THE PRESSURE PEAKING PHENOMENON: VALIDATION FOR UNIGNITED RELEASES IN LABORATORY-SCALE ENCLOSURE

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ABSTRACT

This study is aimed at the validation of the pressure peaking phenomenon against laboratory-scale experiments. The phenomenon was discovered recently as a result of analytical and numerical studies performed at Ulster University. The phenomenon is characterized by the existence of a peak on the overpressure transient in an enclosure with vent(s) at some conditions. The peak overpressure can significantly exceed the steady-state pressure and jeopardise a civil structure integrity causing serious life safety and property protection problems. However, the experimental validation of the phenomenon was absent until recently. The validation experiments were performed at Karlsruhe Institute of Technology within the framework of the HyIndoor project (www.hyindoor.eu). Tests were carried out with release of three different gases (air, helium, and hydrogen) within a laboratory-scale enclosure of about 1 m^3 volume with a vent of comparatively small size. The model of pressure peaking phenomenon reproduced closely the experimental pressure dynamics within the enclosure for all three used gases. The prediction of pressure peaking phenomenon consists of two steps which are explained in detail. Examples of calculation for typical hydrogen applications are presented.

Keywords

Hydrogen, unignited release, pressure peaking phenomenon, model, ventilation, experiments, validation

1.0 INTRODUCTION

The HyIndoor project (www.hyindoor.eu) has shed a light on potential consequences of hydrogen releases indoors. Original analytical [1] and numerical [2], [3] studies were carried out to facilitate the commercialisation of hydrogen-powered fuel cell vehicles. All high-pressure gas storage and distribution systems have to be equipped with PRDs [4]. The US fuel cell council car chart [5] shows that all car manufacturers are working to present their own hydrogen powered vehicle. One possible accident scenario is unexpected unignited release of hydrogen from on-board storage in a garage or maintenance shop when pressure relief device (PRD) is activated by whatever reason or fault.

The pressure peaking phenomenon (PPP) is a transient process of pressure change with pronounced peak in an enclosure with ventilation. The phenomenon is characteristic for released gases lighter than air and the mostly distinct for hydrogen. For the first time the PPP was discussed in [6]. The scenario of hydrogen release through a PRD of 5.08 mm internal diameter into the enclosure of 30.4 m^3 with a vent was considered. It was shown that for 35 MPa storage pressure the rate of discharge through the PRD will be 390 g/s. If the vent is of a brick size 25x5 cm then the peak overpressure will be significantly above 10-20 kPa to which civil structures could withstand. The garage would collapse in a couple of seconds. This phenomenon is applicable for lighter than air gases such as hydrogen and helium, and it is not valid for heavier than air gases such as propane. The numerical simulation confirmed the analytical model [6]. However, experiments for the validation of the phenomenon were practically unavailable until recently.

The most recent paper on the pressure peaking phenomenon [7] presents the model details. Engineering nomograms were developed for different hydrogen inventory, enclosure volumes, ventilation rates and storage pressures allowing to calculate a safe PRD diameter and the time of blowdown. The safe diameter was considered as the one which would not generate overpressure above 20 kPa in the enclosure in the case of hydrogen release.

This paper outlines the methodology and an engineering nomogram that allows to find out whether a hydrogen release is likely to produce a pressure peaking and then compares the predictions of a previously developed analytical model, to calculate PPP, with new experimental data.

2.0 METHODOLOGY

For pressure peaking phenomenon to occur, the hydrogen release rate should be comparatively high and vent(s) area comparatively small that finally the hydrogen concentration within enclosure will reach 100% with time. To calculate this lower mass flow limit the following equation was derived in [1],

$$\dot{m}_{H_2} = C_D A \sqrt{H} \cdot \sqrt{\frac{8 g \rho_{H2}(\rho_{air} - \rho_{H2})}{9}}, \quad (1)$$

where C_D is the discharge coefficient, A and H are the area and the height of the vent respectively (m), ρ_{H2} and ρ_{air} are densities of hydrogen and air respectively (kg/m^3), and g is the acceleration of gravity (m/s^2).

Equation (1) was used to build the nomogram for calculation of the lower limit of mass flow rate of hydrogen for the pressure peaking phenomenon to occur depending of vent height and width. The nomogram is presented in Figure 1.

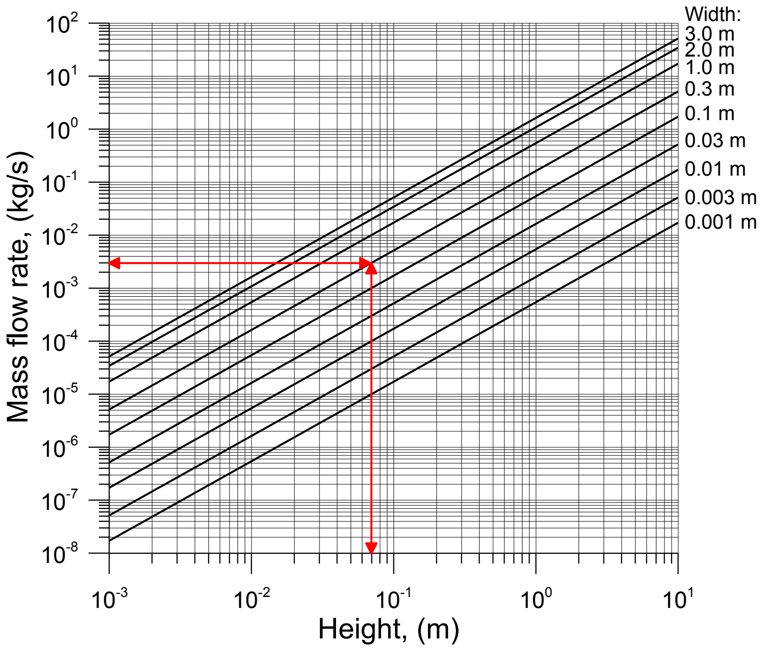


Figure 1. The nomogram for graphical calculation of the lower limit of hydrogen mass flow rate in an enclosure with one vent, which leads to 100% of hydrogen concentration, by the vent height and width.

The nomogram was built using the discharge coefficient C_D=0.85. It allows to calculate the vent dimensions which, for a given steady release rate, will eventually result in 100% hydrogen concentration in the enclosure. In order to find these vent dimensions, firstly a hydrogen release rate should be selected on the y-axis and a horizontal line to be drawn until the intersection with one of the inclined lines corresponding to the vent width of your choice. Secondly, a vertical line should be drawn from the intersection point to the x-axis to find out the required vent height. In inverse problem formulation, the nomogram can be used to find out the lower limit of release rate for a vent of known sizes when the assessment of PPP potential is needed.

In the last case, if the release rate determined from the nomogram is lower than an actual release rate from a storage or equipment then PPP will occur. Once it is demonstrated that PPP could occur, then the methodology described in [7] is applied to calculate the pressure peaking phenomenon.

3.0 EXPERIMENTAL FACILITY

The experimental facility was built inside the test-chamber at the hydrogen test centre HYKA at KIT. The test-chamber has the dimensions 5.5x8.5x3.4 m with a volume of approximately 160 m^3. The walls of the chamber were made of a framework structure covered by damping material and special corrugated metal sheets to absorb shock waves. It is equipped with a powerful and explosion proof venting system which is capable to produce air flow up to 24000 m^3/h, corresponding to more than two complete air exchanges in the chamber per minute. The chamber is placed on a solid concrete foundation below its ground floor. Due to the design it is possible to perform release and dispersion, as well as combustion experiments inside the chamber. Figure 2 shows a drawing of the test chamber with its different levels and a sketch of the experimental facility.

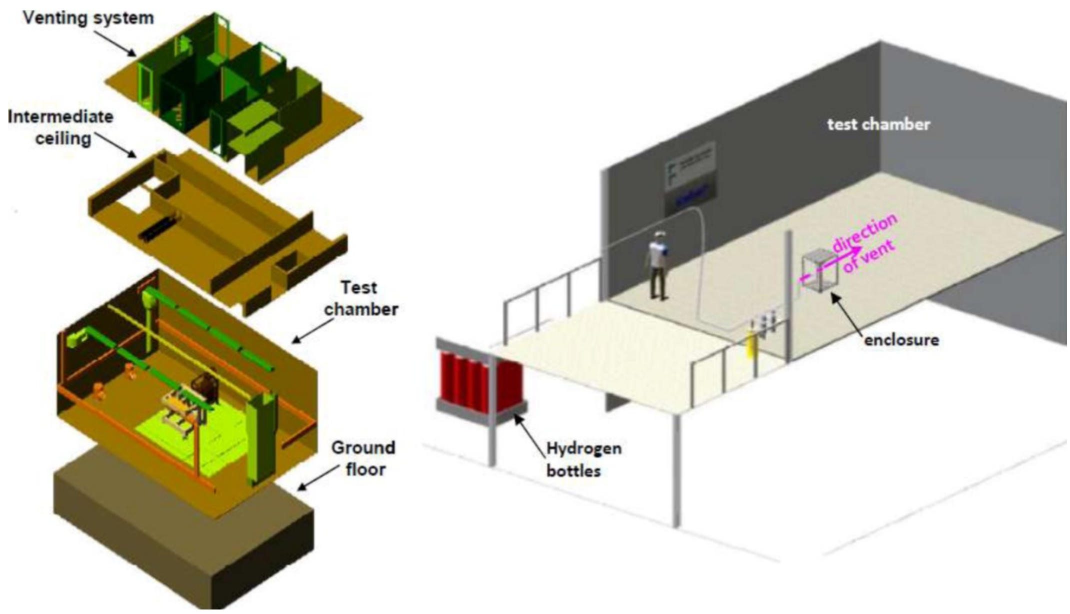
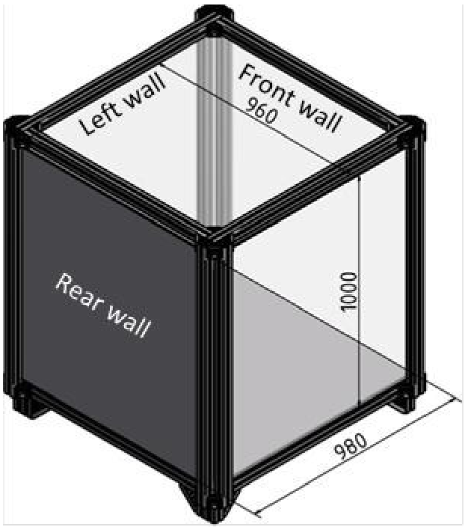


Figure 2. Sketch of the test-chamber and the experimental facility in the hydrogen test centre HYKA at KIT.

Figure 3 shows the framework structure of an experimental enclosure of size *HxWxL*=1x0.98x0.96 m, which is made of aluminium profile rails 45x45 mm fixed together by assembly brackets, bolts and nuts. Rear, bottom and front walls (with opening) are made of aluminium plates of 10 mm thickness. The front plate (not in place in Figure 3) is used to provide different vent openings. Transparent left, top and right walls are made of a composite of the inner part made of fire-protection composite glass of 5 mm thickness, and the outer part made of Plexiglas, 15 mm thick. The internal diameter of the release nozzle is specified to 5 mm, located at the centre of enclosure 10 cm above the floor and directed vertically upward. Round vents of area from 1 to 2 cm^2 were located centrally at the top or at the bottom of the front panel.

In this series of experiments the hydrogen is injected into the enclosure with known mass flow rate that was measured and controlled by a Coriolis mass flow meter (type Emerson CMF010P, up to 30 g/s of hydrogen) with a digital output to the data acquisition system. The lower mass flow rates (< 0.2 Nl H2/min) were measured by Bronkhorst EL-Flow (Type F-220AV-M20, 0.2 - 273 Nl H2/min). To provide required mass flow rate a bulk pressure of hydrogen was also controlled by a pressure sensor.

To record the overpressure history during an experiment one slow pressure transducer GEMS 2200 SG 1B6, for relative pressure in the range from -0.1 MPa (vacuum) to 1 MPa and U-shape differential manometer filled with water were used.



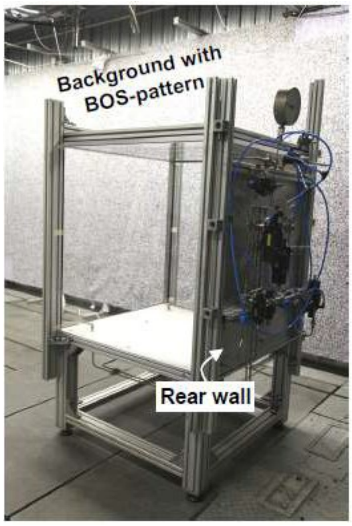


Figure 3. The sketch and a side view of the test enclosure inside the test-chamber.

4.0 VALIDATION EXPERIMENTS

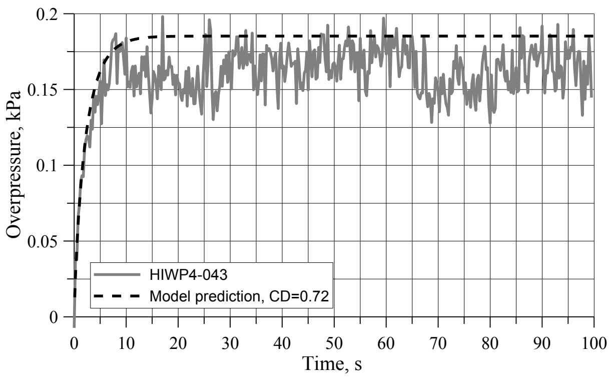
In total 19 laboratory scale experiments were performed to investigate the pressure peaking phenomenon. The experiments were carried out with different mass flow rate in the range from 0.1 to 2.8 g/s and three released gases, i.e. air, helium, hydrogen. The enclosure was either closed or had a round vent of 11 mm or 16.5 mm diameter. The experimental data were compared against calculations by the model of the pressure peaking phenomenon [7]. Table 1 shows the details of the test matrix including parameters of experiments and registered maximum overpressure.

Table 1. Validation experiments.

Experiment	Gas released	Mass flow rate, g/s	Vent diameter, mm/Location	Injection duration, s	Maximum overpressure, kPa
HIWP4-001	Helium	0.22	11/Top	300	0.27
HIWP4-002	H2	0.1086	11/Top	300	0.26
HIWP4-003	H2	0.5486	16.5/Top	60	1.99
HIWP4-004	H2	0.1086	11/Top	300	0.35
HIWP4-040	Helium	0.22	11/Top	516	0.24
HIWP4-041	Helium	0.5	11/Top	134	1.01
HIWP4-042	Helium	0.985	11/Top	96	2.92
HIWP4-043	Air	1.444	11/Top	108	0.2
HIWP4-044	Air	2.798	11/Top	128	0.65
HIWP4-045	Helium	0.22	11/Bottom	911	0.41
HIWP4-046	Helium	0.985	11/Bottom	73	2.53
HIWP4-047	H2	0.1086	11/Top	182	0.26
HIWP4-048	H2	0.5486	11/Top	43	3
HIWP4-049	H2	0.5486	11/Top	101	3.1
HIWP4-050	H2	1.086	11/Top	67	6.43
HIWP4-051	H2 Leak Test	0.287	None	39	2.54
HIWP4-052	H2 Leak Test	0.287	None	47	2.62
HIWP4-055	Helium	1	16.5/Top	362	0.85
HIWP4-056	H2	1.086	16.5/Top	78	2.37

5.0 RESULTS AND DISCUSSION

Figure 4 shows the results of two experiments with release of air with flow rates 1.44 g/s and 2.8 g/s respectively into the enclosure with a round vent of 11 mm diameter. Comparison with the model prediction gave a very good agreement (C_D=0.72), both in dynamics and the steady-state overpressure. There is no pressure peak as predicted by the theory [7], and pressure monotonically grows to stabilise at the steady-state condition overpressure. This is due to the fact that there is no difference in densities between the released gas (air in this case) and the gas initially being in the enclosure (always air in these experiments).



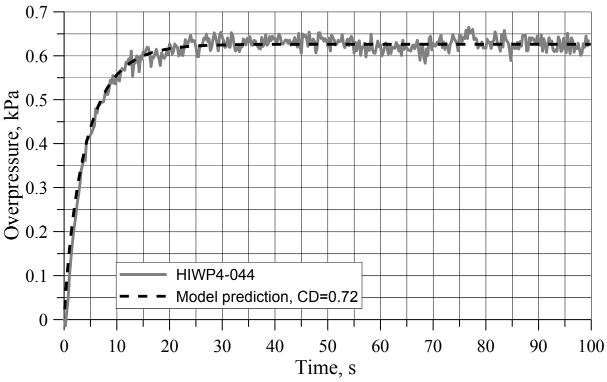
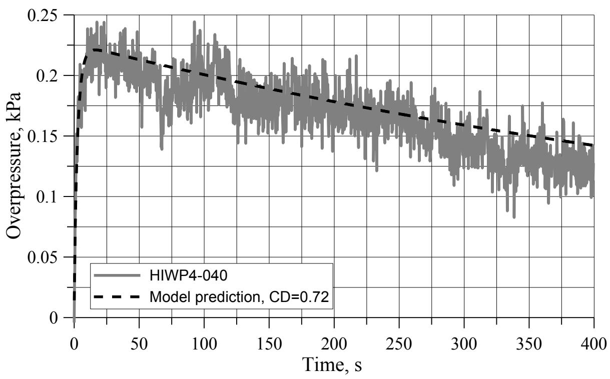


Figure 4. Pressure dynamics by the PPP model (black dashed lines) against experimental pressure transients (grey solid lines): air release at flow rate 1.44 g/s (left), and 2.8 g/s (right).

Figure 5 compares the model prediction against experimental results of helium release with flow rate 0.22 g/s and 0.50 g/s respectively and a vent of 11 mm diameter. The same discharge coefficient C_D=0.72 was applied in the model. There are pressure oscillations that can be seen in all figures. The absolute amplitude of the oscillations remains the same independent of maximum level of the pressure signal and might be explained by the influence of acoustic waves on pressure sensor during gas release.



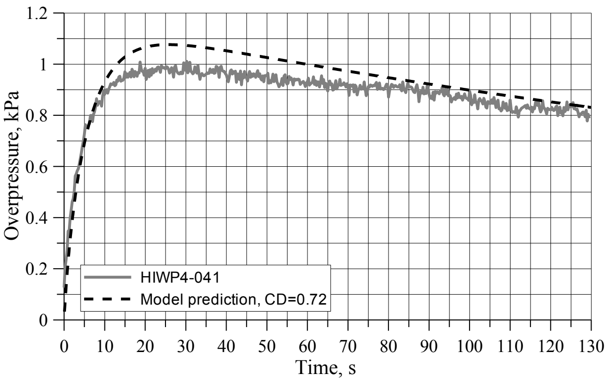


Figure 5. Pressure dynamics by the PPP model (black dashed lines) against experiments (grey solid lines): helium release at flow rate 0.22 g/s (left), and 0.5 g/s (right).

Figure 6 demonstrates results of helium release at the rate of 0.958 g/s for the same vent size of 11 mm diameter but different location, i.e. at the top (left) and the bottom (right) of the wall. The inverse problem method gave C_D=0.82 and C_D=0.85 respectively. This is somewhat larger than for smaller releases when the overpressure was below 1 kPa. This is in line with the known fact that the discharge coefficient increases with the increase of gas velocity through the vent. The prediction of pressure dynamics by the model is excellent with some under-estimation (up to 20% at the end of measurements) in Figure 6 (right).

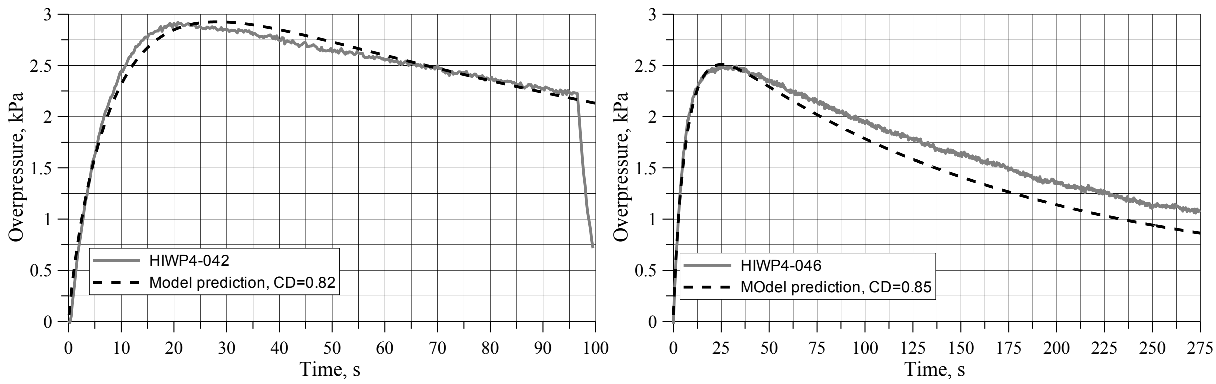


Figure 6. Pressure dynamics by the PPP model (black dashed lines) against experiments (grey solid lines): helium release at rate 0.958 g/s, top vent (left), and bottom vent (right).

Two experiments, one with release of helium and one with release of hydrogen, are compared in Figure 7. In the experiment with helium the mass flow rate was twice higher compared to the experiment with hydrogen. In spite of this difference, the experimental pressure transients look very similar. This can be explained by the fact that the molecular mass of helium is twice of the hydrogen molecular mass. This means that the volumetric flow rate was the same in both experiments. The discharge coefficient C_D=0.68 is a bit smaller but close to value C_D=0.72 in Figure 5 (left).

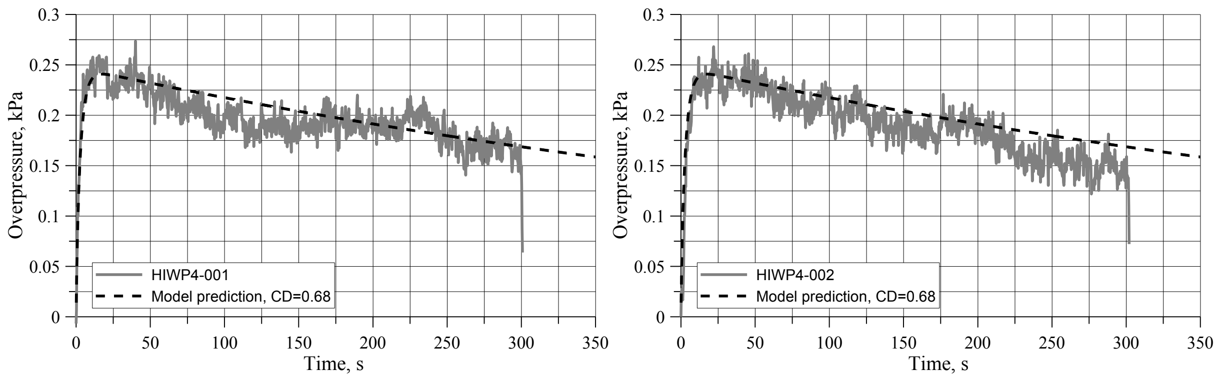


Figure 7. Pressure dynamics by the PPP model (black dashed lines) against experiments (grey solid lines): helium release at rate 0.22 g/s (left), and hydrogen release at rate 0.1086 g/s (right).

Figure 8 shows comparison of experimental pressure dynamics for two hydrogen releases with mass flow rate 0.5486 g/s and 0.1086 g/s respectively with the model prediction. It can be seen that the general trend is well reproduced, however the discharge coefficient is somewhat lower C_D=0.54-56. This probably can be explained by the fact that real mixing of hydrogen and air in the enclosure varies from one experiment to another and differs from the perfect mixing assumption (uniform mixture) in the model.

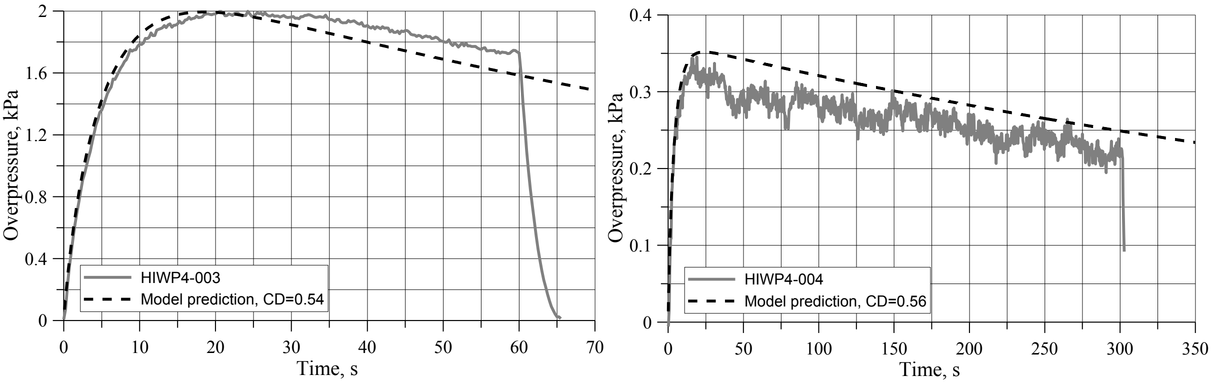


Figure 8. Pressure dynamics by the PPP model (black dashed lines) against experiments (grey solid lines): hydrogen releases at rate 0.5486 g/s, vent diameter 16.5 mm (left); and 0.1086 g/s, vent diameter 11 mm (right).

Figure 9 (left) shows pressure dynamics for helium release in the enclosure with a bottom vent of 11 mm diameter and release rate of 0.22 g/s. Figure 9 (right) shows pressure dynamics for hydrogen at release rate of 0.1086 g/s in the enclosure with a top vent of the same area. The same C_D=0.65 is applied for both releases. It can be seen that for the same volumetric flow rate the pressure peak in the case of helium release and the bottom vent is not that pronounced compared to the case with hydrogen release and the top vent of the same size.

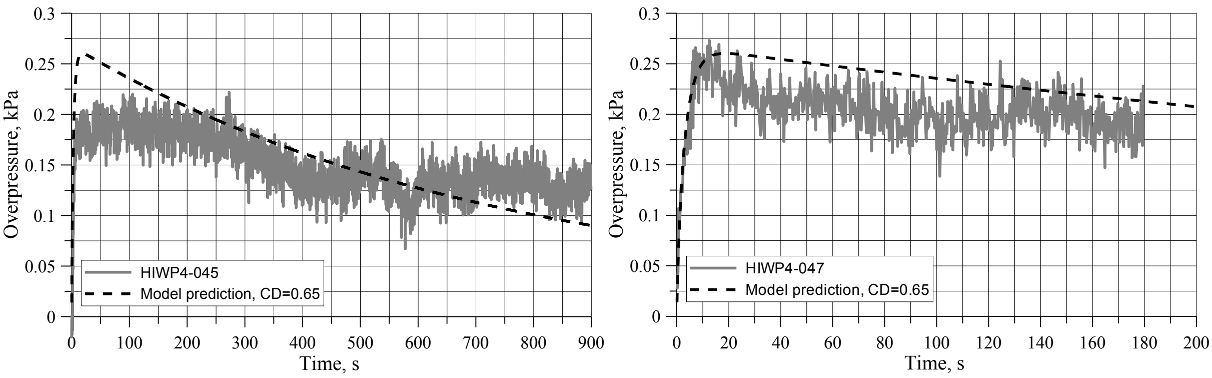


Figure 9. Pressure dynamics by the PPP model (black dashed lines) against experiments (grey solid lines): helium release at rate 0.22 g/s, bottom vent (left); hydrogen release at rate 0.1086 g/s, top vent (right).

Figure 10 demonstrates two experiments with release of hydrogen at the same conditions of release and venting, but with different duration experiments. The dynamics of pressure is close to each other during the first 45 seconds (duration of one of experiments). The discharge coefficient C_D=0.85 applied in both cases gives maximum deviation of about 12% at the end of the longer duration experiment.

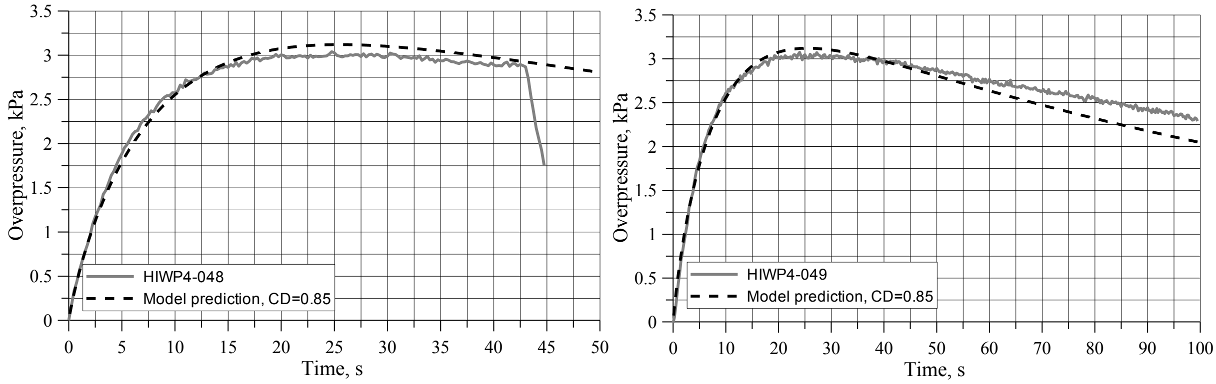


Figure 10. Pressure dynamics by the PPP model (black dashed lines) against two experiments at the same conditions but different duration (grey solid lines): hydrogen release at rate 0.5486 g/s.

Figure 11 (left) shows a significant deviation and then drop of experimental pressure after 3 kPa compared to calculated pressure dynamics for hydrogen release of 1.086 g/s. This can be explained by the fact that established during experiments overpressure higher than 3 kPa, the enclosure starts to "breathe" resulting in "additional uncontrolled opening" that depends on the overpressure attained. The increase of vent area from 1 cm^2 to 1.8 cm^2 in calculations resulted in overpressure of 6.5 kPa observed in the experiment. To calculate pressure dynamics C_D=0.72 was applied. This particular experiment demonstrated that even with relatively small release rate of 1 g/s the experimental enclosure didn't withstand generated overpressure that resulted in the "additional opening". In a garage-like enclosure and release rate 390 g/s from the 35 MPa storage through a typical PRD diameter of 5 mm the release would have serious consequences.

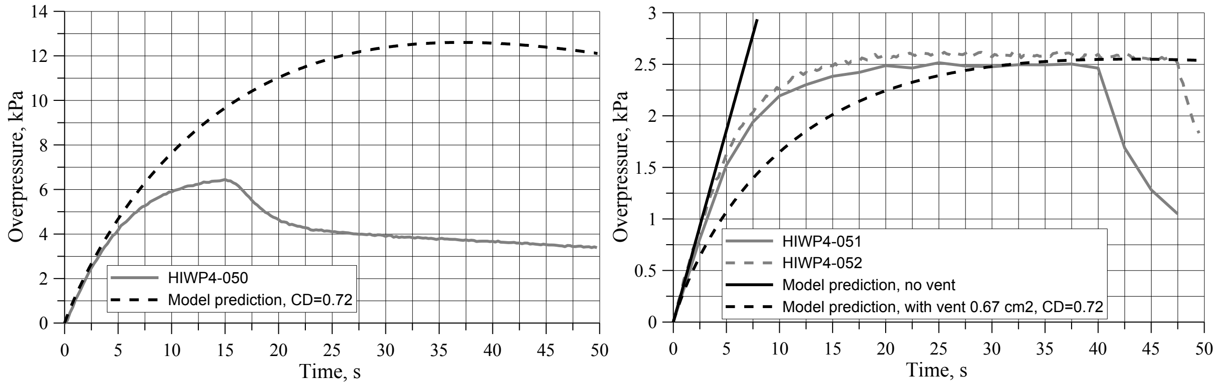


Figure 11. Pressure dynamics by the PPP model (black dashed lines) against experiments (grey lines): hydrogen release at rate 1.086 g/s (left), enclosure with top vent of 11 mm diameter; and at rate 0.287 g/s in the enclosure without a vent (right).

Figure 11 (right) shows calculated pressure dynamics in completely closed enclosure with no vents (black solid line), calculated pressure transient for a vent of 0.67 cm^2 area (black dash line), and two experimental pressure-time curves in the "closed" enclosure for two identical tests, HIWP4-051 and HIWP4-052. In the beginning of release experimental pressure transients follow the calculated pressure-time curve in closed vessel. However, later in the process due to deformation of walls under the overpressure the "additional openings" are formed and the experimental pressure stabilises at about 2.5 kPa. This steady-state level of pressure is achieved in simulations if the "additional openings" area is taken as 0.67 cm^2 (C_D=0.72).

The analysis of Figure 11 (right) shows that "additional openings" or unscheduled leaks appear when the overpressure in the enclosure exceeds about 1.0-1.5 kPa. This means that experiments had randomly an additional unmeasured venting area which was not accounted in simulations explicitly. However, this conclusion helps to explain why the discharge coefficient, C_D, was changing from one experiment to another in quite close conditions. Indeed, the existence of uncontrolled “additional openings” in the experiment would be “compensated” by the increased discharge coefficient in the model calculations, as the vent area and the discharge coefficient are presented as a product of one by another in the equations for outflow rate.

Figure 12 represents the comparison of the model predictions of overpressure with experimental data in the enclosure with the biggest diameter of a vent of 16.5 mm. The discharge coefficient C_D=0.72 gives the best match with the experimental curve both in dynamics and maximum overpressure for helium release with 1 g/s (left graph). The experimental and calculated curves for hydrogen release (right graph) give overpressure just under 2.5 kPa. However, the value of discharge coefficient for this case is higher C_D=0.9. This is thought due to the “additional openings” as mentioned above.

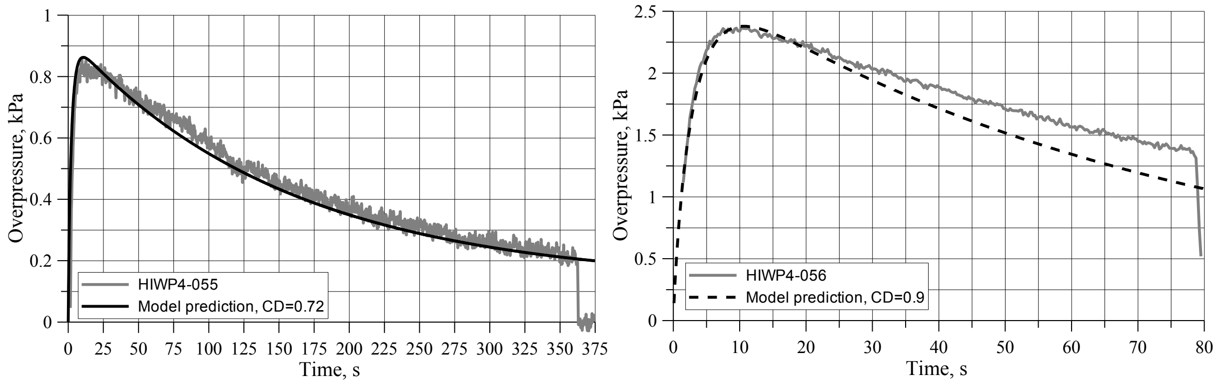


Figure 12. Pressure dynamics by the PPP model (black dashed lines) against experiments (grey solid lines) for vent diameter of 16.5 mm: helium release at rate 1 g/s (left), hydrogen release at rate 1.086 g/s (right).

6.0 CONCLUSIONS

A series of 19 experiments with releases of air, helium, and hydrogen into the laboratory-scale enclosure has been performed at KIT to prove the existence of the pressure peaking phenomenon experimentally. Three gases were selected in order to confirm that the pressure peaking phenomenon is applicable to lighter than air gases, as predicted by the theory developed previously at Ulster. The lower and upper vent locations were compared and it was confirmed that the location of the vent has no practical influence on the pressure dynamics. The discharge coefficient was found to be in the range C_D=0.54-0.90 for performed experiments. This scatter is thought due to the “breathing” of the enclosure, i.e. the creation of non-controlled “additional openings” through which gas was leaking. The average value of discharge coefficient through the series of test is C_D=0.72, the conservative value is C_D=0.54.The pressure peaking is a new hazardous phenomenon, especially pronounced for hydrogen. It must be an essential part for consideration when carrying out routine hydrogen safety engineering for indoor use of hydrogen and fuel cell systems.

7.0 ACKNOWLEDGEMENTS

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