Experimental and Analytical Study of Hydrogen Jet Fire in a Vented Enclosure

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ABSTRACT

An experimental and numerical study of hydrogen jet fire in a confined space was performed for hydrogen safety purposes within the European HyIndoor project (www.hyindoor.eu). An existence of two combustion regimes was numerically found and then experimentally confirmed. Depending on hydrogen mass flow rate, volume of the enclosure and vent area a well-ventilated or under-ventilated jet fire may occur. A chamber of 1x1x1 m^3 with upper and lower vent positions, vent areas from 1 to 90 cm^2 and different hydrogen mass flow rates from 0.027 to 1.087 g/s were used for numerical simulations and experimental validation. A lower axial position of a jet fire produced by immediate ignition of a hydrogen leak was established in the tests. A Background Oriented Schlieren (BOS) technique combined with high speed camera, pressure and temperature measurements were utilized in the tests to evaluate dynamics of the combustion process.

In case of small hydrogen release rate and large vent area, a relatively stable well-ventilated regime leading to over-pressure not more than 0.8 mbar and a maximum internal temperature of 540 C was established. In case of very high hydrogen mass flow rate and relatively small vent sizes three different scenario of under-ventilated jet fire behaviour with self-extinction, re-ignition and external flame modes leading to very high overpressure of 10-100 mbar and maximum temperatures of 1000-1200 C were experimentally measured. Strong influence of steam condensation on under-ventilated jet fire behaviour results in reduced sub-atmospheric pressures inside the chamber and intensive air ingress into the chamber. It may result in re-ignition of the quenched flame and then again to the extinction.

KEYWORDS: hydrogen, jet fire, safety, steam condensation, venting, enclosure

INTRODUCTION

Hydrogen leak in an enclosure and its immediate ignition leads to formation of a hydrogen jet fire. In the case of immediate ignition, the pressure inside the enclosure may be higher than the ambient one. This happens due to the hydrogen injection and expansion of combustion products. There is no data in the literature on overpressure and thermal effects for indoor hydrogen jet fire.

A number of experimental studies relevant to enclosure fires are published in the literature but very few studies relate to under-ventilated hydrogen fires with an exception of Ekoto et al. [1] recently presenting the data on a fire from hydrogen powered forklift in an enclosure. Froude number relationships were applied for scaling of the problem. The main purposes of the experiments were to validate the numerical models for full scale enclosure.

Jet fire development in an enclosure depends on flow rate, flame interaction with side walls and presence of vents [2]. Without vents the flame will deplete the oxygen in the enclosure until either fuel or oxygen is consumed and the flame will extinguish. The existence of vents may lead to different scenarios of flame development. If there is sufficient ventilation in the enclosure then the flame is fuel controlled and can be considered to be well ventilated. In the case of insufficient ventilation, the flame will be vent-controlled and may be considered to be under-ventilated.

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Since the product of hydrogen combustion is water, it is possible in the case of limited ventilation that the water vapor combined with the depletion in oxygen may lead to self-extinction of the flame if the mixture inside the enclosure is beyond the flammability limits for H_2-air-steam [3]. The presence of hot surfaces in an enclosure could lead to re-ignition and a potential explosion of unburned hydrogen with air ingress via the vent. It can be a reason for secondary pressure peaks.

An occurrence of oscillating and ghosting flames was experimentally shown in papers [4-6] for under-ventilated fires in an enclosure. It was observed that if ghosting flame reaches the vent, a re-ignition could occur due to fresh air ingress into the compartment and ignition of fuel excess.

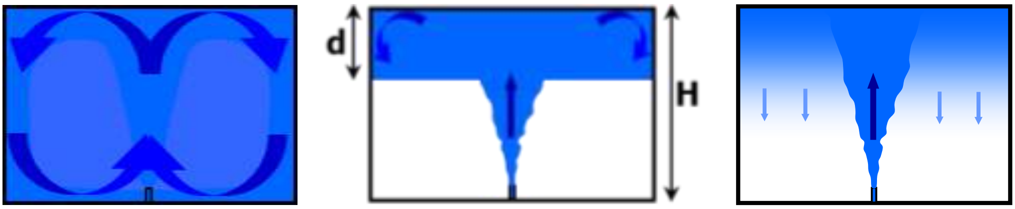
A series of indoor fire experiments using both natural and forced ventilation [7-8] showed that the vent size and geometry had a significant impact on the temperature and oxygen concentration profiles. Using non-dimensional analysis, it was shown that temperature and flame heights correlated with heat release rate and window geometry. An external flame was clearly observed.

A number of CFD simulations relevant to enclosed fires were performed. A fire extinction phenomenon and an external flame for under-ventilated regime were numerically captured in [9-10]. Only a few of CFD application relevant to hydrogen enclosure fires are known [1, 11-12]. The development of a flammable atmosphere and its subsequent ignition from hydrogen fuel cell was experimentally investigated in real scale and accounted in the simulations [1, 11]. A jet fire in a volume of 4.5x2.6x2.6 m^3 similar to real garage with vent and a hydrogen leak rate of 390 g/s was simulated in [12]. It was found that hydrogen combustion within the garage will consume oxygen and generate water. Self-extinction event in the enclosure could be expected shortly.

The hydrogen jet fire behavior is similar to the build-up of light gas concentration profile within an enclosed volume due to an injection of the light gas [13-15]. The difference is that the light density gas in the case of hydrogen jet fire is provided by hot combustion products. According to [13-15], the regime of indoor hydrogen jet fire may depend on volume Richardson number Ri_v:

$$Ri_V = g\frac{\rho_a - \rho_0}{\rho_0}\frac{V^{1/3}}{U_0^2}, \qquad (1)$$

where g = 9.81 m/s^2 is the gravity acceleration; ρ_a, ρ_0 are the densities of air and combustion products; V is the volume of the enclosure; U_0 is the speed of the source flow. Depending on the Richardson number, the dispersion of combustion products can be momentum or buoyancy dominated (Figure 1).



(a) (b) (c)

Figure 1. Regimes of light gas dispersion: (a) fully homogeneous (Ri_v < 0.0025); (b) stratified with a homogeneous layer (0.0025 < Ri_v: < 3); (c) stratified well-mixed layer (Ri_v > 3) [12-14].

A critical Richardson number of Ri_v=0.0025 was found for a homogeneous distribution of a light gas in air [13]. Another bound Richardson number of Ri_v = 3 was found for stratified well-mixed layer [14]. For homogeneous distribution, the homogeneity layer thickness $d = H$, where H is the height of the system. The homogeneity layer thickness for stratified distribution is based on empirical correlation [13]:

$$\frac{d}{R_0} = \frac{C}{\sqrt{Ri_V}}, \qquad (2)$$

where C = 25 is the empirical constant; R_0 is the radius of the source. Thus, the behavior of jet fire in an enclosure can be similar to the light gas dispersion. For instance, for momentum dominated jet fire, in case of higher mass flow rates, the extinction of the flame can be expected due to mixing of air with combustion products. For buoyant plume a quasi-steady layered distribution of combustion products can be expected. Thus, the similarity of hydrogen jet fire behavior and light gas dispersion within an enclosure should also be investigated.

NUMERICAL SIMULATIONS

A parametric study of hydrogen jet fire in an enclosure with single upper, single lower and two vents (upper and lower) is considered to study the phenomena of well- and under-ventilated jet fires in a cube of 1 x 1 x 1 m^3 with vent(s). Numerical tests were performed using ANSYS Fluent pressure-based solver with SIMPLE pressure–velocity coupling algorithm, first order spatial discretization and with gravity forces [16]. A series of 8 numerical simulation tests, to be validated against experimental data, was performed to capture different regimes of enclosed jet fire development (Table 1). The appearance of different combustion regimes was provided by changing of hydrogen mass flow rate through a 5-mm id nozzle 100-mm above the floor and a vent geometry. The volume Richardson number is also given in the Table 1 as a measure of momentum or buoyancy driven dispersion of combustion products in an enclosure. For well-ventilated regime the values of volume Richardson numbers for Tests No.1 and No.2 in the range $Ri_v = 0.0236 \div 0.377$ are typical for homogeneous stratified layer ($Ri_v > 0.0025$, according to [13]). For $Ri_v < 0.0025$, the only under-ventilated regimes with self-extinction (No.3 and No.6) and external flames (No.7 and No.8) were numerically captured. There are some transient regimes belong to the under-ventilated regimes but with $Ri_v > 0.0025$ (No.4 and No.5).

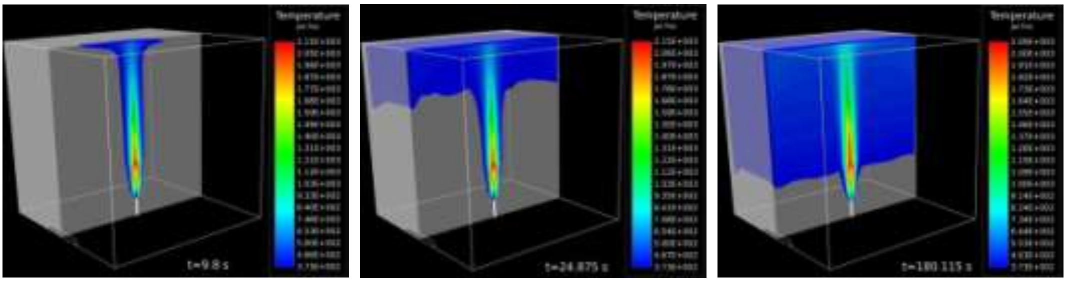
Table 1. Numerical simulation tests to be experimentally validated.

Test No.	Vent size, HxW [cm^2]	Flow velocity, [m/s]	Flow rate [g/s]	Time to reach the result [s]	Volume Richardson number	Result
1	Horizontal 3x30 (LV)[a]	15	0.0272	-	0.3773	WV
2	Vertical 30x3	60	0.1086	65	0.0236	WV [a]
3	Horizontal 3x30	300	0.5486	90	0.0009	UV,SE [a]
4	Horizontal 3x30 (LV)	60	0.1086	100	0.0236	SE
5	Horizontal 3x30	150	0.2714	140	0.0038	EF [a]
6	2 horizontal vents (Up: 3x15; Low: 3x15)	600	1.0857	92	0.000236	UV,SE
7	2 horizontal vents (Up: 3x15; Low: 3x15)	600	1.0857	40	0.000236	UV,EF
8	Horizontal 3x30 (LV)	600	1.0857	-	0.000236	UV,EF

[a] LV - lower position; SE - self-extinction, WV - well-ventilated; UV - under-ventilated; EF - external flame.

Well-ventilated enclosed jet fire

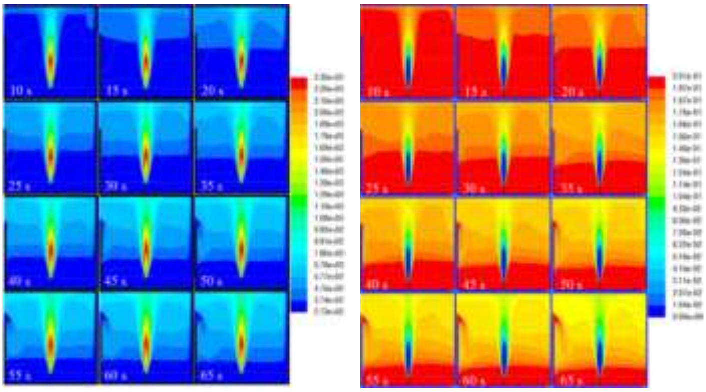
Numerical experiment No.1 represents a well-ventilated case for lower vent. Figure 2 shows dynamics of well-ventilated hydrogen jet fire (central cross-section area of the enclosure is shown) with velocity of release of 15 m/s. Horizontal vent is located at the left wall (bottom position). Semi-empirical evaluation of the thickness of turbulent mixing layer (Eq. 1) gives the value d~100 mm. The maximum temperature at the ceiling is in the range of 734-914 K.



(a) (b) (c)

Figure 2. Dynamics of temperature profile for jet fire Test No.1: (a) t=9.8s; (b) t=24.9s; (c) t=180.1s.

Figure 3 shows dynamics of well-ventilated hydrogen jet fire in numerical experiment No.2 (central cross-section area is shown) with release velocity of 60 m/s. The vertical vent is located at the left wall. The reaction zone, which is associated with hydroxyl radical OH, increases in the period from 10 s to 65 s. Then, at the end of numerical experiment the fire is at quasi-steady state conditions with formation of well-mixed layer of combustion products according to $Ri_v > 0.0025$ criterion. Due to completeness of combustion, there is practically no hydrogen in the chamber. An oxygen deficit due to the hydrogen combustion (less than 21%) shown in yellow-green colors (Figure 3 b). The oxygen deficit for further combustion is compensated by fresh air ingress through the vent. It is visible as a jet of fresh (21%O_2) cold air in Figure 3 (upper left corner). Rough evaluation of the thickness of turbulent mixing layer of combustion products (Eq. 1) gives the value d~400 mm. The maximum temperature at the ceiling is about 1000K (Figure 3 a). The steadiness of the process indicates that the fire is well-ventilated in Test No.2.

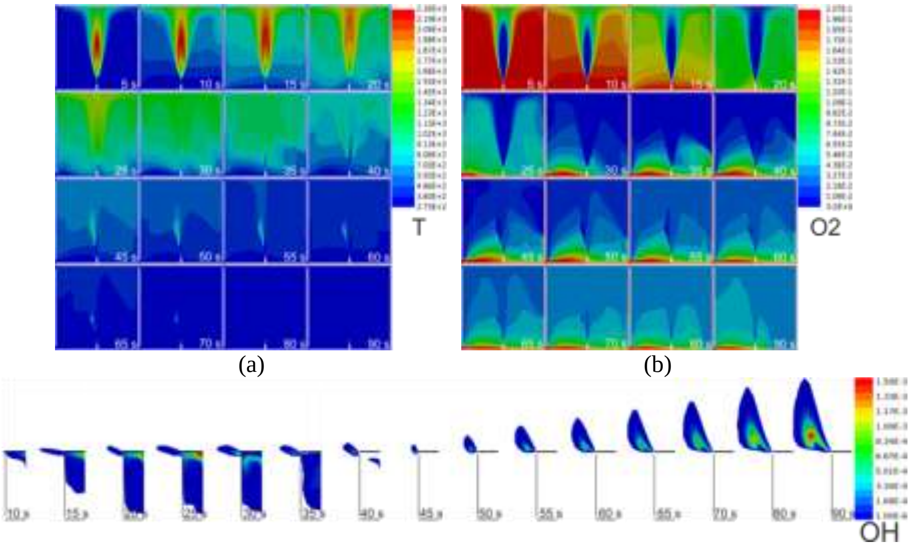


(a) (b)

Figure 3. Well-ventilated jet fire Test No.2: (a) temperature profile; (b) oxygen concentration profile.

Under-ventilated jet fire

External flame and self-extinction phenomena were numerically investigated for under-ventilated regime for hydrogen jet fire. In Test No.7 with two vents 3 x 15 cm^2 and a flow velocity 600 m/s an external flame was observed (Figure 4). The process develops in two stages. The first one is the oxygen depletion due to reaction with hydrogen and an enrichment of the enclosure with combustion products steam and nitrogen. Due to the oxygen deficit, a part of hydrogen released through the vent and burns in ambient air with production of OH radicals (Figure 4 c). It happens in 30-35 s from jet ignition. The second, further increase of oxygen deficit leads to suppression of internal jet fire and an increase of unreacted hydrogen release through the vent with formation of a steady external jet fire (frames after 40-45 s, Figure 4 c). For instance, the mixture composition at 50 s of experiment is very pour with about 2% O_2, 21% H_2, 26% H_2O and 51% N_2. According to flammability limits [3], the oxygen concentration below 5% does not support hydrogen combustion. The maximum temperature at the ceiling reaches 1600-1700K in 20s after ignition moment and then reduced to 400-500K when internal flame is quenched (more than 45s).



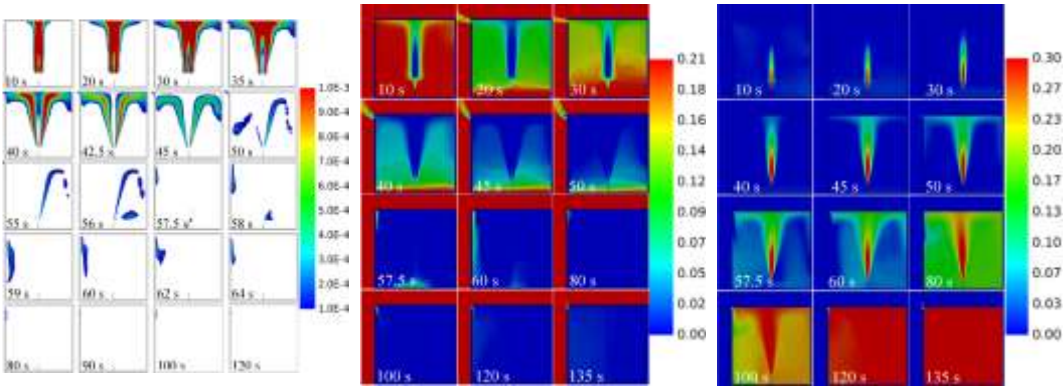
(a) (b)

(c)

Figure 4. Under-ventilated jet fire in Test No.7: (a) temperature profile; (b) O_2 concentration profile; (c) external OH concentration profile.

Self-extinction of hydrogen flame indoors was simulated and analyzed for numerical experiment No.3 with horizontal vent and release velocity of 300 m/s (Table 1). It was found that there is a period of time from 27.5 s to 70 s when the whole vent area is occupied by the flow of air into the enclosure. Figure 5 shows the dynamics of OH mole fraction, O_2 and H_2 concentration profiles for simulation Test No.3. Reaction contour (OH mole fraction of 1E-04) moves out of the enclosure at about 30 s (Figure 5 a). This zone of reaction outside the enclosure separates from the reaction zone inside the enclosure at 45 s and exists until about 56 s. At about the same time of 56-57 s there is air ingress into the enclosure that supports a weak reaction (re-ignition like) just below the vent. This local reaction zone practically ceases at about 120 s. Contrary to the Test No.7 there are no conditions for the external flame in Test No.3. Hydrogen jet fire is fully quenched after 50s because oxygen concentration below 5% surrounded the jet does not support the combustion (Figure 5 b). The chamber starts to be filling with pure hydrogen and its concentration reaches more than 30%H_2 after 120 s (Figure 5 c). In case of re-ignition it may lead in reality to very strong explosion of almost stoichiometric mixture if local ignition source will appear inside or outside the enclosure.

Characteristic time to establish the self-extinction or external flame regimes for different hydrogen mass flow rates was found in numerical experiments. We may roughly evaluate this time as the time t_c for complete consumption of air depending on mass flow rate $\dot{m}$ as follows:



(a) (b) (c)

Figure 5. Under-ventilated jet fire Test No.3: (a) OH concentration profile; (b) O_2 concentration profile; (c) H_2 concentration profile.

$$t_c = V_b \cdot \rho_a / (34.3 \cdot \dot{m}), \tag{3}$$

where $V_b = V - V_u$ is the test volume V=1 m^3 with an exception of unburnable part V_u= 0.05*4.76*V = 0.238 m^3 (below 5% O_2 (mol.) according to flammability limits [3]); ρ_a = 1.2 kg/m^3 is the density of air at ambient conditions; 34.3 is the stoichiometric mass ratio of air to hydrogen $(m_{air}/m_{H2})_{st}$. The data obtained in numerical simulations will be compared with experimental data.

EXPERIMENTAL DETAILS

Experimental facility

The test facility consists of a cubic enclosure with inner dimensions of 1000x960x980 mm³, two transparent and four solid metal plates reinforced by aluminum profile rails. Four aluminum plates with a thickness of 10 mm cover the upper, bottom, front and rear sides of the enclosure, while two transparent walls (composite of 5 mm fire-protection glass (Pyran) and 15 mm of Plexiglas (Makrolon) cover left and right side Transparent windows allow an optical access for BOS-technique to visualize the flame and combustion products in the tests. A tube nozzle of 5 mm id diameter is located at the center of bottom metal plate, 100 mm above the floor. The ignition source is 2 cm above the nozzle and 1 cm from centerline to provide most efficient ignition of released hydrogen. The spark plug starts to operate simultaneously with hydrogen release so that it was no time for unignited hydrogen accumulation. Horizontal vents of 3x15 and 3x30 cm^2 or a vertical vent of 30x3 cm^2 are located at the top or bottom positions of the front plate. An orifice of 1 cm^2 area (∅11mm) at upper center position was also investigated.

Instrumentation

Jet fire regimes in an enclosure are investigated as function of vent size and hydrogen mass flow rate. The mass flow rate is measured and controlled by a Coriolis mass flow meter (type Emerson CMF010P, < 30 g/s H_2). Lower mass flow rates (< 0.2 Nl H_2/min) is measured by Bronkhorst EL-Flow (Type F-220AV-M20, 0.2 - 273 Nl H_2/min). To provide required mass flow rate a bulk pressure of hydrogen was also controlled by a pressure sensor.

The main characteristics of an enclosed jet fire are the position of the flame front, the pressure and temperature inside the enclosure. To gain information about the flame front position, a BOS-technique is used, which allows visualization of density gradients in transparent media [17]. The method is applied to the record of in- and ex-vessel processes using two high speed cameras (~70 fps) and two Canon photo cameras (1-30 fps). To record the overpressure history a pressure transducer GEMS 220SG1B601A3UA001, for relative pressure in the range of -1 – 10 bar and U-shape differential manometer filled with colored water were used. Fourteen NiCr/Ni (Type K) thermocouples without protective coating (time resolution 10 ms) are installed in different positions to record the temperature history. Several of the thermocouples are positioned outside the vessel, close to the vent, to measure temperature of released combustion products and to distinguish the external flame. The signals of all sensors are recorded with a data acquisition system with a sampling rate of 1 Hz.

Test matrix

Two series of experiments on hydrogen jet fire in an enclosure have been performed within the European HyIndoor project (www.hyindoor.eu) at the KIT HYKA test site to evaluate the combustion overpressure and temperature distribution, and to confirm the results of blind numerical simulations on indoor fire regimes. Upper and lower vents with vent area 1-90 cm^2 and hydrogen mass flow rate in the range 0.027-1.087 g/s were varied in the tests. Maximum pressure and temperature are given in the Table 2 as integral characteristics of the process. According to the conditions of blind numerical tests shown above, only 7 of total 39 tests have been chosen for the further analysis of two principal regimes (Table 2): (1) well-ventilated experiments with rather big vent area and relatively low hydrogen mass flow rate providing sufficient amount of air for a stable jet fire; (2) under-ventilated ignited jet with an oxygen deficit due to the higher hydrogen mass flow rate and insufficient vent area leading to self-extinction of the jet fire in an enclosure and re-ignition of released hydrogen due to additional air ingress through the vent. Self-extinction and re-ignition as well as internal and external flames not attached to the jet-fire itself were distinguished as particular cases of under-ventilated regime.

Table 2. Experimental conditions and main results.

Test No.	Vent size, HxW [cm^2]	Flow rate [g/s]	Time to reach the result [s]	P_{max}, [mbar]	T_{max}, [°C]	Result
26/1[a]	Horizontal 3x30 (LV)[a]	0.0272	50/548	0.72	242	WV[b]
25/2	Vertical 30x3	0.1086	40/205	0.77	541	WV
58/3	Horizontal 3x30	0.5486	70/90	13.5	1171	RI[b],SE[b]
62/4	Horizontal 3x30 (LV)	0.1086	139/255	1.4	557	UV,SE
28/5	Horizontal 3x30	0.2714	95/106	33.8	853	RI,SE
59/6	2 horizontal vents (Up: 3x15; Low: 3x15)	1.0857	14/27.5	12	1162	RI,SE
59/7	2 horizontal vents (Up: 3x15; Low: 3x15)	1.0857	27/27.5	12	1162	RI,SE
61/8	Horizontal 3x30 (LV)	1.0857	11/30	23.4	1191	UV[b],RI

[a] a number of corresponding numerical test from Table 1 is shown after "/" in column "Test No."
[b] LV - lower position; SE - self-extinction, WV - well-ventilated; UV - under-ventilated; RI – re-ignition.

RESULTS AND DISCUSSIONS

Well-ventilated jet fire

General behavior of jet fire based on BOS images is shown in Figure 6. The well-ventilated hydrogen jet fire (Tests 25-26, Table 2) is very similar to CFD simulations (Tests 1-2) with the difference that the BOS images cannot distinguish an interface between reaction zone and combustion products. We may see ignited hydrogen jet structure, gathering at the top combustion products and its release through the vent. After few seconds, jet fire burns 200-550 s with formation of a stationary temperature distribution inside the enclosure (Figure 7). The maximum temperature at the center of ceiling, above the nozzle position, is measured in the range of 515-830K (Table 2) or 100-200K lower than calculated. Second difference is that the condensation wave appears in the tests as a dark, not transparent zone, moving downward. Since the CFD code has not a condensation model, such phenomena could not be numerically simulated. According to hydrogen mass flow rate and injection time (Table 2), the theoretical amount of condensed water should be 200-300 g. In reality, due to the venting, it was order of 100 g of water after each test gathering as a pool at the floor and as water droplets at side walls.

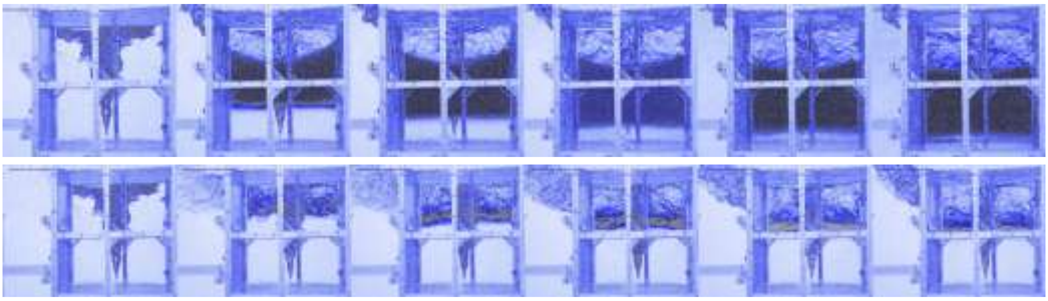


Figure 6. BOS images of enclosed jet fire for well-ventilated regime (test 25, 60 m/s, m=0.1086 g/s H_2): upper - whole process (1 fps, every 30th is shown); lower – initial part (1 fps, every 2nd is shown)

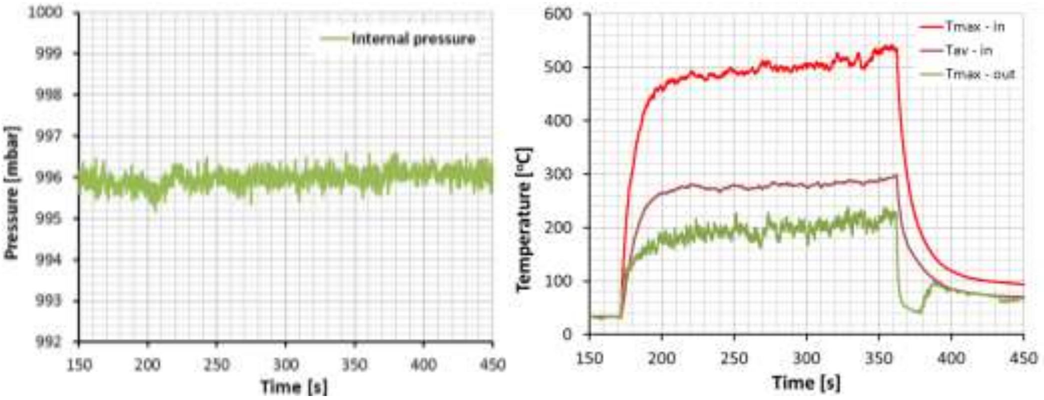


Figure 7. Typical pressure transients (left) and temperature histories (right) for well-ventilated jet fire regime (Test 25: release of hydrogen 0.1086 g/s, upper vent area of size 30x3 cm^2).

One of the tests, Test 62 (0.10857 g/s), should be classified as well-ventilated jet fire according to the volume Richardson number $Ri_v > 0.0025$ [13]. Nevertheless, the self-extinction is occurred at 139 s, same as for CFD simulations (Test 4). Characteristic time to reach the self-extinction, t_c = 139 s, is very close to that obtained numerically, t_c = 100 s (see Table 1). The danger of such scenario is that hydrogen release continues 117 s after the quenching, gathering in the vessel until the valve switched off. The volume of accumulated unreacted hydrogen of 140 liters could explode if the maximum temperature at the top would not be so low (500K).

Under-ventilated jet fire

Initial phase of experimental jet fire looks very similar to numerical simulations (Figure 8). The difference is that rather strong explosion with overpressure of about 10 mbar initially occurs due to ignition of released hydrogen (Figure 9). Then, a period of quasi-steady process is established. It may take 5-15 seconds until the maximum temperature of 1300-1450K is established. Such temperature is in 300-350K lower than for numerical simulations. Then the temperature above the jet fire rapidly decreases up to 600-700K due to consumption of oxygen and local flame extinction after that steam condensation will dominate compared to the expansion of combustion products. This leads to air ingress inside the vessel caused by negative pressure and re-ignition of unreacted hydrogen with pressure increase up to 10-20 mbar. The flame is localized at the vent interface as external-internal flame. Such oscillating process of extinction-re-ignition may be repeated many times during 10-60 s. The evidence of external flame might be external temperature of the order 800-900K. This was the major difference with numerical simulations which did not take into account the steam condensation process.

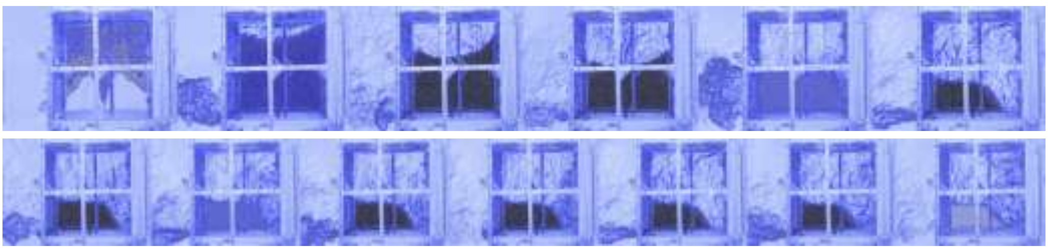


Figure 8. BOS images of under-ventilated jet fire with extinction-re-ignition and external flame (test 61): upper - whole process (2fps, every 10th is shown); lower – 2 re-ignitions with external flame (47-53 s)

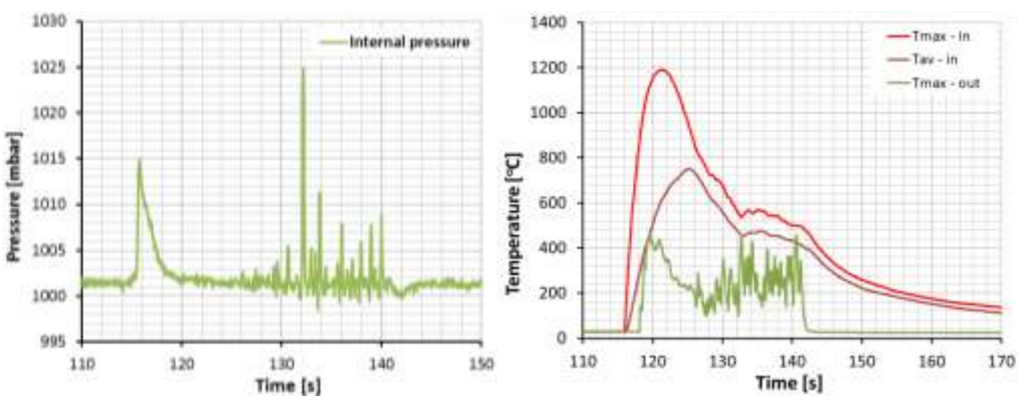


Figure 9. Typical pressure transients (left) and temperature histories (right) for under-ventilated jet fire regime (Test 61: release of hydrogen 1.086 g/s, lower vent area of size 3x30 cm^2).

CONCLUSIONS

A series of experiments on ignited hydrogen jet fire in an enclosure have been performed within the European HyIndoor project (www.hyindoor.eu) at the KIT HYKA test side in order to evaluate maximum combustion pressure and temperature and to validate blind numerical simulations performed at UU (UK) for different combustion regimes. The experiments were carried out in the presence of different geometries of vent area (multiple or single vents, different areas) and different hydrogen mass flow rates to provide the conditions for well-ventilated and under-ventilated jet fire leading to internal-external flame or self-extinction.

Pressure, temperature and high speed BOS imaging were used in the tests. The pressure signal consists of a primary pressure rise due to the pressure peaking phenomena, then steady state equilibrium atmospheric pressure and then, finally, oscillating pressure up to 20-30 mbar during the re-ignition or external –internal flame behavior.

Strong influence of steam condensation during jet fire experiments was observed in the tests.

The experiments carried out were compared against numerical simulations and demonstrated very good qualitative agreement with an exception of pressure oscillations due to extinction-ignition phenomena governed by steam condensation. However, the numerical simulations clearly explained the nature of different jet fire regimes in an enclosure with vent(s).

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