

Ignition by Plasma Jet in Supersonic Flow

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1 Introduction

Plasma includes many chemically active species such as radicals, NO_x, fuel fragments, ions, excited molecules and electrons. Therefore, since the experimental research by Weinberg et al. [1,2] in the 1970s, ignition and combustion enhancement by plasma has been a major topic in the field of combustion research. In particular, quite recently, ignition enhancement by using non-thermal plasma [3] is the hottest topic. As for ignition and combustion enhancement in a scramjet engine, the plasma jet (PJ) torch has been studied as a forced igniter [4,5] and it has been actually used as the igniter in the sub-scale scramjet combustor [6,7]. One advantage of a thermal plasma such as the PJ against non-thermal plasma is that thermal effect (high temperature effect) in addition to chemical effect strongly enhances ignition and combustion reactions. Therefore, thermal plasma was more effective for ignition enhancement than non-thermal plasma at very severe flow condition such as low static temperature. The other advantage of the PJ is its selectivity of supplied species to combustion field by changing components of the feedstock gas. In this paper, the author summarizes his experimental works [8-11] about the influence of components of plasma feedstock gas on the effectiveness of the PJ.

2 Experimental apparatus

The ignition tests were conducted using an intermittent suction type wind tunnel connected to the exit of the test section. Figure 1 schematically illustrates the test section. Air at atmospheric condition was inhaled and accelerated to supersonic speed through a two-dimensional contoured nozzle. The test section had a 30-mm square uniform cross section. The PJ torch and the fuel injector were placed on the centerline of the bottom wall of the test section. The success of ignition by the PJ was evaluated based on the wall pressure measured by a strain gauge pressure transducer.

Figures 2 and 3 present a photograph and a schematic of the PJ torch, respectively. The PJ torch was attached to the bottom wall. The cathode was covered by hafnium to attain high durability when oxygen was used as the feedstock. The anode and the nozzle were made of O₂-free copper. The diameter of nozzle throat was 1.5 mm. Arc discharges were started by a high-voltage initiator, and the direct current power unit supplied 1.5 kW to 3.5 kW electric power input to the torch. The torch was water-cooled to allow high electric power input. Various feedstocks (e.g., O₂, N₂, Ar, O₂/N₂, H₂/N₂, CH₄/N₂, H₂/Ar, O₂/Ar, CH₄/Ar, O₂/H₂/N₂, and O₂/CH₄/N₂) were tested in the authors' research activity.

The main fuel was perpendicularly injected into the main stream at the speed of sound from an orifice located at $X_i = 24$ mm (downstream of the PJ) or $X_i = -24$ mm (upstream of the PJ). The diameter of the orifice was 1.0 mm. Various fuels (e.g. H₂, CH₄, C₂H₄, C₃H₈, and DME) at room temperature were tested.

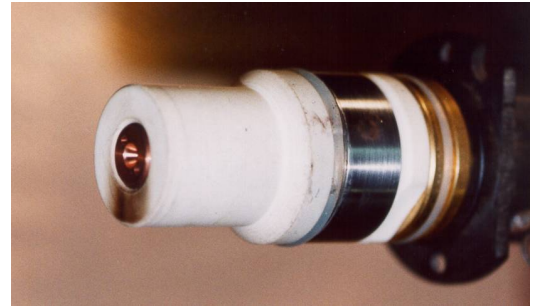
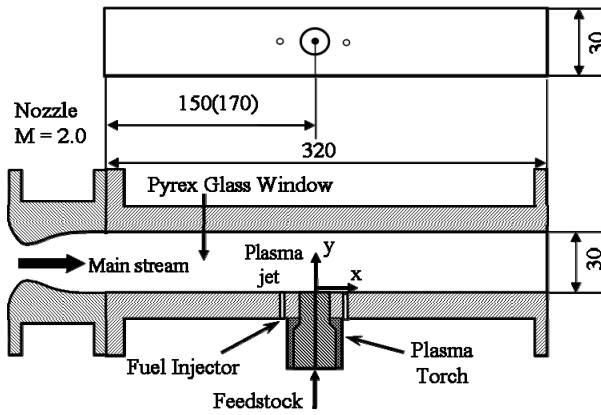


Fig.1 Schematic of test section

Fig.2 Direct photograph of PJ torch

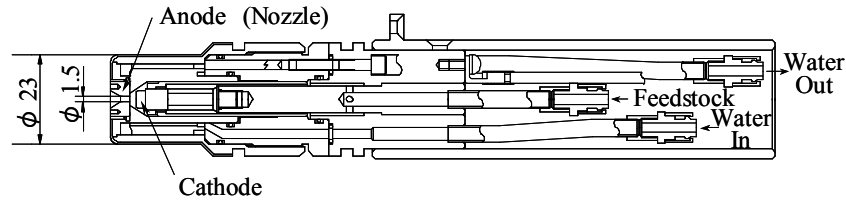


Fig.3 Schematic of PJ torch

3 Results of ignition tests

Wall pressure increase is proportional to the degree of heat release due to combustion and it is directly related with the thrust in the case of supersonic flow. Therefore, effectiveness of the PJ was discussed mainly based on the wall pressure data. Fig.4 and Fig.5 depict wall pressure distributions for C_2H_4 fuel combustion in $M = 2.0$ flow ignited by the PJ. The PJ was injected upstream ($X_i = -24$ mm) of the fuel injection position ($X = 0$ mm). Fig.4 is a result for N_2 PJ and Fig.5 is that for $CH_4(10\%)/N_2(90\%)$ PJ. Data for only PJ injection without fuel injection are also depicted in the figures for comparison with combustion case. The wall pressure increases due to C_2H_4 combustion for both PJs increased with electric power inputs.

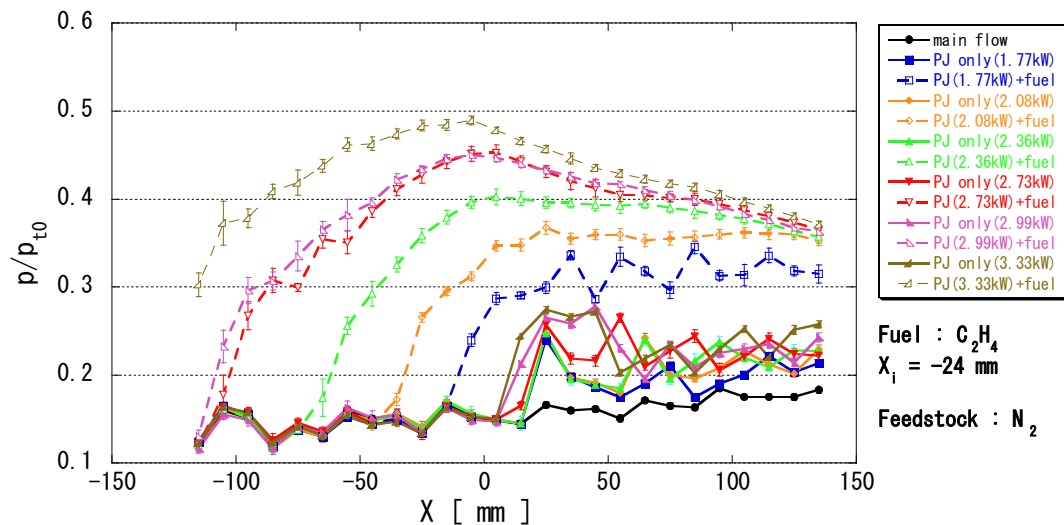


Fig.4 Wall pressure distribution of flowfield with C_2H_4 fuel and N_2 PJ injection

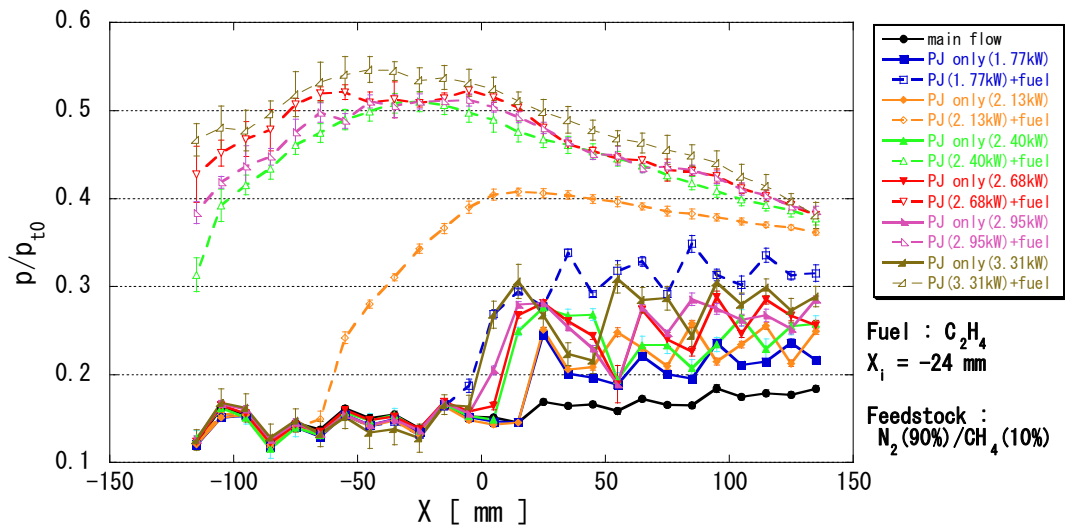


Fig.5 Wall pressure distribution of flowfield with C_2H_4 fuel and $CH_4(10\%)/N_2(90\%)$ PJ injection

On the whole, the wall pressure for $CH_4(10\%)/N_2(90\%)$ PJ was larger than that for N_2 PJ, and the starting point of wall pressure increase for $CH_4(10\%)/N_2(90\%)$ PJ went further upstream than that for N_2 PJ at high electric power input. The pseudo-shock wave (PSW) reached at the entrance of the test section at more than $P_{IN}=2.4$ kW for $CH_4(10\%)/N_2(90\%)$ PJ. On the other hand, the PSW reached at the entrance at $P_{IN}=3.3$ kW for N_2 PJ. These results suggest that $CH_4(10\%)/N_2(90\%)$ PJ is more effective than N_2 PJ for ignition and combustion enhancement.

Figures 6 and 7 show wall pressure distributions for only PJ injection without fuel injection. Fig.6 is a result for N_2 PJ and Fig.7 is that for $CH_4(10\%)/N_2(90\%)$ PJ. The wall pressure increase for $CH_4(10\%)/N_2(90\%)$ PJ was larger than that for N_2 PJ at high electric power input, though they were almost the same level at low electric power input. The main components of CH_4/N_2 PJ at equilibrium condition other than N_2 are H_2 , H and HCN species [11]. A large amount of H_2 dissociated from CH_4 quickly reacts with the main airflow as high-temperature fuel, and its combustion heat enhances reactions of the main C_2H_4 fuel. This is the reason for larger wall pressure increase for $CH_4(10\%)/N_2(90\%)$ PJ than that for N_2 PJ.

Comparison of effectiveness of the PJ for other feedstocks such as O_2 , N_2/O_2 , Ar , Ar/O_2 , Ar/H_2 , Ar/CH_4 , N_2/C_2H_4 and so on will be demonstrated in the presentation.

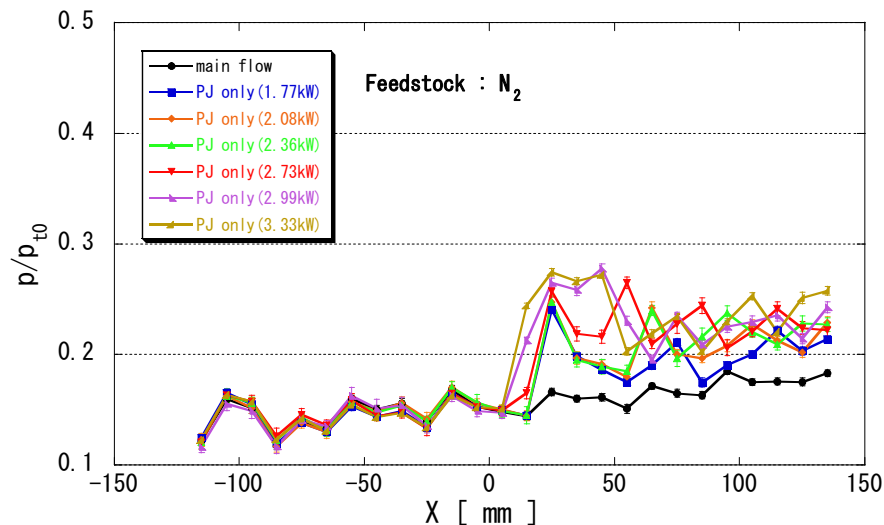


Fig.6 Wall pressure distribution of flowfield with N_2 PJ injection

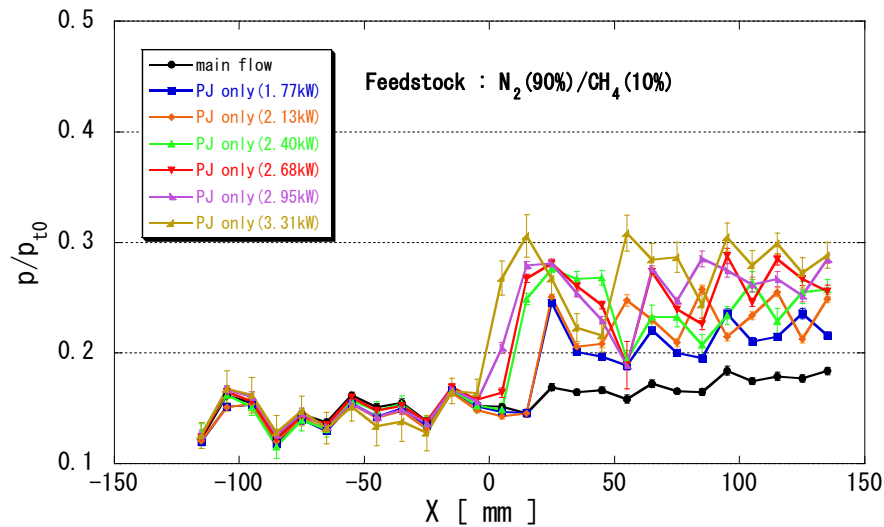


Fig.7 Wall pressure distribution of flowfield with CH₄(10%)/N₂(90%) PJ injection

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