STUDY OF HYDROGEN DIFFUSION AND DEFLAGRATION IN A CLOSED SYSTEM

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ABSTRACT

A total of 12 ventilation experiments with various combinations of hydrogen release rates and ventilation speeds were performed in order to study how ventilation speed and release rate effect the hydrogen concentration in a closed system. The experiential facility was constructed out of steel plates and beams in the shape of a rectangular enclosure. The volume of the test facility was about 60m^3. The front face of the enclosure was covered by a plastic film in order to allow visible and infrared cameras to capture images of the flame. The inlet and outlet vents were located on the lower front face and the upper backside panel, respectively. Hydrogen gas was released toward the ceiling from the center of the floor. The hydrogen gas was released at constant rate in each test. The hydrogen release rate ranged from 0.002 m^3/s to 0.02 m^3/s. Ventilation speeds were 0.1, 0.2 and 0.4 m^3/s respectively. Ignition was attempted at the end of the hydrogen release by using multiple continuous spark ignition modules on the ceiling and next to the release point. Time evolution of hydrogen concentration was measured using evacuated sample bottles. Overpressure and impulse inside and outside the facility were also measured. The mixture was ignited by a spark ignition module mounted on the ceiling in eight of eleven tests. In the other three tests, the mixture was ignited by spark ignition modules mounted next to the nozzle. Overpressures generated by the hydrogen deflagration in most of these tests were low and represented a small risk to people or property. The primary risk associated with the hydrogen deflagrations studied in these tests was from the fire. The maximum concentration is proportional to the ratio of the hydrogen release rate to the ventilation speed within the range of parameters tested. Therefore, a required ventilation speed can be estimated from the assumed hydrogen leak rate within the experimental conditions described in this paper.

1.0 INTRODUCTION

A variety of research development and demonstration (RD & D) projects including stationary fuel cells (FC), fuel cell vehicles (FCV) and hydrogen supply infrastructure are being conducted in Japan. In order to ensure safety of these commercial stationary FCs, FCVs, hydrogen stations, and other hydrogen related facilities, it is important to characterize the diffusion and explosion properties of hydrogen by experiments. Deflagration studies of pre-mixed gas and hydrogen releases in open systems and partially confined systems have been performed [1-3]. However hydrogen concentrations tend to be higher in a closed systems under the same release condition. Overpressure caused by the deflagration of hydrogen air mixtures in closed systems can be larger than that in open systems due to confinement. Mechanical ventilation should be used to decrease the hydrogen concentration to levels below the lower flammability limit (LFL) in closed systems. In order to reduce the risk associated with hydrogen use in confined spaces it is necessary to study how ventilation speed and release rate effect the hydrogen concentration in a closed system. In this paper, the hydrogen concentration dependence on release rate and ventilation speed is presented. This work is intended to aid in the estimation of an appropriate ventilation speed for a confined space in which hydrogen is stored or used.

2.0 EXPERIMENTAL FACILITY AND PROCEDURE

The test facility was constructed at SRI International's Corral Hollow Experiment Site (CHES). Figure 1 (a), (b) (c) and (d) show the test facility. The facility has been constructed out of welded steel and was designed to be able to withstand an internal detonation. The dimensions of the facility are 2.72 m high, 3.64 m wide, and 6.10 m long. The volume of the facility is about 60 m^3. As shown in Figure 1 (a), the ventilation exhaust duct measured 0.38 m in diameter and was located on the rear wall. The open end of the facility was covered with a sheet of 0.0076 mm high density polyethylene (HDPE) for the tests. This allowed visible and infrared cameras to capture images of the flame. A ventilation intake hole measuring 1.22 m wide by 0.09 m high and having an area of 0.11 m^2 was cut at the bottom of the plastic sheet. Figure 1 (d) shows the plastic covering the open end of the facility and the ventilation intake hole. The release nozzle was installed on the center of the floor and the hydrogen gas was released toward the ceiling. A constant hydrogen release rate was obtained by using a regulator to control the pressure upstream of a critical flow venturi. The hydrogen release rate was measured using a thermal mass flowmeter. Overpressures from the hydrogen deflagration were measured with four pressure transducers mounted flush on the walls of the facility and six pressure transducers mounted flush on the ground outside the facility. Figure 1 (b) shows the gas sampling stations mounted on the ceiling. Details of gas sampling procedure are described below. Fast-response coaxial thermocouples were used to measure the time-of-arrival (TOA) of flame front in the facility. Seven electronic spark ignition modules located on the ceiling of the garage and next to the release jet were used to ignite the mixture at the end of the 40-minute and 54-minute releases. When activated, the spark ignition module produces 15-millijoule sparks at a 3 Hz to 5 Hz rate. Each module on the ceiling was individually turned on for 5 seconds and then turned off. Five seconds later the next spark module was turned on for five seconds. Five seconds after the last ceiling spark module was turned off, the first spark module next to the release jet was turned on for five seconds. The time interval between activating the spark modules next to the release jet was 1 second. This system was used in order to ensure that there was only a single ignition point. Ignition time was determined from the thermocouple data. A total of 12 experiments with various combinations of hydrogen release rates and ventilation speeds were performed. Table 1 shows the test matrix.

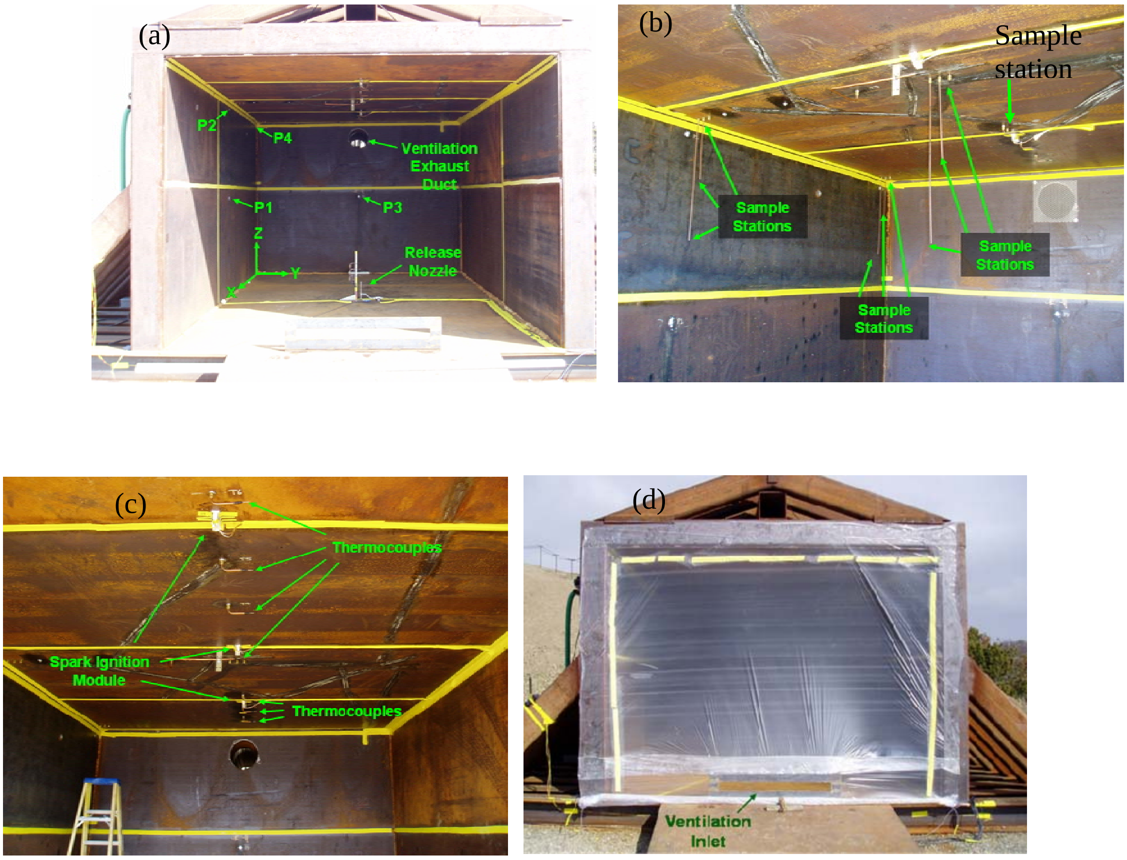

Figure 1. Test facility; (a) Locations of the release nozzle, ventilation duct and pressure transducers (b) gas sampling station layout for Test 16 and Test 17 through Test 26, (c) Thermocouples for TOA measurement and three spark ignition modules on the ceiling, (d) Plastic covering over the open end of the facility.

Table 1. Test Matrix.

Test No	H2 Release Rate (Nm^3/s)	Ignition Time (min)	Ventilation speed (Nm^3/s)
16	0.002	54	0.2
17	0.010	40	0.1
18	0.010	40	0.2
19	0.010	40	0.4
20	0.020	40	0.1
21	0.005	40	0.1
22	0.005	40	0.2
23	0.005	40	0.4
24	0.0150	40	0.1
25	0.0150	40	0.2
26	0.0150	40	0.4

In Test 16, The duration of hydrogen release was 54 min. Gas sampling was performed every 2 minutes in order to obtain the detailed time evolution of hydrogen concentration. The location of the gas sampling point for Test 16 is shown in Figure 1 (b). A schematic that details the time sequence of Test 17 through Test 26 is shown in Figure 2. Prior to the test, the ventilation speed was measured. Then the hydrogen was released at a constant rate. The hydrogen and air mixture near the ceiling was sampled at 3 times and 9 different locations. The spark ignition modules installed on the ceiling were activated for 5 seconds just after the third gas sampling. The time interval between spark ignition modules was 5 seconds for those located on the ceiling. The time interval for the spark ignition modules located next to the nozzle was 1 second. This procedure of timing the spark ignition modules ensures that there is only a single ignition point. The hydrogen gas release was stopped after the last spark ignition module was turned off.

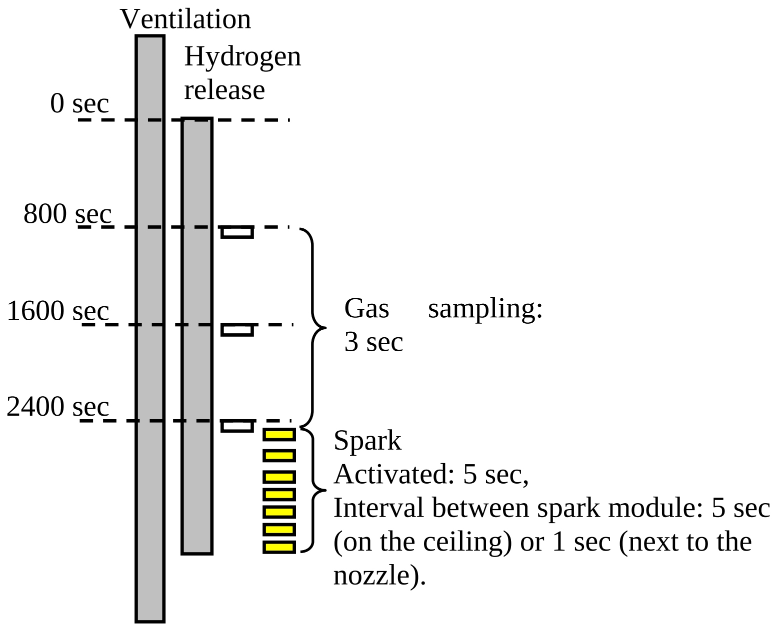

Figure 2. Schematic time sequence for Test 17 through 26. In Test 16, the gas was sampled every 2 minutes; Duration of hydrogen release was 54 min.

The hydrogen concentrations in the test facility were captured during the release prior to ignition by using a gas sampling system. The sampling system is shown in Figure 3(a) and consists of an evacuated one-liter lecture bottle connected through tubing to the sampling port. Remotely operated solenoid valves control the sampling system, and a manual ball valve on the lecture bottle allows it to be removed from the system for analysis. A vacuum pump is connected through valve 2, valve 1 is closed, and valve 3 is opened along with the manual ball valve on the lecture bottle. The lecture bottle and tubing are pumped down to remove the air from the system. Valve 2 is then closed, and the vacuum pump is removed. Figure 3 (b) shows the setup for analysis. The lecture bottle is attached to the manifold. A vacuum pump removes the air from the interconnecting tubing and the chamber that contains the hydrogen sensor. The chamber volume is minimized so that when the manual ball valve is opened on the lecture bottle, the pressure drop will be very small. An absolute pressure piezoresistive sensor records the pressure in the chamber, and this is used to correct the reading obtained from the hydrogen sensor.

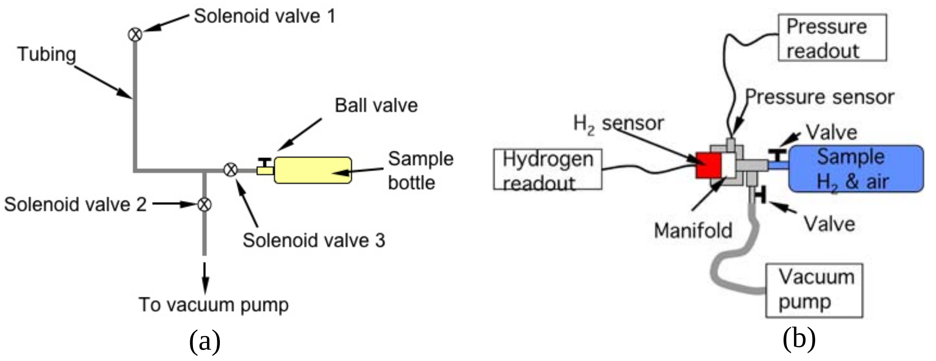

Figure 3. (a) Gas sampling system, (b) measurement of hydrogen concentration in the sample bottle.

Ventilation rates were measured using a hot wire anemometer. The wind velocity profile in the ventilation duct was measured by placing the anemometer at different heights and taking the 10-second average at a given location. Measurements were taken at heights of 1 cm, 5.6 cm, 11.2 cm, 16.8 cm, 22.4 cm, 28.0 cm, and 32.7 cm inside the duct. Figure 4 shows a schematic of the measurement locations. The velocities measured at these locations were then averaged in proportion to the circular area represented by the measurement point in order to obtain the average bulk flow velocity. The anemometer was then placed at the centerline of the ventilation tube, and the data were recorded for at least 10 minutes prior to the test. This centerline velocity was then averaged. The average centerline velocity was then multiplied by the percentage of the bulk average velocity from the profile data. This gave an average bulk flow velocity that was multiplied by the duct's area to obtain an average volumetric flow rate for the ventilation of the facility.

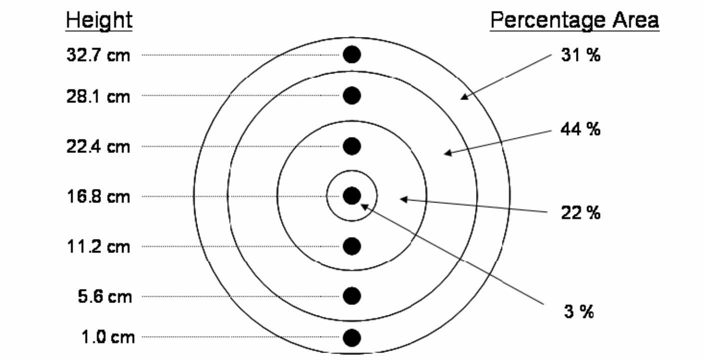

Figure 4. Ventilation duct linear transverse measurement points.

Experimental conditions for the tests are tabulated in the Table 2. Figure 5 shows combinations of the ventilation speed and the hydrogen release rate. The hydrogen release rate was nearly constant for each test. The ventilation speed was relatively constant for each test. The release rate and ventilation speed for Test 16 are shown in Figure 6 (a) and (b) as an example. The ignition time of Test 16 and all other tests were 54 and 40 minutes, respectively. The air temperature, the average wind speed, and the relative humidity for each test were measured by a weather station located at the experimental site.

Table 2. Experimental conditions (measured values).

Test No	H2 Release Rate (Nm^3/s)	Ignition Time (min)	Ventilation speed (Nm^3/s)	Air temperature(°C)	Average wind speed (m/s)	Relative humidity (%)
16	0.0021	54	0.17	12.0	3.6	75.5
17	0.0102	40	0.115	11.8	3.8	48.5
18	0.0103	40	0.19	17.7	2.5	51.5
19	0.0101	40	0.42	16.2	2.2	58.5
20	0.0207	40	0.10	20.8	3.7	30.0
21	0.0051	40	0.10	20.6	3.4	34.0
22	0.0047	40	0.20	17.4	1.6	27.0
23	0.0048	40	0.38	19.5	5.1	10.0
24	0.0152	40	0.10	19.4	1.8	60.5
25	0.0154	40	0.19	11.0	2.7	83.5
26	0.0152	40	0.38	13.4	0.9	60.5

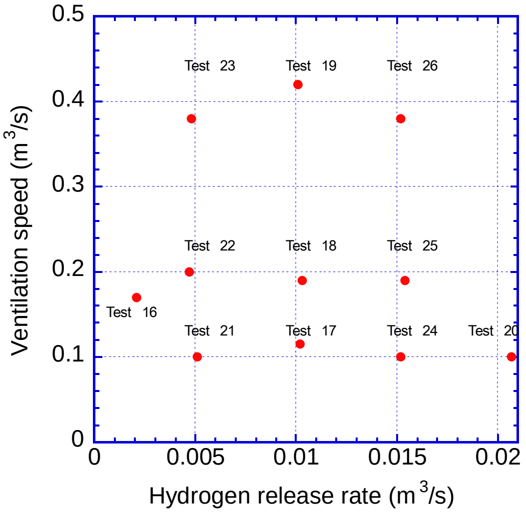

Figure 5. Combinations for the ventilation speed and the hydrogen release rate.

(a) (b)

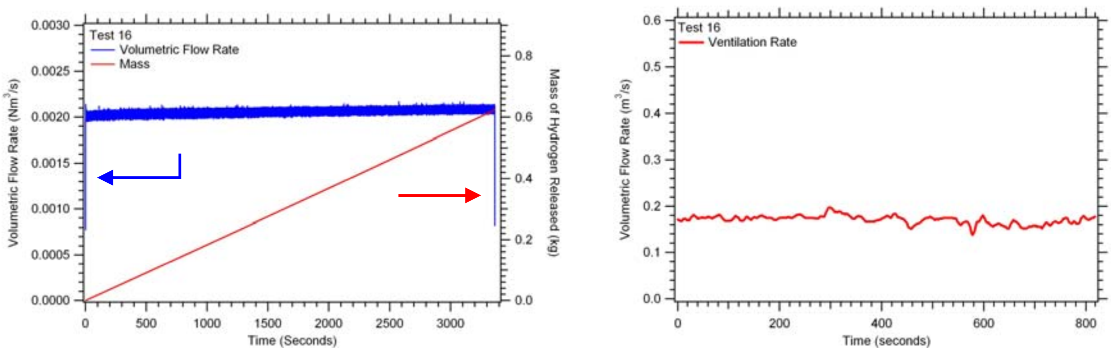

Figure 6. (a) Time evolution of the hydrogen release rate and the mass of hydrogen released (b) the ventilation speed in Test 16.

3.0 RESULTS AND DISCUSSION

Figure 7 shows time evolution of hydrogen concentration near the ceiling (X = 1.70 m, Y = 1.82 m and Z = 2.70 m) in Test 16. As mentioned above, the time interval between gas sampling was every 2 minutes to obtain a detailed time evolution of the hydrogen concentration. The objective of this test was to determine when the hydrogen concentration became almost constant in order to decide the release duration in the following tests. The hydrogen concentration reached about 1.5% at 4 minutes. Although the data are somewhat scattered, the hydrogen concentration seems to increase very slightly until 30 min. Based on this result, a release duration of 40 min was chosen for Test 17 through Test 26.

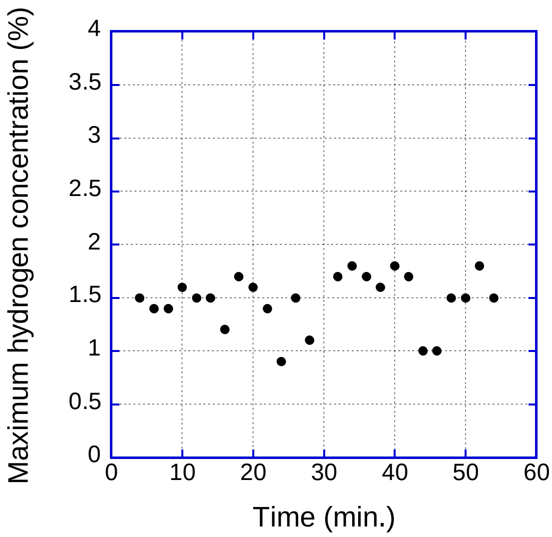

Figure 7. Time evolution of hydrogen concentration near the ceiling in test 16. The hydrogen release rate and ventilation speed were 0.002 and 0.2m^3/s, respectively.

Figure 8 shows the overpressure and impulse from pressure transducer P3 for Test 20 where the highest hydrogen concentration was measured. The hydrogen-air mixture was ignited by spark ignition module 1 located on the ceiling (X = 4.596 m, Y = 1.824 m and Z = 2.68 m). A pressure pulse was generated when the hydrogen-air mixture ignited on the ceiling. The highest overpressure and impulse occurred during Test 20 where the maxium overpressure was measured to be 0.77 kPa and the peak impules was 110 Pa-sec. The flame speed estimated from the TOA data was the highest of all tests and accelerated from 9.6 m/s to 13.7 m/s in this test.

The maximum hydrogen concentrations measured in Test 16 through Test 26 are summarized in Table 3 (a). For the same ventilation rate, the hydrogen concentration increases with the release rate and the hydrogen concentration tends to decrease as the ventilation speed increases for the same hydrogen release rate. Table 3 (b) shows the maximum overpressures from Test 16 through Test 26. The lower detection limit of the pressure transducer used in these tests is approximately 0.02 kPa. Measurable overpressures were generated in Test 20 and Test 24 when the mixture was ignited by a spark ignition module mounted on the ceiling. When the gas mixture was ignited by a spark ignition module located next to the release jet a measurable overpressure was generated because the flame rapidly propagates into the turbulent release jet. However, overpressures measured in most of these tests were very low and represented a small risk to people or property. Only Test 20, with a release rate of 0.0207 Nm^3/s and a ventilation rate of 0.1 m^3/s, generated a significant overpressure (0.77 kPa). The primary risk asosheated with these hydrogen releases was the hydrogen fire.

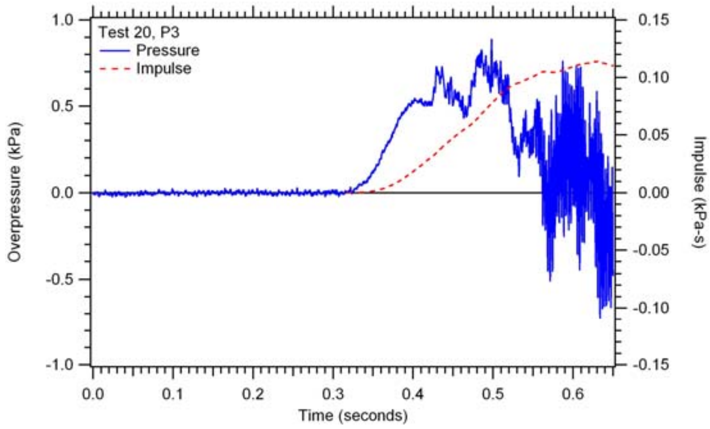

Figure 8. Overpressure and impulse from P3 for Test 20.

Table 3. (a) Maximum hydrogen concentration in Test 16 through Test 26

Maximum hydrogen concentration (%)		Hydrogen release rate(m^3/s)				
		0.002	0.005	0.01	0.015	0.02
Ventilation speed (m^3/s)	0.1		5.2	8.6	13.1	18.8
	0.2	1.8	3.6	7.2	8.6	
	0.4		4.0	7.2	7.3	

Table 3. (b) Maximum overpressure in Test 16 through Test 26 in the case that the mixture was ignited by the module mounted on the ceiling.

Maximum overpressure(kPa)		Hydrogen release rate(m^3/s)				
		0.002	0.005	0.01	0.015	0.02
Ventilation speed (m^3/s)	0.1		<0.02*	<0.02*	0.053	0.77
	0.2	0.051**	0.056**	<0.02*	0.041	
	0.4		0.069**	<0.02*	<0.02	

* Lower detection limit: 0.02kPa
** Mixture was ignited by spark ignition modules mounted next to the nozzles. Others were ignited by the spark ignition modules mounted on the ceiling.

Figure 9 shows the correlation between the ratio of the hydrogen release rate to ventilation speed and the maximum hydrogen concentration. The maximum hydrogen concentration denotes the highest concentration among the sample stations in one test. As shown in Figure 6 the maximum concentration is proportional to the ratio of the hydrogen release rate and the ventilation speed within the range of parameters tested in the present study, though the data are slightly scattered. Therefore a required ventilation speed can be estimated from the assumed hydrogen leak rate within the present experimental conditions. Further experiments in closed systems are necessary varying parameters, such as volume, the direction of the nozzle, and location of the duct for ventilation since the experimental conditions applied in the present study were relatively simple.

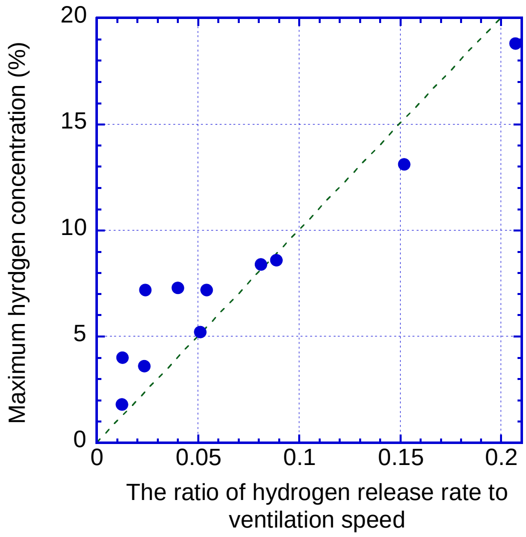

Figure 9. Correlation between the ratio of the release rate to ventilation and the maximum hydrogen concentration.

SUMMARY

Experiments were performed to study how the ventilation speed and the release rate effect the hydrogen concentration in a closed system. Various combinations of hydrogen release rates and ventilation speeds were explored in a test facility made from steel. The hydrogen release rate ranged from 0.002 m^3/s to 0.02 m^3/s. The ventilation speed varied from 0.1 m^3/s to 0.4 m^3/s. The volume of the facility was about 60 m^3. The release nozzle was vertically oriented at the center of the floor in the facility. Spark ignition modules to ignite the mixture were mounted on the ceiling and next to the nozzle. Hydrogen concentrations were measured using a system of evacuated lecture bottles. Overpressures generated by the hydrogen deflagration were measured inside and the outside of the facility. The mixture was ignited at the ceiling for eight out of eleven tests. In the other three tests, the mixture was ignited by spark ignition modules mounted next to the nozzle. Overpressures measured in all but one of these tests were very low and represented a small risk to people and property. The main risk from the hydrogen deflagrations studied in these tests was from the fire. The maximum concentration inside the enclosure was proportional to the ratio of the hydrogen release rate and the ventilation speed within the range of parameters tested. Therefore a required ventilation speed can be estimated from the assumed hydrogen leak rate within the experimental conditions described in this paper.

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