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Some Governing Parameters of Plasma Torch Igniter/Flameholder in a Scramjet Combustor

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Effects of various operational parameters of plasma torch igniters/flameholders were experimentally studied in a hydrogen-fueled supersonic combustor with a rectangular cross section. The stagnation temperature of the airstream at the ignition limit almost linearly decreased as input electric power increased, although it did not significantly change with the flow rate of feedstock. Effectiveness of the argon plasma torch igniter was remarkably improved by adding a small fraction of hydrogen, but it showed rather modest improvement for further increase of the hydrogen contents. Modification of the combustor top wall design led to successful ignition of fuel jets injected from opposing side walls by a single plasma torch igniter and great reduction of airstream temperature at the ignition limit.

Nomenclature

G = gap between side walls at combustor entrance
h = step height
P = plasma torch input power
q = volume flow rate of feedstock
T = temperature
ΔT = temperature rise
x, y, z = Cartesian coordinate
η_{th} = thermal conversion efficiency of plasma torch
ϕ = fuel equivalence ratio

Subscripts

a = air
B = bulk
t = stagnation
w = wall

Introduction

SCRAMJET engines are expected to accelerate an aerospace plane at about Mach 4 and above. Autoignition of hydrogen fuel injected into a scramjet combustor does not occur at low flight Mach number[1,2] and an igniter is required. Several kinds of igniters[3–5] have been tested. One of the most promising igniters is a plasma torch for a supersonic combustor. It is not pyrophoric, toxic, or corrosive, and therefore, is safe and reliable to use in a propulsion system of an aerospace plane.

Plasma torch ignition in low-speed gas flow such as in internal combustion engines has been extensively studied by Weinberg and co-workers.[6] Kimura et al.[7] first applied the plasma torch to ignite a fuel jet in supersonic airstream. Northam et al.[8] found that an argon-hydrogen plasma torch is an effective igniter and developed an uncooled long duration torch.[9] They showed a strong sensitivity of the plasma igniter performance to the combustor geometry and/or fuel distribution,[8] and designed a new injector suitable for the plasma igniter.[10,11] The present authors[12] developed and tested a new plasma torch with oxygen or air as a feedstock which may be advantageous from the viewpoint of the total aerospace plane system.

However, effects of the parameters governing characteristics of the plasma torch igniter have not been well documented. Among the parameters, input electric power, feedstock flow rate, and number of torches required for stable ignition are important from a viewpoint of on-board resources consumption. The effects of these parameters are studied in this article.

Experimental Apparatus

Plasma Torches

The plasma torches used in the present experiment are the same as those used in our previous work.[12] Detail of the torches are shown in Fig. 1. One of the torches, P-1, was for a nitrogen, oxygen, or air feedstock, and the other, P-2, for an argon-hydrogen mixture. Both of the torches were cooled by water. In order to prevent oxidization and deterioration of the cathode by feedstocks containing oxygen, the cathode of the P-1 torch was made of hafnium embedded in copper.

Electric power for the plasma torch was supplied by a dc power unit. The open circuit voltage and the maximum current of the power unit were 250 V and 70 A, respectively. The values of voltage and current to operate the torch at a certain wattage changed with the feedstock used and its flow rate. A high-frequency circuit was attached to the power unit to initiate the plasma arc.

Feedstocks were provided from high-pressure bottles. Pressure of the feedstock was reduced to 0.6 MPa by a regulator.

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Flow rate of the feedstock q could be varied from 3 to 40 l/min. When the argon-hydrogen mixture was used as a feedstock, the plasma torch was started with argon and then hydrogen was added. Other feedstocks could start by themselves and argon was not necessary to initiate the plasma arc.

Combustor

Duct Configuration

A short supersonic combustor schematically shown in Fig. 2 was used in the present experiment. Except for some modifications which will be mentioned later, this combustor was also used in our previous works on autoignition,[2] which will be mentioned later, and plasma torch forced ignition.[12]

The combustor had a rectangular cross section of 32-mm wide by 147.3-mm high at the entrance, and was enclosed by a top wall, two side walls, and a bottom wall. The side wall on the right when looking downstream is called the right-side wall, and the other the left-side wall. All the walls were replaceable and, in some runs the top wall and the left-side wall were replaced by sight glasses to take photographs in the combustor.

There was a rearward-facing step on each side wall at the same streamwise location. The height of the step h was 3.2 mm. The side walls downstream of the step were parallel to each other. The side walls began to diverge at a half-angle of 1.7 deg 96-mm downstream of the step.

We introduce a Cartesian coordinate, the origin of which is at the center of the combustor cross section at the step location. The x coordinate is taken in the streamwise direction, while the directions of the y and z coordinates are as shown in Fig. 2.

Two geometrically different top walls were tested. One was a flat-top wall used in the previous tests.[2,12] The other had a 3.2-mm high rearward-facing step at the same streamwise location as the side walls, and had a ramp from 64- to 96-mm downstream of the step. The bottom wall was flat.

Air Inflow Conditions

The combustor was directly connected to a hydrogen vitiation air heater[13] which supplied a Mach 2.5 supersonic airstream. The stagnation temperature of the vitiated airstream T_{ta} was changed from 800 to 2500 K, while the stagnation pressure was kept at 1.0 MPa. Nonuniformity in temperature and gas composition of the vitiated air at the combustor entrance was less than 5% of the average. The stagnation temperature of 800 K corresponds to the low-speed flight condition for scramjet engines.

Main Fuel Injector

The main fuel was gaseous hydrogen at room temperature, and was perpendicularly injected from circular orifices on the combustor walls at the sonic condition. The right-side wall had four main fuel injection orifices, whereas, the left-side wall had five. The orifices on the right-side wall are designated as A, B, C, and D from the top to the bottom. Streamwise location of the orifices on the side walls was 12.8 mm, or 4 h, downstream of the step. Lateral spacing between the orifices was the same as G, namely, 32 mm. The orifices on the opposite side walls were arranged in staggered positions. The diameter of the main injection orifice was 4.0 mm except for the two outermost orifices on the left-side wall, which were 2.8-mm diam.

Several patterns of main fuel injection were tested. In single-orifice injection, fuel was injected only from the orifice C on the right-side wall. In two-orifice injection, another orifice on the right-side wall was added for fuel injection. In single-wall injection, fuel was injected from all four orifices on the right-side wall. In double-wall injection, all orifices on both side walls were used for fuel injection.

Pilot Fuel Injector

In some cases, pilot fuel, which is also gaseous hydrogen at room temperature, was injected from sonic orifices on the top wall. There were three injection orifices 4.0-mm diam on the centerline of the flat-top wall. Fuel was injected from only one of them. On the stepped top wall, there were three orifices of 1.0-mm diam in 12-mm lateral spacing at $x = -48$ mm and one orifice of 4.0-mm diam at $x = 12.8$ mm. Three orifices of 1.0-mm diam were injected together and, in this case, the pilot fuel flow rate was less than 2.5% of the main fuel flow rate for the double-wall injection.

Wagner et al.[11] reported that a fuel injector with pilot fuel injection significantly improved effectiveness of a plasma igniter. In their injector block, the main fuel was injected directly downstream of the pilot injection orifices on the same wall. In the present study, the pilot fuel and the main fuel were injected from different walls.

Plasma Torch Location

The plasma torch igniter was attached on either the right-side wall or the top wall at $x = -20$ mm. When the torch was attached on the right-side wall, it was located on the centerline of the orifice C. On the top wall, it was attached on the wall centerline.

Instrumentation

There were many pressure taps of 1.0-mm diam on the combustor walls. Wall temperatures were measured using 0.5-

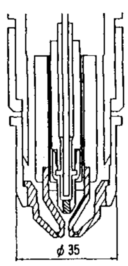
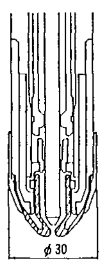
Item \ Type		P-1	P-2
Feed Stock		Air, O_2, N_2	Ar $-H_2$
Electrode	Cathode	Hafnium embedded in Copper	2% Thoriated Tungusten
	Dia. (mm)	$\phi 1.6$	$\phi 3.2$
	Anode	Copper	Copper
	Throat Dia. (mm)	$\phi 1.4$	$\phi 3.2$
	Cooling	Water	Water
Design		 ϕ 35	 ϕ 30

Fig. 1 Schematic diagram of plasma torches.

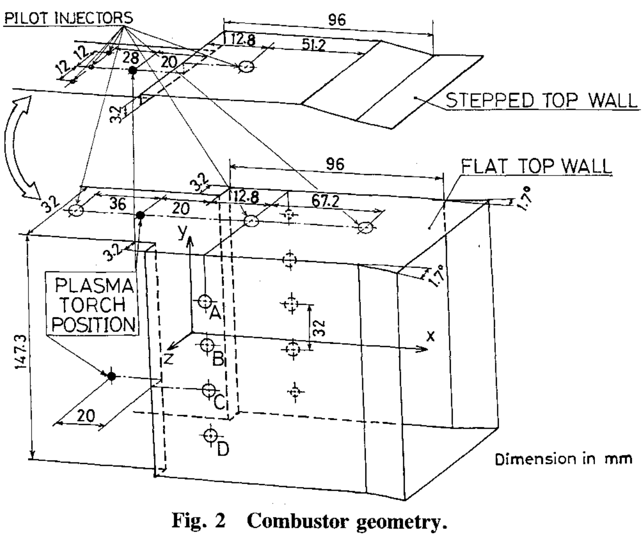


Fig. 2 Combustor geometry.

mm diam chromel-alumel thermocouples inserted into the pressure taps. The pressure taps were also used for wall gas sampling. The sample gas was analyzed by a gas chromatograph with a molecular sieve 5A column.

Procedures

The experiment was controlled by a sequential timer. A typical time sequence was as follows. At 0.4 s after the timer started, valves of main air and plasma feedstock were opened. At 7.0 s, plasma torch was started. At 11.0 s, valves of hydrogen and oxygen for vitiation were opened and a spark plug ignited the air heater. It took about 3.5 s to establish a steady heated airstream. Then, at 15.8 s hydrogen fuel was injected into the supersonic combustor and its ignition was observed. At 17.2 s, when the hydrogen fuel was still being injected, electric power for the plasma torch was turned off. At 18.0 s, valves of hydrogen and oxygen for the air heater and the supersonic combustor were shut. Then the main air and feedstock of the plasma torch were finally shut down.

Ignition was considered to occur when the measured wall temperature rises both upstream of the fuel injection orifice and near the combustor exit were significant, e.g., more than 100 K, as in the previous works.[2,12] ΔT_w was defined as temperature difference just before and 1.5 s after the beginning of fuel injection.

Results and Discussion

Plasma Torch Operating Conditions

In order to understand the overall ignition characteristics with the plasma torch, the effects of its operating conditions (such as the input electric power and the feedstock flow rate) on the ignition limit were examined first. Additionally, a peculiar feature of the argon-hydrogen feedstock, which will be shown later, was investigated further by varying its mixture ratio.

The flat-top wall was used and the plasma torch was attached on the right-side wall. There was no data for the double-wall injection, because the plasma torch on the right-side wall with the flat-top wall could not ignite fuel jets injected from the left-side wall.

Input Electric Power

Figure 3 shows the effect of P for constant feedstock flow rate. The feedstock flow rates q were 5 and 10 l/min for air and the other feedstocks, respectively.

As P increased, the airstream stagnation temperature at the ignition limit almost linearly decreased from that at the autoignition limit. There was no significant difference among four feedstocks for the single-orifice injection, and an average ignition temperature reduction rate was about 0.07 K/W.

For the single-wall injection, however, ignition temperature with the argon-hydrogen torch was less than 800 K, which was the lowest temperature the vitiated air heater could generate. This was much lower than those with other feedstocks. The average value of the ignition temperature reduction rates with other feedstocks was about 0.08 K/W and was slightly higher than that for the single-orifice injection.

Feedstock Flow Rate

Effects of feedstock flow rate are shown in Fig. 4. The value of P was 5.5 kW. For constant input power and thermal conversion efficiency, bulk temperature of the feedstock at the torch exit would increase as q decreased. Because of the higher plasma jet temperature, lower ignition temperature was expected for lower feedstock flow rate. Surprisingly, the ignition temperature was almost unchanged with q up to 40 l/min except for the oxygen feedstock. This result suggests that the lower feedstock flow rates might be more quickly diluted by air than that in higher flow rate, and degrees of ignition enhancement for lower and higher feedstock flow rates did not differ much. In order to assess the effect of

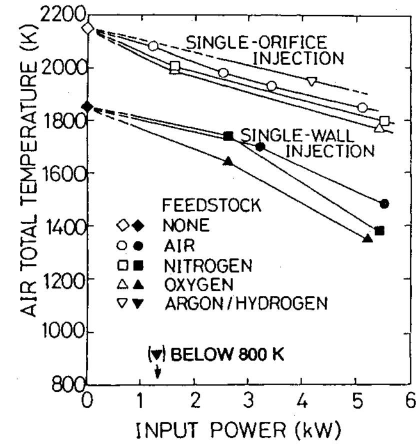


Fig. 3 Effect of input electric power on ignition limit; q = 5–10 l/min.

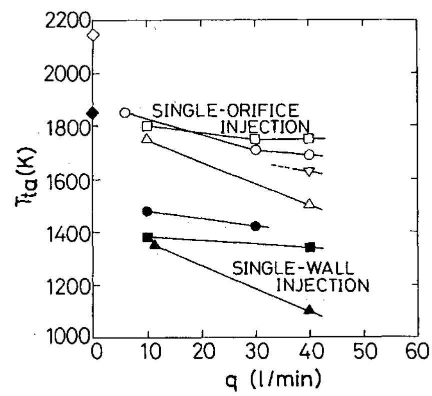
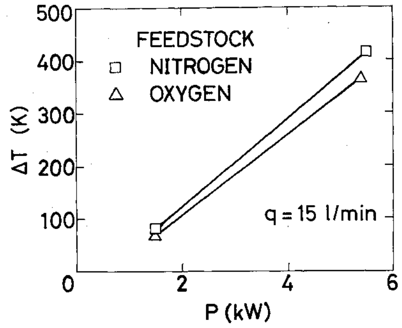


Fig. 4 Effect of feedstock flow rate on ignition limit; P = 5.5 kW. (Symbols: see Fig. 3. There are no data of argon/hydrogen feedstock for single-wall injection.)

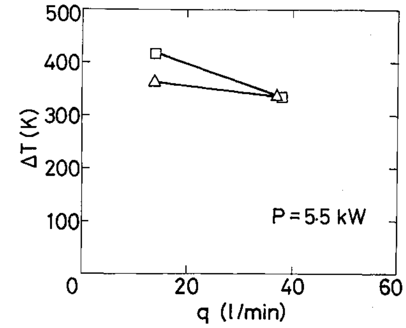
dilution, temperature rise due to the plasma torch, which was defined as temperature difference between those measured just before and 1.5 s after the plasma torch-off, was measured by a thermocouple inserted 1.6-mm into the stream from a wall pressure port at x = 4.0 mm. The air stagnation temperature was about 1050 K and fuel was not injected. Results are shown in Figs. 5a and 5b. The temperature rise increased with increase of the input electric power as expected from Fig. 3. However, temperature rise did not change significantly with the feedstock flow rate, clearly indicating the abovementioned dilution effect.

The temperature rise due to the plasma torch and the ignition temperature reduction at the same input electric power and feedstock flow rate are cross-plotted in Fig. 6. There is a fairly good correlation between them. Since the temperature rise was measured at only one spatial point, this result should be considered as a qualitative one.

In Fig. 4, the ignition temperature of the oxygen plasma torch even decreased as the feedstock flow rate increased. This may be partly due to the difference in degree of thermal output of the plasma torch among the feedstocks as pointed out by Sakuranaka et al.[14] They measured the thermal conversion efficiency η_{th} of the torches used in the present experiment. The thermal conversion efficiency was defined as a ratio of the thermal energy taken out by feedstock to the input electric energy. According to their result, the value of η_{th} for the oxygen torch increased as the input electric power per unit feedstock flow rate decreased, while that of the nitrogen torch did not change. A chemical effect of oxygen plasma jet might be another possible reason of this phenomena. Further studies are necessary to clarify relative importance of these effects.



a) **Effect of input electric power**



b) **Effect of feedstock flow rate**

Fig. 5 Temperature rise by plasma jet. (x = 4.0 mm, $z - z_w$ = 1.6 mm, T_{ta} = 1050 K, no fuel injection.)

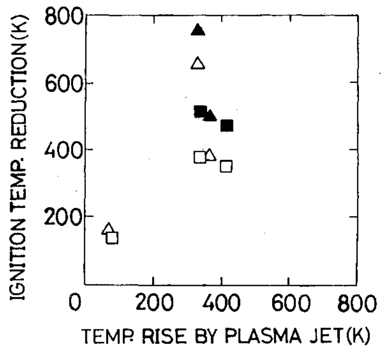


Fig. 6 Correlation between temperature rise by plasma jet and ignition temperature reduction. (Symbols: see Fig. 3.)

Argon-Hydrogen Mixture Ratio

As mentioned above in relation to Fig. 3, the argon-hydrogen mixture feedstock for the single-wall injection was much more effective than other feedstocks. Though data are not shown in Figs. 3 or 4, pure argon had very poor ignition enhancement ability. Wagner et al.[11] considered that a chemical effect due to hydrogen atoms produced by plasma arc was the main reason for effectiveness of the argon-hydrogen torch. On the other hand, Sakuranaka et al.[14] reported that the thermal conversion efficiency of the argon-hydrogen torch moderately increased with hydrogen fraction. Their result suggests that a thermal effect of the plasma torch due to high thermal energy of the plasma jet would be another reason.

In order to compare the chemical and thermal effects, the ignition temperature of the single-wall injection was measured for the argon-hydrogen feedstock with hydrogen volume fraction of 0–50%. As shown in Fig. 7, addition of less than 5% hydrogen into pure argon resulted in significant reduction of the ignition temperature, i.e., 700 K. However, further increase of hydrogen fraction up to 50% caused only a moderate reduction of 250 K.

The thermal effect was rather moderate and not likely to produce a steep change in the small hydrogen fraction region. In addition, the thermal output difference between the 1:1 argon-hydrogen mixture and the pure argon was about 20%

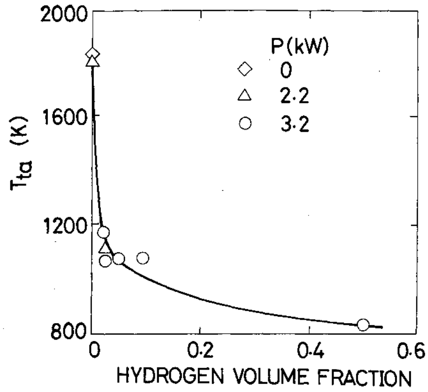


Fig. 7 Effect of argon-hydrogen mixture ratio on ignition limit; q = 40 l/min.

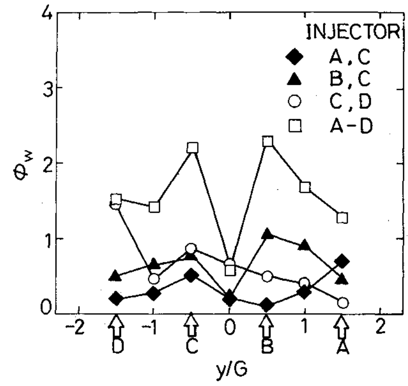


Fig. 8 Local equivalence ratio distribution on side wall at x = 0.5 mm. (T_{ta} = 1600 K, without combustion.)

of the input power,[14] and corresponding reduction in the ignition temperature for the 1:1 argon-hydrogen mixture was estimated less than 100 K from Fig. 3. Therefore, the thermal effect is insufficient to result in such great reduction of the ignition temperature. The chemical effect would mainly be responsible for the result shown in Fig. 7.

In the single-orifice injection, effectiveness of the 1:1 argon-hydrogen feedstock was almost the same as other feedstocks. It is not clear why effectiveness of the 1:1 argon-hydrogen feedstock differs so much with the fuel injection pattern.

Location of Injection Orifices

The ignition process of multiple fuel jets using a plasma torch is considered to start with the fuel jet directly downstream of the torch, and then the established flame propagates through the recirculation region behind the step to ignite adjacent fuel jets. If a flame cannot propagate in the recirculation region, the plasma torch can ignite only the fuel jet directly downstream of the torch, but not off-axis jets.

In order to investigate the required condition for the flame propagation in the ignition period, ignition tests of two-orifice injection were conducted. The plasma torch was attached on the right-side wall. One orifice used was directly downstream of the plasma torch, the orifice C, and the other was one of three other orifices A, B, or D on the right-side wall. At T_{ta} = 1600 K and ϕ_B = 0.2, the flame which formed around the orifice C could ignite only the fuel from the orifice D but could not ignite the fuel from orifices A or B.

The local equivalence ratio distribution on the wall ϕ_w in the recirculation region of the side wall step was measured at x = 0.5 mm for the same experimental conditions above, but without combustion by removing the plasma torch. The distributions are shown in Fig. 8 with that of the single-wall injection with the same fuel flow rate for one orifice. Open symbols correspond to cases in which the plasma torch was successful in igniting the fuel from an off-axis orifice, while solid symbols indicate unsuccessful cases. The values of ϕ_w

on the middle line between adjacent orifices were 0.5 or more for the open symbols and 0.2 or less for the solid symbols.

This result suggests that ϕ_w in the recirculation region behind the step should be above a certain value, e.g., 0.4, to achieve flame propagation in the ignition period.

Top Wall Configuration

Ignition tests of the double-wall injection with a single plasma torch on one of the side walls were conducted in both unconfined[10] and ducted[10,12] conditions without success in igniting fuel injected from the side wall. In the ducted condition,[10,12] no fuel was injected from the top or bottom wall and there was no step on either top or bottom.

In order to ignite the double-wall injection with a single torch, the plasma torch was moved from the side wall to the top wall. The top wall is a desirable position to attach a plasma torch in a combustor of an airframe integrated scramjet engine with a rectangular cross section because fuel injection struts or side walls might not have sufficient space for plasma torches.

The plasma torch on the flat top wall without pilot fuel injection failed to ignite fuel injected from either of the side walls. Pilot fuel injected from an orifice 36-mm upstream of the torch was ignited by the torch, but its flame could ignite other fuel jets only outside of the combustor.

Gas samples taken from the pressure taps on the top wall and the side walls indicated that the fuel injected from the top wall did not contact with that from the side walls within the combustor.

As stated previously, the recirculation region was very effective for flame propagation in the ignition period. Therefore, the flat-top wall was replaced by the stepped-top wall. Some orifices for the pilot fuel injection were installed on it to establish sufficient fuel concentration in the recirculation region behind the step. The step also provided a low speed region to stabilize a pilot flame when the plasma torch was turned off.

A preliminary test without attaching the plasma torch was conducted to measure fuel distribution at the step on the top wall. It was found that the fuel injected from the side walls spread into the recirculation region behind the top wall step, as shown in Fig. 9. When the pilot fuel was not injected, however, the minimum value of ϕ_w was as low as that for the no-ignition cases of the two-orifice injection. Higher ϕ_w was achieved by the pilot fuel injection at the same injection pressure as the main fuel. The upstream pilot injection from three 1.0-mm diam orifices resulted in more uniform fuel distribution than the downstream injection from a single 4.0-mm diam orifice.

The plasma torch was then attached on the stepped-top wall and ignition tests for the double-wall injection were conducted with and without the pilot fuel injection. The feedstock was oxygen and its flow rate was 17 l/min. The input power was 3.2 kW.

For the stepped-top wall without any pilot fuel injection shown in Fig. 10a, the ignition limit was almost the same as the autoignition limit. This result might be expected from the low value of ϕ_w as shown in Fig. 9.

Figures 10b and 10c show that the ignition limit was substantially extended by the upstream or downstream pilot fuel injection. Near the ignition limit, two kinds of unstable ignition were observed as shown in Fig. 10. One was delayed ignition which represented ignition that occurred a few seconds after the beginning of fuel injection. The other was one-sided ignition for which significant temperature rises were observed on the top wall and near the step of the left side wall but not on the right side wall. Higher values of ϕ_w near the left side wall than that near the right side wall in the recirculation region behind the top-wall step caused the one-sided feature.

The ignition limits for the stepped-top wall with the pilot fuel injection depended almost entirely on the bulk fuel equivalence ratio ϕ_B. For ϕ_B of 0.6 or more, ignition occurred at an air stagnation temperature of 800 K, which was the lower limit value of the air heater used in the present experiment and corresponds to a flight Mach number less than 4. Even with the input electrical power of 1 kW, the plasma torch could ignite the fuel of ϕ_B = 0.67 at T_{ta} = 850 K.

Ignition limits of the double-wall injection by the plasma torch attached on the right-side wall are shown in Fig. 11. Ignition of the fuel from the left-side wall occurred only when

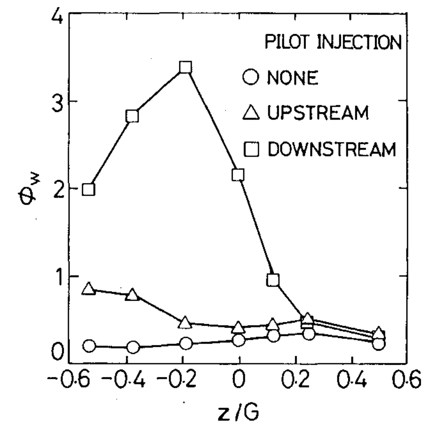


Fig. 9 Local equivalence ratio distribution on stepped top wall at x = 0.5 m. (T_{ta} = 1500 K, without combustion.)

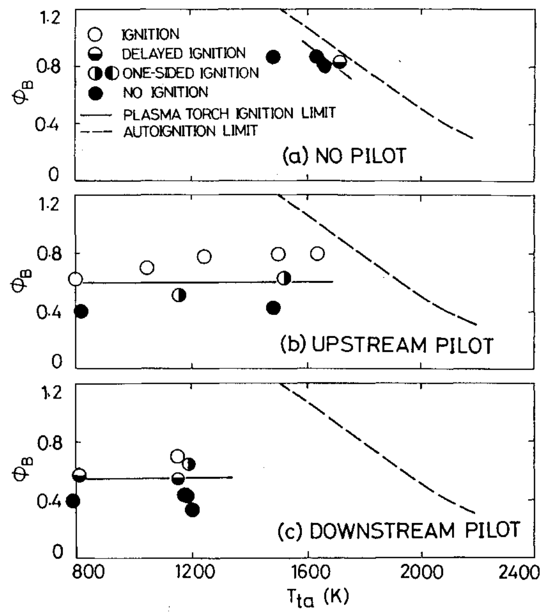


Fig. 10 Ignition limit of double-wall injection with plasma torch on stepped top wall.

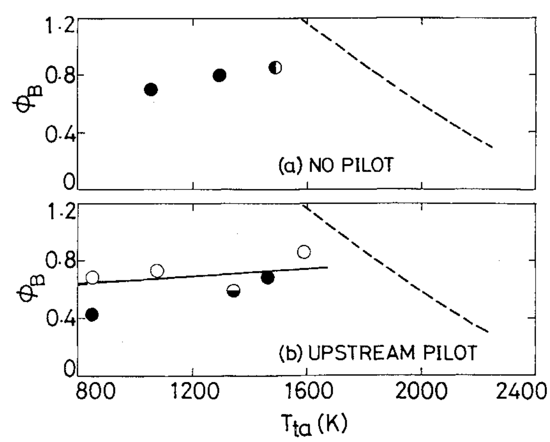


Fig. 11 Ignition limit of double-wall injection with plasma torch on side wall. (Symbols: see Fig. 10.)

the pilot fuel was injected from the stepped top wall. Ignition limits were almost the same as those for the torch attached on the stepped-top wall.

Conclusions

Effects of various operational parameters of plasma torches as well as combustor geometry and fuel injection location on the ignition of hydrogen were experimentally studied in a supersonic combustor with a rectangular cross section. The following results were obtained:

1) The ignition temperature almost linearly decreased as the input electric power increased.

2) The ignition temperature did not significantly change with the feedstock flow rate except for oxygen, which resulted in notable reduction of the ignition temperature with flow rate.

3) Effectiveness of the argon plasma torch igniter for the single-wall injection was remarkably improved by adding small fraction of hydrogen. The chemical effect of the plasma torch was considered to be the main reason of this improvement.

4) The minimum value of the local equivalence ratio in the recirculation region behind the step between two adjacent fuel injection orifices should be about 0.4 or more for flame propagation to occur in the ignition period.

5) For the stepped-top wall with pilot fuel injection, a single plasma torch igniter attached on either the top wall or the side wall successfully ignited the fuel jets injected from the opposing two side walls.

6) The plasma torch with the stepped-top wall and the pilot fuel injection resulted in significant reduction of the ignition temperature.

References

[1]McClinton, C. R., "Autoignition of Hydrogen Injected Transverse to Supersonic Airstream," AIAA Paper 79-1239, 1979.

[2]Sato, Y., Sayama, M., Masuya, G., Komuro, T., Kudou, K., Murakami, A., Tani, K., and Chinzei, N., "Experimental Study on Autoignition in a Scramjet Combustor," *Proceedings of the 9th International Symposium on Air Breathing Engines*, Athens, Greece, Sept. 3–8, 1989, pp. 569–576; see also *Journal of Propulsion and Power*, Vol. 7, No. 5, 1991, pp. 657, 658.

[3]Spaddaccini, L. J., and Chinitz, W., "Supersonic Combustion of Propane," *AIAA Journal*, Vol. 6, No. 7, 1967, pp. 1391–1393.

[4]Beach, H. L., Jr., Mackley, E. A., Rogers, R. C., and Chinitz, W., "Use of Silane in Scramjet Research," *17th JANNAF Combustion Meeting*, Vol. 1, CPIA Publ. 329, Laurel, MD, 1980, pp. 639–659.

[5]Diskin, G. S., and Northam, G. B., "Evaluation of a Storable Fluorine Based Pilot for Scramjets," AIAA Paper 86-0372, Jan. 1986.

[6]Weinberg, F. J., "Electrical Discharge-Augmented Flames and Plasma Jet in Combustion," *Advanced Combustion Method*, Academic Press, New York, 1986, Chap. 5, pp. 277–330.

[7]Kimura, I., Aoki, H., and Kato, M., "The Use of a Plasma Jet for Flame Stabilization and Promotion of Combustion in Supersonic Air Flows," *Combustion and Flame*, Vol. 42, No. 3, 1981, pp. 297–305.

[8]Northam, G. B., McClinton, C. R., Wagner, T. C., and O'Brien, W. F., "Development and Evaluation of a Plasma Jet Flameholder for Scramjets," AIAA Paper 84-1408, June 1984.

[9]Stouffer, S. D., O'Brien, W. F., and Roby, R. J., "Improved Plasma Torch for Ignition and Flameholding in Supersonic Combustion," AIAA Paper 89-2945, July 1989.

[10]Wagner, T. C., O'Brien, W. F., Northam, G. B., and Eggers, J. M., "Design and Evaluation of a New Injector Configuration for Supersonic Combustion," *Proceedings of the 8th International Symposium on Air Breathing Engines*, Cincinnati, OH, June 14–19, 1987, pp. 390–397.

[11]Wagner, T. C., O'Brien, W. F., Northam, G. B., and Eggers, J. M., "Plasma Torch Igniter for Scramjets," *Journal Propulsion and Power*, Vol. 5, No. 5, 1989, pp. 548–554.

[12]Sato, Y., et al., "Effectiveness of Plasma Torches for Ignition and Flameholding in Scramjet," AIAA Paper 89-2564, July 1989; see also *Journal of Propulsion and Power*, Vol. 8, No. 4, 1992, pp. 883–889.

[13]Murakami, A., Komuro, T., Kudou, K., Masuya, G., and Chinzei, N., "An Air Heater for Scramjet Combustor Test" (in Japanese), National Aerospace Lab. Technical Rept., NAL TR-912, Tokyo, Japan, Sept. 1986.

[14]Sakuranaka, N., Mitani, T., Izumikawa, M., Sayama, M., and Ohwaki, K., "Thermal Efficiency of Plasma Torch Igniters" (in Japanese), *Proceedings of the 33rd Space Science and Technology Conference*, Japan Soc. Aeronaut. Space Sci., Nagoya, Japan, Oct. 31–Nov. 2, 1989, pp. 56, 57.