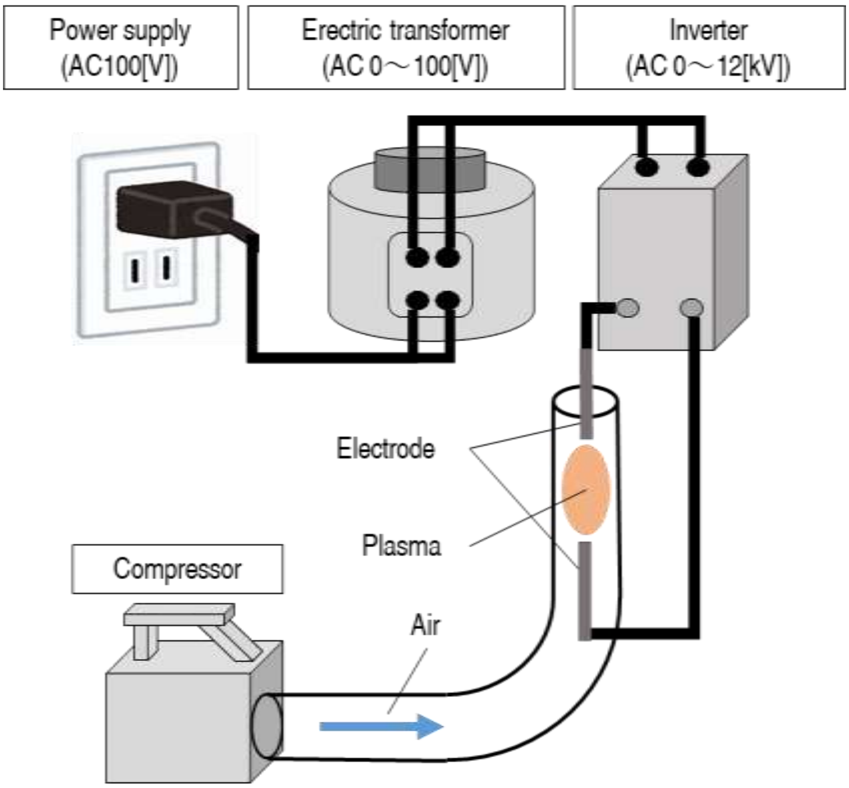
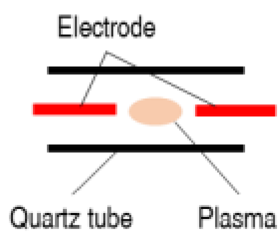
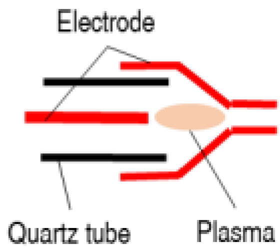
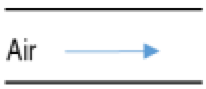
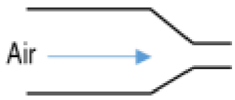


Figure 3 – Experimental set-up

2.2 Plasma nozzle types

In this experiment, two types of nozzles are used. An overview of each nozzle is given in Table 1 and Figure 4. In nozzle type “A”, the electrodes are inserted from both sides of the quartz tube, and the flow path is straight. Nozzle type "B" has a smaller nozzle outlet area to reduce the air mass flow rate. Also, the electrode and nozzle are integrated into a single unit.

Table 1 – Nozzle type

Nozzle type	A	B
Electrode		
Nozzle shape	 (Straight nozzle)	 (Converging nozzle)

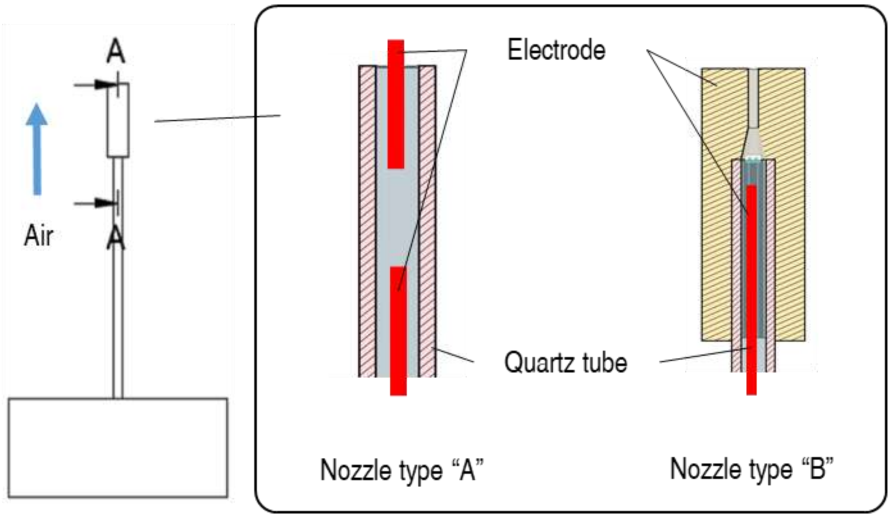


Figure 4 – Electrodes type

2.3 Thrust measurement

In the thrust measurement, air flow is supplied to quartz tube by the compressor, simulating air breathing flow of the engine. Plasma is generated by electrical discharge. Figure 5 shows an overview of the thrust measurement set-up. We fabricated a fixture to fix the plasma-generating nozzle vertically to the ground. A load cell is used to measure the small amount of thrust generated by plasma jet. And in to accurately measure the slight change in thrust, we used soft vinyl tubing for the piping for the air flow supply. For the same reason, a thin copper wire with a diameter of 0.3 [mm] was used for wiring the electrodes. However, when the plasma is generated, electromagnetic waves are also generated at the same time, causing errors in the thrust force measurement. As a countermeasure, aluminum foil is spread between the load cell and the experimental apparatus to electromagnetically isolate the load cell and ensure accurate thrust measurement.

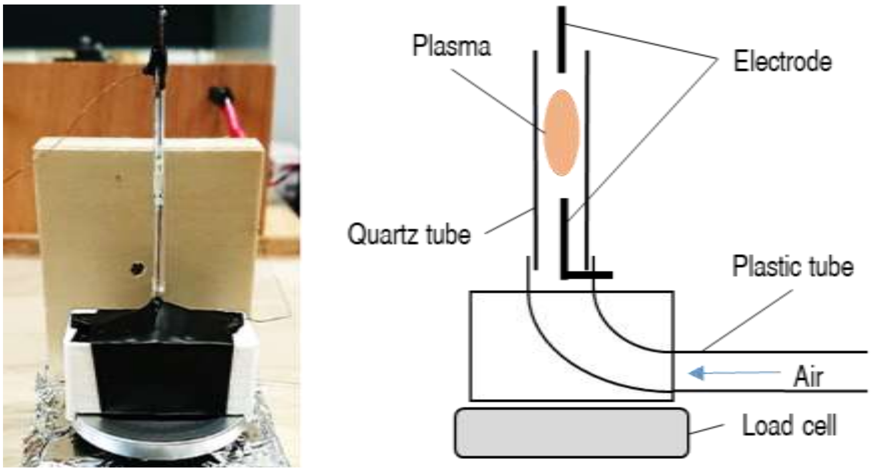


Figure 5 – Thrust measuring set-up

3. Experimental conditions

The experimental conditions are shown in Table 2. In this experiment, we generate plasma and measure thrust caused by the plasma jet using an experimental device that we made ourselves. Plasma is generated for conditions 1, 3, and 5. We measure thrust in conditions 2, 3, 4, and 5. In this way effect of the plasma existence on thrust is also evaluated.

Table 2 – Experimental conditions

Condition	1	2	3	4	5
Nozzle type	A	A	A	B	B
Pressur	Vacuum	Ambient	Ambient	Ambient	Ambient
Air-flow	×	○	○	○	○
Plasma	on	off	on	off	on

4. Results

Table 3 shows the measured results of maximum thrust and mass flow rate in each condition. Also, I_{SP} is obtained from the following equation. I_{SP} shows the thrust generated per fuel flow rate. Input voltage is 12[kV] for each conditions.

$$I_{sp} = \frac{F}{\dot{m} \cdot g} \quad (1)$$

($F[N]$: Thrust, $\dot{m}$[kg/s]: Mass flow rate, $g[m/s^2]$: Gravity acceleration)

Table 3 – Summary of the results

Condition	1	2	3	4	5
Nozzle type	A	A	A	B	B
Pressur	Vacuum	Ambient	Ambient	Ambient	Ambient
Air-flow	×	○	○	○	○
Plasma	on	off	on	off	on
Thrust [mN]	*	14.2	15.7	14.1	14.6
Mass flow rate [g/min]	*	5.4	5.4	2.1	1.4
I_{SP} [s]	*	16.1	17.8	41.7	59.6

4.1 Plasma generation

Figure 6, Figure 7, Figure 8 shows the observed plasma. The input voltage to start the discharge in Condition 1 is 1 [kV]. The input voltage to start the discharge in Condition 3 is 7 [kV] and in Condition 5 is 5 [kV].

From the experiment, it is found that the voltage required to generate the plasma varies greatly depending on the pressure and flow conditions. The required voltage is higher in ambient pressure than in vacuum condition. Also, the required input voltage increases when the flow velocity is high.

In addition, the shape of the discharge is different between vacuum condition and ambient pressure. Therefore, it is thought that pressure affects not only the minimum discharge voltage but also the discharge shape. In Condition 5, we can visualize the plasma jet from the nozzle.

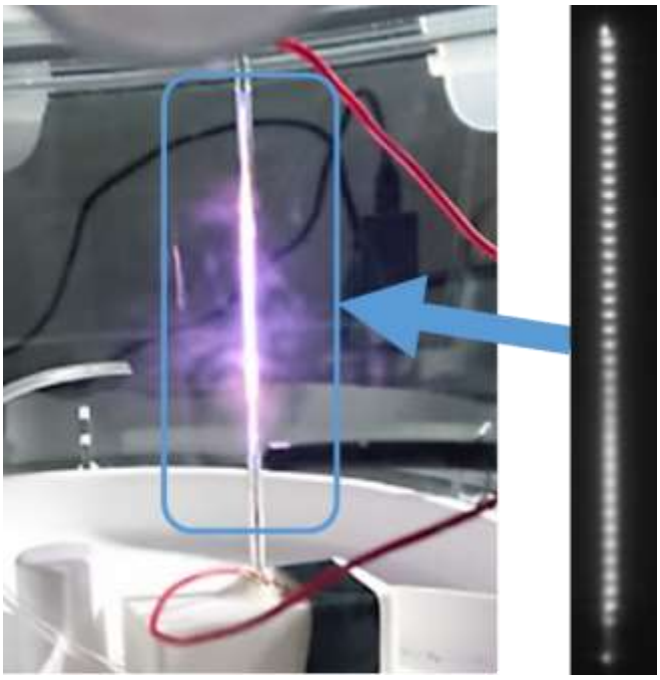


Figure 6 – Plasma in Condition 2
Ambient pressure (Nozzle type “A”)

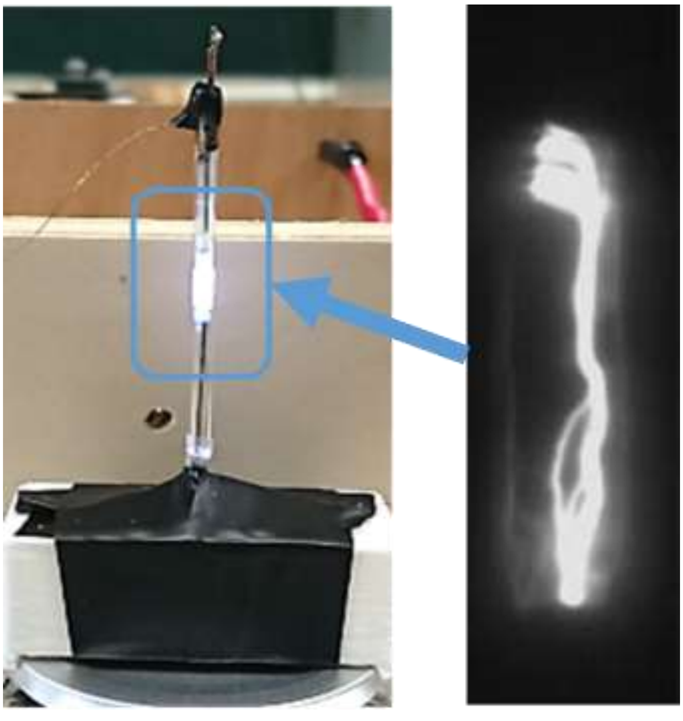


Figure 7 – Plasma in Condition 3
Ambient pressure (Nozzle type “B”)

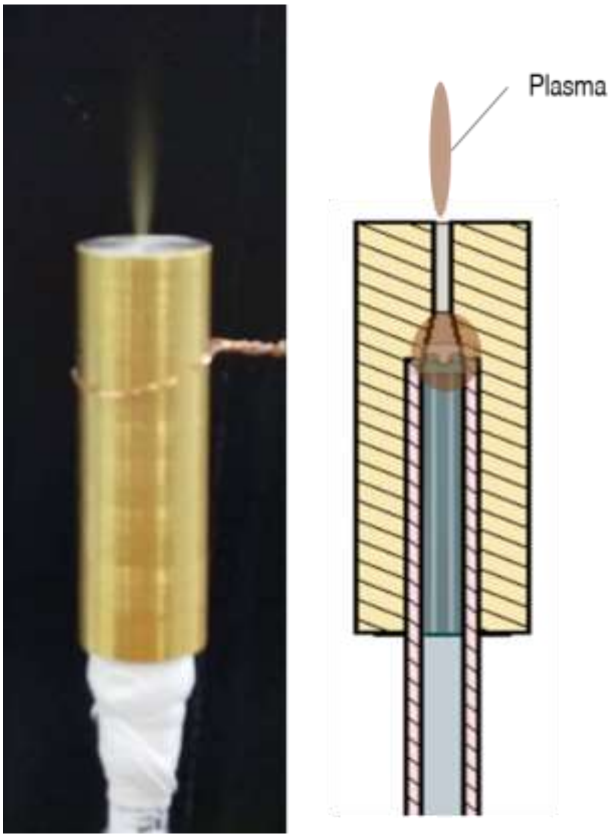


Figure 8 – Plasma in Condition 3
Ambient pressure (Nozzle type "B")

4.2 Thrust measurement and I_{SP} evaluation

Figure 9 shows the results of the thrust measurement in Condition 3. In this experiment, the discharge started when the input voltage is 7 [kV]. The thrust measurement results in the Figure 9 also show that the thrust increase started at an input voltage of 7 [kV]. As shown in the table 3, the maximum thrust generated by the plasma is 15.7 [mN], and since the maximum thrust in the case of air flow alone is 14.2 [mN], the increase in thrust is approximately 10 [%].

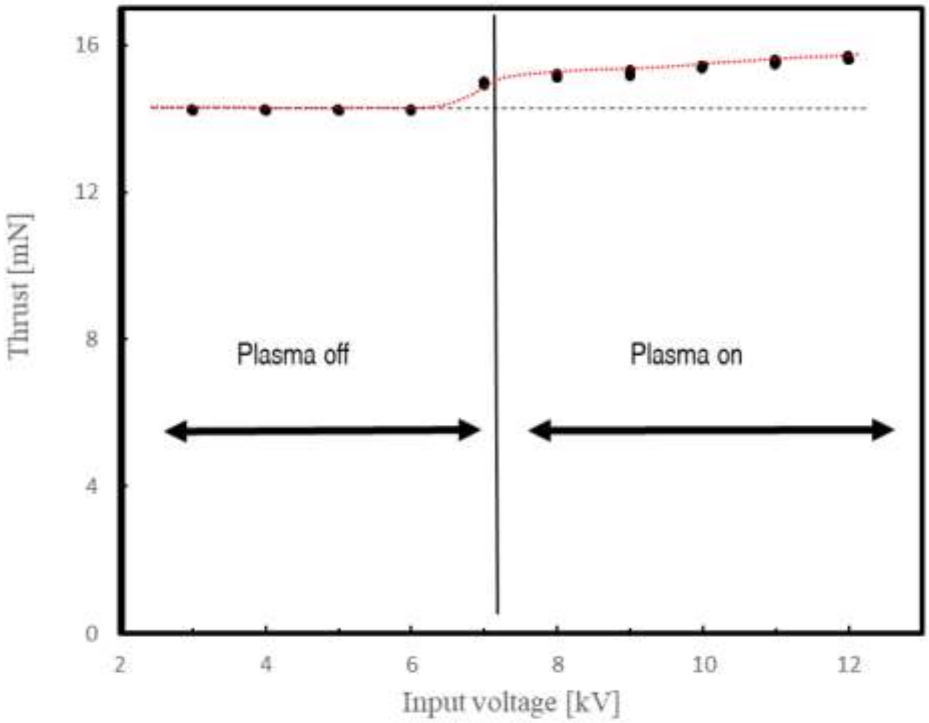


Figure 9 – Thrust in Condition 3

In Figure 10, the change in I_{SP} for conditions 3 and 5 are shown. In the experiment of Condition 5, the discharge started when the input voltage is 5 [kV]. As previously described, we can see that the rate of increase of I_{SP} is 10 [%]. And in condition 5, nozzle type B, the rate of increase of I_{SP} is 42 [%]. This shows that the air was heated efficiently at nozzle B because of the reduced flow rate.

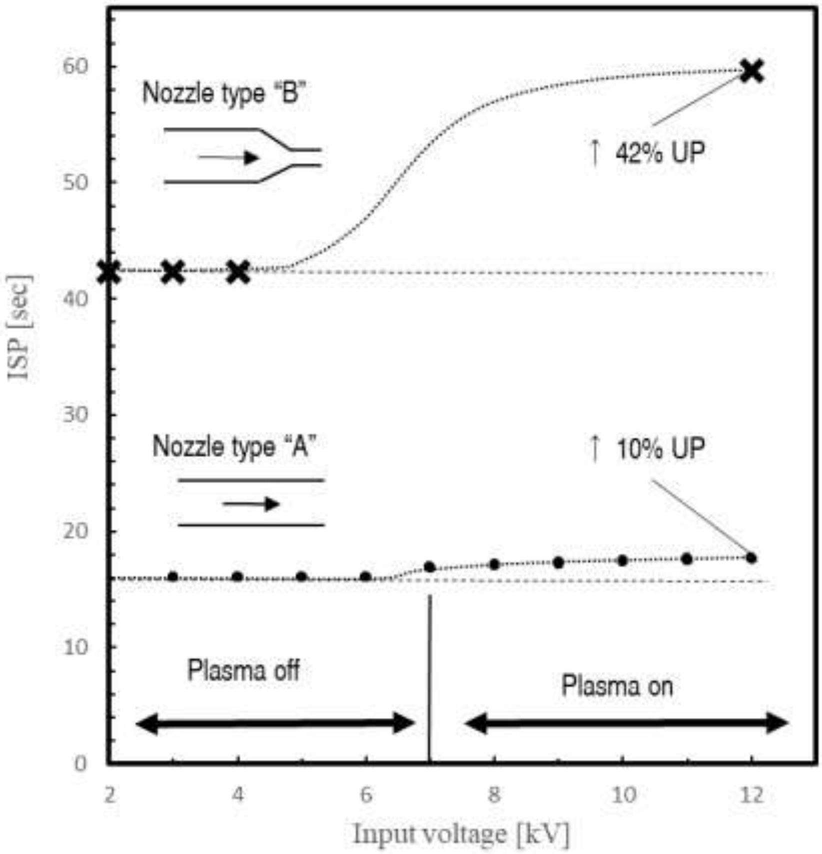


Figure 10 – Comparison of I_{SP} between Condition 3 and Condition 5

5. Conclusion

We have experimentally generated air plasma at atmospheric pressure and at a lower pressure, and visualized the difference in the plasma shape. I_{SP} was also evaluated from the results of thrust and air mass flow rate measurements. The results showed that I_{SP} increased at nozzle B, where the plasma power remained the same but the flow rate was reduced. This indicates that engine performance can be improved by efficient heat transfer between plasma and air.

6. Future work

In the near future we would like to further our research by bringing the experimental conditions closer to the actual flight environment. We also hope to reproduce the experimental heat transfer conditions through numerical simulations. Using the analytical model shown in the Figure 11, we plan to investigate more efficient methods of heat transfer from the plasma to the air.

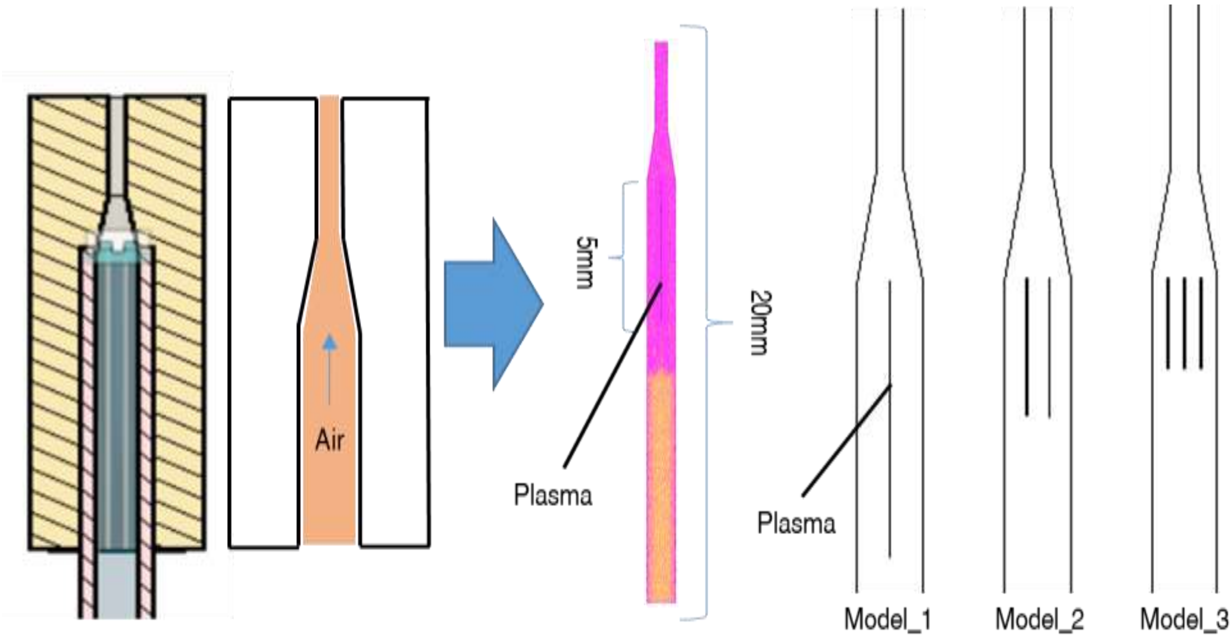


Figure 11 – Analysis Model

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8. Copyright Statement

Acknowledgments

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