TIME SERIES MEASUREMENTS OF MIXING CONDITION OF HYDROGEN – AIR SUPERSONIC MIXING LAYER

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Abstract

An experiment was carried out to confirm the validity of time series evaluation of supersonic mixing condition by using catalytic reaction on a platinum wire. Gaseous hydrogen was injected parallel to supersonic free-stream ($M_\infty \approx 1.81$) from a slit injector, which was located at backward facing step. Time series condition of supersonic mixing was evaluated by using W-type probe which has a platinum wire and reference wire (nickel wire). The evaluation was done by simultaneously measuring each electric power supplied by each electric circuit which kept the temperature of wire constant. Specifically supplied electric power to Pt wire depended on catalytic heat release rate (giving hydrogen concentration) and flow convection. Meanwhile that to Ni wire depended on flow convection. The result showed that correlation coefficient between these electric powers increased when mixing developed. Investigations were also conducted for helium, air and no secondary injection cases to compare with the hydrogen injection case. The results indicated that it was possible to measure the time-series behavior of air-hydrogen supersonic mixing layer or coherent motion of turbulence by using this evaluation.

1 Introduction

The SCRAMJET engine will be one of the propulsion system of space transportation or hypersonic vehicles in the future[1]. However, some problems must be solved to put it to practical use. For example, the freestream remains supersonic in the combustor. Therefore the mixing of fuel jets with free-stream must be quick. Some injection schemes for SCRAMJET engine have been suggested to enhance the mixing[2]-[11]. Wedge shaped injector schemes[2],[3] and its derivations[4],[5], ramp injector schemes[6],[7] and its derivations[8],[9] and inclined injector schemes[10],[11] have been suggested in the past studies.

It is obviously important to evaluate the mixing condition in the SCRAMJET engine in order to suggest or develop aforementioned injection schemes. Thus some evaluation techniques of the mixing condition have suggested or developed as well as the injection schemes of SCRAMJET engine. Direct sampling is one of conventional evaluation. This method cannot be applied to the time-series evaluation of mixing condition. Laser diagnostic techniques, which are Laser Induced Fluorescence (LIF)[6], Mie scattering[10] and so on, are attractive because these methods are non-intrusive and have the ability to achieve data with high spatial resolution. These devices are, however, very expensive and complicated because of using laser system. Thus these techniques are not also easy to be applied to the time-series evaluation of mixing condition. We have developed a new method for evaluation of mixing condition to solve these lacks of conventional devices as described in our previous papers[3],[7],[11]-[17]. It was conducted by using catalytic reaction on a platinum wire. It was used to investigate the time-averaged mixing condition of 2-D hydrogen-air supersonic mixing layer in the previous studies[15],[16]. It was clarified that our technique was a useful and easy way to evaluate the mixing condition between the supersonic free-stream and the hydrogen jet.

An experiment was conducted to clarify whether this technique can be applied to time-series evaluation of a supersonic mixing condition in the present study. Specifically gaseous hydrogen, helium or air was injected from a slit injector at the base of a backward facing step into a supersonic free-stream. A W-type probe, which has both a platinum (catalytic reaction) wire and a nickel (reference) wire, was installed to 2-D air and hydrogen (or, helium or air) supersonic mixing layer. Helium and air injection cases were also investigated to compare with hydrogen injection case. The time-series evaluation was conducted by measuring each electric power to the platinum wire and the nickel wire from each electric circuit simultaneously.

2 Experimental Apparatus and method

2.1 Experimental Apparatus

A suction type supersonic wind tunnel was used in the present study. Figure 1 shows the schematic diagram of experimental apparatus. The cross section of test section was 30mm × 30mm. The backward facing step was located on the base of the test section. The step was 3mm height. The coming free-stream Mach number was about 1.81. In an isentropic condition, the static temperature in the test section would be about 180K. Gaseous hydrogen was injected parallel to the free-stream from a slit injector as shown in Fig.2. Gaseous helium or air was also injected as well as hydrogen to compare with the result for hydrogen injection case. The slit injector was installed at the base of the backward facing step. The slit injector was sonic nozzle, 1.1mm width and 18mm length at the exit. The jet-to-free-stream momentum flux ratio was $J \approx 1.0$ in all cases. Convective Mach number[18] is $M_c \approx 0.485$, 0.342 and 0.292 for hydrogen, helium and air cases, respectively.

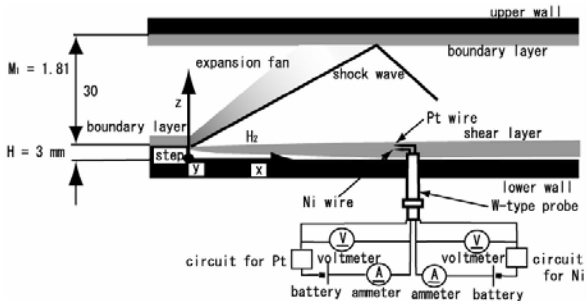

Fig. 1 Experimental Apparatus

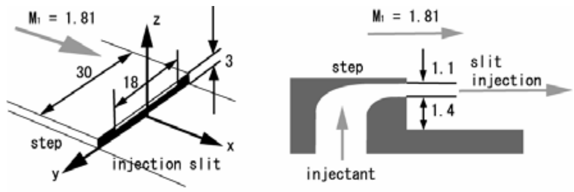

Fig. 2 Slit injector

Nano-pulse (the exposure time was about 30×10^{-9} sec.[19]) Schlieren photographs were taken to investigate the behavior of supersonic mixing layer and jet/free-stream interaction. The probe which measured the mixing condition is shown as a W-type probe in Fig.1. This probe had both a thin platinum wire and a thin nickel wire. These wires were 1.4mm long and 0.025mm in diameter. These wires were arranged normally to free-stream. The interval of them was 1.5mm. Each wire was connected to each electric circuit to keep constant temperature (about 870K). There was heat due to catalytic reaction on the platinum wire. On the other hand, there was not heat due to catalytic reaction on the nickel wire. The mixing condition was evaluated by comparing this difference between platinum and nickel wire cases. Electric circuits, used in the present study, work as the same as the technique of constant temperature type hot-wire anemometer. The frequency response of differential amplifier in the electric circuit was about 40kHz at 70 % amplification. It was shown that the response time of a current probe to the variation of convection was less than or equal to about 0.01 ms in the previous study[20]. And the response time depending on hydrogen concentration was the response time which could not be confirmed at the response time of 0.7 ms (less than 0.7 ms)[20]. These should be noticed. The sampling frequency of A/D converter was set as 100 kHz taking account into above results. The air free-stream and hydrogen jet velocities were about 480m/s and 1180m/s, respectively. Thus the flow moves 4.8mm and 11.8mm per one sampling plot in air free-stream and hydrogen jet cases, respectively. Hence the flow structure of mixing layer is seemed to move about average of 4.8mm and 11.8mm per one sampling plot. This order is the almost same as the order of thickness of the mixing layer (the thickness was about 4.4mm at x = 14mm obtained from Schlieren photograph). These indicate that the sampling frequency set up in the present study is adequate for the time-series evaluation of the coherent motion in the mixing layer. The sampling time was set up as 0.05 sec. The time-series measurements of mixing condition were conducted by contemporary measuring each supplied electric power to a platinum and a nickel wire. The W-type probe was installed into the flow field at (x, z) = (14, 2), (49, 4) and (84, 7) positions on the centerline of the lower wall (y = 0), where x, y and z (mm) was the streamwise distance from the base of the step, spanwise direction from the centerline of the lower wall and height from the lower wall, respectively.

2.2 Heat Release due to Catalytic Reaction

The energy balance on a thin wire in the flow field is given as follows:

$$Q + P = C_1(T^4 - T_w^{\ 4}) + C_2(T - T_g) + Q_{tc} \quad (1)$$

If a thin nickel wire is used, there are no cases where heat release occurs due to the catalytic reaction (regardless whether it is in the mixing layer or out), so that Q is neglected. Hence Equation (1) yields,

$$P_{Ni} = C_1(T_{Ni}^{\ 4} - T_w^{\ 4}) + C_2(T_{Ni} - T_g) + Q_{tc} \quad (2)$$

In the case of using a platinum wire, Q is not neglected in the mixing layer region because there is the possibility of heat release due to the catalytic reaction. Then, Equation (1) yields,

$$Q + P_{Pt} = C_1(T_{Pt}^{\ 4} - T_w^{\ 4}) + C_2(T_{Pt} - T_g) + Q_{tc} \quad (3)$$

By comparing Eq.(2) with Eq.(3), a time-series evaluation on supersonic mixing of hydrogen

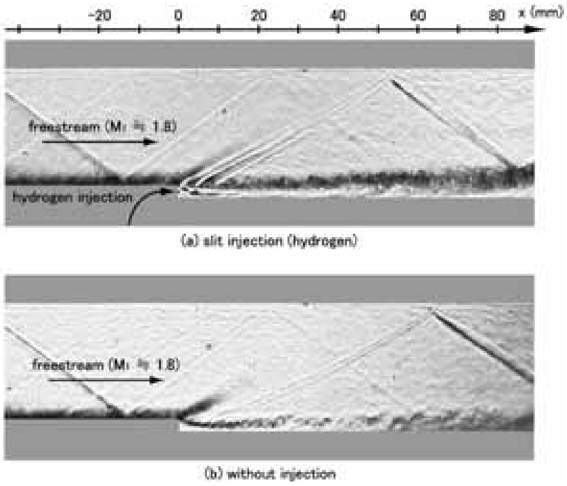

Fig. 3 Typical result obtained from Schlieren visualization

with air can be carried out. Specifically, if it has good correlation between each time variation of each supplied electric power to each platinum wire and nickel wire, then correlation between velocity fluctuation (depending on supplied electric powers to both nickel and platinum wires) and fluctuation of hydrogen concentration (depending on supplied electric power to platinum wire only) is better. In other words, it can be thought that the mixing of hydrogen jet with air free-stream is developed. If it has no good correlation, then correlation between velocity fluctuation and fluctuation of hydrogen concentration becomes worse. That is, the mixing does not developed yet. These were explained in detail later.

3 Results and Discussions

3.1 Flow Visualization

Figure 3 shows the typical result obtained from Schlieren visualization. Injecting gas species is gaseous hydrogen. The flow direction was from left to right. Gaseous hydrogen was injected from the slit injector parallel to free-stream. Mixing shear layer of hydrogen and air was extended into a supersonic free-stream. Some shock waves occurred near the injector. It was because the collision of hydrogen jet with free-stream occurred. And it was shown that some waves propagated from upstream of the step.

These waves occurred from terminal area between Laval nozzle and the test section.

3.2 Supplied Electric Power

Figure 4 shows the typical result of supplied electric power to thin wires ((*x*, y, *z*) = (49, 0, 4), hydrogen injection). Figure 4 is the local result abstracted from the whole sampling time. In Fig.4, there was the good case of correlation between supplied electric power to platinum wire and nickel wire in time-region 1. Time-region 2 was the bad correlation case. In compared time-region 1 with 2, when time variation of supplied electric powers to thin wires has good correlation like time-region 1, the mixing ratio of hydrogen jet to air free-stream (or catalytic heat release rate) seems to be constant with time as aforementioned. In other word, it may imply that the mixing has already developed much than time-region 2. On the other hand, in bad correlation case of time-region 2, the mixing ratio was changed with time. That is, the diffusion of hydrogen into free-stream has not done yet.

A relation between the time variation of supplied electric power to a platinum wire and a nickel wire and the mixing condition must be simplified to explain this relation. Figures 5 and 6 show simplified models of correlation between time variations of supplied electric powers and of the mixing condition. It was assumed that the variation of supplied electric power was only dependent on heat release due to catalytic reaction (thus the influence of convection was neglected). Figures 5 and 6 show the cases of bad correlation between supplied electric power to platinum wire and to nickel wire, and good correlation, respectively. In case that the mixing does not develop in flow field, a probe contacts both the mixture gas of hydrogen with air and the no mixed gas as shown in Fig.5. Therefore the supplied electric power to platinum wire is changed with time. As the result, the correlation between the time variation of supplied electric power to platinum wire and to nickel wire becomes worse (referred time-region 2 of Fig.4). If the probe contacts only the mixture gas, as shown in Fig.6, the mixing condition does not change with time. Thus the heat release due to catalytic reaction does not change. As the result, the correlation between the time variation of supplied electric power to platinum wire and to nickel wire becomes better. In such case, time variations of supplied electric powers to platinum wire and to nickel wire are fluctuated in sync even though

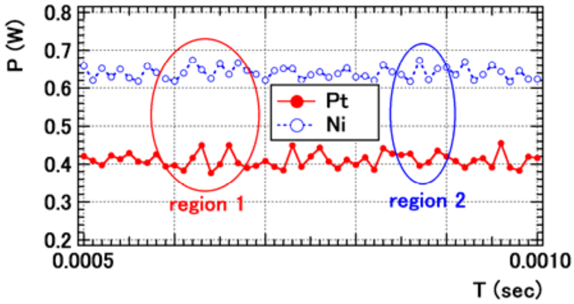

Fig. 4 Supplied electric power in hydrogen case

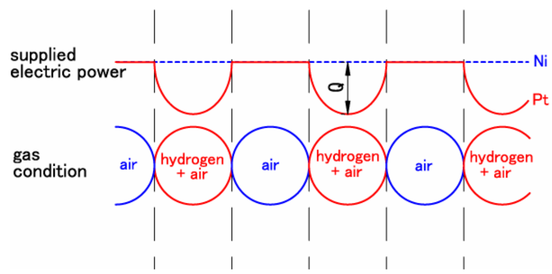

Fig. 5 Simplified model in bad correlation case

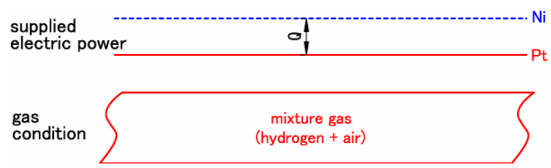

Fig. 6 Simplified model in good correlation case

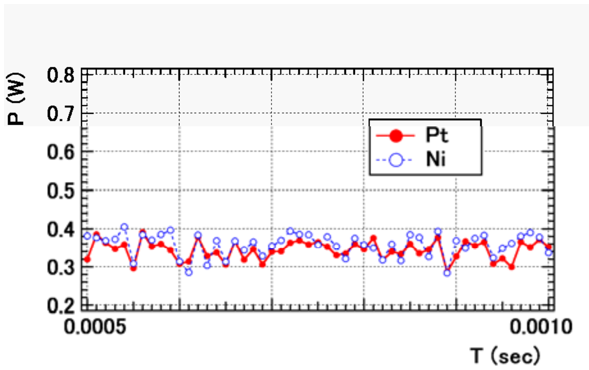

Fig.7 Supplied electric power in air case

the flow convection is considered. After all, the correlation becomes better (referred time-region 1 of Fig.4).

If above simplified model is valid, the correlation of supplied electric powers is supposed to become better in the case that secondary gas is non-reactive gas except with hydrogen and other reactive gases, because time variations of supplied electric powers are in sync fluctuated in the case that heat release does not occur due to catalytic reaction. Therefore experiments were done in the cases of some gas species except with hydrogen. Gaseous air and helium were chosen as injectants in the present study. Figure 7 shows the typical result of supplied electric powers obtained in case of air injection ((x, y, z) = (49, 0, 4)). Figure 7 is the local result abstracted from whole of sampling time. Comparing Figs.7 with 4, it is seemed that the correlation of supplied electric powers is better in the case of air injection (Fig.7) than hydrogen injection (Fig.4). These results indicated in Figs. 4 and 7 are, however, local results.

3.3 Correlation Coefficient of Supplied Electric power to a platinum wire and a nickel wire

Correlation coefficient of supplied electric powers for whole measurement time would be deduced to discuss the relation between the supplied electric power and the mixing condition quantitatively.

3.3.1 Variation of Gas species

Figure 8 shows correlation coefficients of supplied electric powers in the variation of gas species. These were deduced from results observing at (x, y, z) = (49, 0, 4). There is worse correlation in hydrogen injection case than in helium and air. Results in helium and air injection cases were obviously under no heat release due to catalytic reaction. These correlations in the cases of helium and air were better than that in the hydrogen injection case under heat release due to catalytic reaction as aforementioned. Thus this result indicates that current evaluation can be used as time-series evaluation of air-hydrogen supersonic mixing layer. A result in without injection case was, however, worse correlation than that in the hydrogen case. This result may imply that the scale of flow structure is quite smaller than those in other cases.

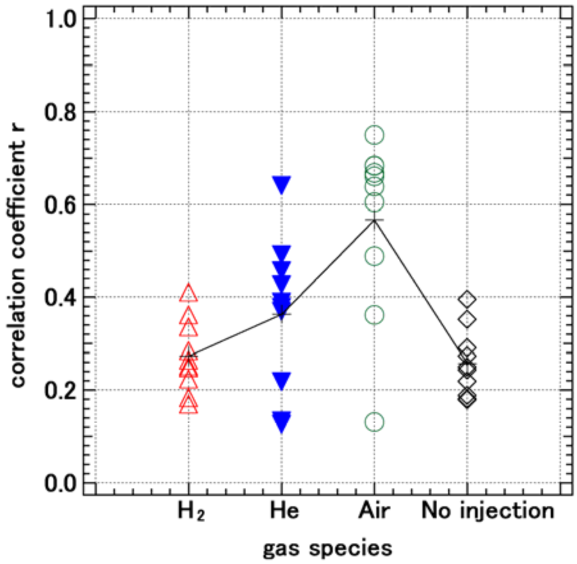

Fig.8 Correlation coefficient of supplied electric powers in the variation of gas species

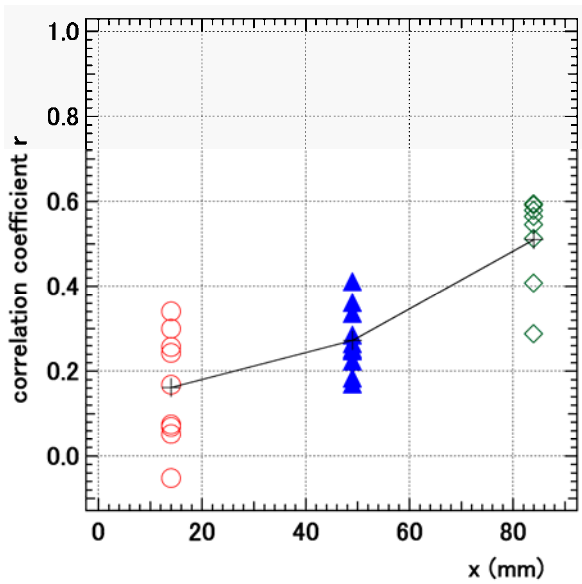

Fig.9 Correlation coefficient of supplied electric powes in measurement positions

3.3.2 Variation of Measurement positions

Figure 9 shows correlation coefficients of supplied electric powers with the measurement positions. The gas species is hydrogen. The correlation coefficient was increased as x

increased in Fig. 9. This indicated that the mixing developed when the measurement position went downstream. In other words, the farther downstream measurement position went the much the hydrogen diffused into air free-stream. Correlation coefficient at (x, y, z) = (84, 0, 7) was much higher than at other positions.

3.4 Application

In this chapter, let you know application of this experimental method. Figure 10 and 11 shows Alternating Inclined and Parallel injections (AIP injector) we proposed[21]. In order to investigate the availability of this AIP injector, time series evaluation by using a catalytic reaction on a platinum wire was carried out. All parallel injector to free-stream (only 7 parallel injector ports, called as 0° injector below) and all inclined injector (30° inclined to supersonic free-stream, 7 ports, called as 30° injector below) cases were also investigated. Figure 12 shows typical result of correlation coefficient of supplied electric power obtained from AIP injector, 0° injector 30° injector cases. Figure 12 shows correlation coefficient between time variations of supplied electric power to platinum wire and nickel wire. The higher correlation coefficient is, the much mixing was developed as aforementioned. In Fig.12, the correlation coefficient in the AIP injector case was higher than those in the other cases although data was spread. This result indicated that AIP injector is useful in the point of mixing enhancement.

4 Concluding Remarks

Gaseous hydrogen was injected from the slit injector parallel to supersonic free-stream. The flow-field was evaluated by the time-series measurement of the mixing condition by using catalytic reaction, which was conducted by measuring supplied electric power to a platinum wire and a nickel wire, simultaneously. Flow-fields in helium, air and without injection cases were also evaluated to compare with the hydrogen injection case. The result of supplied electric power in the hydrogen injection case indicated that there are both good correlation

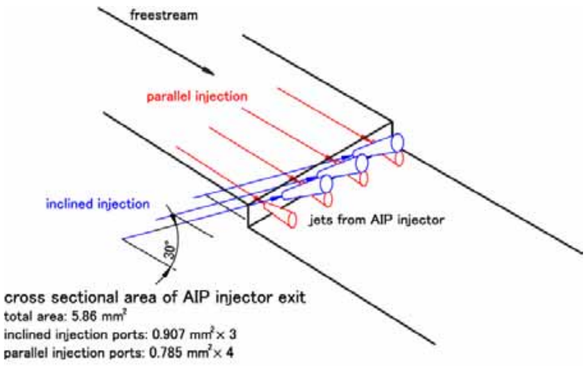

Fig.10 Schematic diagram of AIP injector

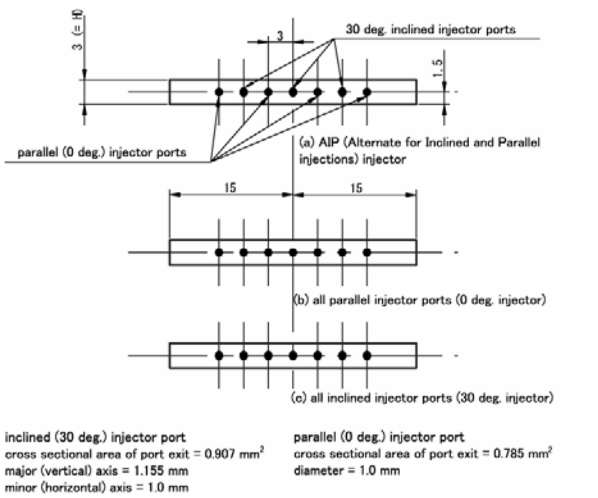

Fig.11 detail of injectors (from point of view of –x)

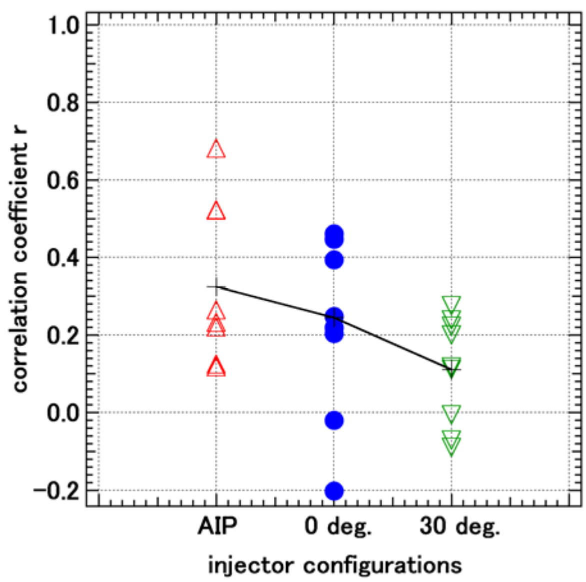

Fig.12 Correlation coefficient of supplied electric powers in various injectors

and the bad one between the time variations of supplied electric powers within one sampling time.

Correlation coefficients between the fluctuations of supplied electric powers in the variation of gas species were deduced to clarify the correlation between the time fluctuations of supplied electric powers quantitatively. The result clarified that this evaluation can be used to measure the time-series behavior of air-hydrogen supersonic mixing condition.

Correlation coefficients between the fluctuations of supplied electric power to a platinum wire and to a nickel wire were also deduced in the variation of the measurement positions. The result indicated that the correlation coefficient was higher when the measurement position went downstream. It was inferred that the good correlation between the fluctuations of supplied electric powers appeared as the mixing was developed.

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