Characteristics of Hydrogen Combustion in an Experimental Lean Premixed Combustor

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An experimental lean premixed hydrogen combustor has been made and tested to demonstrate low NOx emissions. In this combustor, an air jet film which surrounds the premixed gas was used to suppress the flash-back.

NOx emissions were less than 10 ppmv (0%O_2 dry). The air jet film for the flash-back suppression was slightly effective to widen the operation range of the combustor.

1. Introduction

Aiming at the environmental protection, stringent regulations to reduce the NOx emission from combustion sources have been implemented. As a key technology for this requirement, lean premixed combustors with an advantage of low NOx emissions have been adopted. On the other hand, combustion instabilities such as flash-back, blow-off and the thermo-acoustic instability are observed during the operation of the combustors.

For the global environmental protection, the reduction of the greenhouse effect gases is also required. In particular, the reduction of CO_2 emission is a tough issue. Hydrogen will be a solution for it. It can be a good candidate for the future renewable energy medium.

A lean premixed combustor using hydrogen as a fuel has features of low NOx emission and no CO_2 emission. However, wide operation range is necessary for its practical use.

Combustion instabilities due to high flammability of hydrogen will be the hurdle to widen operation range. In this study, suppression of flash-back is the main target of the combustion control. Flash-back occurs in the vicinity of the premixer wall where the turbulence structure is different from far wall region, and the interaction between turbulence and flame plays a very important role. Therefore the control of the near-wall turbulence seems to lead to the control of the flash-back.

As the first-step to the lean premixed hydrogen combustor, a experimental premixed combustor, a coaxial dump combustor with a venturi-type premixer, was made and its fundamental performance was tested. At the present stage of the study, influences of various air and fuel flow conditions on combustion stability and NOx emissions of the combustor were investigated at atmospheric pressure. In particular, effectiveness of a suppression method against the flash-back for wider operation range were investigated.

2. Experimental Facilities

2-1 Experimental Apparatus

Fig.1 shows the outline of the experimental setup. It consists of an air feed duct which contains an electric air heater, a coaxial dump combustor, an exhaust gas cooler and an exhaust duct. A wire mesh of No.40 and two perforated plates of 3mm thick with holes of 10mm diameter and pitch of 12.5mm are installed before the combustor. Flow rates of combustion air are measured using a thermal mass flow meter. The inlet-air temperature can be controlled using the air heater within error of ±1K.

Hydrogen is supplied to the main and pilot fuel nozzles of the combustor using thermal mass flow controllers.

Exhaust gas from the combustor is cooled to the temperature lower than 773K by water-cooled gratings to quench NOx formation reactions and is stirred as well. After the exhaust gas passes the water-cooled gratings, exhaust gas is sampled on the centerline of the exhaust duct using a stainless steel probe which is cooled with water at 333K.

The sampled gas is firstly sent to a NO_2/NO converter through a line heated at 363K. In the converter, NO_2 in the gas is converted into NO with a catalytic reaction. This procedure reduces errors of NOx concentrations due to absorption of NO_2 into condensed water. Then, the sample is dehumidified with an electric cooler, finally the dry gas sample is analyzed for concentrations of NOx, unburned hydrogen, and O_2.

In this study, NOx emissions are reported on a dry basis, corrected to 0% O_2. Overall combustor equivalence ratios are calculated from fuel and air-flow meter readings.

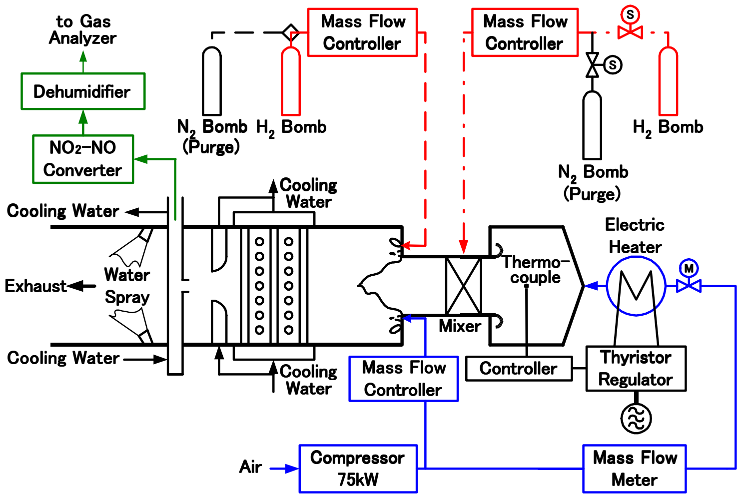

Fig. 1 Schematic Flow Sheet of Test System

2-2 Experimental Combustor

Fig.2 shows a cross-section of the experimental combustor. It has a premixer which consists of seven venturis and a mixing tube. The throat diameter is 10mm and the cone angle of each venturi is 14degrees. Each of these venturis contains eight nozzles of 0.75mm diameter through which hydrogen is ejected perpendicular to the center axis of the venturi.

Flame is held by hot combustion gas in a recirculation zone around the premixer exit. The combustion chamber consists of a quartz glass tube for visual observation and its inner diameter and length are 100mm and 300mm respectively.

Aiming at suppressing the flash-back of flame into the premixer, premixed gas is surrounded by an air jet of 1mm thick at the exit of the premixer.

Hydrogen for pilot flame is introduced into the recirculation zone from four pilot nozzles of 0.5mm diameter on the upstream wall of the combustion chamber. The four diffusion pilot flames are used only for start-up.

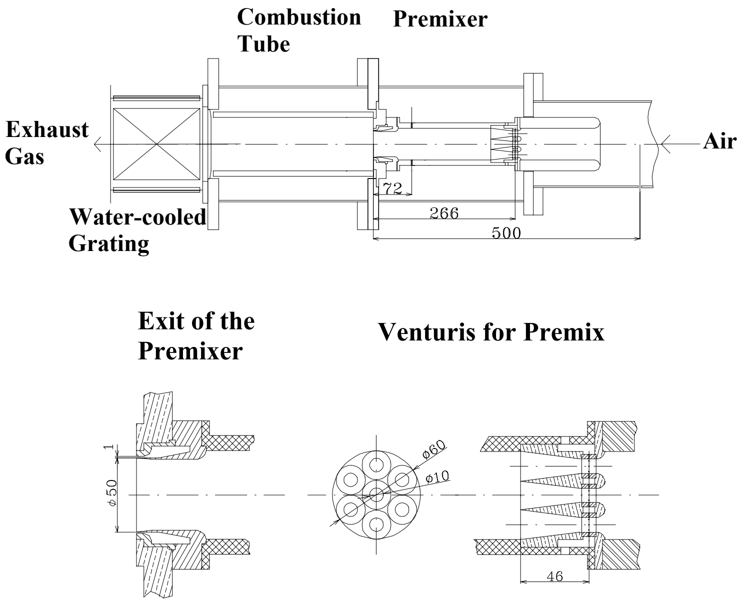

Fig. 2 A Cross-section of the Experimental Combustor

3. Results and Discussion

3-1 Flash-back Characteristics

Experiments were performed at atmospheric pressure, equivalence ratio of 0.24 - 0.5 and inlet air temperature of 288 - 423K.

Photo 1 shows a stable flame like a cone shape. Stable flames are visible when the equivalence ratio is higher than about 0.4. As the premixed gas is getting richer, the flame cone becomes brighter and shorter, and finally flash-back occurs. On that occasion, the root of the flame cone goes upstream along the wall of the premixer. Sometimes the flame-tilt occurs, that is, the root of the flame cone stays near the exit of the mixing tube for a while after the flame goes into the premixer.

Fig.3 shows the equivalence ratio at the moment of flash-back. The symbols show the points at which flash-back occurs and stable combustion regions are defined as the left side of each symbol. The following procedure determines the critical flash-back equivalence ratio. First, hydrogen flow rate and combustion air flow rate are regulated so that a stable flame is obtained. Then, hydrogen flow rate is increased until flash-back occurs, and the equivalence ratio

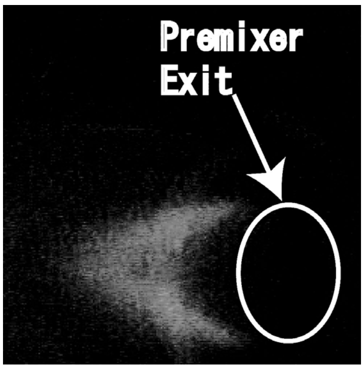

Photo 1 Stable Flame

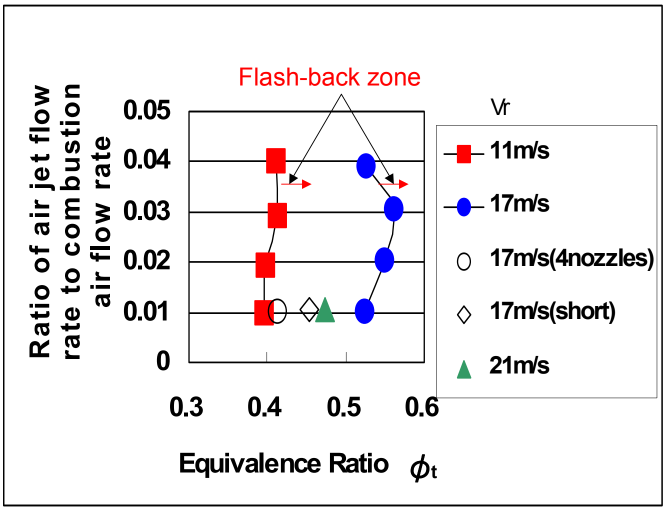

Fig. 3 Deterrent Effect of Air Jet to Flash-back

when the flash-back occurs is defined as the critical flash-back equivalence ratio. If the flame does not go into the premixer until 3 minutes passes after setting hydrogen and combustion air flow rates at given value, the flame is regarded to be stable in this study.

The velocity, Vr, in Fig.3 and others indicates the mean value at the premixer exit on the basis of the mass flow rates of main air and hydrogen. At Vr of 11m/s and 17m/s, effectiveness of the air jet was investigated by changing its flow rate. In the region where the air jet flow rate was less than 3% of combustion air flow rate, the stable region seems to be widened for both Vr of 11m/s and 17m/s. At flow rate higher than 3%, however, the stable region narrowed. The air jet seems to be effective to a certain extent for the suppression of flash-back in the region where the flow rate of the air jet is less than 3%.

When the venturis are changed with those with four 1.06mm nozzles, or when the length of premixer is shortened, whose mixing length is 166mm, the critical equivalence ratios become lower. This is considered to be caused by worse air-fuel mixing.

The stable combustion region at Vr of 17m/s is wider than at Vr of 11m/s for each air jet flow rate. It seems that the higher premixer outlet velocity gives the wider stable combustion region. However, at Vr of 21m/s (air jet flow rate of 1%), it narrows. Flow field should be investigated in detail to clarify its influence on the flash-back.

As the first step, the time-averaged velocity profile and the velocity fluctuation profile at 5mm after from the premixer exit are measured with a hot-wire anemometer. Fig.4 shows the time-averaged velocity profile in axial direction and the r.m.s. value of the velocity fluctuation in the case that only combustion air is supplied to the premixer without air jet. The distance from the centerline is nondimensionalized by the radius of outlet of the premixer, 25mm. The velocity fluctuation profile has a pronounced peak located very close to the wall, about 2mm from the wall, and its value is about 0.2 times of the cross-sectional mean velocity. The burning velocity is considered to be maximum around this position because turbulent burning velocity increases with the augmentation of the turbulence intensity[1]. It should be noted that the time-averaged velocity at such point in the region of the boundary layer is generally much lower than the cross-sectional mean velocity. The time-averaged velocity must be larger than the burning velocity in order to prevent flash-back. However, around the point of maximum velocity fluctuation, the time-averaged velocity can be so small as to allow the flash-back. The modification of the air injection is required for more effective suppression of the flash-back.

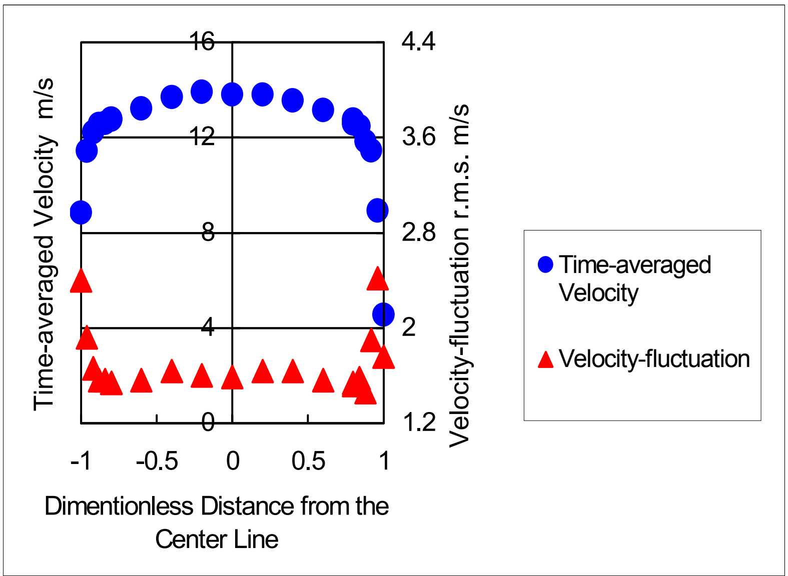

Fig. 4 Distributions of Mean Velocity and Fluctuation

3-2 Combustion Efficiency

The combustion efficiencies are shown in Fig. 5. Results mentioned below are obtained in the stable combustion range. The value of the equivalence ratio in Fig.5 and others, ϕ_t, means the total equivalence ratio given by the flow rate of main air, that of air jet for the flash-back suppression and that of hydrogen. The combustion efficiencies are higher than 99.8% when the equivalence ratio is larger than about 0.3.

3-3 NOx Emission

The overall NOx emissions are shown in Fig. 6. The NOx emissions increases as the equivalence ratio increases, although the NOx emissions are lower than 10 ppmv in the region where the adiabatic flame temperatures are less than about 1700K. The influences of the combustion air flow rates on the NOx emissions are not observed.

Fig. 7 shows influences of inlet air temperatures of the combustion air on the NOx emissions. At the same equivalence ratio, the higher inlet temperature increases the NOx emissions, and the great part of the increase in the NOx emission is explained by the effect of increase in adiabatic flame temperature.

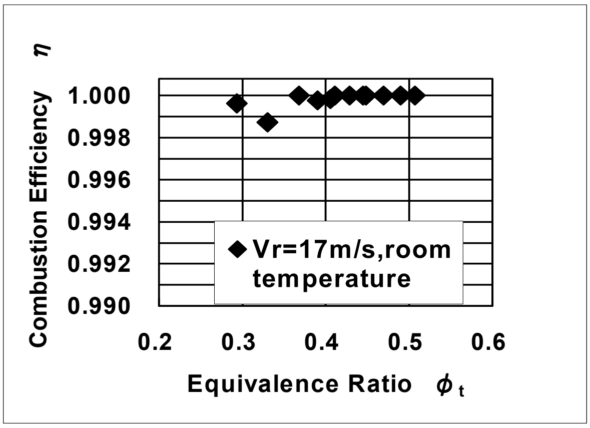

Fig. 5 Combustion Efficiency

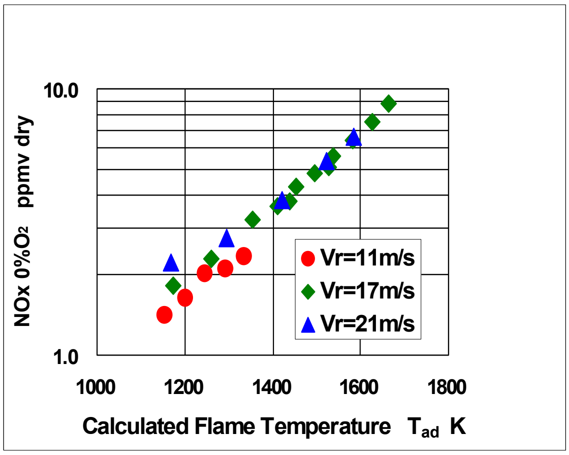

Fig. 6 Overall NOx Emissions

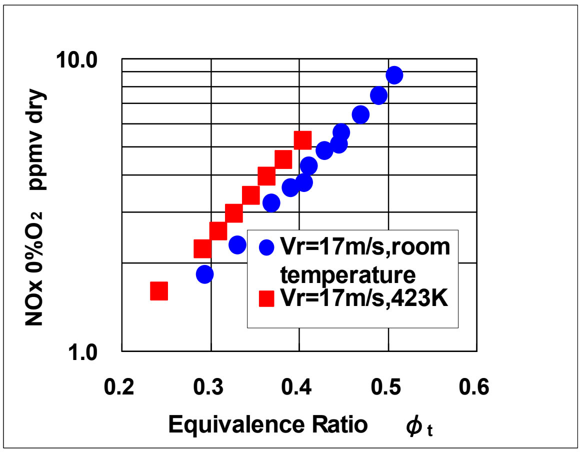

Fig. 7 Effects of Inlet Air Temperature of the Combustion Air on NOx Emissions

4. Conclusions

An experimental lean premixed hydrogen combustor has been made and tested to demonstrate the low NOx emissions and effectiveness of a simple mechanism to suppress flash-back.

Results are summarized as follows:

(1) The air jet is slightly effective to prevent flash-back and to widen the operation range of the combustor. However, flow rates of the air jet higher than 3% of combustion air flow rate reduce its

effectiveness.
(2) The observed NOx emissions increase exponentially as the calculated adiabatic flame temperature increases. It has been observed that they are less than 10 ppmv (based on 0%O_2 dry) at the adiabatic flame temperatures lower than 1700 K.
(3) When flash-back occurs, it is observed that the root of the flame cone goes upstream along the wall of the premixer. Sometimes the flame-tilt occurs, that is, the root of the flame cone stays near the exit of the mixing tube for a while after the flame goes into the premixer.

The results suggest that the possibility of enlargement of the stable combustion range by modification of the way of air injection. The air injection near the wall of the premixer will be expected to improve the distribution of the time-averaged velocity and the velocity-fluctuation of the premixed gas near the wall and to suppress flash-back.

REFERENCE

[1] Bernard Lewis and Guenther von Elve, *Combustion, Flames and Explosions of Gases*, New York, Academic Press, 1961.