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Study on the Fire Response of Vehicles with Compressed Hydrogen Cylinders

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Abstract

To investigate the events that could arise when fighting fires in vehicles with compressed hydrogen CFRP (carbon fiber reinforced plastic) composite cylinders, we conducted experiments to examine whether a hydrogen jet flame caused by the activation of the pressure relief device (PRD) can extinguished and how spraying water influences the cylinder and PRD. The experiments clarified that the hydrogen jet flame cannot be extinguished easily with water or dry powder extinguishers and that spraying water during activation of the PRD may result in closure of the PRD, but is useful for maintaining the strength of CFRP composite cylinders for vehicles.

1 Introduction

For gas fires in common buildings, the compressed industrial cylinders are cooled by spraying water to prevent rupture of the vessel due to the heat of fire [1]. However, the vessels used in facilities are made of steel, and there have been no reports on whether the measures used for steel cylinders can also be applied to CFRP storage cylinders that are now being used on vehicles.

On the other hand, according to the emergency response guide of the compressed hydrogen fuelled vehicle [2], water should not be sprayed on the vent section of the jet flame because of the risk of explosion when the hydrogen jet diffusion flame is extinguished.

This paper reports experiments that evaluate what risks may be present if firefighters spray water on burning composite cylinders and extinguish the jet flame. This information can be used to re-evaluate common guidance that firefighters do not extinguish fire involving onboard gaseous storage.

2 Extinguishment Test of Hydrogen Jet Flame

We investigated whether the hydrogen jet flame can be extinguished with water spray or powder quenching.

2.1 Test method

Figure 1 schematically depicts the test apparatus.

Hydrogen gas supplied from the vessel (15 MPa, 47 Liters) blows out into the atmosphere through the vent port (blowout aperture: 4.2 mm), simulating a gas emission hole in the event of PRD activation, and is ignited by an electric spark. The spraying water or a dry powder extinguishing agent (ABC fire extinguishing agent for automobiles) was aimed directly at the vent port. A water-spray nozzle with a maximum water discharge volume of 500 $L/min \cdot m^2$

and a 2 inch nominal diameter was used for extinction with water spray. A vehicle fire simulator was tested on asphalt pavement by connecting vent tubes to it.

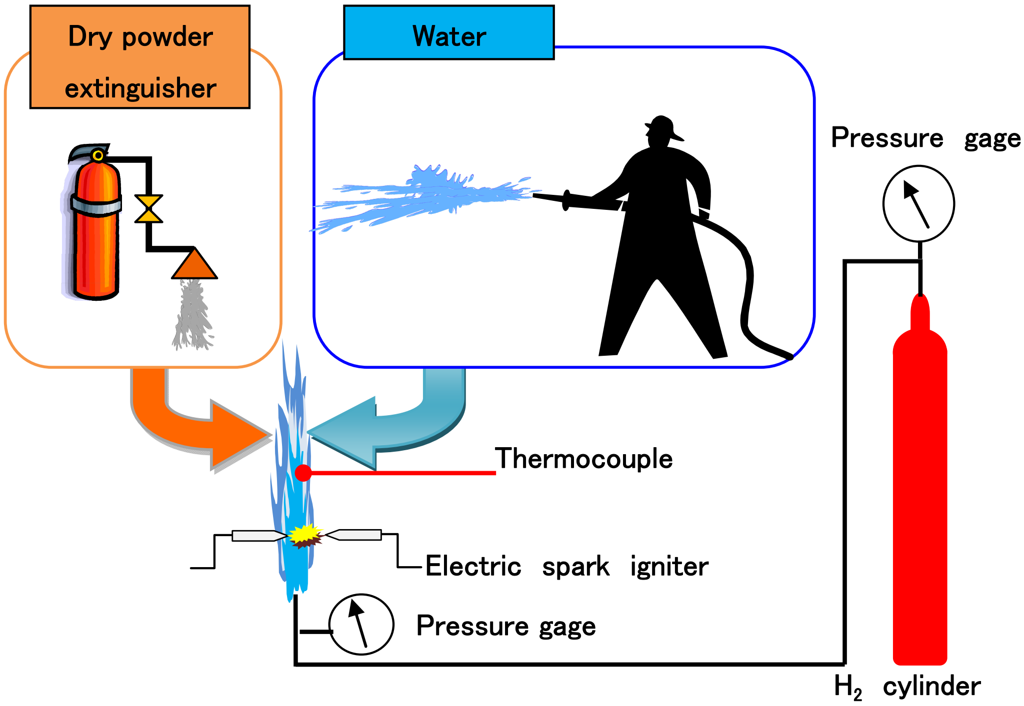


Figure 1: Schematic of test system.

Two directions of vent port were used: upward and inclined downward by 45°. The vent port directed upward was installed at the centre of the rear portion of the roof of the vehicle simulator, and that inclined downward was installed under the floor near the rear-wheel shaft of the vehicle.

The fire fighting was executed from forward or the rear side of the vehicle within the range from 1 to 5 meters.

Whether the flame was extinguished or not was determined by a thermocouple and infrared thermography.

2.2 Results

Figure 2 depicts an example of testing, and Table 1 presents the test results.

In the case of upward hydrogen discharge under the conditions shown in Table 1, it was not possible to extinguish the hydrogen jet flame by water spray or powder quenching at the vent port. Similarly the hydrogen jet flame was not easily extinguished in the case of 45° downward hydrogen discharge; however, extinction was observed in Test #4 when the blowout pressure from the vent port declined to 0.9 MPa. At a blowout pressure level of 0.9 MPa, the flame length was less than 50 cm while for a hydrogen storage cylinder of up to 50 litres capacity the blowout pressure would further drop to zero within a minute. In Tests #7 and #8, the hydrogen jet flame was extinguished at a blowout pressure of 0.3 and 0.2 MPa respectively; then, reignition occurred seconds after extinction due to the heated asphalt. In the vehicle fire simulator experiment, however, reignition even when it occurred did not cause any harmful events such as an explosion because the experiment was conducted on an open-air site with no enclosed spaces for hydrogen to gather.

These results suggest that the hydrogen jet flame generated by activation of the PRD of an actual vehicle cannot be easily extinguished by water spray or powder quenching; however, after once being extinguished, reignition at a low exhaust pressure is not harmful.

(a) Test 1, Upward vent, Water

(b) Test 7, 45 deg. diagonal backward vent, dry powder extinguisher

Figure 2: Bonfire test scene.

Table 1: Results of hydrogen jet flame extinguishing test.

#	Venting direction	Extingusher (Orientation)	Results
#1	Upward	Water (Forward side of the vehicle)	Non-extinguished
#2		↓	
#3	↓	Dry powder extinguisher (Rear side of the vehicle)	↓
#4	45 degree diagonal backward	Water (Forward side of the vehicle)	Extinguished at the vent pressure 0.9MPa.
#5		↓	Non-extinguished
#6		Water (Rear side of the vehicle)	↓
#7		Dry powder extinguisher (Rear side of the vehicle)	Extinguished at vent pressure 0.3MPa. Reignition by the hot asphalt. No-explosion.
#8	↓	↓	Extinguished at vent pressure 0.2MPa. Reignition by the hot asphalt. No-explosion.

3 Influences of Water Spray in Fighting Fire around the Cylinder and PRD

We investigated the events that occur in the cylinder and PRD when they are heated by fire and then cooled by water spray, as well as the influences of water spray on the strength of the cylinder.

3.1 Test method

Figure 3 schematically depicts the test process for observing the cylinders and PRD after being heated by fire and then sprayed with water and evaluation of the influences on the strength of cylinders.

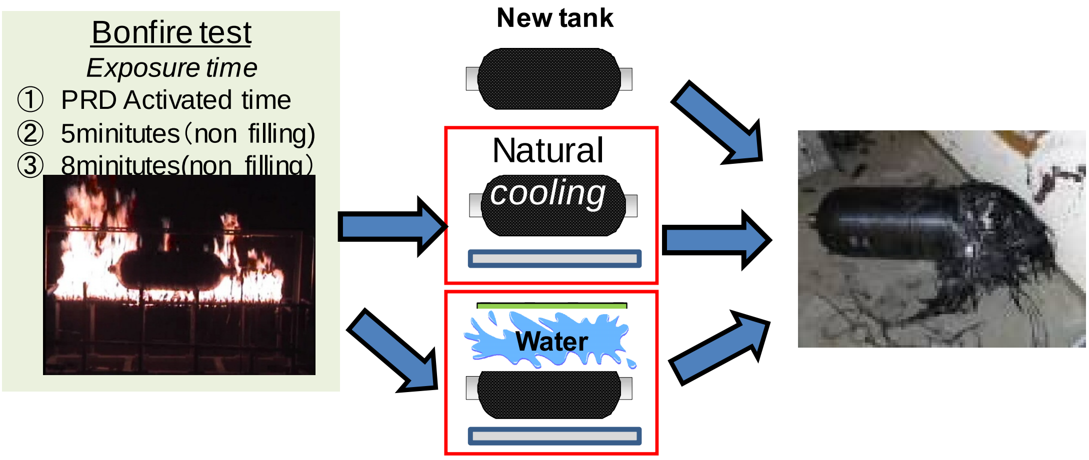


Figure 3: Test process for evaluation on the strength of cylinders.

An aluminum lined carbon fiber wrapped cylinder (Type 3; maximum filling pressure 35 MPa; capacity 39 Litters) was used for the sample cylinder, and tests (sample preparation) were conducted under the following six conditions.

Sample 1

The test cylinder equipped with in-tank solenoid valve was filled with hydrogen gas at 35 MPa. A PRD (activated temperature 105±5ºC) was mounted directly on In-tank valve. The bottom of the cylinder placed on its side was exposed to the flame from a propane burner. The burner was turned off as soon as the PRD operated. Water was then sprayed over the whole cylinder.

Sample 2

A test cylinder without hydrogen was exposed to the flame during the same period as for Sample 1, and then left alone after the burner was turned off.

Samples 3 and 4

The test cylinder without hydrogen was exposed to the flame for 5 min. Sample 3 was cooled by water spray, and Sample 4 was left alone.

Samples 5 and 6

The test cylinder without hydrogen was exposed to the flame for 8 min. Sample 5 was cooled by water spray, and Sample 6 was left alone (natural cooling). It should be noted that when this cylinder was filled with hydrogen at 35 MPa and exposed to the flame with no PRD installed, it ruptured in 416 sec (about 7 min) [3]. Therefore, the strength of the cylinder definitely deteriorates when the cylinder is exposed to the flame for 8 min.

In addition to the above cylinder Samples 1 through 6, cylinders with a history of non-exposure to flame were also tested to measure their withstanding pressures as an indicator of the deterioration of cylinder strength.

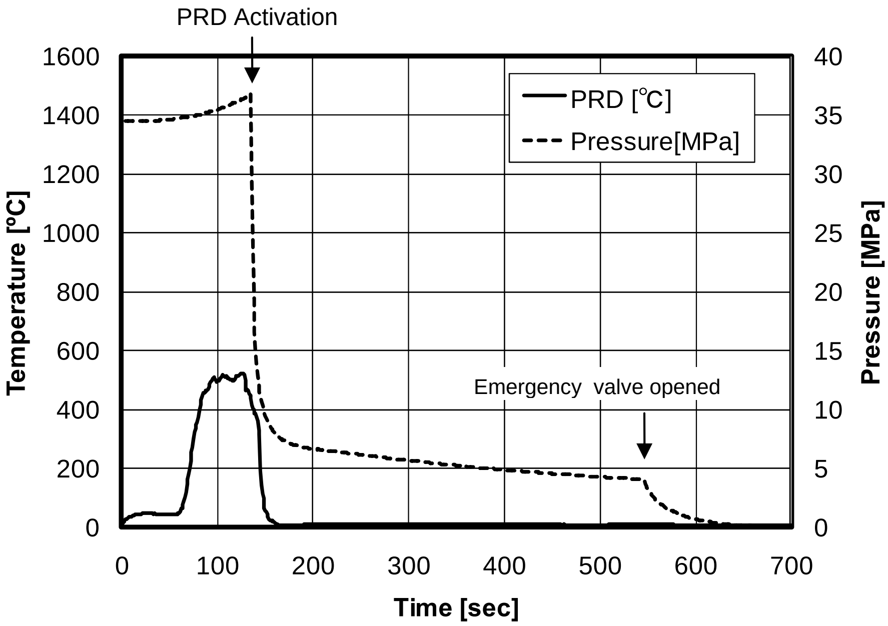
The cylinder prepared under each of these conditions was subjected to the burst tests specified in Japanese Hydrogen Storage Regulations (JARI S-001) [4] to check its burst pressure.

3.2 Test results

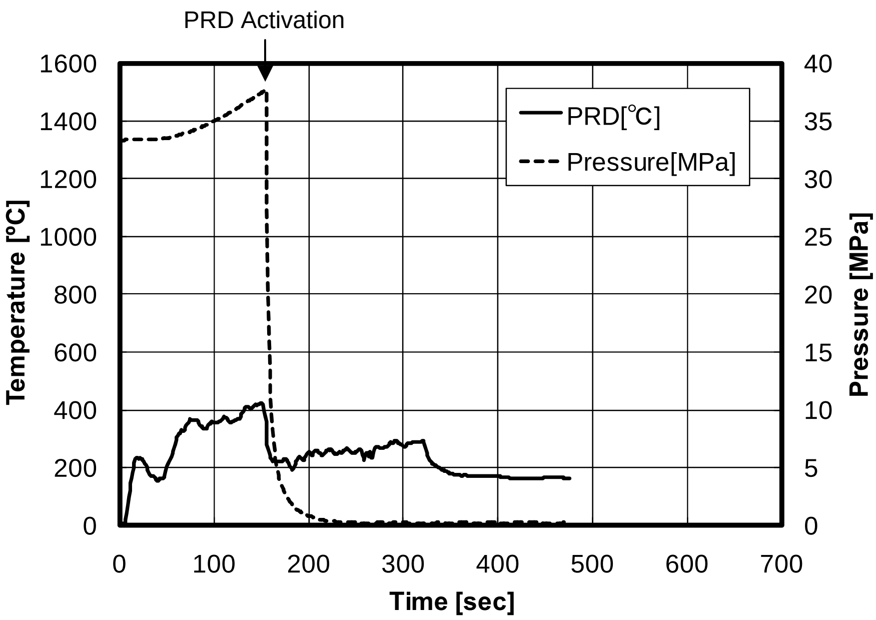
Figure 4(a) depicts the testing situation on Sample 1 when the PRD was activated, and Figure 4 plots the internal pressure of the cylinder and the ambient temperature of the PRD. When the whole cylinder was cooled with water while the PRD was activated, hydrogen was vented for 4 minutes or more. Therefore, to conduct the test safely, the gas in the cylinder was forcibly exhausted by installing a separate emergency vent valve.

Figure 4(b) indicates the internal pressure of the cylinder and the ambient temperature of the PRD of the same cylinder when it was not cooled with water, as had been done previously, for comparison.

Usually, the vent of hydrogen gas ends 1 minute after the PRD is activated. The fusible plug of the PRD, which is composed of a metal with a low melting point, could have resolidified by cooling, resulting in partial closure of the channel for exhausting hydrogen and extending the time for the hydrogen to exhaust. Incidentally, although the current rules do not include any regulation on reclosure of PRDs, PRDs constructed to avoid reclosure have already been developed and put into practical use.



(a) Cooled by water spray after activation of PRD



(b) Natural cooling

Figure 4: Internal pressure and PRD temperature.

Figure 5 depicts the relationship between the duration of flame exposure and the burst pressure in the burst test.

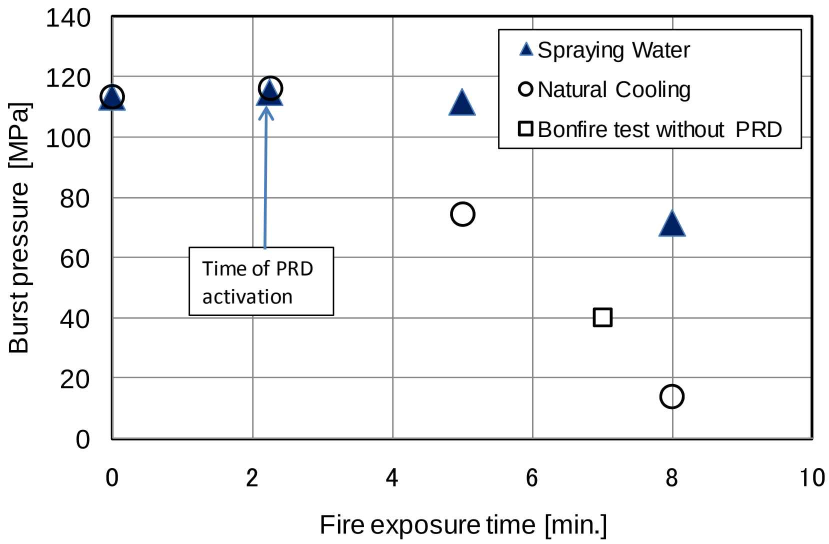


Figure 5: Influence of increase in flame exposure time on burst pressure of cylinders after bonfire tests.

Here, the burst pressure indicated at a flame exposure of 0 min is the withstanding pressure of the test cylinder itself (110.3 to 116.2 MPa). The □ mark shows the burst pressures and burst time of cylinders having no PRD and filled with hydrogen to a 35 MPa internal pressure in bonfire tests [3].

Regardless of whether the cylinder was cooled with water or left alone immediately after flame exposure to flame was stopped till the activation of the PRD (in 2 minutes and 15 seconds), the withstanding pressure of the cylinder was the same as that of the test cylinder itself; therefore, no deterioration in burst resistance strength was observed.

After 5 minutes of exposure to the flame, the burst pressure decreased only when the cylinder was left alone. Furthermore, after 8 minutes exposure to the flame, the burst pressure decreased for both cooling with water and leaving alone; however, the strength of the cylinder was still higher when the fire was extinguished with water spray.

The reason for the difference in cylinder strength between cooling with water and leaving alone when the cylinder was exposed to the flame for 5 minutes or more is considered to be as follows. When this cylinder is exposed to the flame for 5 minutes or more, the cylinder itself burns; thus, combustion continues after the fire source is removed when the cylinder is left alone, and the cylinder remains at a high temperature for a longer time. Combustion of the CFRP compound cylinder itself is caused by heat decomposition of the resin used to bundle carbon fibers. More resin comes off as combustion continues[5], resulting in deterioration of the cylinder; therefore, it can be assumed that the withstanding pressure differed between cooling with water and leaving alone when the cylinder was exposed to the flame for 5 minutes or more. From these results, it was determined that the CFRP compound cylinder is advantageous in terms of strength when self-combustion is prevented by cooling with water rather than letting it cool slowly by leaving it alone.

In addition, the present study indicated that it is also possible to evaluate deterioration of the strength of cylinders by conducting burst tests.

4 Conclusions

To identify problems and to examine and prepare countermeasures for firefighting and rescue activities for fires of vehicles with compressed-hydrogen cylinders, we investigated (1) the possibility of extinguishing the hydrogen jet flame that forms when the PRD activates and (2) the influences of water spray on the cylinder and the PRD for firefighting. We clarified the following:

1. The hydrogen jet flame that is formed when the PRD operates cannot be extinguished easily with water spray or powder quenching.
2. If water spray for firefighting is applied directly on the cylinder or PRD while the PRD is operating, the type of PRD used in this study could reclose.
3. The strength of the CFRP compound cylinder is better maintained when water spray is used for firefighting. These results suggest that neither a large explosion nor deterioration of the strength of the cylinder is caused by extinction of the jet flame in an open space if the vehicle is equipped with a PRD that does not reclose upon fire extinction with water spray.

Many issues remain unexplored. It has not been determined whether the cylinder remains filled with hydrogen gas after the fire has been extinguished; if it does, it is not known how to dispose safely of such a cylinder. Therefore, it is necessary to examine and develop measures for such cases.

Acknowledgements

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