

Combustion Behavior of Leaking Hydrogen and Effects of Ceiling Variations

2011-01-0254

Published
04/12/2011

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doi:10.4271/2011-01-0254

ABSTRACT

Hydrogen concentration during combustion in a confined space with a ceiling was investigated. The results indicated that steady-state hydrogen concentration was highest at the ceiling surface for all hydrogen flow rates. When hydrogen concentration was 10-20%, weak flame propagation occurred at the ceiling surface, with the most easily burnable spots being dented areas such as seams, pores and creases on the ceiling surface. The unstable and limited nature of flame propagation at the ceiling surface was attributed to the relationship between temperature and hydrogen concentration in a confined space.

INTRODUCTION

In confined spaces with a ceiling, such as the passenger and engine compartments of motor vehicles, leaking hydrogen tends to gather near the ceiling because hydrogen gas is lighter than air⁽¹⁾. If the ceiling is made of textured plastic or other fabric material, leaking hydrogen may penetrate into the inner pores of these ceilings. For fire safety purposes, therefore, it is necessary to examine the combustion behavior of leaking hydrogen in the event of ignition in a confined space.

For the evaluation of structural safety in preventing hydrogen buildup, we previously studied the diffusion and ignition of leaking hydrogen inside passenger and engine compartments⁽¹⁾⁽²⁾. The tests resulted in the observation of

two distinct types of combustion behavior at the ceiling surface as summarized in (A) and (B) below.

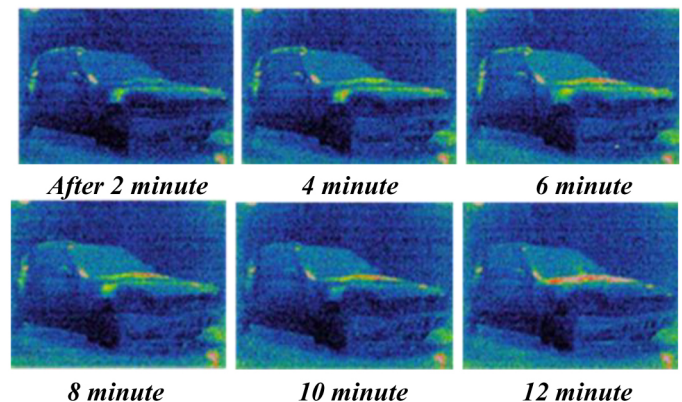


Figure 1. Combustion in engine compartment after ignition (IR images taken diagonally forward from vehicle)

(A). In the first test, hydrogen was discharged upward at a flow rate of 131 NL/min from a nozzle (4 mm inner diameter) located on the floor of the passenger compartment and at a point 0.5 m rearward from the center of the overall vehicle length. Attached to the center area of the engine compartment ceiling were a hydrogen densitometer and an igniter that was set to generate sparks when the hydrogen concentration reached 14%. Test results: Since no combustion of leaking hydrogen was observed for 200 s after ignition, this test was stopped temporarily. Several minutes

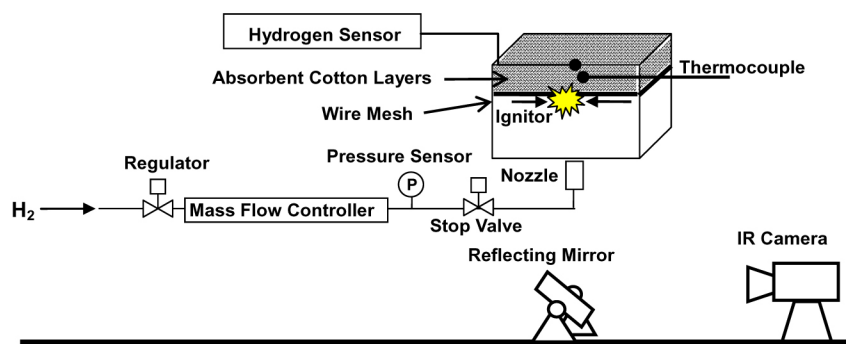


Figure 2. Schematic of test setup

later, however, the felt material in the center area of the ceiling of the engine compartment began to smolder (see Figure 1) whereupon the smoldering fire was extinguished. Specifically, burns were found around the opening made in the felt material in order to attach the igniter.

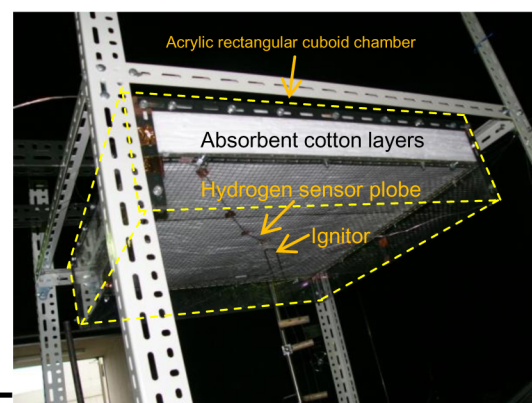
(B). In the second test, hydrogen was discharged upward at 10 NL/min from a nozzle (4 mm inner diameter) located on the floor of the passenger compartment. As soon as the hydrogen concentration reached 13%, hydrogen supply was stopped and the igniter attached to the ceiling was activated to generate sparks. After ignition, surface flash occurred and flames propagated over the ceiling surface but quickly self-extinguished. Minutes later, however, infrared (“IR”) thermography revealed a rise in ceiling temperature and the ceiling material began to smolder. Examination after putting out the fire indicated that the smoldering had taken place along the edge of the felt material where the ceiling light had been removed in order to affix a measuring instrument.

Assuming that the above combustion behaviors (A) and (B) were associated with the penetration of hydrogen into the inner pores of the fabric ceiling, the present test on leaking hydrogen was carried out using a test chamber with an open bottom and a ceiling made of absorbent cotton. The test method and results are described below in terms of hydrogen concentration, ignition and combustion behavior.

TEST METHOD

Figure 2 shows a schematic of the test setup. An acrylic rectangular cuboid chamber (W800 × D800 × H200 mm) with an open bottom was employed. A mass flow controller was interposed to control the hydrogen discharge through a nozzle (4 mm inner diameter) from the bottom to the interior of the chamber. The nozzle position was 500 mm below the center of the chamber ceiling. Three different hydrogen flow rates (10, 50, 100 NL/min) were applied.

As a porous combustible ceiling, layers of absorbent cotton (Japanese Pharmacopoeia: refined cotton W560 × D470 × $t \approx 7$ mm) were used at three thickness variations - 50, 100, and 0



mm (no cotton or ceiling). For a thickness of 50 mm, eight layers of cotton were piled together for a total weight of 1,100 g. For 100 mm in thickness, 15 layers were stacked for a total weight of 2,060 g. The bottom of the cotton ceiling was supported by stainless steel netting with 2.5-inch mesh size.

Figure 3 below shows the points in the chamber where hydrogen concentration was measured in the present test:

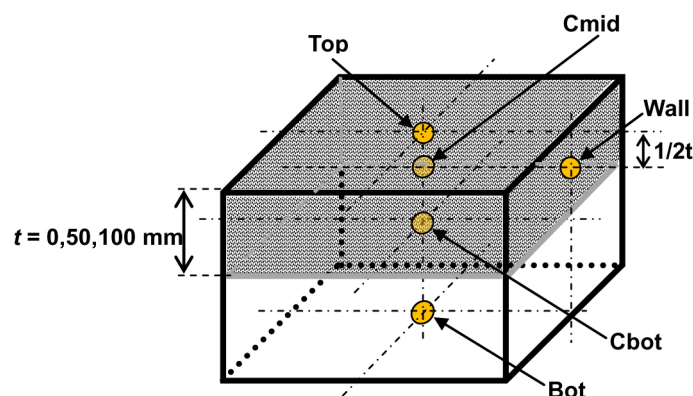


Figure 3. Hydrogen concentration measurement points

“Top” represents the center of the chamber upper surface; “Cmid” the center of the cotton block; “Cbot” the center of the ceiling surface; “Bot” the center of the chamber bottom; and “Wall” is located at 1/2 the ceiling thickness or equal to Cmid in height. In the absence of cotton layers ($t = 0$) or with no ceiling, measurement points Cmid and Wall were set at 100 mm below the chamber upper surface while no measurement was made at Cbot. Measurement was performed using one of two types of hydrogen concentration meters according to the characteristics of concentration variation. Where the variation in hydrogen concentration would be gradual, a hydrogen sensor based on thermal conductivity (New Cosmos Electric Co. Ltd. XP-314) was employed. Where the variation would be rapid, immediately after ignition, highly responsive and sensitive hydrogen ion

sensors⁽³⁾ (Nohmi Bosai Ltd. HX07i, 20 ml/min suction) were used. In both cases, probes were installed at the measurement points. The response lag due to differences in capillary length had been compensated by actual measurement conducted before the test.

For Top, Cmid, Wall and Cbot points, all of which are located within the test chamber, hydrogen supply was terminated after the concentration had stopped increasing and reached a constant level at all these points; then, the hydrogen gas inside the chamber was ignited by sparks using the igniter located at point Cbot at the center of the cotton ceiling surface.

Combustion behavior was recorded by a CCD camera and an IR camera (including a mirror to observe the chamber bottom area). For temperature measurement, an exposed K-type thermocouple with wire diameter of 0.1 mm was employed and was synchronized with the hydrogen densitometer by an external trigger.

The test was performed in the explosion-resistant fire testing facility of the Japan Automobile Research Institute, Inc., which is immune to the effects of rain, wind and other weather conditions.

TEST RESULTS

HYDROGEN CONCENTRATION

Figure 4 below shows the test results on hydrogen concentration at the various measurement points in relation to time:

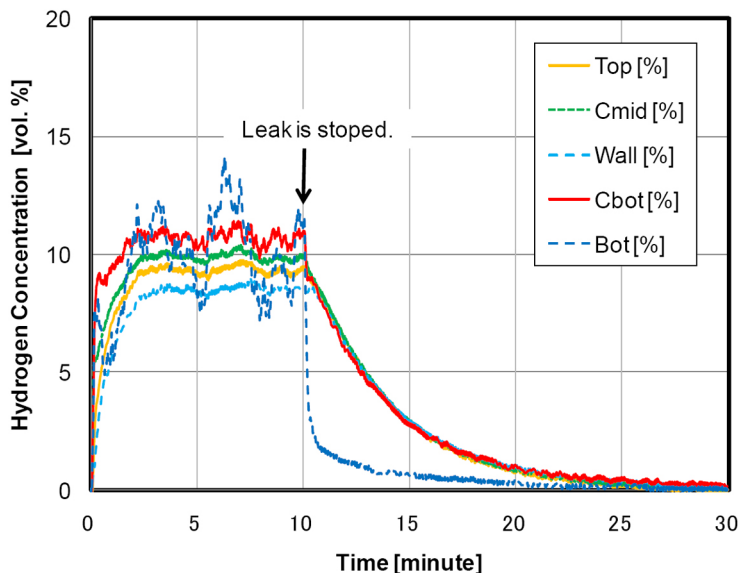
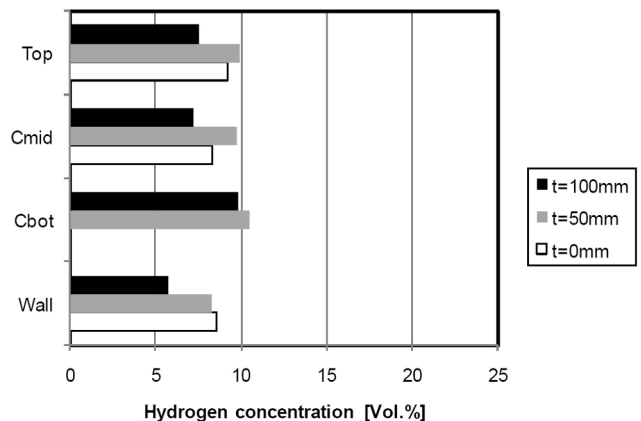


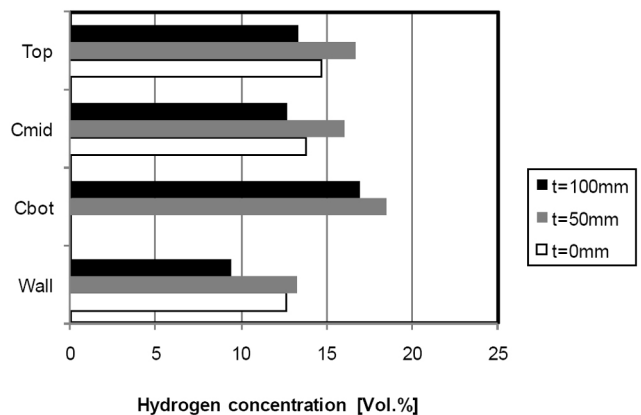
Figure 4. Hydrogen concentration in relation to time
(Hydrogen flow rate = 50 NL/min; $t = 50$ mm)

Upon supply of hydrogen, the concentration at Top, Cmid, Wall and Cbot points steadily increased and then became practically constant as the quantity of hydrogen inflow and outflow to/from the chamber was balanced. In contrast, hydrogen concentration did not become constant at Bot on the chamber bottom where the inner and outer gases bordered on one another. When the hydrogen supply was stopped, the concentration plummeted rapidly at Bot but declined slowly at the other points within the chamber.

Figure 5(a)-(c) shows the measured values of steady-state hydrogen concentration at Top, Cmid, Wall and Cbot for the three hydrogen flow rates of 10, 50 and 100 NL/min.



a). Hydrogen flow rate = 10 NL/min



b). Hydrogen flow rate = 50 NL/min

Figure 5. Hydrogen concentration at constant level