PLASMA JET ENHANCED COMBUSTION OF HYDROGEN IN SUPERSONIC AIR FLOW

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Abstract

The supersonic combustion of hydrogen fuel with chemical radicals supplied from a plasma torch has been experimentally investigated. The experiments were performed by employing tandem transverse injection of hydrogen gas and plasma jet into Mach 1.8 airflow. The range of airflow total temperature was below 1000K. The experimental results revealed that the plasma jet was quite effective in combustion enhancement when placed at the position downstream of the fuel injector. Whilst at relatively high air temperature of about 900K, the plasma jet of pure argon was found to enhance combustion due to its thermal effect, the argon-oxygen plasma providing oxygen radicals achieved successful ignition at the air temperature well below 600K, thus showed clearly its chemical effect upon the combustion enhancement.

Introduction

An effective device of enhancing chemical reaction for Supersonic Combustion Ramjet (SCRamjet) combustor is a plasma torch. It enables supersonic combustion of hydrogen gas at the lower airflow temperature. There have been increasing experimental efforts to provide plasma jet at some appropriate distance from the primary fuel gas injection. Kimura et al. applied 4.7kW hydrogen plasma and succeeded in hydrogen ignition at very low static temperature of 154K in Mach 2.1 airstream. Pure Argon, which exhibits good plasma stability, is often employed for a working gas of plasma jet. However, it yields only a thermal effect and contains no chemically active radicals that will help the combustion, whilst the addition of small quantity of either H₂, O₂, or N₂ is known to contribute significantly to ignition and flame holding. For example, Babii et al. and Wagner et al. reported that the Argon-Hydrogen plasma established the ignition of hydrogen gas injection behind a step in Mach 2 flow at the temperature well below the autoignition limit and the flame persisted even when the plasma jet was turned off. Similar experiments were performed by Saito et al. and Masuya et al. in which a plasma torch was located at the upstream of a step to promote the combustion of H₂ gas injected in the recirculating flow region behind the step. Amongst the working gases tested, oxygen was found to be the most effective for ignition and flame holding, compared with the other gases like nitrogen, argon-hydrogen and air. The experimental work presently concerns the plasmajet-assisted ignition of transverse hydrogen injection in which a torch is placed flush in tandem with the fuel injector to one of the parallel side walls of a supersonic (Mach1.8) wind tunnel.

Transverse Hydrogen Injection

Attention is primarily focused upon an improved understanding of the near-injector flow field that has significant importance for flame stabilization, evolving eventually a fully reacting mixing layer. To support the experiments, numerical flow simulation was also carried out, wherein hydrogen injection through a choked circular hole in the transverse direction to a flat wall in a supersonic wind tunnel was treated. Fig.1 shows an example of the grids to describe a half of the actual test section geometry of the corresponding experiments. The spacing of grid lines is not uniform, but densely arranged to yield better spatial resolution near the injector position.

Numerical scheme was based upon LU-ADI approximate factorization TVD Finite Difference formulation of Reynolds averaged Navier-Stokes equations. Conservation equations for chemical species and internal energy had to be incorporated. Turbulence model was not taken into account. The chemical kinetic 8 reaction model listed in Table.1, due to Evans and Schexnayer, was employed. Amongst 7 chemical species, N₂ molecule was treated as inert gas and every species was assumed to behave like a perfect gas.

\[
\begin{align*}
1: & \quad H_2 + M \leftrightarrow H + H + M \\
2: & \quad O + M \leftrightarrow O + O + M \\
3: & \quad H_2O + M \leftrightarrow OH + H + M \\
4: & \quad OH + M \leftrightarrow O + H + M \\
5: & \quad H_2O + O \leftrightarrow OH + OH \\
6: & \quad H_2O + H \leftrightarrow OH + H_2 \\
7: & \quad O + H \leftrightarrow OH + O \\
8: & \quad H + O \leftrightarrow OH + H 
\end{align*}
\]
Chemical Kinetics
The role of plasma jet exists not upon the thermal activation, but the production of rich radicals responsible for chemical kinetics. More favorable oxygen contribution than hydrogen for ignition may be explained according to the schematic shown in Fig.2. The reaction process due to atomic oxygen is primarily dependent upon $H_2 + O = H + OH$ and $H_2 + OH = H_2 O + H$. Throughout the process, relating activation energy and endothermic energy are kept to be low, so the reaction process proceeds easily. On the other hand, the reaction process involving atomic hydrogen is rather complicated, but two main routes are specified: either $O + H = O + OH$ and $H_2 + OH = H_2 O + H$ or $H + O = H_2 + M$ and $H_2 + HO = H_2 O + H$. The former includes a very large endothermic reaction, so that this route has a disadvantage under low temperature state, whilst the latter includes a huge exothermic reaction but hardly occurs because of three body recombination reaction. The main reaction route is thus thought to be the former. Between the branching reactions of $H_2 + O = H + OH$ and $O + H = O + OH$, the former has the smaller endothermic energy, so that O plasma tends to be more productive of OH radicals with $H_2$, even at lower temperature, which activates chemical kinetics to yield better possibility of sequential reaction occurrence. Therefore, our suggestion for achieving the most effective enhancement is to supply abundant number flux of atomic oxygen plasma.

Injection Flowfield
Computation was first attempted at the main airflow condition of Mach 2.0, total pressure 7.8 atm and total temperature 2160K, corresponding to SCRam jet flight of Mach 6.2 at 40 km altitude. Hydrogen was injected sonically at 9.5 atm and 960K, so that it would suffice self-ignition. The main airflow was assumed to consist of $N_2$ 80% and $O_2$ 20% in molar concentration. Boundary conditions were non-slip and adiabatic on the bottom plate and symmetrical at the centre plane that included the injector. Upon the other side wall and top plane, the reflective surface condition was imposed, instead of non-slip condition, due to coarse grid lines there.

Fig. 3 shows a numerical schlieren picture of the injection flow field, which shows a complex shock wave structure around the injector.

Fig.4 shows an enlarged view of the flow reversal ahead of the injector. The existence of an elongated re-circulating region in the separated boundary layer was clearly seen. Hydrogen was carried upstream close to the bottom plate and consumed by chemical reaction in the central part of this re-circulation region, as seen from the color-scaled map of hydrogen mole fraction.

Fig.5 shows the flow field behind the injector. There appeared also a re-circulation region associated with the reattachment of the boundary layer. Besides, very intense flow entrainment was observable around the trailing edge of the injector, forming a pair of vortices normal to the wall. The wall reverse flow at the centre axis was thus more intense than in the recirculation region. From the above results and examinations of detailed vortical patterns at several cross sections along the flow path, the present numerical code was proved to be capable of predicting adequately the 3D flow structure associated with transverse hydrogen injection.

Tandem injection effect of oxygen plasma jet upon the hydrogen injection (Sonic, 4.7 atm, 360K) into the main airflow (Mach 1.8, 4.0 atm, 100K) was next simulated for both cases of front and rear plasma torches. Two typical cases were compared, in which atomic oxygen was provided at the distance 20 mm either in front or rear of the primary injector position. The plasma state of total pressure and temperature was assumed to be 3.1 atm and 8,000K for the front torch, and 5.3 atm and 5,044K for the rear torch. It should be noted that there was 2,000K difference in static temperature, but the flow rate through a choked torch was kept to be the same between the oxygen supplies from both torches. Fig.6a-b show $H_2 O$ mole fraction patterns at the centre and bottom planes and the exit cross section. In case of the rear torch (Fig. 6a), $H_2 O$ pattern was well observed at the centre plane, but showed very narrow extent at the exit section, namely, a sheet-like combustion along the centre plane. A small pattern was also observable ahead of the injector leading edge, which indicated the reaction at the reversed flow region near the wall. In case of the rear torch (Fig.6b), $H_2 O$ pattern at slightly off-centre and its larger extent at the exit cross section indicated more complex flame structure than a thin sheet, thus better reaction. There was no sign of $H_2 O$ pattern observable near the injector. Oxygen radicals from the torch were extinguished immediately. Taking into account the temperature difference of 2,000K between the two cases, it will be concluded that $O$ radical supply at the rear of the primary hydrogen injection helps significantly the downstream combustion.
Experiments

Plasma Torch

Figure 7. shows a schematic view and a photograph of the plasma torch, which is a water-cooled DC arc jet developed for providing oxygen radicals. To prevent electrode erosion and to stabilize the arc, argon is supplied as the primary working gas. Oxygen as a secondary working gas was additionally supplied from the circumference. Mixed with argon plasma, oxygen molecules dissociate into atomic radicals. The anode, which forms itself a converging nozzle of the 2mm dia. exit, is made of tungsten. The cathode is a 5mm dia. rod of thoriated tungsten with a conical end. The mixer of argon plasma and oxygen is made of boron nitride with four oxygen gas passages which lead to the nozzle injector (2 mm dia.). Plasma was obtained by applying DC electric power of 1kW (50A, 20V) at a standard argon flow rate of 4SLM. The oxygen flow rate was varied from zero (pure argon) to 3 SLM.

Test Facility

The plasma torch above was installed at the Mach 1.8 high enthalpy wind tunnel of Figure 8. A pebble heater can raise the air temperature up to the maximum 1700K at the airflow rate of 1 kg/s. Presently, the total temperature Tt of air was varied from 300K up to 1000K, while the total pressure Pt was kept constant at 0.4 MPa throughout the experiments. The test section is 200 mm in length and rectangular of shape with 45mm width by 36mm height. The side walls are all transparent for optical visualization except the bottom injector plate made of stainless steel. The diameter of the hydrogen injector was 1.5 mm, and the plasma torch was arranged to be in tandem, either in front or rear of the H₂ injector, at a distance of 15 mm. The latter distance was the minimum possible due to the geometrical restriction. 23 static pressure taps of 0.8 mm diameter were also arranged on the bottom plate downstream the fuel injector.

Results

Preliminary

The plasma torch was first operated alone in a cold (Tt=300K) airflow, by employing nitrogen instead of oxygen as the secondary working gas. Fig.9a gives a picture showing that a jet from the torch is turned in the direction by the airflow to be carried about 45mm downstream. Fig.9b corresponds to the case where nitrogen gas was together injected in tandem from the fuel injector downstream of the torch. Due to the tandem injection, the boundary layer separation was induced, so that most of the plasma jet was lifted up and drifted along the bow shock into the recirculation region associated with the boundary layer reattachment. This picture also indicated that the mixing boundary between the air and injectant might be visualized by the luminous emission due to the plasma jet.

Hydrogen Combustion

Main experiments have been performed under various temperature level of the main airstream. Two series of the test runs were conducted.

In the first series of the test runs, the Ar flow rate was 4 SLM and the secondary working gas was oxygen at a fixed flow rate of 3SLM. The torch position was changed, either upstream or downstream of the fuel injector (i.e. front or rear torch), and the effect of the main airstream temperature was examined. Table.2 shows a summary of the experimental results (Runs #1-4). When the torch is located upstream of the hydrogen injector, no flame was observable under all the conditions (Run #1). It seemed that oxygen radicals never survived at such a long distance of 15 mm between the torch and injector, recombing into molecules. On the other hand, when the torch was at the downstream position, a clear indication of ignition enhancement was obtained by comparing the cases between pure Ar and the mixture of Ar plus O₂. At the airflow temperature between 850K and 950K (Run #2), even pure argon plasma enhanced the chemical reactions (Fig.10), but with O₂ added, more intense flame was observed (Fig.11). Against our previous conjecture, the intensity of this flame was not dependent upon the increase of mass flow rate of O₂. At the airflow temperature between 700K and 750K (Run #3), flame was initially observable in the pure argon case, but blown out unexpectedly. Since the airflow temperature decreased at a rate of 25°C per minute during the wind tunnel operation, the temperature level might have crossed the ignition limit of the pure argon torch. It should be pointed out that, by using the Ar + O₂ torch, ignition was successful even at the air temperature below 600K. Some flame instability, however, was also observed at such a low temperature. Fig.12 shows that the combustion zone moved to-and-fro quickly from its stable downstream position up to the injector.

In the second series of test runs, the interior of the test section was made smoother to yield the lower freestream disturbances. The volume flow rates of Ar and the additive gas were varied, as well as the fuel injection pressure. For the additive gases, oxygen and hydrogen were tested. The separation between the torch and the fuel injector was unchanged. Table 3 shows the summary results. (Runs #5-13) Again, no flame was observed in the cases of the front torch. It was interesting that the test section improvement resulted in the higher ignition temperature than that of the first series. For instance, in the case of Ar plus O₂ torch, the firing was achieved in almost every run (Run #2-4) in the first series, whilst a threshold
seemed to exist around 900K (Run #5-9) in the second series. Freestream disturbances were presently thus influential to the ignition process. With a decrease of Ar flow rate (Run #9), the ignition became unsuccessful despite an increase of additive O₂. It must be emphasized that the corresponding radicals are produced only after the additive gas be activated by merging with the working gas plasma, therefore, need enough Ar flow rate. In the case when H₂ was used as the secondary working gas, it was expected that the plasma torch would dually act as a fuel injector and an igniter. Runs #11-13, however, showed no sign of flame within the test section, perhaps, because the main airflow temperature was not high enough. In fact, at Run #11, the region very close to the plasma injector was trampled by flamelet illumination, which however ceased instantly due to the cold H₂ injection at the upstream injector.

**Concluding Remarks**

The supersonic combustion of hydrogen fuel with oxygen and hydrogen radicals supplied from a plasma jet of Ar primary working gas has been investigated experimentally.

Concerning the relative location of a plasma torch against the fuel injector, only the rear torch, that is, the torch being placed downstream of the injector, was successful in ignition at low airflow temperature.

Several test runs resulted that oxygen radicals be better than hydrogen radicals in effectiveness for the ignition and combustion enhancement.

In plasma torch operation, the primary working gas, currently argon, to achieve the plasma stability needed to be fed enough to ensure the production of chemically active radicals of the secondary working gas. Freestream disturbance level will be also influential to the fuel gas ignition threshold.

A great help of Prof. Y. Arakawa’s laboratory, Department of Aeronautics and Astronautics, University of Tokyo, should be acknowledged for the design and practice of the current plasma torch.

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**References**


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<td>Ar</td>
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**Table 2: Plasma Torch Experiments (The 1st Series)**

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**Table 3: Plasma Torch Experiments (The 2nd Series)**
Fig. 1 Computational Grids-125×50×40(streamwise, in height and width direction, respectively)

Fig. 2 Chemical Kinetics of Hydrogen-Oxygen Combustion

Fig. 3 Schlieren Picture

Fig. 4 Reversed Flow Field ahead of Injector

Fig. 5 Flow Field behind Injector

Fig. 6a Front Torch -- H₂O Mole Fraction

Fig. 6b Rear Torch -- H₂O Mole Fraction

Fig. 7 Plasma Torch
Fig. 8 Test Facility

Fig. 9a Plasma Torch Injection

Fig. 9b Tandem Nitrogen Injection

Fig. 10 Combustion with pure Ar Torch

Fig. 11 Combustion with Ar + O₂ Torch

Fig. 12 Flame Instability