EFFECT OF MECHANICAL VENTILATION ON ACCIDENTAL HYDROGEN RELEASES – LARGE SCALE EXPERIMENTS

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ABSTRACT

This paper presents a series of experiments on the effectiveness of existing mechanical ventilation systems during accidental hydrogen releases in confined spaces like underground garages. The purpose was to find the mass flow rate limit hence the TPRD diameter limit that will not require a change in the ventilation system. The experiments were performed in a 40 ft ISO container in Norway and hydrogen gas was used in all experiments. The forced ventilation system was installed with a standard outlet 315 mm diameter. The ventilation parameters during the investigation were British Standard with 10 ACH and British Standard with 6 ACH. The hydrogen releases were obtained through 0.5 mm and 1 mm nozzle from different hydrogen reservoir pressures. Both types of mass flow: constant and blowdown were included in the experimental matrix. The analysis of hydrogen concentration of created hydrogen cloud in the container shows the influence of the forced ventilation on hydrogen releases, together with TPRD diameter and reservoir pressure. The generated experimental data will be used to validate a CFD model in the next step.

INTRODUCTION

Existing mechanical ventilation systems used in semi-confined spaces are designed for conventional fuels only. The increasing amount of hydrogen-driven vehicles needs investigation if the change in those ventilation systems is needed.

Hydrogen releases in semiconfined spaces can be significantly dangerous than in the open air. The released hydrogen can form a cloud/layer under the ceiling and build up its concentration increasing hazards of ignition and explosion. The wide range of hydrogen flammability limit (4% - 75%) [1,2] obliges investigation in the mitigation system to keep concentration within safety limits. There are many studies on hydrogen dispersion in semiconfined enclosures [1,3–8]. The concentration levels in the enclosure mainly depend on the hydrogen leakage source (mass flow rate, its pressure, location, and direction) and ventilation area [4,6,7]. Insufficient ventilation results in higher concentrations and a longer time of reducing it under the flammability limit [9]. A study by Merilo et al. [5] investigates the risks of deflagration in a private garage as a result of leakage from the car. The concentration results from mass flow rate from1.52 kg/h to 9.22 kg/h results in well-mixed layers under the ceiling (with natural and mechanical ventilation). The results showed a decrease in concentration with an increase in ventilation rate. Tests with the highest mass flow rates 4.92 kg/h and 6.7 kg /h with the lowest ventilation rate result in average concentration (at the ignition time) over 10% increasing hazards of deflagration.

When hydrogen is released with a low-momentum jet (low Froud number)[10], the formated cloud will be a result of buoyancy motion. As a consequence, the stratification of hydrogen will form hydrogen layers in the enclosure. The buoyancy effect is less significant from the releases from the high pressurized reservoir when the high-momentum jets (high Froud number) are occurring [10,11]. It results in a well-mixed system where hydrogen will mix with surrounding gases [12]. The authors developed a simple analytical model to investigate the consequences of hydrogen releases from high pressurized releases with natural and forced ventilation. The releases from a 40 MPa container with 1 to 5 ACH (air change per hour) were studied through 6 mm, 3 mm, and 1 mm nozzle. The overpressures that occurred during the releases were much higher for releases through a 6 mm nozzle. The analytical model results showed with increasing forced ventilation the duration of flammable H_2-air mixture will decrease. A similar study [13] was performed in a full-scale residential garage to validate the analytical model. The model results in overpredicting 1% of forced ventilation. The study showed a significant effect of forced ventilation on the reduction of flammable concentration in an enclosure.

The level of hydrogen concentration is crucial to limit flame acceleration [14,15]. The limits for slow flame acceleration have been developed by Dorofeev et. all [16] to be under 10% hydrogen in air. Minimum ignition energy (MIE) for 10% H_2-air mixture significantly decreases from 0.052mJ for 10% to 0.017 mJ for 20% air mixture [15]. The MIE of hydrogen-air mixtures compared to other fuels (order of 0.1 mJ [17]) has higher ignition risks. Therefore the hydrogen concentration in the enclosure has to be kept under flammability limits or et least under 10%vol above which the flame propagation is more violent.

A numerical investigation of hydrogen release in the naturally ventilated enclosure was performed by Hussein et all. [18]. The study examined the hydrogen concentrations resulted from blowdown type releases from 700 bar through different diameters of TPRD (Thermal and Pressure Relief Device). The release source was located under the car, between the back wheels. TPRDs with diameters larger than 0.5 mm resulted in a flammable cloud filling out the major part of the enclosure in less than 20 s. The author outlined the unacceptable large diameters of TPRD which lead to high concentrations in a short time and may result in pressure peaking phenomena described in previous studies, also by authors of this article [19–22]. Forced ventilation as a mitigation method in the semi-closed space was investigated by Malakhov et all [23]. The computational fluid dynamics (CFD) methods and conducted experiments resulted in concentration distribution from horizontal hydrogen release. The results show the effect of mechanical ventilation on the hydrogen jet behavior, its length, and on reduction of the hydrogen concentration in a tested compartment.

In this study, a series of experiments were conducted to investigate the effect of existing standards of ventilation rates on concentration in the hydrogen cloud. The 40 ft ISO container was used to create a scenario of accidental hydrogen releases in a parking garage, with a release source under the car (placed 4.5 m from the ventilation). The hydrogen concentrations from blowdown and constant mass flow releases from low and high pressurized reservoirs will be presented. The authors put a major focus on the releases through 0.5 mm TPRD diameter as proposed by Hussein et. all [18]. The experimental results will be used to validate the CFD model in further work developed within the HyTunnel consortium (https://hytunnel.net/).

METHODS

The 40 ft ISO container (Figure 1) with isolated walls was used for all experiments with open exit doors. Its inner dimension LxWxH: 11885 x 2240 x 2285 mm gives a total volume of 60.8 m^3.

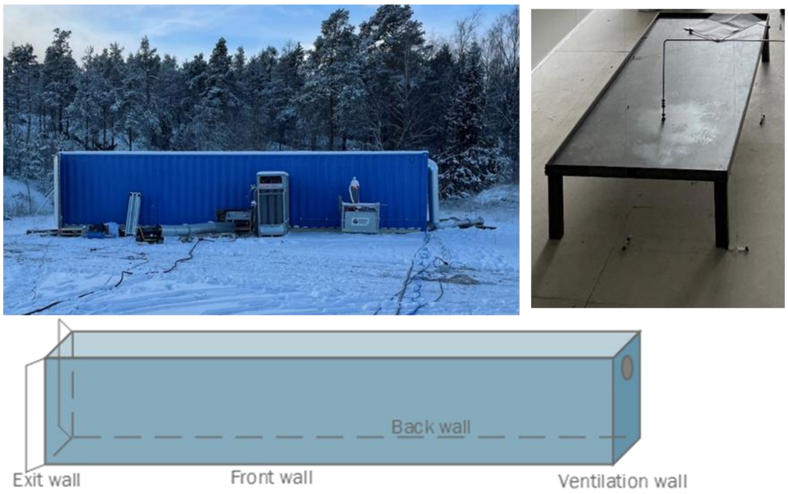

Figure 1. 40 ft ISO container with installed equipment and instrumentation.

For all experiments, the Coriolis mass flowmeter for high-pressure flows (up to 1043 bar) was used and forced ventilation with an outer diameter 315 mm was installed at the ventilation wall (center 207.5 mm mm from the ceiling). The ventilation was a blowing type ventilation (exit at the open doors). The ventilation rate (ACH) was measured by airflow at an IRIS damper with GAMS differential pressure transmitter. Inside the container a steel table (scaled 1:4 of a hydrogen car) with dimensions LxWxH: 1965x730x250 mm was placed 4500 mm from the ventilation wall with a center 1120 mm from the side front/back wall (Fig 2). The hydrogen was discharged vertically downwards through the steel table. The nozzle outlet was placed 250 mm above the floor, 1120 mm from the front/back wall, and 5000 mm from the ventilation wall.

The experiments were performed with constant and blowdown type of flow with two hydrogen supply setups:

1. **Constant mass flow releases.** The hydrogen flowed from the hydrogen crate (12 bottles with 200 bar) through the Coriolis mass flow meter and was released through a 1 mm or 0.5 mm nozzle inside the container. The initial pressure was set by a pressure relief valve at the H_2 crate. The release pressure was constantly measured at the exit of the Coriolis mass flow meter with an ESI pressure transmitter.

2. **Blowdown type mass flow releases.** The hydrogen was pumped from the hydrogen crate by a gas booster pump (Haskel-Proserv operating pressure 1600 bar) to the hydrogen tank (Hexagon, Type 4 composite high-pressure tank-carbon fiber). During experiments, hydrogen flowed from the tank through the Coriolis mass flow meter and was released through a 0.5 mm nozzle. The release pressure was constantly measured at the exit of the tank with an ESI pressure transmitter.

The uncertainty of all the instrumentation is listed in the table below. The absolute measurement uncertainty includes the derived uncertainty of the Air Changes per Hour. The data used in the analysis are averages of more than 25 kilo-samples and effectively reducing the uncertainty of the data. The CAN bus network for the XEN-5320 CAN sensors (Xensor catharometres) were used to measure hydrogen concentration. XEN-sensors with a data rate of 3 Hz, gave the concentration measurements pointwise every 0.33 s.

Table 1. Uncertainty of measurements

Equipment	Measurement uncertainty	Absolute measurement uncertainty
ESI Pressure transmitter	±1% FSO BFSL	±10 bar
GAMS Differential pressure transmitter	±1% FS	±15 m^3/h (±0.2 ACH)
Mass flow	±0.2% of flow rate	
Concentration	±2%/%	±0.18% (max. conc)

The hydrogen concentration was measured in the container with the 30 CANbus hydrogen sensors, (mounted under the ceiling, 500 mm under the ceiling, and under the table) and 8 WIFI hydrogen sensors (mounted on the back wall of the container). Sensor location is illustrated in Fig. 2 and Fig. 3.

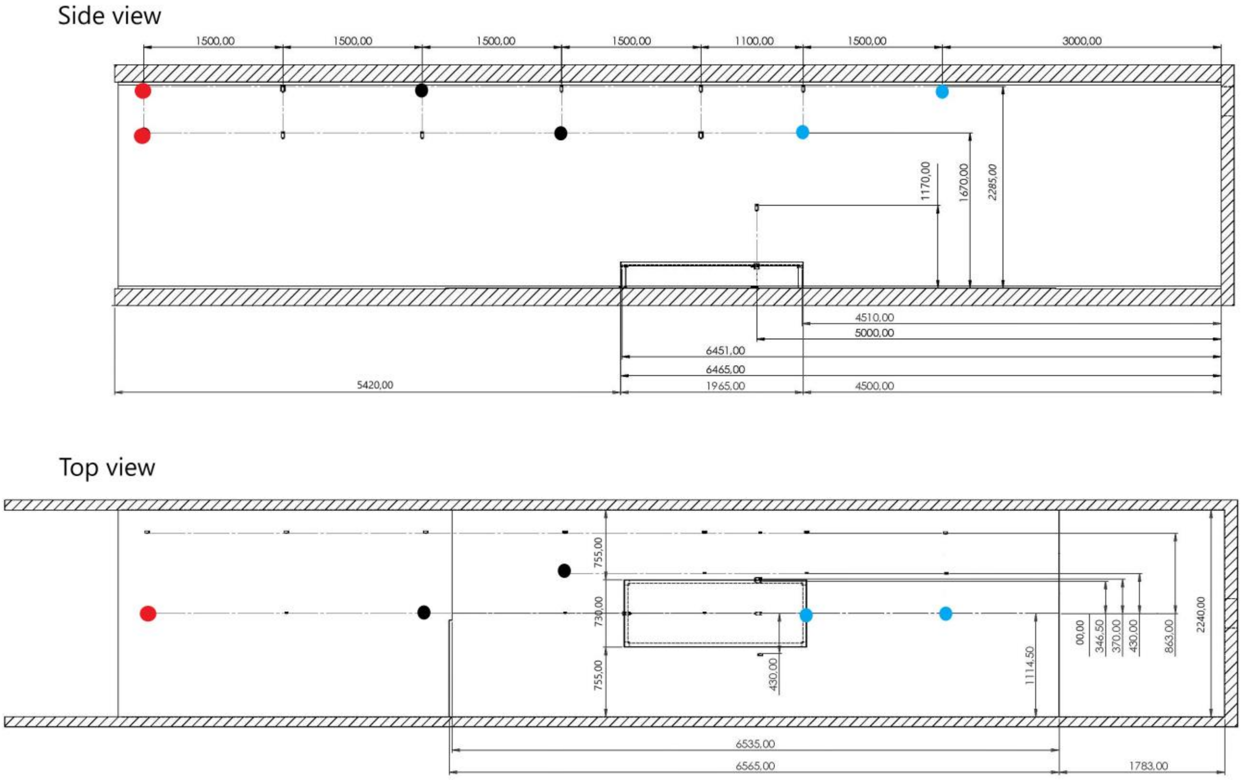

Figure 2. Location of the hydrogen sensors. Circle markers: red- S1,S2, black-S5,S21, blue-S13,S12 present sensors used in the plot on Fig. 5 and Fig.6.

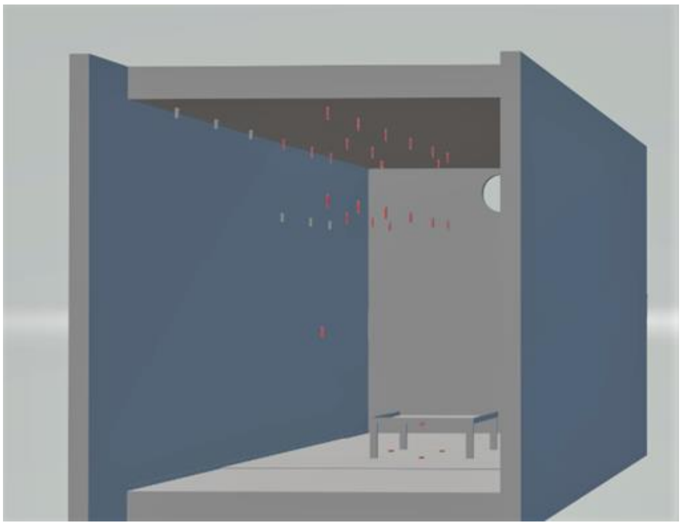

Figure 3. Hydrogen sensors’ placement in the container. Red-CANbus sensors, grey-WIFI sensors.

The experiments were designed for two ventilation volumetric airflow rates according to British Standard for 10 ACH and 6 ACH (Table 2). The needed airflow rate was calculated to be 608 m^3/h and 365 m^3/h for 10 ACH and 6 ACH 6 accordingly. The effect of the forced ventilation (ACH) on the hydrogen cloud concentration and duration was tested. The hydrogen was released through 1 mm and 0.5 diameter nozzle from 60 bar, 120 bar, and 160 bar reservoir pressures (constant releases) and 0.5 mm from 200 bar, 350 bar, and 700 bar reservoir pressure (blowdown). The pressure at the hydrogen crate and nozzle diameter was the controlling method for mass flow rates during constant mass flow releases while the pressure at the hydrogen tank, obtained during the filling process, was the controlling method for blowdown releases.

RESULTS AND ANALYSIS

Experiments were performed in January 2021, regardless of weather conditions. The results and parameters of each experiment are listed in Table 2. Due to low temperatures (up to -19 ºC) freezing issues occurred during experiments. That is why Exp 1-3 and Exp 17-18 have not representative data and are not included in Table 2. The volumetric airflow was constantly measured during experiments and the averaged ACH is listed in Table 2 (column 3). The initial pressure was read by the pressure transmitter (Table 2, column 4) and mass flow rate (MFR) by the coriolis mass flow meter (Table 2 column 5). The concentration for each experiment was calculated using MFR and volumetric flow of air (from measurements). The maximum concentration is presented in Table 2 (column 7). For the calculations, only the conservation of mass, $dm_{H_2}/dt = \dot{m}_{in} - \dot{m}_{out}$ was applied with a perfect mix assumption.

$$\frac{dC}{dt} = \frac{1}{V \cdot \rho_{H_2}} \cdot \left(\dot{m}_{in} - \dot{V}_{vent} \cdot C \cdot \rho_{H_2}\right) \tag{1}$$

Where C is the concentration,%; V is the volume of the container, m^3; ρ_{H_2} is the hydrogen density, kg/m^3; $\dot{m}_{in}$ is the hydrogen mass flow (experimental data), kg/s and $\dot{V}_{vent}$ is the airflow at the ventilation output (experimental data) m^3/s.

Table 2. Experimental parameters

Exp	Nozzle Diameter [mm]	ACH measured [1/h]	Measured p_0 [bar]	MFR [g/s]	H2 release Time [s]	Max calculated conc. [%]
3	0.5	9.5	-	1.1	30	-0.7
4	0.5	9.8	-	0.8	60	1.0
5	0.5	9.8	-	1.1	60	1.4
6	0.5	6.0	166	1.0	60	1.0
7	0.5	6.0	121	0.7	60	0.9
8	0.5	6.0	60	0.4	60	0.4
9	1.0	6.0	157	6.0	60	6.4
10	1.0	10.0	165	6.0	60	6.2
11	1.0	10.0	140	5.2	60	5.4
12	1.0	10.0	120	4.2	60	4.2
13	1.0	6.0	121	4.2	60	4.6
14	1.0	6.0	59	2.2	60	2.4
15	1.0	9.8	55	2.2	60	2.6
16	1.0	9.8	144	5.3*	1000	22.0
19	0.5	10.2	721	7.9*	1000	12.6
20	0.5	6.2	713	7.8*	1000	15.2
21	0.5	6.2	362	4.2*	1000	8.8
22	0.5	6.2	209	2.5*	1000	5.7
23	0.5	10.2	359	4.2*	1000	7.5

The higher hydrogen mass flows occurred with increasing reservoir pressure and/or nozzle diameter. The mass flow rates during all experiments were chocked at the nozzle. Hence, the non-reacting hydrogen jets (formed under the table) were momentum-dominated jets. Nevertheless, with a higher

MFR the concentration in the cloud increased (Fig.4). Increasing nozzle diameter to 1 mm resulted in an MFR 6 times higher than the MFR that resulted during releases through a 0.5 mm diameter nozzle from the same reservoir pressure (Fig. 4). The hydrogen concentration in the cloud, accordingly, was ~3 times higher. Decreased diameter with much higher reservoir pressure (Fig. 4 c- blowdown MFR) resulted in concentrations similar to those that resulted from releases through 1 mm (Fig. 4 a- constant MFR). While MFR increased the calculated concentration increased, showing high over predictions for blowdown releases. The difference between calculated concentration results from blowdown and constant releases with a 1 mm diameter nozzle (while the MFR's are similar) is caused by the simplicity of the model where the density was assumed to be constant. The releases from the high pressurized reservoir result in much higher densities (cold gas) at the nozzle which was not included in the model.

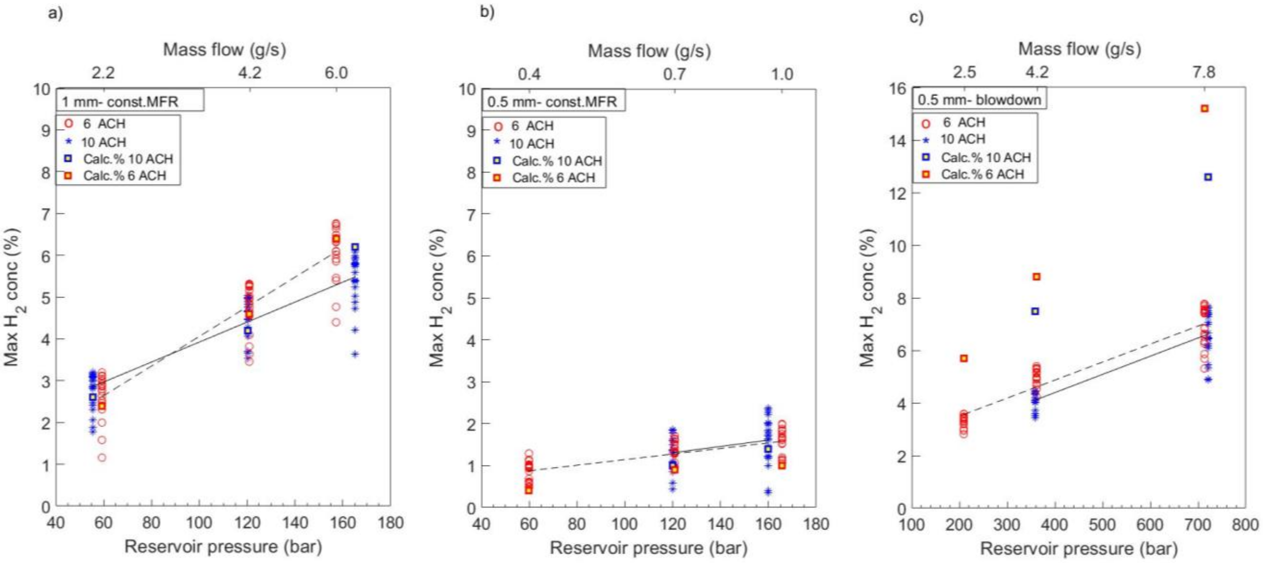

Figure 4. Maximum hydrogen concentration resulted with 6 ACH (dash line) and 10 ACH (solid line) during constant mass flow releases (a) through 1 mm diameter nozzle, (b) 0.5 mm diameter nozzle, and (c) blowdown mass flow releases through 0.5 mm nozzle. Maximum concentrations at each sensor during 10 ACH (blue star) and 6 ACH (red circle). The squere represents maximum calculated concetration for each experiment.

The effect of the mechanical ventilation on the concentration is shown in Fig.4. The red-circle markers represent the maximum concentration from each sensor during the experiment with 6 ACH. The blue-star marker, accordingly, represents the maximum concentration from each sensor with 10 ACH. The results of maximum concentration (constant mass flow releases a) and b) and blowdown releases c)) with 6 ACH and 10 ACH were compared with each other in Fig 4. The dashed line shows a straight line fit to the experimental data with 6 ACH and the solid line with 10 ACH. The results in Fig.4 do not decisively show a decreased concentration with increased ventilation rate in this particular geometry. The maximum concentrations from 10 ACH and 6 ACH from releases at the same reservoir pressure overlap with each other showing small differences.

The concentration results from experiments with 10 ACH (Exp.10. solid lines) and 6 ACH (Exp.9, dash lines) are shown in Fig. 5. The color of the line corresponds to the sensor's location marked (with the same color) in Fig. 2. The top plot shows concentration results from sensors mounted under the ceiling and the bottom plot for chosen sensors mounted 50 cm below the ceiling. The results from sensors mounted under the ceiling showed similar concentrations to sensors mounted 50 cm below the ceiling (Fig. 5). Since sensors were not mounted closer to the container floor the results indicate the cloud was at least 50 cm high, as the concentrations are more or less equal. By following lines colors the cloud propagation is observed from sensors closest to the nozzle, -blue line (3.0 m and 4.5 m from the ventilation wall), - black line (7.1 m and 8.6 m from the ventilation wall), and –red line (11.6 m from the ventilation wall). The highest concentration was observed under the ceiling, closest to the ventilation wall (behind the table, upstream the ventilation flow). The hydrogen plume from under the table (car) rises towards the ceiling and the increased concentration is measured simultaneously on both the blue and the black sensors. This indicates that there are plumes rising in front and behind (as well as along the sides) the table. For lower mass flows, the plumes are mostly at the rear of the table (closes to the nozzle). During blowdown releases, the plume at the front of the table decreases and disappears as the mass flow rate (and tank pressure) decreases.

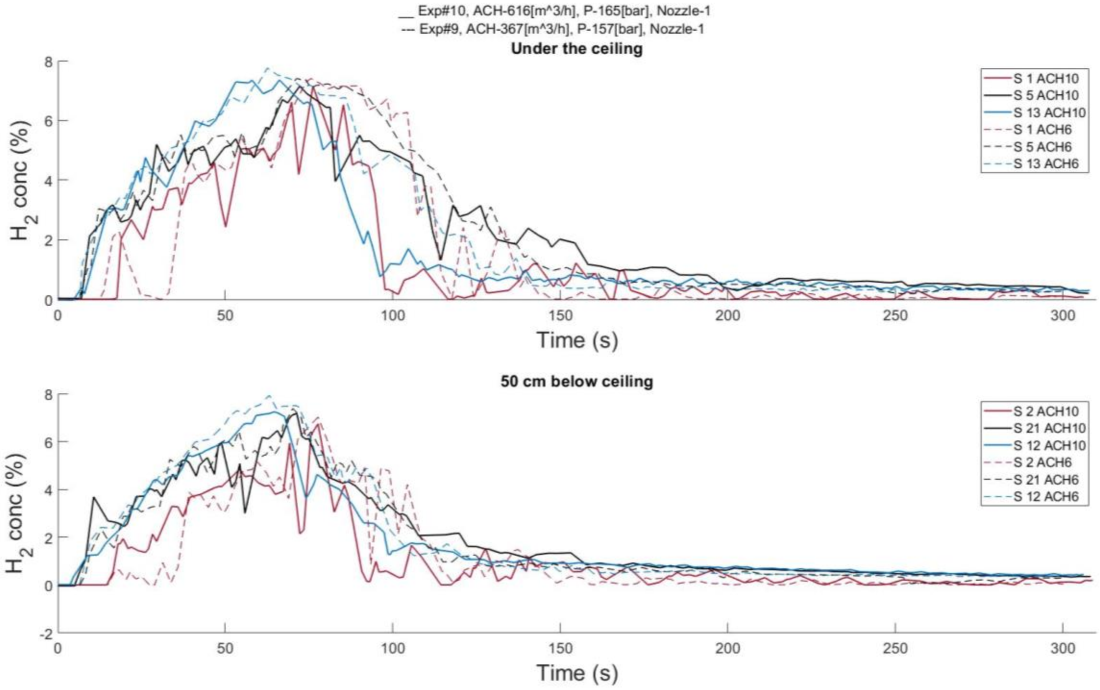

Figure 5. Concentration in the cloud and its propagation from hydrogen releases with 10 ACH and 6 ACH.

The effect of the ventilation on the duration of the flammable cloud is investigated further for the blowdown hydrogen releases. The blowdown experiments recorded the mass flow rate for a total of 900 seconds, after which the remaining pressure in the tank was 2-3% of the initial pressure. A hydrogen-air cloud can ignite when the concentration is within 4 % - 75% by volume. In table 3 the total time, t_f (column 6), when the cloud is flammable is presented together with time when the concentration in the cloud reached 4% for the first time, t_{f0} (column 7). T_f is the sum of time for each sensor when the concentration measurments showed ≥ 4%.

Table 3. The flammable time during blowdown releases.

Exp Nr	$P_{reservoir}$ [bar]	ACH [1/h]	Blowdown time [s]	P_{end} [bar]	Total flammable time t_f [s]	t_{f0} [s]
22	209	6.0	900	6	11	82
23	359	10.2	900	12	83	30
21	362	6.2	900	10	195	32
19	721	10.2	900	16	285	16
20	713	6.2	900	17	336	18

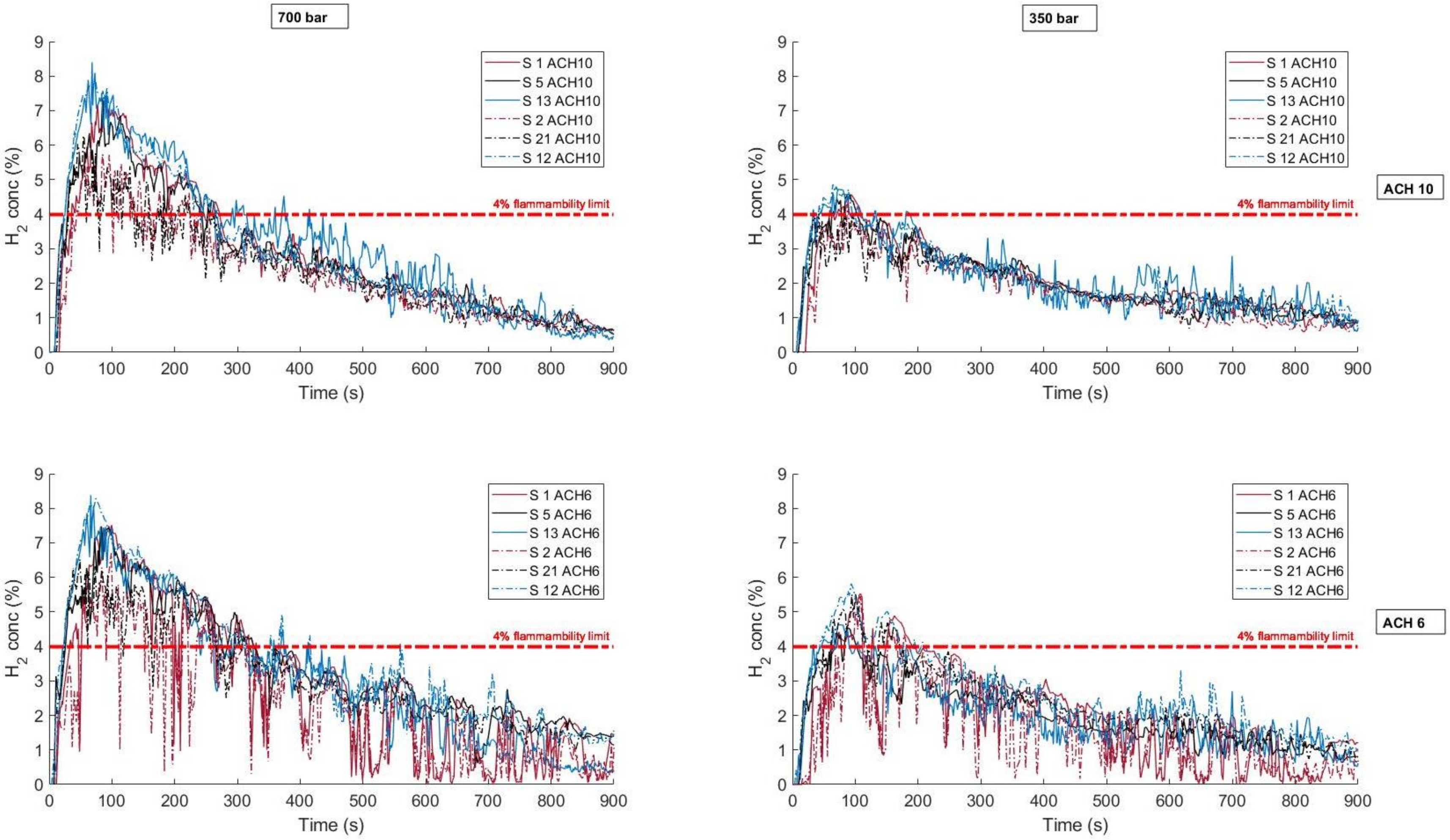

Figure 6. Concentration results from blowdown hydrogen releases with ventilation 10 ACH and 6 ACH. Solid lines-sensors mounted under the ceiling, dash lines-sensors mounted 50 cm under the ceilin

The total time when the hydrogen cloud is flammable is longer when the ventilation rate is lower (6 ACH), see Fig.6 and table3. When we compare exp 23 (p_0=359 bar, 10.2 ACH) with exp 21 (p_0=362 bar, 6.2 ACH), we observe that the total flammable time is almost 2 minutes longer. A 1 minute increased in duration was observed when we compare the 700 bar experiments (exp 20 and exp 19). Since the MFR from reservoirs with higher pressure is higher, the natural consequence is that the flammable cloud occurs faster from those releases. Nevertheless, the ventilation rate has no (or very little) effect on the time when the cloud starts to be flammable. It is important to notice that the flammable time presented in table 3 and Fig.6 is only for the geometry used during the experiments. However, the difference between flammable time resulting from the releases with 6 ACH and 10 ACH demonstrate the effect of higher ventilation rate on the time of risk of ignition or explosion. The shorter flammable time as an effect of increasing forced ventilation rate was presented earlier by Prasad et al. [13].

The concentration results from all experiments did not exceed 9 %. This is below the 10% limit for fast flames described by Dorofeev et. all [16]. The authors, nevertheless, can not state it was due to applied ventilation rates since 'no-ventilation' case has not been performed. However, the concentrations are above the 4 % lower flammability limit. The flame propagation in a slow regime is regarded to result in mainer consequences.

CONCLUSION

The effect of the forced ventilation was investigated. The results of the presented experiments show the relation between hydrogen concentration from mass flow rate, reservoir pressure, and ventilation rate.

The maximum concentration results for 6 ACH and 10 ACH did not show a significant difference. The time when the cloud becomes flammable (reaches the minimum flammability limit 4%) has been observed differently for hydrogen releases with the same mass flow rate and different ventilation rates. The strongest effect observed during experiments is on the duration of the flammable cloud which reduces the duration twice for ventilation rate with 10 ACH.

As the recommendation for regulation codes and standards, it is recommended to keep the TPRD diameter small. Preferably 0.5 mm since the releases through 1 mm TPRD resulted in 3 times higher maximum concentrations. In the case of unintended hydrogen releases in the parking garage, the ventilation rate should be 10 ACH (or higher). Lower ventilation rates will result in a longer duration of flammable cloud.

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