EFFECT OF FLOW SPEED ON IGNITION CHARACTERISTICS OF HYDROGEN/AIR MIXTURES

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ABSTRACT

A fuel cell vehicle has a purging system for exhausting contaminated hydrogen gas. Notwithstanding the allowable hydrogen emissions levels in the purging system are regulated by the GTR, a further research on the safety requirement of emissions concentrations is therefore needed for the vehicle design into a more rational system. In the present study, the effects of flow speed, concentration, humidity on ignition characteristics of hydrogen/air mixtures were experimentally investigated. The results demonstrate that the value of Lower Flammable Limit increased with an increase in the velocity of hydrogen/air mixtures and slightly increased with a decrease in oxygen concentration.

1. INTRODUCTION

In fuel cell vehicles (FCVs), hydrogen gas purging is performed in order to discharge hydrogen gas containing impurities accumulated in the fuel cells to the outside of the vehicle. The hydrogen concentration in the purge gas is specified in the HFCV-GTR Phase 1 (GTR No. 13) [1] for the safety, and the maximum allowable hydrogen concentration of purged gas to be 4 Vol% on 3-second average and 8 Vol% at any time. This is based on the results of ignition tests [2] under continuous flow of hydrogen/air premixtures simulating the exhaust pipe of the FCV. However, the hydrogen gas purge in an actual FCV differs from the conditions of the simulated experiment in some respects. For example, in the simulated experiment, the air used to dilute the hydrogen gas was the air in the atmosphere, but the purge gas in the actual FCV is a humid environment with a lower oxygen concentration and more water vapor than the oxygen concentration in the atmosphere because the oxygen is consumed by the polymer electrolyte fuel cell (PEFC). In addition, the simulated experiment was evaluated under the condition that a constant hydrogen/air premixtures were continuously discharged, but in the actual purging of FCVs, hydrogen was mixed singularly during air discharge and purged. Therefore, it is assumed that the combustion characteristics such as the lower flammable limit (LFL) and the flame holding limit (FHL) are different due to the effect of oxygen concentration and humidity during hydrogen purging. In this study, the combustion characteristics of FCVs under exhaust conditions were investigated with the aim of contributing data for the rationalization of vehicle systems.

2. EXPERIMENTS

The combustion characteristics of hydrogen/air mixtures under continuous purging were investigated to understand the lower flammable limit, flame holding limit, and flashback limit with the parameters of premixture concentration, discharge flow velocity, oxygen concentration, and humidity. The schematic of experimental apparatus is shown in Fig. 1. The experimental apparatus consisted of a 1/2-inch pipe from the gas cylinders, a 1-inch pipe for mixing the hydrogen and air, and a 2-inch straight pipe. The end of the exhaust port of the purge pipe is a 250 mm stainless pipe (SUS), and the upstream side of the stainless pipe is a 2000 mm colorless transparent polycarbonate pipe (PC). The inner diameter of the tube was 52 mm, which is similar to the diameter of the purge tube of an actual FCV. The hydrogen and air flow rates were controlled by a mass flow controller (MFC). The concentration of the hydrogen/air mixtures was calculated from the ratio of the air and hydrogen gas flow rates and validated by the mass spectrometer. It was confirmed that there was no discrepancy between the calculated and the measured concentration. In the present test, the flow velocity conditions of the hydrogen/air mixtures were set at 0.4, 4, and 16 m/s. These conditions encompass the flow velocity of purge gas in an actual vehicle. To investigate the effect of oxygen concentration on the ignition characteristic, the tests with different oxygen concentration of 10.0 and 20.8 Vol.% were carried out. In addition, the influence of humidity (0 and 99 RH%) on the ignition characteristic was also investigated. For the test with 99 RH% relative humidity, hot water was added to a chamber (300 L) in the air flow line, and water vapor was added by bubbling the air. The relative humidity after the addition of water vapor was measured at the outlet of the exhaust pipe. The ignition operation was performed when the hydrogen/air mixtures were released for more than one minute in order to stabilize flow velocity. The ignition was performed by a DC discharge with a gap length of 3 mm and ignition energy of 30 mJ at the center of the purge tube, 10 mm from the outlet end of the purge tube. When combustion was confirmed, the discharge was stopped. The combustion behavior of the hydrogen/air mixtures was observed afterward. The combustion was determined and captured using an infrared thermal imaging camera. The ignition test was conducted in an indoor test facility (18 m in diameter and 16 m in height) in Japan Automobile Research Institute, which was not affected by wind and weather.

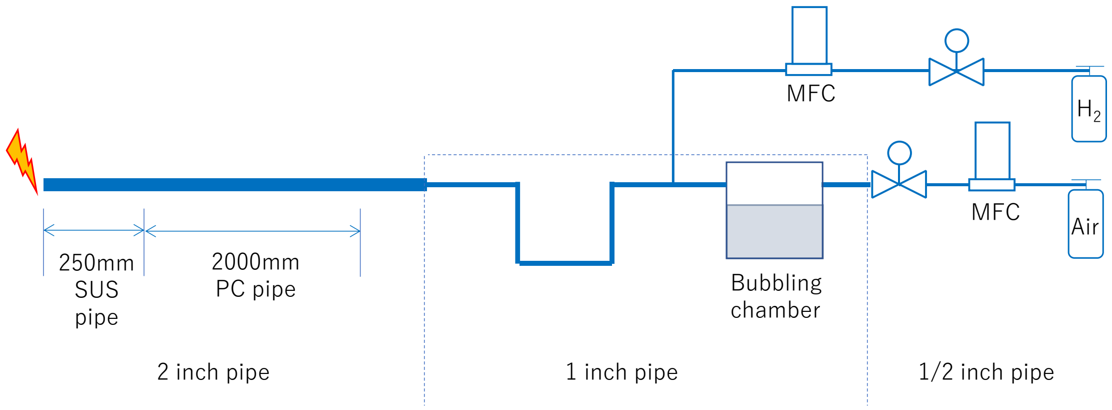

Figure 1. Schematic of purge pipe model

3. EFFECT OF FLOW VELOCITY ON IGNITION CHARACTERISTICS

Infrared thermal images of ignition behavior for hydrogen concentrations of 4.4 vol.%, 7.9 vol.%, and 8.6 vol.% at a flow velocity of 0.4 m/s are shown in Figs. 2, 3 and 4. Combustion characteristics were organized into four categories: No ignition, no flame retention (flame kernel formed but not propagated), flame holdings, and flashback.

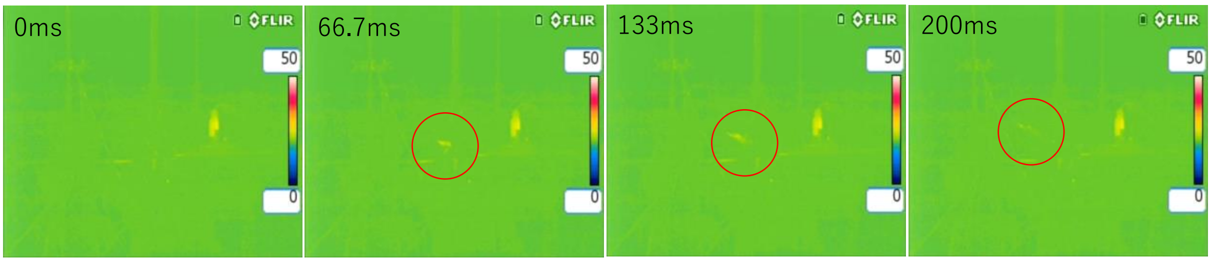

Figure 2. No flame retention（4.4 Vol.%,　Flow velocity : 0.4 m/s）

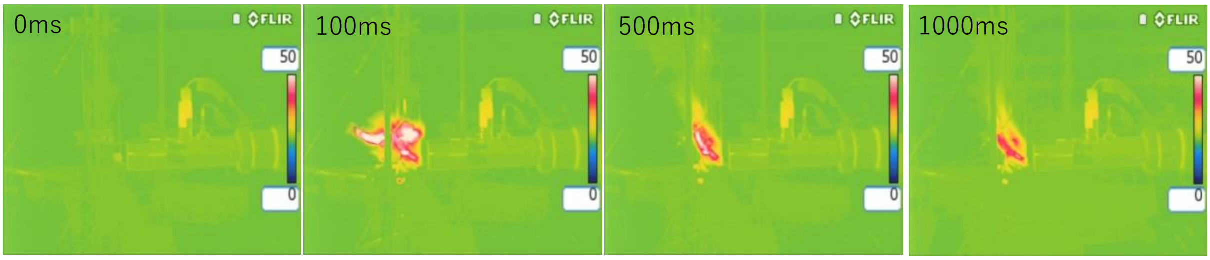

Figure 3. Flame holding（7.9 Vol.%,　Flow velocity : 0.4 m/s）

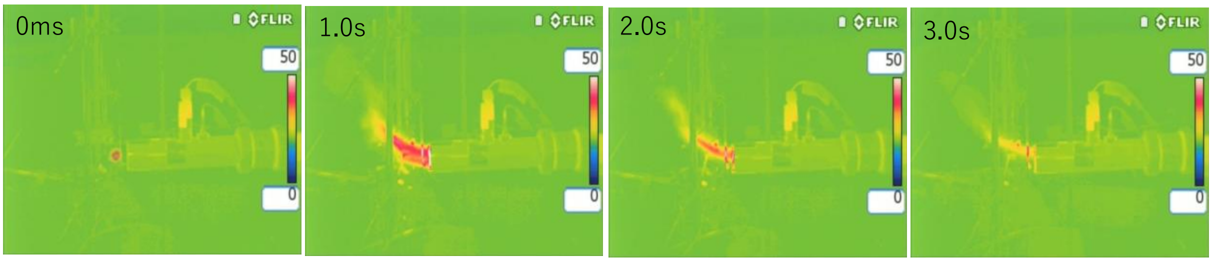

Figure 4. Flashback（8.6 Vol.%,　Flow velocity : 0.4 m/s）

Figure 2 shows that flame kernel was observed near the base of the igniter only during discharge. On the other hand, flame propagation did not occur even though the hydrogen/air mixture of 4.4 vol % was supplied continuously. When the discharge was stopped, the generated flame kernel disappeared. In the present study the concentration corresponding to the observation of flame kernel was defined as a lower flammable limit, notwithstanding the flame was not propagated. As the concentration increased, the combustion occurred after the ignition operation at near the end of the pipe as shown in Fig. 3. After the discharge was stopped, the flame stabilization was captured. As seen in in Fig. 4, the flashback which is defined as the upstream flame propagation back into the pipe was observed with an increase in the hydrogen concentration. This is because the flame speed increases with an increase in the hydrogen concentration. An imbalance in the flame speed and flow velocity causes the flame flashback. The ignition probability as a function of hydrogen concentration for various flow velocities are shown in Figs. 5, 6 and 7. Each ignition probability was calculated by each applicable case divided by the total number of tests. Figure 8 summarizes the results of Figs. 5 to 7.

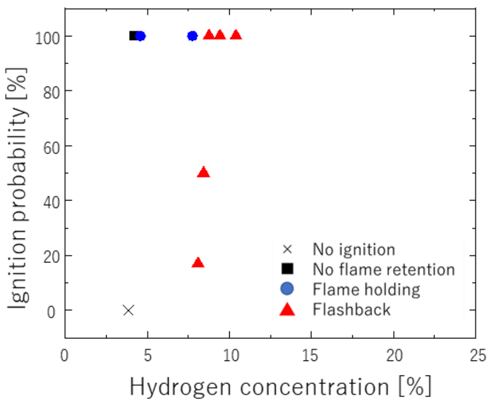

Figure 5. Effect of flow velocity on the ignition probability of the hydrogen/air mixture（0.4m/s）

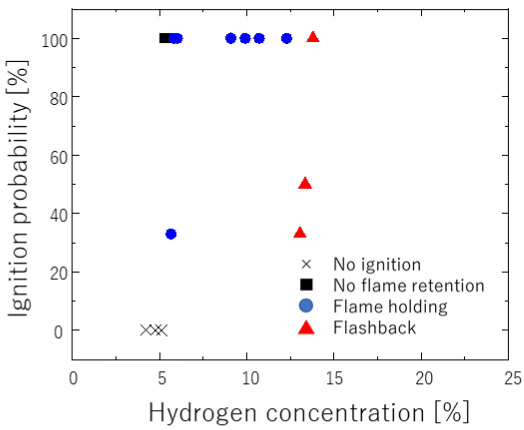

Figure 6. Effect of flow velocity on the ignition probability of the hydrogen/air mixture（4 m/s）

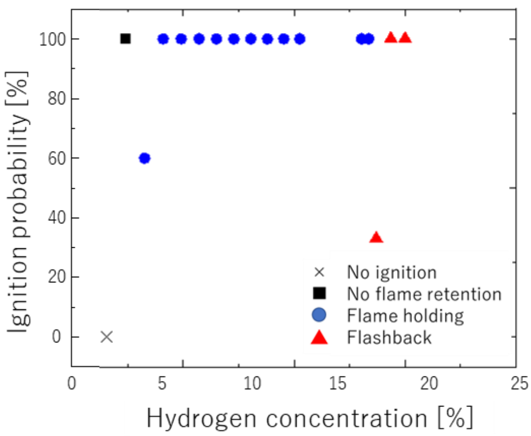

Figure 7. Effect of flow velocity on the ignition probability of the hydrogen/air mixture（16 m/s）

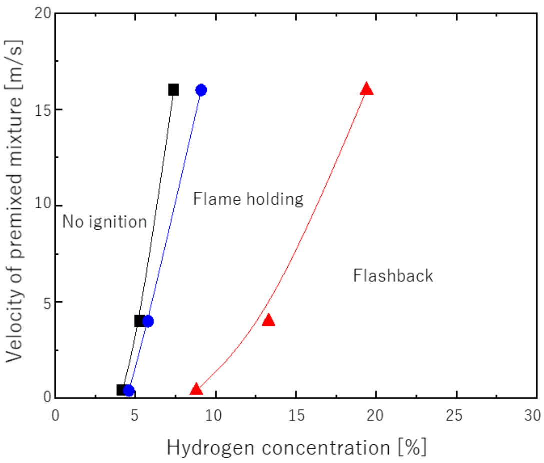

Figure 8. Effect of flow velocity on the ignition characteristics of the hydrogen/air mixture

Table 1. Summary of experimental results

Flow velocity (m/s)	O_2 conc. (vol.%)	Relative humidity (RH%)	Lower limit of hydrogen concentration (Vol.%)		
			No flame retention	Flame holding	Flashback
0.4	20.8	0	4.2	4.6	8.8
4			5.3	5.8	13.3
16			7.4	9.1	19.4
4	10.0		4.2	4.9	9.1
16	20.8	99	4.6	5.7	9.7

The results demonstrated that the lower flammable limit, the limitations of flame holding and flashback shifted toward higher concentrations with the increase in the flow velocity. The lower flammable limit was 4.2 vol.% at the flow velocity of 0.4 m/s. The flame holding at 4.6 vol.% and the flashback at 8.8 vol.%, which was almost consistent with the literature on the ignitability of hydrogen concentration and flow velocity, were observed [3], [4]. As the flow velocity increased to 4, 16 m/s, the value of lower flammable limit and flame holding limitation slightly increased. The limitation of flashback rapidly increased with the increase in flow velocity from 0.4 m/s to 16 m/s. In addition, it is suggested that the results of the literature [2], which was the basis of the HFCV-GTR, were obtained at flow velocities around 15 m/s from Fig. 8. The experimental results are summarized in Table 1.

4. EFFECT OF OXYGEN CONCENTRATION AND HUMIDITY ON IGNITION CHARACTERISTICS

The effects of oxygen concentration on ignition characteristics were investigated experimentally. The ignition probability as a function of hydrogen concentration for 0.4 and 4 m/s are shown in Fig. 9. The values of the limitation for flow velocity of 0.4 m/s were almost constant although the oxygen concentration decreased from 20.8 vol.% to 10.0 vol.%. For flow velocity of 4 m/s, the lower limit of each concentrations shifted to the high concentration as the oxygen concentration decreased. In addition, when the oxygen concentration was 2.0 vol.%, no combustion occurred despite of the increase in the hydrogen concentration as seen in Fig. 10.

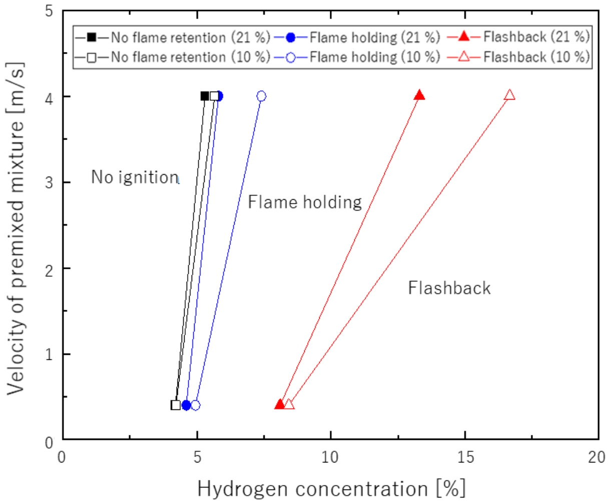

Figure 9. Effect of oxygen concentration on ignition characteristics

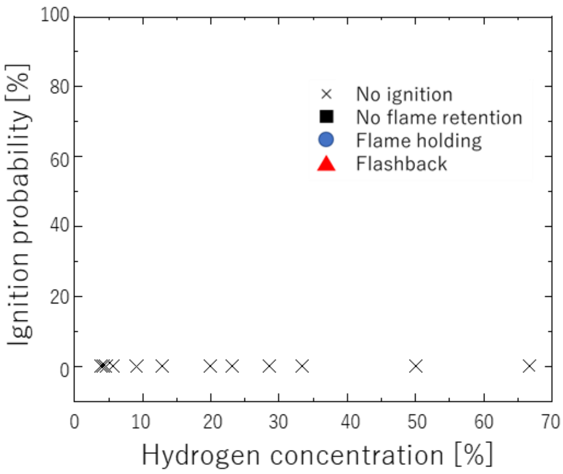

Figure 10. Effect of oxygen concentration of 2.0 vol.% on ignition characteristics at flow velocity of 0.4m/s.

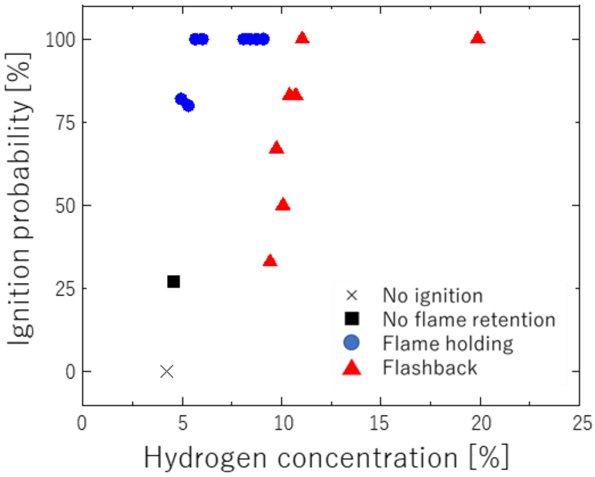

Figure 11. Effect of humidity on ignition characteristics at flow velocity of 0.4m/s and oxygen concentration of 20.8 vol.%.(humidity : 99 RH%))

The influence of humidity on ignition characteristics at flow velocity of 0.4m/s and oxygen concentration of 20.8 vol.% is shown in Fig. 11. Comparing the humidity of 0 RH% and 99 RH%, the concentration of lower flammable limit slightly increased from 4.2 to 4.6 vol.%. In addition, the values of limitation of flame holding and flashback also increased from 4.6 to 5.7 vol.%, and from 8.8 to 9.7 vol.%, respectively. These results of the effect of oxygen concentration and humidity on ignition characteristics also summarized in Table 1. Our data indicate that the lower limit of each concentrations shifted to the high concentration as the humidity increased. Results provide a basis for safety regulation of the purge process of HFCV.

CONCLUSIONS

Combustion characteristics of hydrogen/air mixtures in gaseous flows were investigated in order to contribute data for the rationalization of vehicle systems. As a result, it was found that the lower limit concentrations of flame nucleation, flame holding, and flashback were most affected by the flow velocity, and became higher as the flow velocity increased. It was also found that the oxygen and humidity concentrations also had some influence. In the future, we will compare these results with simulation calculations.

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