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NOx EMISSION REDUCTION IN HYDROGEN COMBUSTION

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ABSTRACT

The characteristics of hydrogen diffusion flames were investigated for utilization in residential sector. High NOx emission is expected because of the high adiabatic temperature of hydrogen flame, and hydrogen flames are hardly detectable by the human eyes. Thus NOx emission reduction and flame detection should be recognized as major challenges.

NOx emission and luminous characteristics of hydrogen flames were investigated and compared with those of methane diffusion flames. NOx emissions from hydrogen flames increased with increasing fuel input although NOx emissions from methane flames were almost constant to fuel input.

The effect of splitting flame on NOx emissions from hydrogen combustion was examined and confirmed as an effective method to decrease NOx emissions. When the nozzle diameters were 1.2 mm and the fuel input per nozzle was less than 0.1 kW, 20 to 25 mm nozzle-interval was required to minimize NOx generation. On the basis of those results, a trial gas stove burner for residential sector with 3.0 kW input was built, and EINOx was found to be 2.3 g/kg-fuel.

Though the hydrogen flames were visible by the human eyes in the dark room, it was not visible in light. Addition of methane to hydrogen flames gave little changes in luminous intensities when the fraction of methane was less than 50 cal%.

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PAPER

1. INTRODUCTION

Much attention is focused on hydrogen as a promising energy source which emits no carbon dioxide. For realizing hydrogen-society it is important to clarify differences in combustion characteristics between hydrogen and conventional gaseous fuels. The objective of our study is to collect technical data on hydrogen combustion to provide a guide for hydrogen gas equipment. Hydrogen flames have some remarkable properties such as extremely high burning velocity and the high adiabatic flame temperature, as shown in Table 1. Due to those characteristics, diffusion combustion is suitable for hydrogen, and NOx emission control and flame detection are some challenges for hydrogen combustion [1] [2]. Figure 1 illustrates the effect of flame temperature on NOx emission [3], and high adiabatic temperature of hydrogen may cause high NOx emission. Since hydrogen flames have no visible light, they are hardly detectable by the human eyes. In our study, practical characteristics such as NOx emission and luminosity and flame length for hydrogen and methane flames were investigated. NOx emission characteristics of the diffusion flames are mainly reported. On the basis of the experimental experiment results, we built a test burner for residential gas stoves and investigated the NOx emission performance of the burner.

Table 1 Properties of hydrogen and methane

	Hydrogen	Methane
Higher Heating Value (HHV, $MJ \cdot m^{-3}_{N}$)	12.75	39.74
Lower Heating Value (LHV, $MJ \cdot m^{-3}_{N}$)	10.79	35.82
Maximum laminar flame speed ($cm \cdot s^{-1}$)	325	44.8
Adiabatic flame temperature (K)	2525	2327
Flammability limit (Lean limit, vol%)	4.0	5.0
Flammability limit (Rich limit, vol%)	75	15

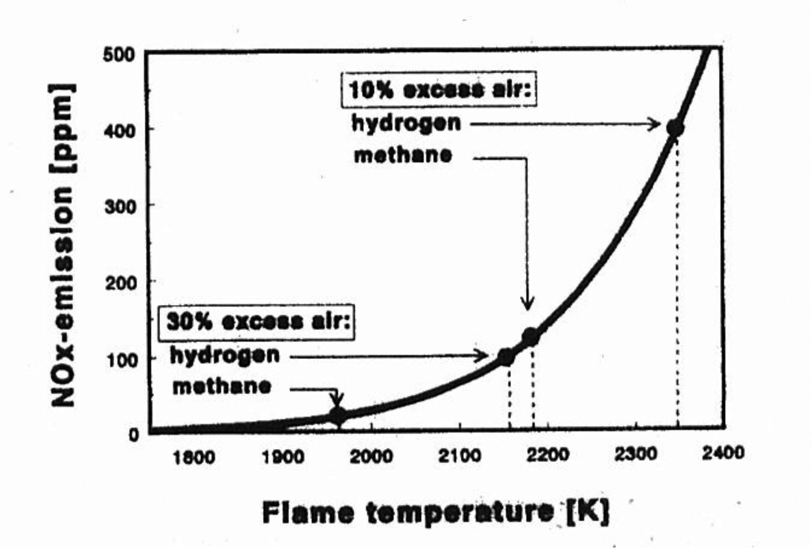


Fig. 1 Rough estimation of NOx emission as a function of flame temperature [3]

2. EXPERIMENTAL

2.1 Basic experiments

The schematic diagram of the experimental apparatus is illustrated in Fig. 2. Combustion gases were collected through a gas hood which was set above the flame. The volumes of the combustion gases were metered after water was removed, and the concentrations of NO and O_2 were measured by using a chemiluminecsence method NOx analyzer (NOA-7000) made by Shimadzu Corporation. Emission index of NOx (EINOx) was calculated on the assumption that all NOx is NO.

Luminous intensities for flames were obtained using an illuminometer [4]. The illuminometer was set 5 cm away from the center of the flames. Flame lengths and widths were measured by photo images taken with a digital camera in a dark room.

Figure 3 illustrates diagrams of test burners. Several kinds of single-nozzle burners (n=1) and multi-nozzle burners with three nozzles (n=3) were used. The experimental conditions are listed in Table 2

2.2 Trial setup of a gas stove burner

Figure 3 shows a photograph of a test burner for gas stoves. Specifications of the test stove burner are shown in Table 3. The NOx property was investigated in the same method as the basic experiments.

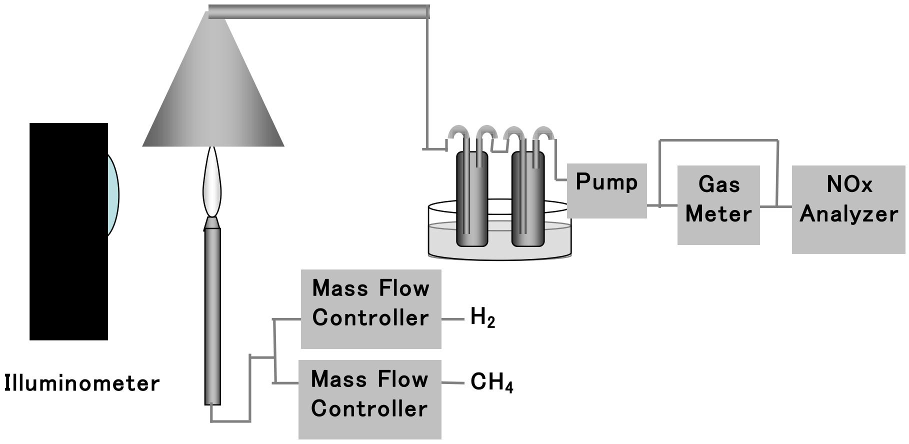
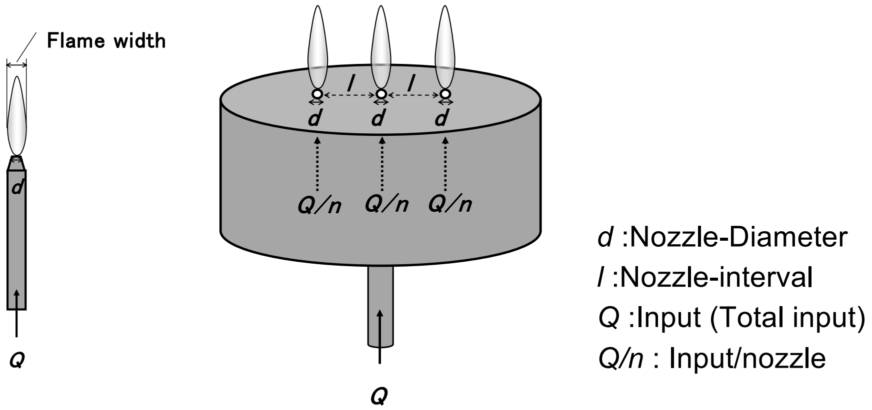


Fig. 2 Schematic diagram of experimental apparatus



(a) Single-nozzle burner (n=1)

(b) Multi-nozzle burner (n=1, 3)

Fig. 3 Test burners for the basic experiments

Table 2 Experimental parameters

Fuel	H_2,CH_4
Nozzle-diameter d (mm)	0.6, 1.2, 2.6, 3.0
Nozzle-interval l (mm)	5, 10, 15, 20, 25
Number of nozzles n	1, 3
Input Q (kW)	0.02 – 0.6

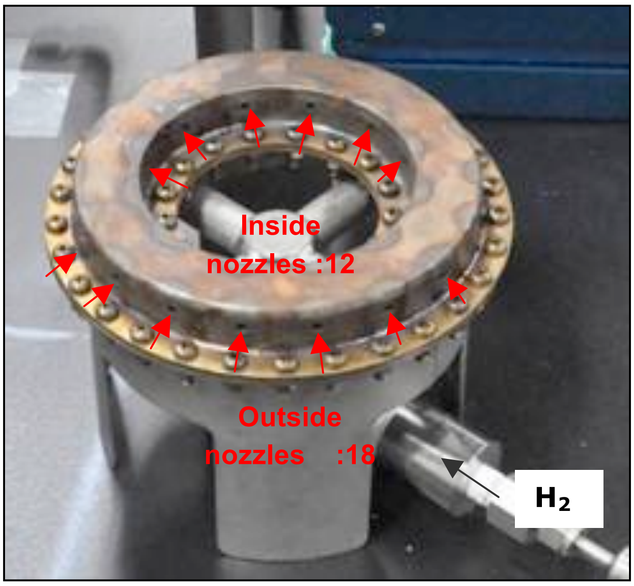


Fig. 4 Photograph of the test stove burner

Table 3 Specifications of the test stove burner

Total input Q (kW)	3.0
Number of nozzles n	30
Number of outside nozzles	18
Number of inside nozzles	12
Input per nozzle Q/n (kW)	0.1
Nozzle-diameter d (mm)	3.0
Nozzle-interval l (mm)	25
External diameter (mm)	15
Internal diameter (mm)	10

3. Results and discussions

3.1 Basic experiments

3.1.1 NOx property

Figure 5 shows emission indices of NOx in hydrogen and methane flames using the single-nozzle burners. Although NOx emissions from methane flames were almost independent of fuel input Q and nozzle-diameter d, NOx emissions from hydrogen flames were significantly dependent on those factors.

The bigger nozzle-diameter made it possible to generate less NOx. NOx emissions in hydrogen flame were increased with increasing fuel input. Those results suggest that splitting flame is an effective method to reduce NOx in hydrogen combustion.

Some experiments were performed with the multi-nozzle burners to investigate the effect of splitting flame on emission indices of NOx as shown in Fig. 6. At the equal total fuel input Q, EINOx at n=3 was lower than EINOx at n=1. In order to observe interaction between the adjacent flames, at the equal input per nozzle Q/n, EINOx at n=3 was compared with EINOx at n=1. Figure 7 shows the ratio of EINOx at n=3 divided by EINOx at n=1, [EINOx (n=3)]/ [EINOx (n=1)], against nozzle-interval l. The NOx emissions at n=3 with short nozzle-intervals were higher than those at n=1. That is because heat loss was probably less in multiple flames than that in a single flame due to the incoming heat from the neighboring flames. Since extending nozzle-intervals results in increasing heat loss, [EINOx (n=3)]/ [EINOx (n=1)] decreased with the nozzle-interval l. In case of d=1.2mm, [EINOx (n=3)]/ [EINOx (n=1)] were almost equal to 1 when the nozzle-interval was over 20 mm. This suggests that there is little interaction between the adjacent flames and each flame is independent of the others. On the other hand, in case of d=3.0 mm [EINOx (n=3)]/ [EINOx (n=1)] was larger than 1 when nozzle-interval was even 25 mm.

Figure 8 shows flame widths against nozzle-diameter d. The flame widths were found to increase with increasing the nozzle-diameter. It is considered that the length of nozzle-interval is required according to the flame width in order to avoid interaction of each flame,

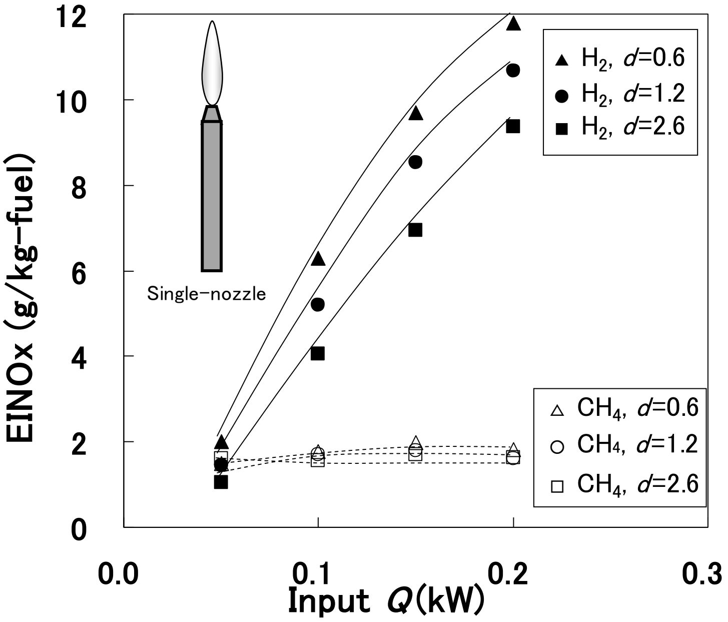


Fig. 5 EINOx in hydrogen and methane flames (*n*=1)

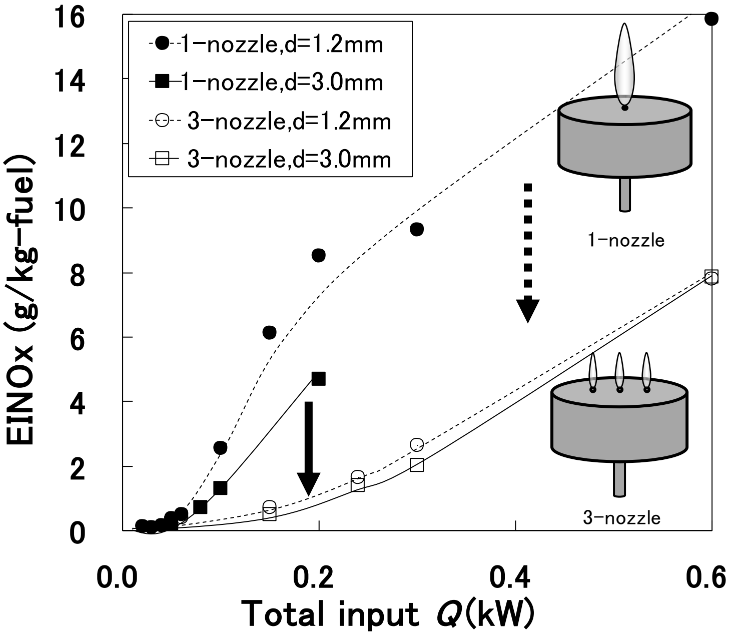


Fig. 6 EINOx in hydrogen flame (*n*=1, 3)

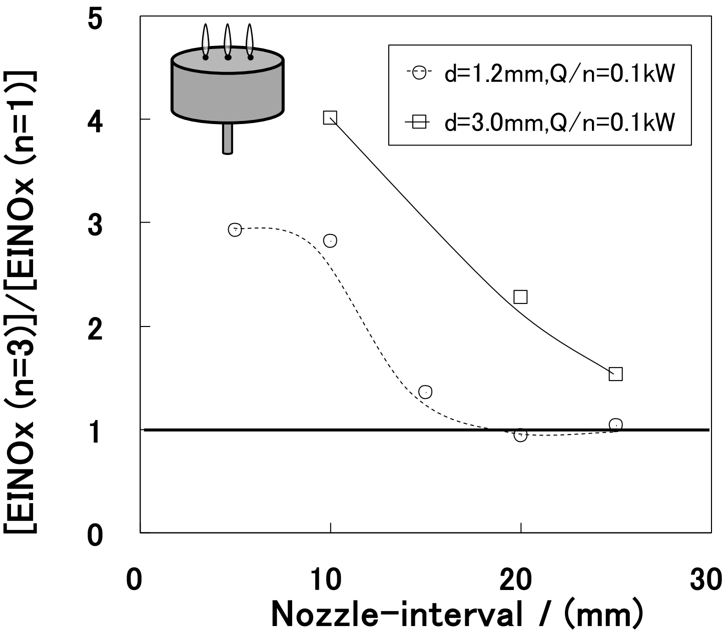


Fig. 7 Ratio of EINOx at *n*=3 to EINOx at *n*=1 against nozzle-interval *l*

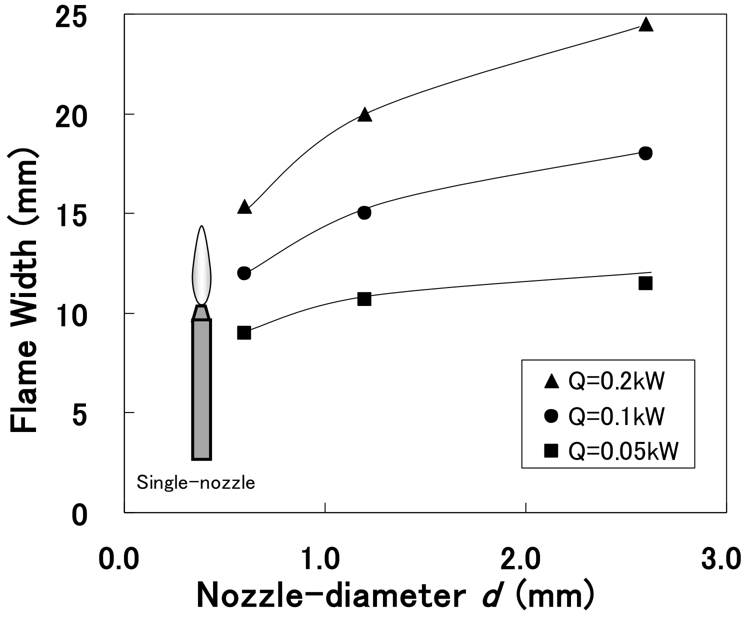


Fig. 8 Flame widths of hydrogen flame against nozzle-diameter *d*

3.1.2 Luminousity

Photographs of flames fuelled with hydrogen, mixture of methane and hydrogen and methane taken in a dark room are shown in Fig. 9. Though the hydrogen flames were visible by the human eyes in the dark room, it was not visible in light [5]. Figure 10 shows luminous intensities of the flames of methane and hydrogen mixture against methane fraction. The luminous intensities were almost constant to methane fraction in 0 to 50 cal% range.

(a) Hydrogen flame

(b) Methane and hydrogen mixture flame
CH_4 fraction = 27 cal%

(c) Methane flame

Fig. 9 Photographs of flames fueled with hydrogen, methane and hydrogen mixture, and methane

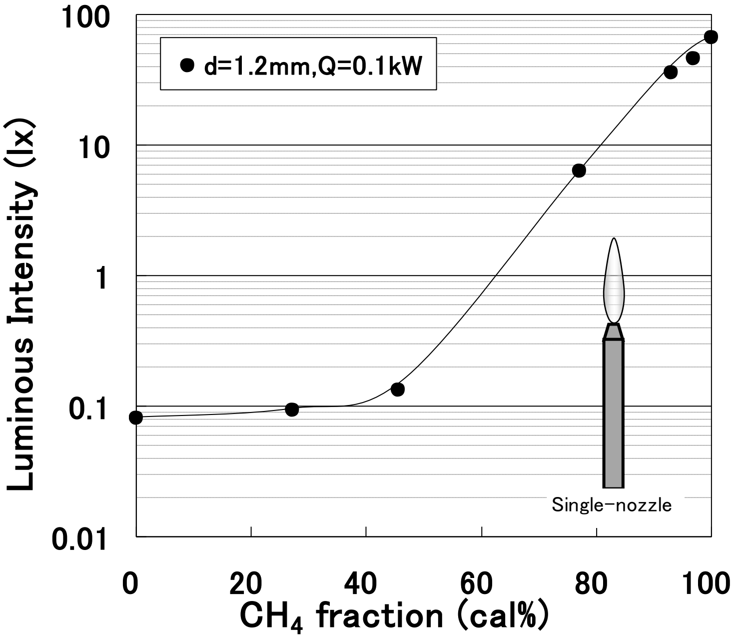


Fig. 10 Luminous intensity of flames fueled with methane and hydrogen mixture flames

3.2 Trial setup of a stove burner

On the basis of the results of the basic experiments, we prepared the test stove burner. The total input of the prototype burner is 3.0 kW, which is an average input of residential gas stoves. 30 nozzles were positioned at intervals of 25 mm in order to reduce NOx. The nozzles were arranged in two concentric circles for high input per unit area. NOx emissions from the test stove burner were shown in Fig. 11. When the input per nozzle was 0.1 kW, which means that total input was 3.0 kW, EINOx was 2.3 g/kg-fuel. Compared with EINOx of the basic experiments using the multi-nozzle burner at Q=0.6kW, EINOx obtained by using the test stove burner at Q=1.5 kW or 3.0 kW were lower even though the input for the stove burner tests is higher than that of the multi-nozzle burner tests. It was apparent that more nozzles generate less NOx. However EINOx was increased at equal input per nozzle when the number of the nozzles was increased as indicated by dashed line. It is considered that combustion temperatures of the stove burner tests were higher than the basic experiments.

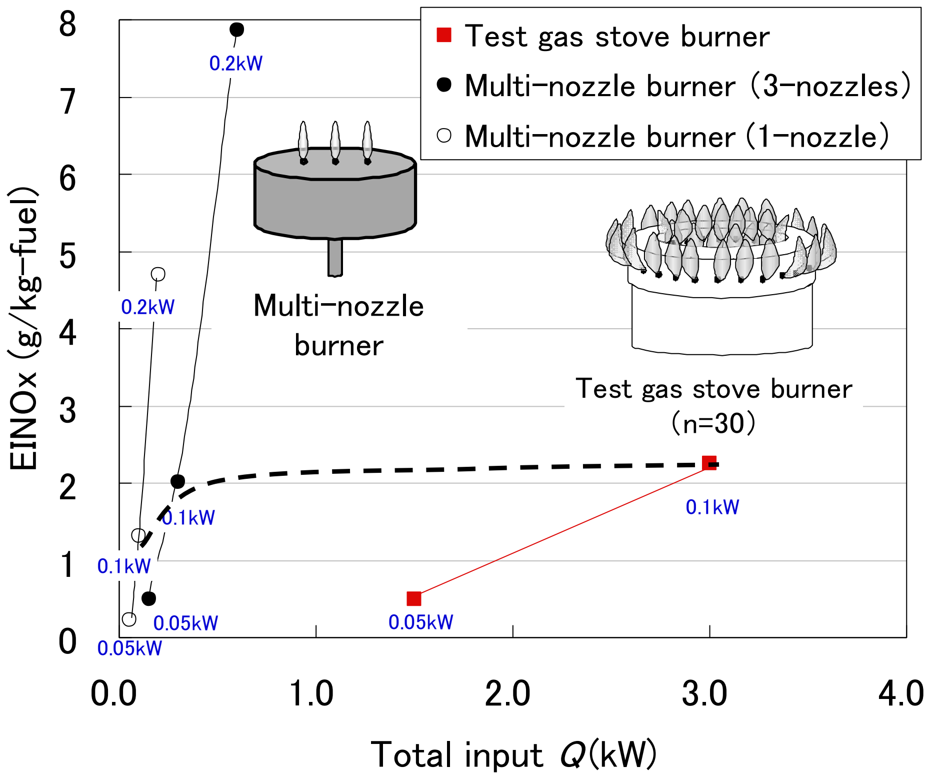


Fig. 11 EINOx in hydrogen flames (*n*=1, 3, 30); Data labels indicates input per nozzle *Q/n*

4. Summary

- NOx emission and luminous characteristics of hydrogen flames were investigated and compared with those of methane flames.
- NOx emissions from hydrogen flames increased with increasing fuel input although NOx emissions from methane flames were almost constant to fuel input.
- Splitting flame is an effective method to decrease NOx emissions from hydrogen flames.
- The larger nozzle-interval made it possible to generate less NOx.
- When the nozzle diameters were 1.2 mm and the fuel input per nozzle was less than 0.1 kW, 20 to 25 mm nozzle-interval was required to minimize NOx generation,
- Addition of methane to hydrogen flames gave little changes in luminous intensities when the fraction of methane was less than 50 cal%.
- A trial gas stove burner for residential sector was built and EINOx was 2.3 g/kg-fuel.

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