Correlation between Velocity Fluctuation and Fluctuation of Hydrogen Concentration in 2-D Air-Hydrogen 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. Geseous hydrogen was injected parallel to supersonic freestream ($M_\infty \approx 1.81$) 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 by simultaneously measuring each electric circuit which kept the temperature of wire constant. Investigations were also conducted for helium, air and no secondary injectant cases to compare with the hydrogen injectant case. The results indicated that it was possible to measure the time series behavior of air and hydrogen supersonic mixing layer or coherent motion of turbulence by using this evaluation.

Introduction

The SCRAMJET engine is one of the propulsion system of space transportation or hypersonic vehicles in the future[1]. However, some problems must be solved to apply it to practical use. For example, the freestream remains supersonic in the combustor. Therefore, the mixing of fuel jets with freestream 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 important to evaluate the mixing condition in the SCRAMJET engine in order to suggest or develop above-mentioned 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 the 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 nonintrusive 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 freestream 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 2-D slit injector at the base of a backward facing step into a supersonic freestream. 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 injectant cases were investigated to compare with hydrogen injectant 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.

Experimental apparatus and method

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 freestream 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 freestream 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 injectant 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-freestream 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. These flow conditions were shown in Table 1.

Nanopulse (the exposure time was about 30×10^{-9} sec.[19]) Schlieren photographs were taken to investigate the behavior of supersonic mixing layer and jet/freestream 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 freestream. 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. 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 operational 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 msec/pts 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 msec/pts (less than 0.7 msec/pts)[20]. These should be noticed. The sampling frequency of A/D converter was set as 100kHz taking account into above results. The air freestream and hydrogen jet velocities were about 480m/s and 1180m/s, respectively. Thus the flow moves 4.8mm and 11.8mm per sampling rate in air freestream and hydrogen jet cases, respectively. Hence the convective velocity of flow structure of mixing layer is seemed to become between these. 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. On the other hand, 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 in a platinum wire and a nickel wire cases. 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.

Heat release due to catalytic reaction

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

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

If a thin 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,

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

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,

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

By comparing Eq.(2) with Eq.(3), a time-series evaluation on supersonic mixing of hydrogen 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 power to nickel wire) and fluctuation of hydrogen concentration (depending on supplied electric power to platinum wire) is better. In other words, it can be thought that the mixing of hydrogen jet with air freestream is developed. If it has no good correlation, then correlation between velocity fluctuation and

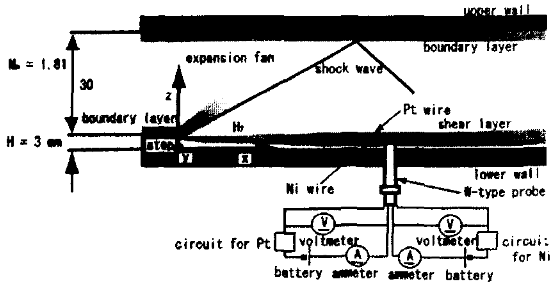

Fig.1 Schematic diagram of experimental apparatus

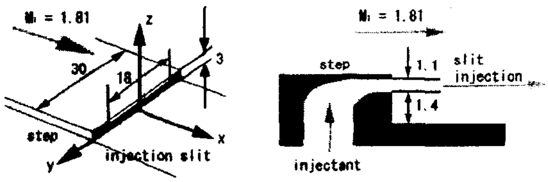

Fig.2 Schematic diagram of slit injector

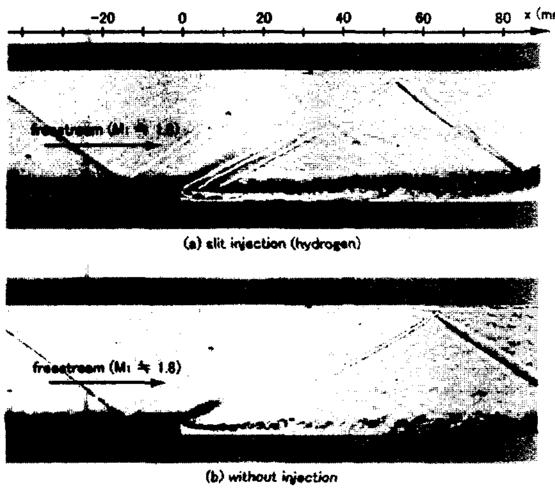

Fig.3 Typical Schlieren photographs

fluctuation of hydrogen concentration becomes worse. That is, the mixing does not developed yet. These were explained in detail later.

Results and discussions

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 freestream. Mixing shear layer of hydrogen and air was extended into a supersonic freestream. Some shock waves occurred near the injector. It was because the collision of hydrogen jet with freestream 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.

Supplied electric power

Figure 4 shows the typical result of supplied electric power to thin wires ((x, z) = (49, 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 to 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 freestream (or catalytic heat release rate) seems to be constant with time as above-mentioned. 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 freestream has not done yet.

A relationship 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 the relationship. Figures 5 and 6 shows 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 shows 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. 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 similarly even though 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

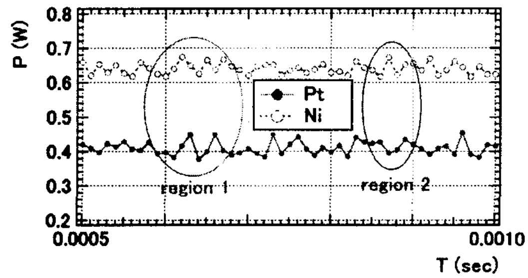

Fig. 4 Supplied electric power in the hydrogen injectant case

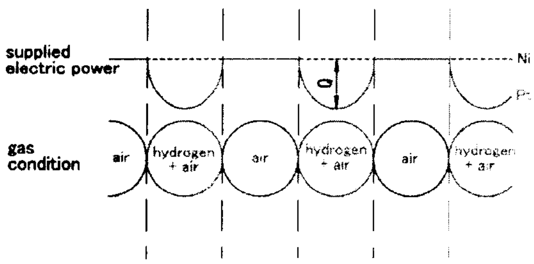

Fig.5 Simplified model in the bad correlation case

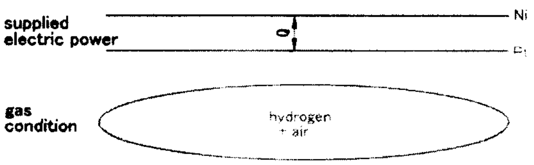

Fig.6 Simplified model in the good correlation case

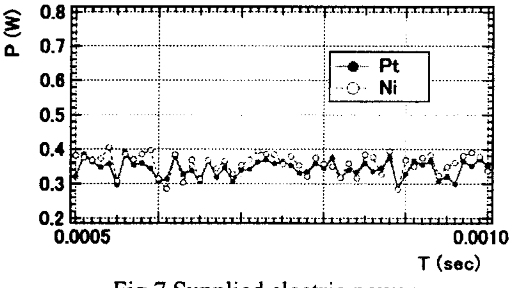

Fig.7 Supplied electric power in the air injectant case

better in the case that secondary gas is non-reaction gas except with hydrogen and other reaction gases, because time variations of supplied electric powers are similarly 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 injectant ((*x*, *z*) = (49, 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 injectant that hydrogen injectant. These results indicated in Figs. 4 and 7 are, however, local results.

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 above quantitatively.

Variation of gas species Figure 8 shows correlation coefficients of supplied electric powers with the variation of gas species. These were deduced on the bases of observing at (*x*, *z*) = (49, 4). There is worse correlation in hydrogen injectant case than in helium and air. Results in helium and air injectant 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 injectant case under heat release due to catalytic reaction as abovementioned. Thus this result indicates that current evaluation can be used as time-series evaluation of air-hydrogen supersonic mixing layer. A result in without injectant 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.

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 is 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 freestream. Correlation coefficient at (*x*, *z*) = (84, 7) was much higher than at other positions.

Frequency analyses

Figures 10 through 12 shows the typical results obtained from frequency analyses (power spectrum density) in the hydrogen injectant case. The inclinations of power spectrums were good agreement with Kolomogorov's -5/3 power law[21]. These results may indicate that this evaluation is available for measuring the time-series behavior of air-hydrogen supersonic mixing layer and coherent motion of

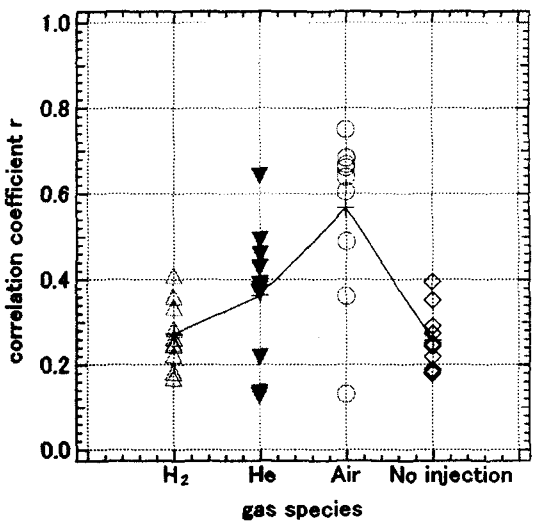

Fig.8 Correlation coefficient of supplied electric powers in the variations of gas species

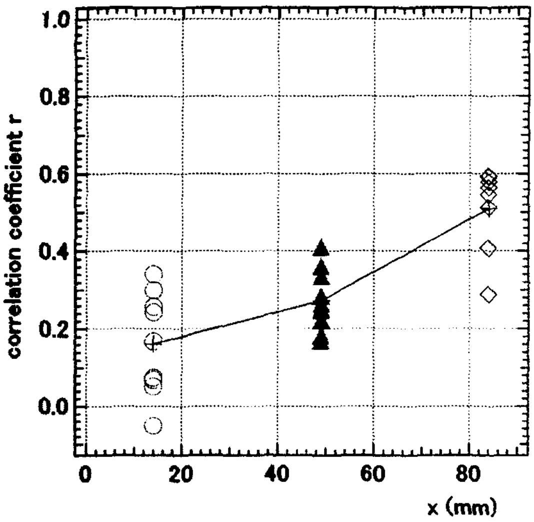

Fig.9 Correlation coefficient of supplied electric powers in the variation of measurement positions

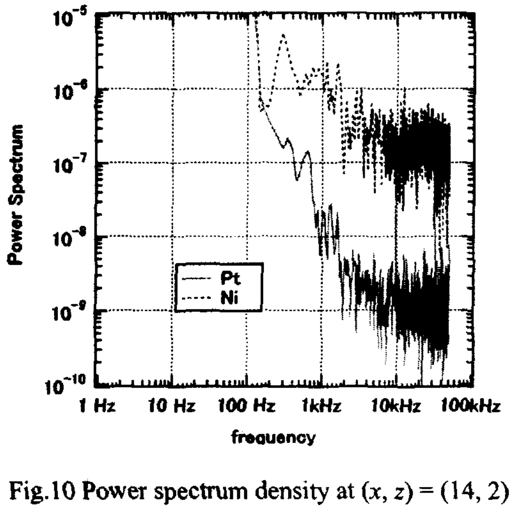

Fig.10 Power spectrum density at (*x*, *z*) = (14, 2)

turbulence. The maximum frequency is, however, 50kHz because of setup sampling frequency (100kHz). This frequency (50kHz) is supposed to be low to measure the supersonic mixing condition in the present study. Therefore the measurement should be done by using higher sampling frequency.

Conclusion

Gaseous hydrogen was injected from the slit injector parallel to supersonic freestream. The flowfield was evaluated by the time-series measurement of the mixing condition using catalytic reaction, which was conducted by measuring supplied electric power to a platinum wire and a nickel wire, simultaneously. Flowfields in helium, air and without injectant cases were also evaluated to compare with the hydrogen injectant case. The result of supplied electric power in the hydrogen injectant case indicated that there are both good correlation and the bad one between the time variations of supplied electric powers within one measurement 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.

The graphs of power spectrum density were deduced from the fluctuations of supplied electric powers. As the result, these inclination was good agreement with Kolomogorov's -5/3 power law.

These results indicated that the time-series evaluation of air-hydrogen supersonic mixing layer can be carried out by using catalytic reaction on the platinum wire.

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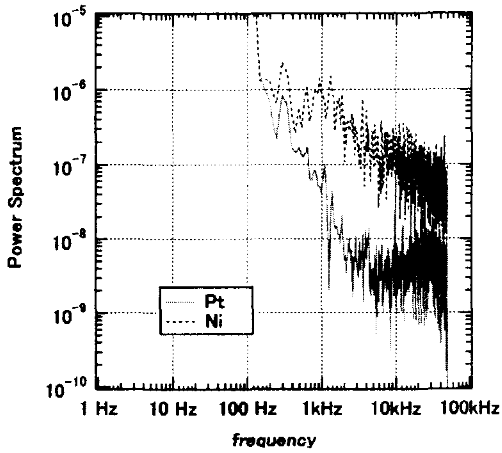

Fig.11 Power spectrum density at (x, z) = (49, 4)

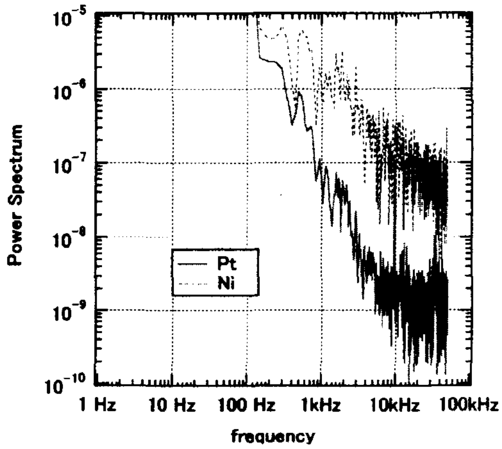

Fig. 12 Power spectrum density at (x, z) = (84, 7)

Nomenclature

C: coefficient of heat transfer
M: Mach number
P: supplied electric power to thin wire
Q: heat release (loss)
r: correlation coefficient between supplied electric power to a platinum wire and a nickel wire
T: temperature
u: velocity
x: streamwise direction
y: spanwise direction
z: vertical direction

Subscripts
1: heat radiation
2: heat convection
c: convective Mach number
g: gas of freestream
j: jet

Ni: nickel
Pt: platinum
tc: heat conduction
w: mean temperature of wall
∞: freestream

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