NATURAL AND FORCED VENTILATION STUDY IN AN ENCLOSURE HOSTING A FUEL CELL.

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1. Abstract

The purpose of the experimental work is to determine the conditions for which an enclosure can guest a fuel cell for civil use. Concerning the installation permitting guide, this study allows the safe use of the fuel cell in case of small not catastrophic leakages. In fact the correct plan of the vents in the enclosure guarantees the low concentration of hydrogen (H_2) below the LFL.

2. Summary

The University of Pisa conducted tests as part of the EC supported HYPER project to determine the ventilation requirements in enclosures containing fuel cells, such that in the event of a foreseeable leak, the concentration of H_2 in air for zone 2 ATEX (2% v/v) is not exceeded. The first assumption concerns the pressure for the leak. The worst case scenario correlates to a value of 5 bar with a leak position before the pressure reducing valve.

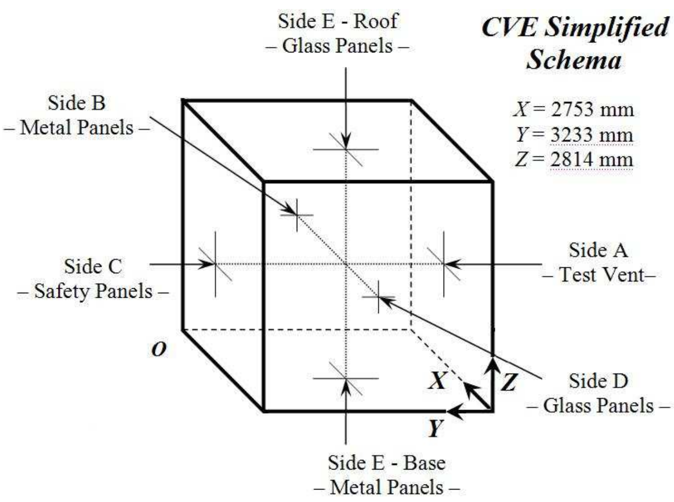
The second main assumption concerns the area for the leak. It has been chosen according to the ATEX guideline for a small accidental leak from a valve. This is analogous to a leak area of 0.25 mm^2 and produces a flow rate of not more than 40 l/min.

Both natural and forced ventilation of enclosures using fans was investigated. Other larger leaks were also tested having areas of 0.5 and 1.0 mm^2. The adequacy of the ventilation in the enclosure has been shown to depend upon four factors: Geometry of vents; Size of vents; Wind speed; the temperature gradient between the inside and outside of the enclosure.

3. General description of the experimental asset

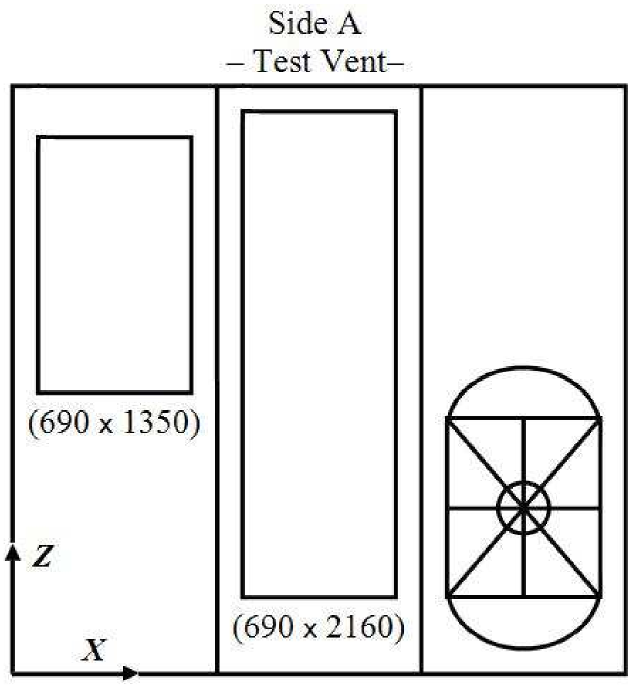
The CVE facility tests the effect of the vent area in function of the pressure during deflagrations of the explosive mixtures, (hydrogen/air or methane/air), in uniform and not uniform conditions. Vented explosion experiments have been carried out in a cubic structure made of steel section bars with an internal volume of 25 m^3.

The roof and one side face are entirely covered with panels of glass in order to follow and to record with digital cameras the evolution of the explosions. All the other faces are covered with steel panels having different functions: the bottom and one side are entirely made of steel strengthened panels which are not removable, while the other two lateral faces, on opposite side, are the test vent and the safety vent respectively (see fig. 1 and fig. 2).



. Figure 1. CVE General description.

Figure 2. CVE General overview



.Figure 3. CVE Side A, vent areas.

Figure 4. CVE Side A, vent overview

The vent is normally covered by plastic material with known pressure of rupture. The free area of the vent is adaptable according to the specification of the experiment.

The area can be fixed from a minimum value of 0.35 [m^2] up to 2.5 [m^2] (completely open). In the fig. 4 the vent window is shown, it is also visible the position of the thermocouple on the bottom of the window.

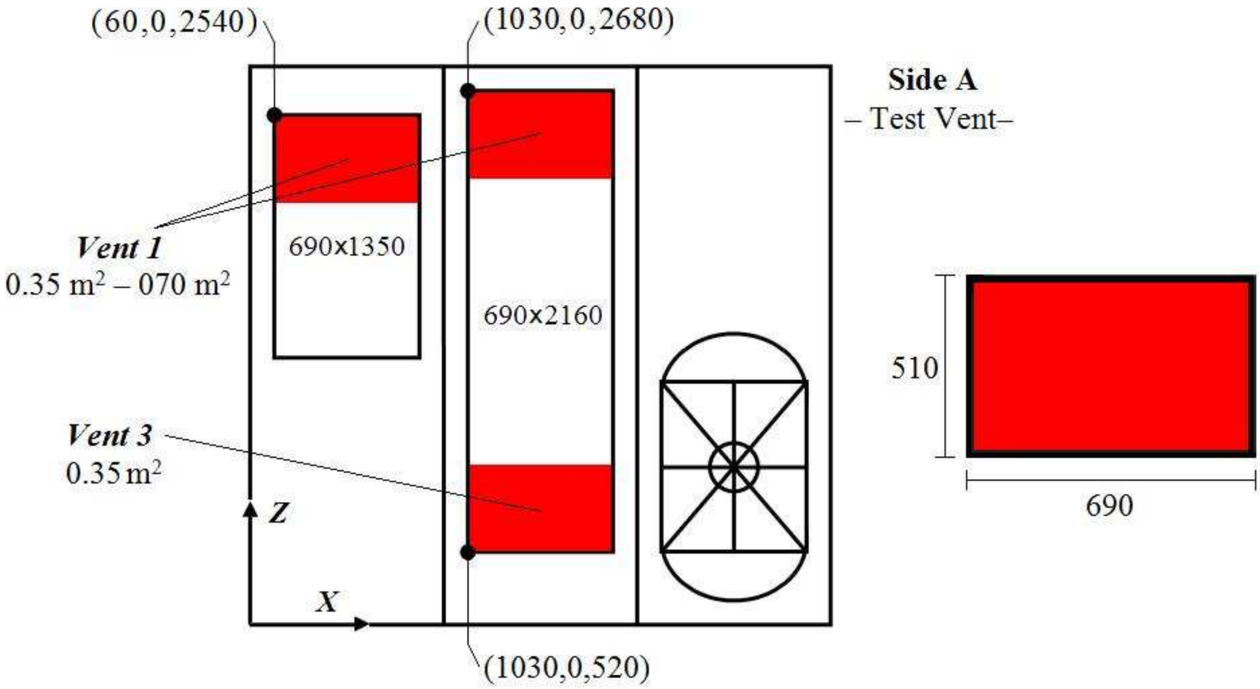


Figure 5. Size and location of Vent 1(Side A) coordinates in [mm];
Vent 1 small = central rectangle 0.35 m^2; Vent 1 big = both rectangles 0.70 m^2.

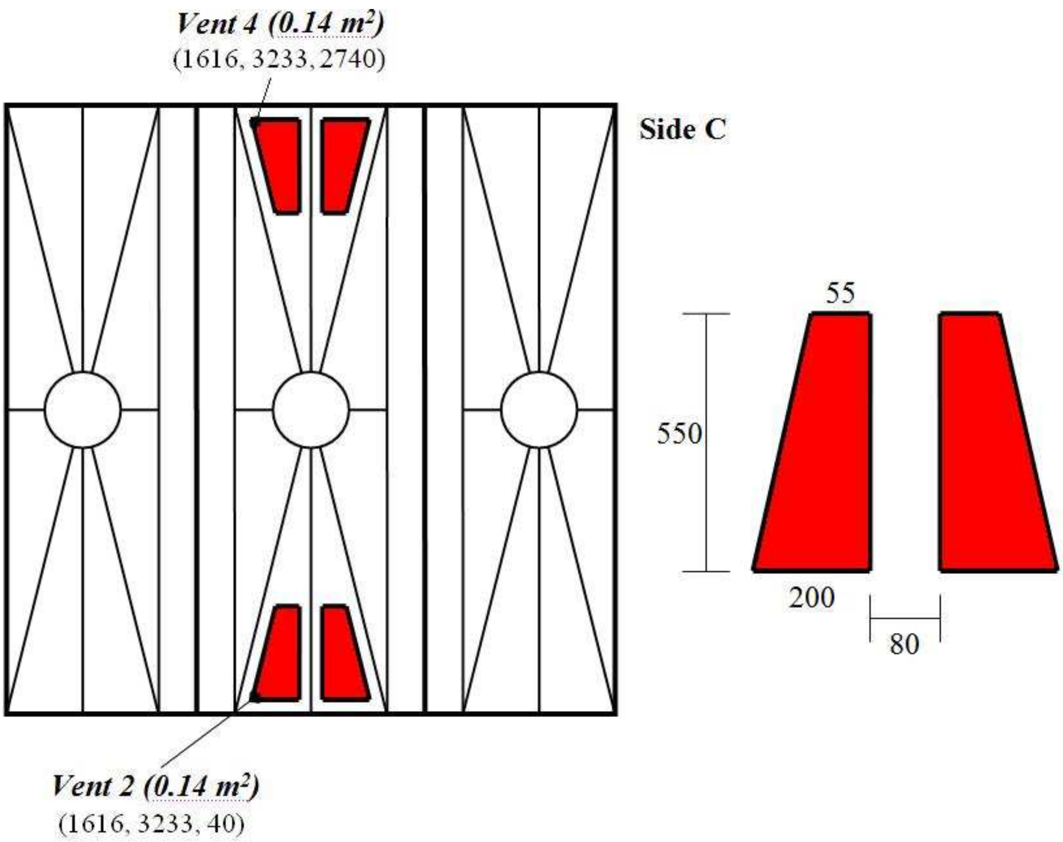


Figure 6. Size and location of Vent 2 and Vent 4 (Side C) coordinates in [mm].

4. The inlet and gas concentration measurement systems

An element of primary importance for the CVE safety is represented from the inlet system of the gas bringing the gas inside to the equipment, feeding the fuel cell PentaH2. The malfunctioning of such system can cause an uncontrolled flow or an unpredictable leak of H_2.

Based on the normative for the inflammable gas transportation, the entire circuit and all the connections among several the elements have been realized in stainless steel, AISI 304 NPA49-117, according to the Norm 1072 UNI 8-10 indications. The CVE inlet circuit is constituted from the compounds in figure 7.

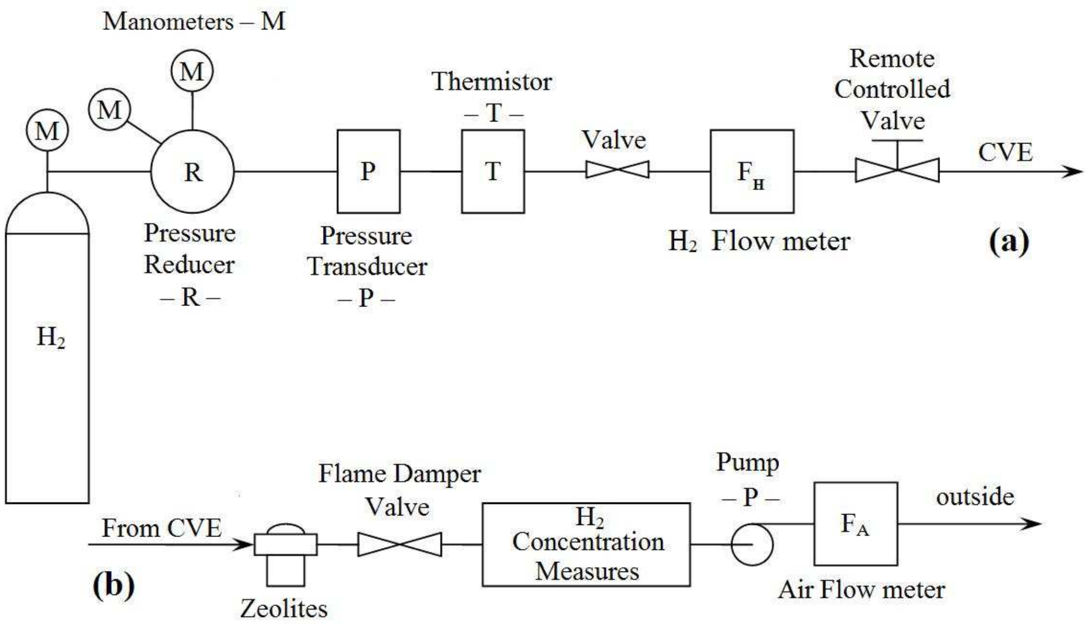


Figure 7. (a) Inlet system scheme; (b) pipeline schema of sampling and the exhausts.

- Four gas cylinders with a initial pressure 200 bars; for safety reasons they are not in direct sight line of CVE. The head valves of gas cylinders are protected by a steel structure in with padlock that can be only removed from the operator.
- two stages pressure reducer in which the gas pressure decreases from 200 to 3 bars;
- one flame damper valve, connected in series to the pressure reducer;
- a thermo resistor and a pressure transducer positioned immediately after the valve flame damper. Such instrumentation is necessary for the measure of the gas flux;
- a mass flux meter with range of measure 0.3-16.6 l/s;
- one micrometric valve for the precise tuning of the gas flow;
- one not return valve and two remote controlled pneumatic interception valves. The second one, placed to the CVE interface (side B), allows to isolate the equipment from the inlet circuit before the test.

The concentration measure circuit of inner gas is constituted like shown in figure 5 (b):

- 5 lines for the aspiration of the inner atmosphere in the CVE, constituted from stainless steel tubes AISI 304 NPA49-117, according to the indications of 1072 UNI 8-10 Norm; the withdrawal (sampling) points are positioned in independent way one from other by the use of flexible tubes in PVC that fit in the steel connections of the aspiration circuit.Clearly they can easily be repositioned;

- valve flame damper positioned on the pipeline with the purpose to protect the concentration H_2 analyzers;
- a zeolites dryer in order to eliminate the humidity from the gas sample, necessary for the correct functioning of concentration H_2 analyzers;
- air flux meter with regulation valve and lower measurable limit of 1,2 l/min in order to stabilize the flow at 1 l/min in operational conditions for each analyzer;
- hydrogen concentration analyzers and natural gas placed in Wall B completely constituted from fixed metallic panels (figure 2); such positioning of the instrument meaningfully reduces the delays due to the length of the sampling pipe connected to the analyzers;
- pump for the aspiration of the inner sample of the CVE; it exists a series of three ways valves with which it is possible to switch from the parallel aspiration configuration to the aspiration in series made for the calibration analyzers phase. During the calibration the five analyzers are connect to calibration gas cylinders, by a bypass used only in this phase;
- flow meter supplies a verification of the inhaled total (integrated) flow pumped into the CVE approximately slightly more then 5 liters every minute for the corrected operation of the concentration analyzers during the tests;
- the drain system of the sample in air to approximately 5 m of height from the level of the ground and not in direct sight of the equipment; such height is sufficient to guarantee the dispersion of the inflammable mixture because the drainage happens totally in free atmosphere and with small flow (total 5 l/min);
- An external fan provides the washing of the inner atmosphere after each explosion and in case of emergency evacuation of the gas. Its air flow is 1340 m^3/h (22.3 m^3/min);
- a fan inside to the CVE to make homogenous the explosive mixture.

Figure 8. Interface between CVE and inlet system.

5. Description of the Fuel Cell Penta H_2 positioning

The fuel cell Penta H2 (size in [mm] 800 x 688 x 1024) has the following characteristics:

Performance
Net electric power: 1 to 5 and Idle
Voltage:120 or 220 VAC
System Electric efficiency at nominal power: 45%

Operating Modes
Start up Time: 12 second to 0.5 kW, 1 minutes to full power
Routine Maintenance Interval: 500 hr
Mass: 200 kg
MTBO: 500 hr
locations: Indoor and Outdoor (protected from rain)
Operating Temperature: 0 to 50°C
Storage Temperature: Above 0°C
Noise: 55 dBA @ 1 m, Outdoor

Hydrogen Supply
Hydrogen Grade: Grade 5.5 (EU)
Inlet pressure: 2-5 bara
Mass flow: Dead end - pulsing
Anode stoichiometric: 1,02
Fuel Consumption: 4,2 Nm3/hr at max power

Primary circuit
Water cooled: 70-75 T°C
Circuit type: Closed circuit with circulating pump
Required Water Quality: DI (< 5 µS/cm)- External water only required for initial fill
Water quantity: 15 litre

Secondary circuit
Water cooled: Inlet min, 20 - max, 55 ; outlet min, 25 - max, 60 T°C
Circuit type: External pump is required
Required Water Quality: No particular requirements

Interfaces
Front panel: Liquid crystal display, with: start ,stop, up, down, insert button under skin
Communication: Rs 232 serial port for remote operation
Hydrogen inlet and outlet on the front endplate: ¼ npt

Lifetime: 3000 hr (before losing 5% of voltage performance at nominal condition)

Operating condition
Environment temperature range for operating: 0°C / +50°C
Start up time up to 50% nominal power @ 0°C: < 5 min
Environment temperature range for depositing on the shelf: -30 °C / + 60°C
Percent of nominal power delivered at extreme temperature: 100%

The fuel cell location inside the CVE is shown in fig. 9. The most credible loss of H_2 is located on the valve of the inlet gas pipeline, before of the pressure reducer. The internal pressure between 2 bar and 5 bar has been considered, after the pressure reducer (inside PentaH2) the pressure value is 350 mbar.

In order to take into account the worst case of loss, the highest pressure value (5 bar) has been chosen. The calculations of the H_2 flow G_{H2} has been performed with EFFECT-SGIS 7.3.

The diameter of the leakage has been chosen according to ATEX limits in order to calculate the *Zone 2*, in that case for pipelines with max diameter 150 mm, the guide refers to a small accidental leakage from a valve (exactly the case of the H_2 inlet pipeline).

The ATEX loss value from a valve is analogous to a flux from an hole with diameter Φ_L = 0.56 mm i.e. area A_L = 0.25 mm^2.

Calculations are referred also to areas of 0.5 mm^2 and 1 mm^2 to get the opportunity to study more dangerous cases then the ATEX one.

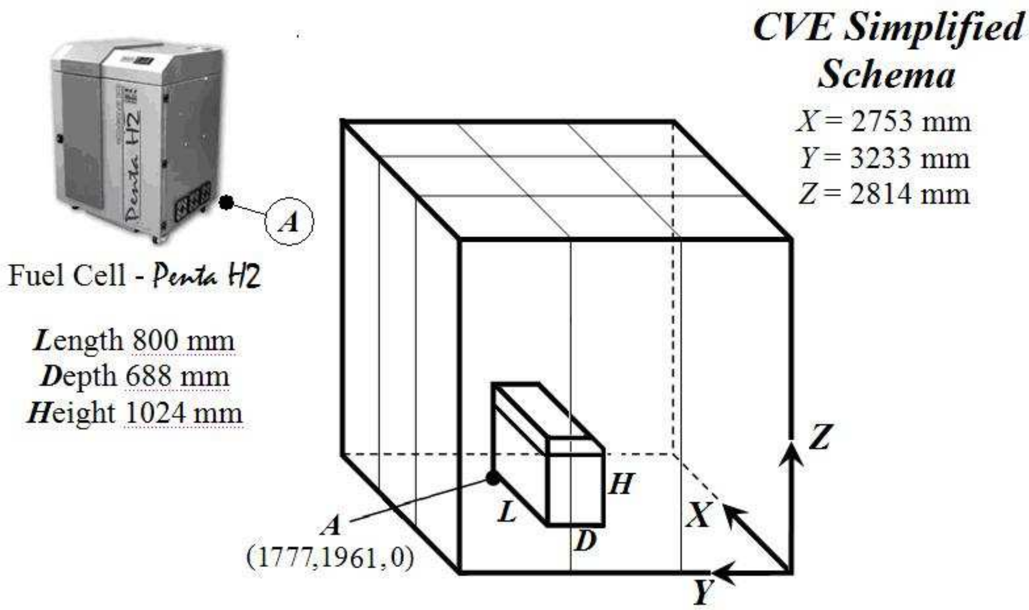


Figure 9. Fuel Cell Penta H_2 positioned inside CVE.

ATEX Limits:

- ***Zone 0 : Continuous leakage → 25%LEL = 1%H_2vol;***
- ***Zone 1 : Operational release → 25%LEL = 1%H_2vol;***
- ***Zone 2 : Occasional leakage → 50%LEL = 2%H_2vol.***

Figure 10. ATEX Limits for not-catastrophic loss of H_2 accidents. LEL is the lower explosive limit.

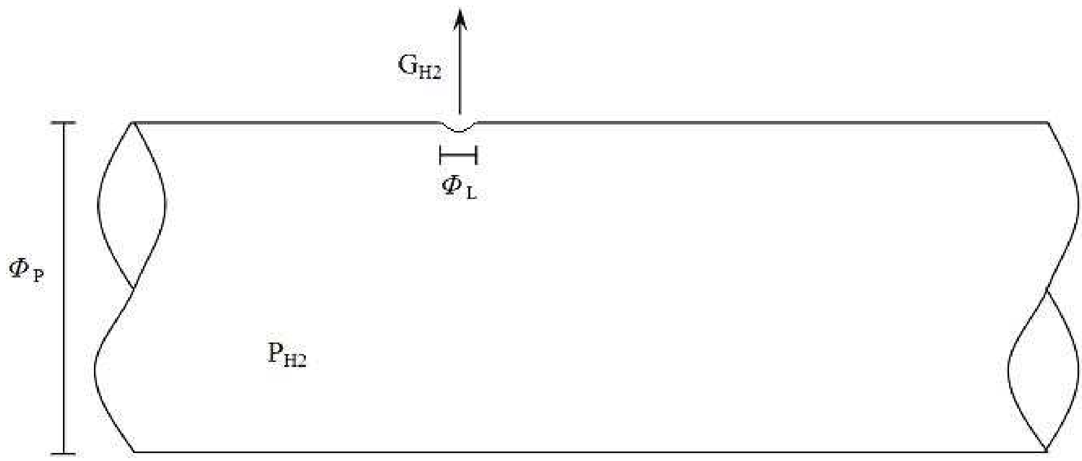


Figure 11. Φ_L = Diameter of Leakage (A_L = Leakage Area); Φ_P = Diameter of Pipeline (6 mm); G_{H2} = H_2 Flow; P_{H2} = H_2 internal pressure (from 2 to 5 bar).

Table 1. G_{H2} [10^{-5} kg/s] values versus P_{H2} and Φ_L (and A_L).

G_{H2} [10^{-5} kg/s]	Φ_L [mm]	A_L [mm^2]	P_{H2} [bar]						
			2	2,5	3	3,5	4	4,5	5
	0,56	0.25	2,47	3,08	3,7	4,32	4,94	5,56	6,18
	0,8	0.50	4,97	6,21	7,46	8,68	9,93	11,2	12,4
	1.13	1.00	9,98	12,34	14,8	17,34	19,8	22,3	24,8

Table 2. G_{H2} [nl/min] values versus P_{H2} and Φ_L (and A_L).

G_{H2} [nl/min]	Φ_L [mm]	A_L [mm^2]	P_{H2} [bar]						
			2	2,5	3	3,5	4	4,5	5
	0,56	0.25	18,25	22,76	27,34	31,92	36,50	41,08	45,66
	0,8	0.50	36,72	45,89	55,12	64,14	73,37	82,76	91,62
	1.13	1.00	73,74	91,18	109,36	128,13	146,30	164,77	183,25

6. The leakage measurement and control system

The measures of diameters refer to the external value; material of the components is AISI – 316. The flow meter contains the regulator system and all the signals are monitored in real time. The list of the components follows the fig. 12.

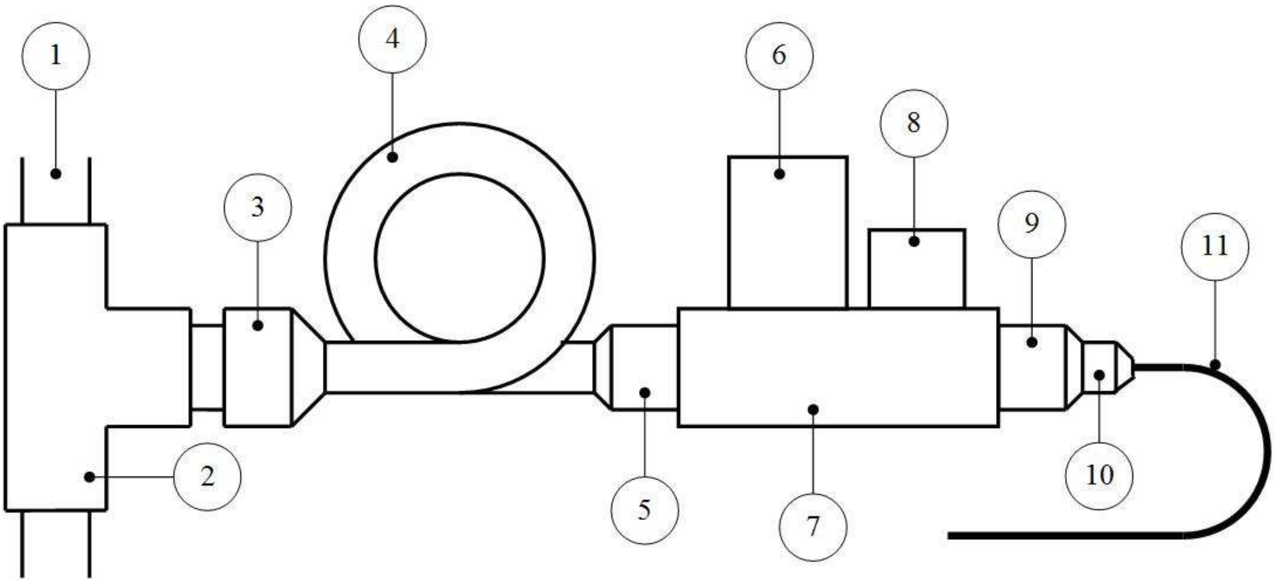


Figure 12. Components for the control and measurement of the H_2 leakage.

1) H_2 inlet pipeline (*Φ* 8 mm ; 5 bar);
2) Tree way connector *Φ* 8 mm;
3) Adaptor from *Φ* 8 mm (main H_2 inlet pipeline) to *Φ* 6 mm;
4) Pipeline *Φ* 6 mm;
5) Adaptor from *Φ* 6 mm to ½ inch
6) H_2 flow regulator;
7) H_2 mass flow central body;
8) H_2 flow measurer;
9) Adaptor from ½ inch to ¼ inch;
10) Adaptor from ¼ inch to $^1/_{16}$ inch;
11) Wire pipeline $^1/_{16}$ inch (1 mm internal diameter).

7. Purpose of the experimental tests

The purpose is to determine the size of *Zone 2* ATEX in case a small accidental leakage of the fuel cell occurs. In this case the limit of H_2 in air is 2% H_2 vol. We have five measurers of H_2 concentration to define the volume around the fuel cell where the limit is not overtaken.

The central venting area (690 x 2160) in fig. 3, will be used performing the experiments, a small opening is made on the down side (wall C) with size of 0.14 m^2 in fig. 6, aiding the internal air recirculation. Only the central venting area will be varied during both passive and active kind of ventilation experiments.

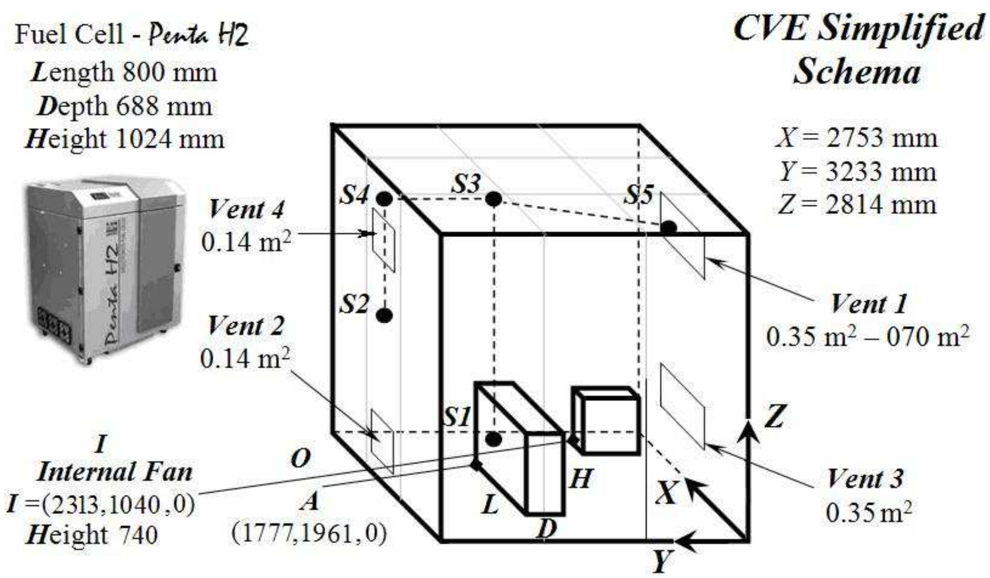


Figure 13. Location of the sampling points and size of the four vent areas (figure is not in scale).

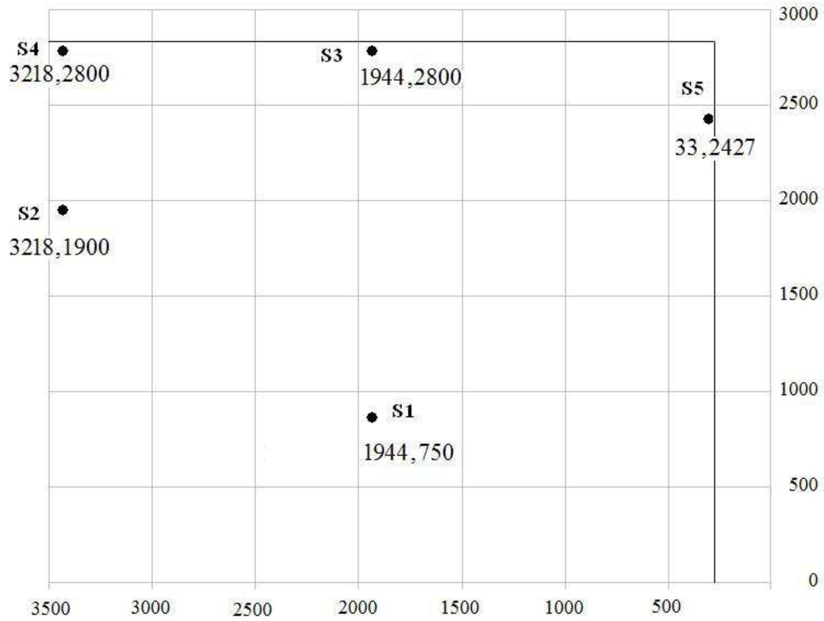


Table 3. Sensors coordinates

	X	Y	Z
S1	1221	1944	750
S2	1221	3218	1900
S3	1221	1944	2800
S4	1221	3218	2800
S5	1221	33	2427

Figure 14. Location of the sensors (y, z) in [mm], plane x = 1221.

8. Experimental matrix

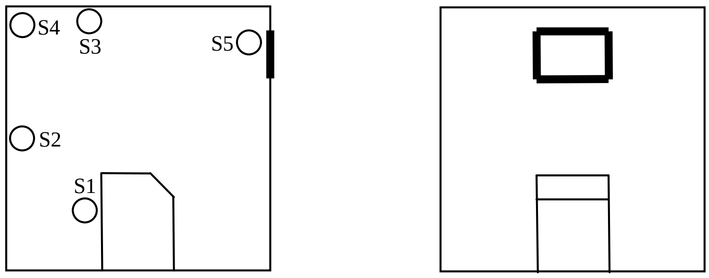
The case study is constituted by two categories, natural ventilation (NV) and forced ventilation (FV). As concern the first NV case the main parameters are:

1) Size of Vent 1: Vent 1 small (V1s) = 0.35 m^2 ; Vent 1 big (V1b) = 0.7 m^2;
2) Size of Vent 2: 0.14 m^2 fixed (V2);
3) Size of Vent 3: 0.35 m^2 fixed (V3);
4) Size of Vent 4: 0.14 m^2 fixed (V4);
5) Leakage flow in [nl/min]: small (GH2s) = 40 ; average (GH2a) = 90 ; big (GH2b) = 180.

As concern the second case study FV the main parameters are the same of the NV together with the air flow from the fan (the sixth parameter):

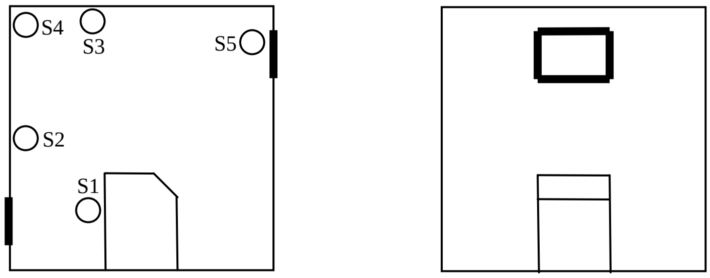
6) Air flow of the fan: Small Air flow = 0.3 m^3/s (AFs) ; Big Air Flow 0.6 m^3/s (AFb).

All the tests will be performed in homogenous condition of temperature. With low temperature (below 20°C) the condition is conservative because a non-zero gradient of temperature between the internal and external part of the CVE can favour the mixing of the hydrogen [1], from the simulations the thermal effect improves the evacuation of the hydrogen [3]. The geometries of the ventilation experiments are shown below.



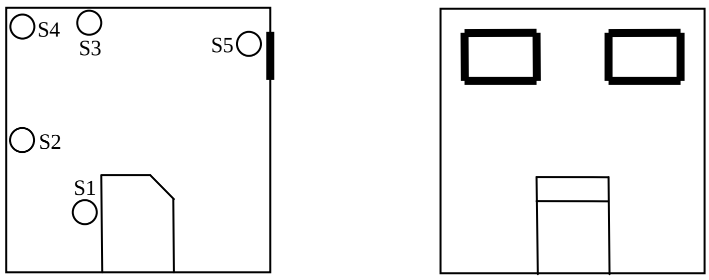
(1) CASE OF
V1s

Area [m^2]
0.35



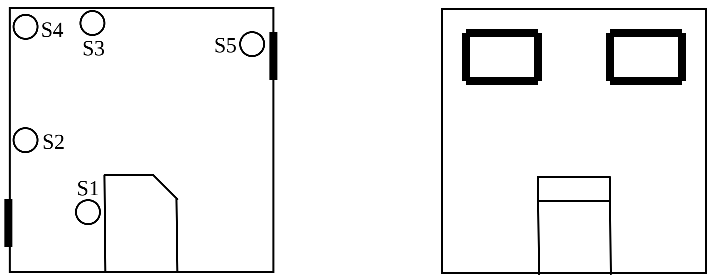
(2) CASE OF
V1s – V2

Area [m^2]
0.35 + 0.14



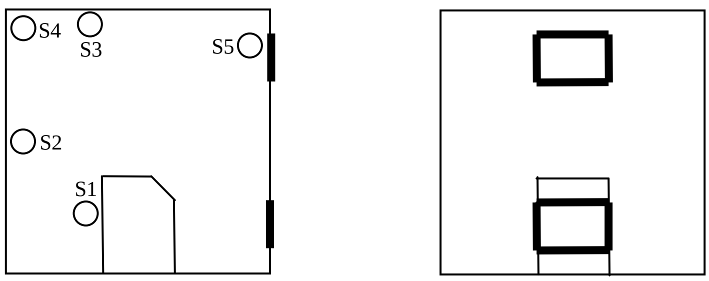
(3) CASE OF
V1b

Area [m^2]
0.70



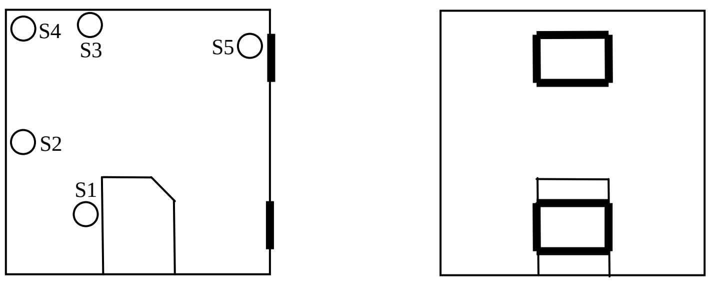
(4) CASE OF
V1b – V2

Area [m^2]
0.70 + 0.14



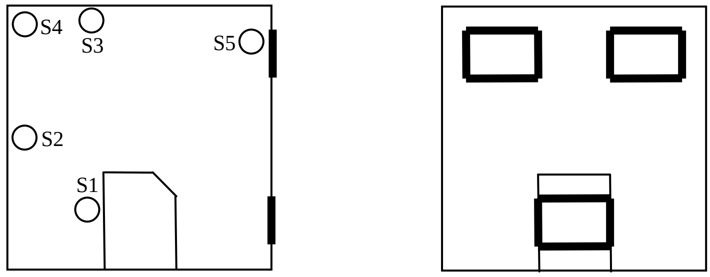
(5) CASE OF
V1s – V3

Area [m^2]
0.35 + 0.35



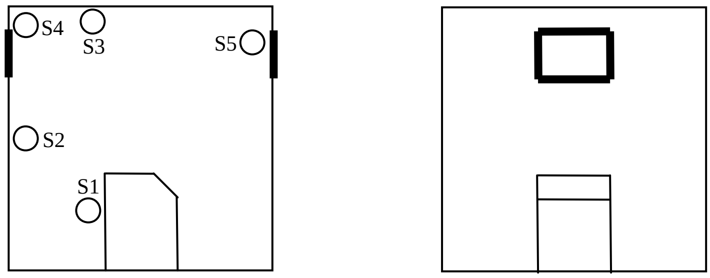
(6) CASE OF
V1s – V3

Area [m^2]
0.35 + 0.35



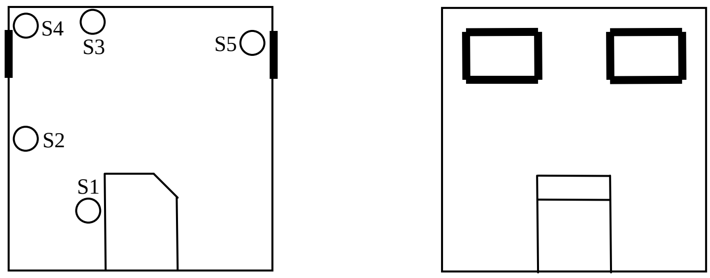
(7) CASE OF
V1b – V3

Area [m^2]
0.70 + 0.35



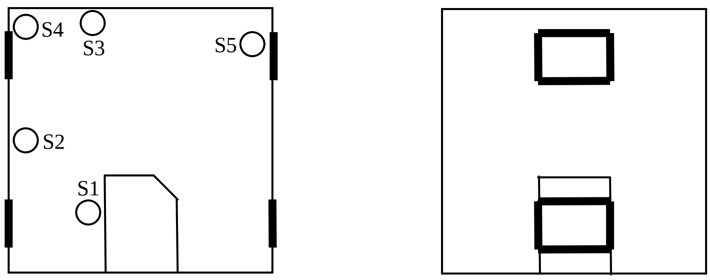
(8) CASE OF
V1s – V3

Area [m^2]
0.35 + 0.14



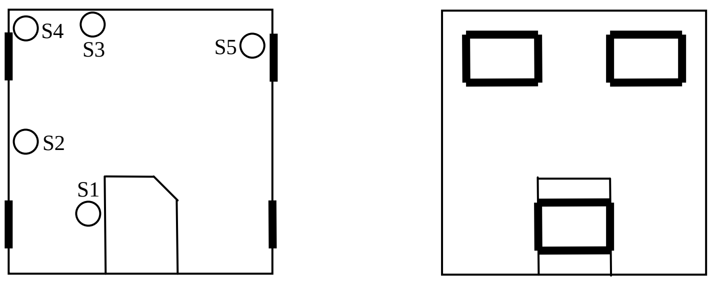
(9) CASE OF
V1b – V4

Area [m^2]
0.70 + 0.14



(10) CASE OF
V1s – V2 – V3 – V4

Area [m^2]
0.35 + 0.35 + 0.14 + 0.14

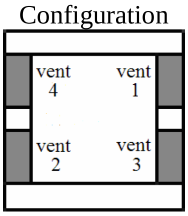
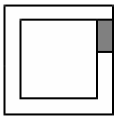
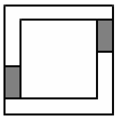
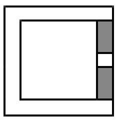
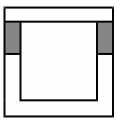
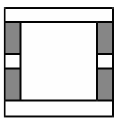


(11) CASE OF
V1b – V2 – V3 – V4

Area [m^2]
0.70 + 0.35 + 0.14 + 0.14

In case of NV the initial value of the vent size is compared with the indication of the norm ATEX. Let be Q_{aw} the air flow of NV, this norm suggests some empirical formulas applicable to various geometries. An overview of this calculus is shown in tab. 4.

Table 4. Calculus of Qaw value in all geometries [1].

Geometrical Configuration	ATEX calculus of air-flow recirculation Q_{aw} Referred to W = 1 m/s (wind speed)	Vent 1 small $V1s = 0.35\ m^2$ Vent 1 big $V1b = 0.70\ m^2$	Theoretical ATEX value of Q_{aw}
			
	$Q_{aw} = 0.025\ A\ W$ $A = V1$	$V1s = 0.35\ m^2$	$Q_{aw} = 0.009\ m^3/s$
		$V1b = 0.70\ m^2$	$Q_{aw} = 0.018\ m^3/s$
	$Q_{aw} = c_s\ A_{aw}\ W\ (\Delta c_p)^{0.5}$ $\frac{1}{A_{aw}^2} = \frac{1}{V1^2} + \frac{1}{V2^2}$ $\Delta c_p = 0.2$ (difficult ventilation) $c_s = 0.65$ (fixed constant value)	$V1s = 0.35\ m^2$	$Q_{aw} = 0.037\ m^3/s$
		$V1b = 0.70\ m^2$	$Q_{aw} = 0.04\ m^3/s$
	$Q_{aw} = 0.025\ A\ W$ $A = V1 + V3$	$V1s = 0.35\ m^2$	$Q_{aw} = 0.018\ m^3/s$
		$V1b = 0.70\ m^2$	$Q_{aw} = 0.026\ m^3/s$
	$Q_{aw} = c_s\ A_{aw}\ W\ (\Delta c_p)^{0.5}$ $\frac{1}{A_{aw}^2} = \frac{1}{V1^2} + \frac{1}{V4^2}$ $\Delta c_p = 0.2$ (difficult ventilation) $c_s = 0.65$ (fixed constant value)	$V1s = 0.35\ m^2$	$Q_{aw} = 0.037\ m^3/s$
		$V1b = 0.70\ m^2$	$Q_{aw} = 0.04\ m^3/s$
	$Q_{aw} = c_s\ A_{aw}\ W\ (\Delta c_p)^{0.5}$ $\frac{1}{A_{aw}^2} = \frac{1}{(V1+V3)^2} + \frac{1}{(V2+V4)^2}$ $\Delta c_p = 0.2$ (difficult ventilation) $c_s = 0.65$ (fixed constant value)	$V1s = 0.35\ m^2$	$Q_{aw} = 0.07\ m^3/s$
		$V1b = 0.70\ m^2$	$Q_{aw} = 0.08\ m^3/s$

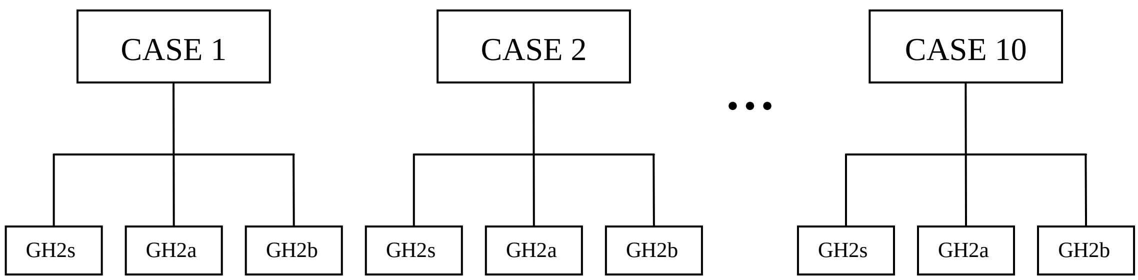
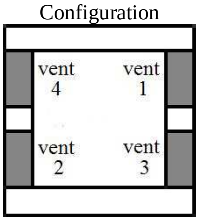
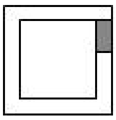
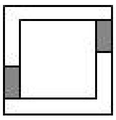
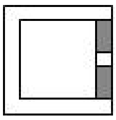
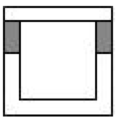
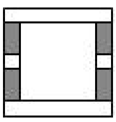


Figure 15. Total redundant number of experiments in case of NV.

Where the natural recirculation fails the FV experiments will be performed to complete the experimental matrix to measure H_2%vol < 2% as the ATEX zone 2 prescribes [1]. The total number of experiments is 23 in case of NV, considering FV case with two values of hydrogen flow (GH2s, GH2b) the total number of experiments rises to 40. During the FV experiments at least two vent areas will be open V1 + V2 or V1 + V4. The reason of this choice is to avoid the depression inside CVE. In fact this depression could be modify the value of the air flux in aspiration of the fan.

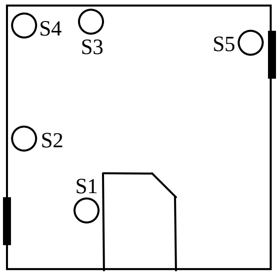
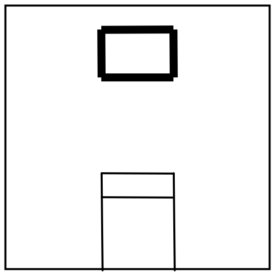
The experimental data will be collected as show in table 4. In that table the geometrical configuration is correlated with the theoretical ventilation ATEX value Q_{aw} and the efficiency of NV referred to three values of H_2 leakage flow (40; 90; 180 nl/min).

Table 5. Results of natural ventilation tests.

Geometrical Configuration 	ATEX calculus of air-flow recirculation Q_{aw} Referred to W = 1 m/s (wind speed)	Vent 1 small V1s = 0.35 m^2 Vent 1 big V1b = 0.70 m^2	Theoretical ATEX value of Q_{aw}	NV 40 l/min	NV 90 l/min	NV 180 l/min
				Efficient Y/N	Efficient Y/N	Efficient Y/N
	$Q_{aw} = 0.025\ A\ W$ $A = V1$	V1s = 0.35 m^2	$Q_{aw} = 0.009\ m^3/s$	N	N	N
		V1b = 0.70 m^2	$Q_{aw} = 0.018\ m^3/s$	Y	N	N
	$Q_{aw} = c_s\ A_{aw}\ W\ (\Delta c_p)^{0.5}$ $\frac{1}{A_{aw}^2} = \frac{1}{V1^2} + \frac{1}{V2^2}$ $\Delta c_p = 0.2$ (difficult ventilation) $c_s = 0.65$ (fixed constant value)	V1s = 0.35 m^2	$Q_{aw} = 0.037\ m^3/s$	Y*	N	N
		V1b = 0.70 m^2	$Q_{aw} = 0.04\ m^3/s$	Y	N	N
	$Q_{aw} = 0.025\ A\ W$ $A = V1 + V3$	V1s = 0.35 m^2	$Q_{aw} = 0.018\ m^3/s$	Y	N	N
		V1b = 0.70 m^2	$Q_{aw} = 0.026\ m^3/s$	Y	N	N
	$Q_{aw} = c_s\ A_{aw}\ W\ (\Delta c_p)^{0.5}$ $\frac{1}{A_{aw}^2} = \frac{1}{V1^2} + \frac{1}{V4^2}$ $\Delta c_p = 0.2$ (difficult ventilation) $c_s = 0.65$ (fixed constant value)	V1s = 0.35 m^2	$Q_{aw} = 0.037\ m^3/s$	Y**	N	N
		V1b = 0.70 m^2	$Q_{aw} = 0.04\ m^3/s$	Y	N	N
	$Q_{aw} = c_s\ A_{aw}\ W\ (\Delta c_p)^{0.5}$ $\frac{1}{A_{aw}^2} = \frac{1}{(V1+V3)^2} + \frac{1}{(V2+V4)^2}$ $\Delta c_p = 0.2$ (difficult ventilation) $c_s = 0.65$ (fixed constant value)	V1s = 0.35 m^2	$Q_{aw} = 0.07\ m^3/s$	Y	Y	N
		V1b = 0.70 m^2	$Q_{aw} = 0.08\ m^3/s$	Y	Y	N

(*) In addiction tests 38; 39: 40; 41 has been performed adopting a different geometry of the sensors.
(**)In addiction tests 34; 35: 36; 37 has been performed adopting a different geometry of the sensors.

Test 11-2008-04-02.

	X	Y	Z	SIDE D VIEW	SIDE A VIEW	H_2 Flow 90 [l/min]
S1	1221	1944	750			Vent Area 0.35 + 0.14 [m^2]
S2	1221	3218	1900			Duration of the leakage 365 [s] (sampling time 420 [s])
S3	1221	1944	2800			Direction of the leakage Y
S4	1221	3218	2800			Coordinates (x ; y ; z) 1200 ; 1900 ; 800
S5	1221	33	2427			Diameter of the nozzle 6 [mm]

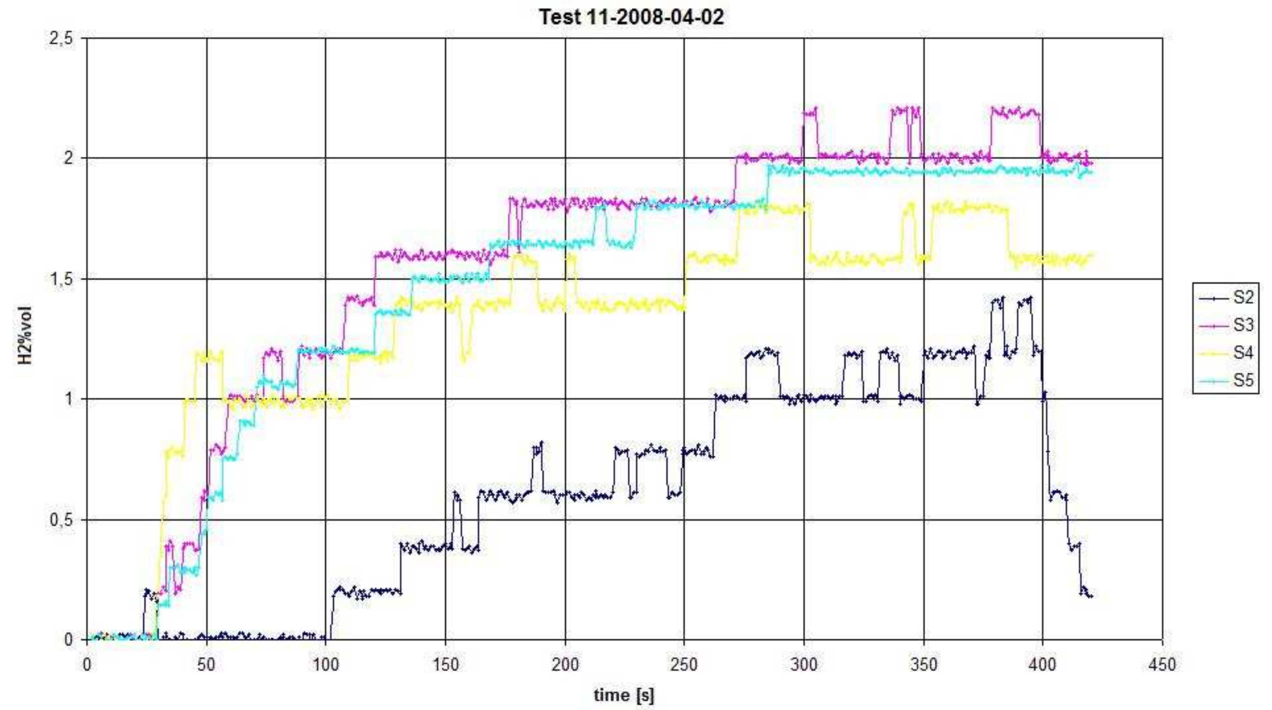


Figure 16. Technical data and results concerning the test 11- natural ventilation analysis. Sensor S_1 is saturated because located in front of the H_2 leakage.

9. The model of natural ventilation in an enclosure

The data in the table are referred to a hydrogen leak from a pipeline with a pressure of 5 bar and diameter of the leak nozzle Φ_L = 1 mm. The hydrogen flow from the leakage has been calculated by the program EFFECT-SGIS 7.3 and its value is 40 nl/min (ATEX value), 90 nl/min and 180 nl/min.

In the table 5 the efficiency of the natural ventilation is shown. For each geometrical configuration the ATEX calculus of the theoretical air-flow Q_{aw} is performed. In the last column the results of experimental test are briefly shown.

The enclosure of reference is 25 m^3 of volume and it is provided of vent areas as the column “Geometrical Configuration” shows. The natural ventilation is “Effective” only if ATEX zone 2 is respected. That zone 2 corresponds to the limit of Hydrogen concentration of 2%vol inside the whole volume.

In conclusion the NV like described in ATEX norm [1] zone II is effective when considering the worst leak (40 l/min) from the 5 bar pipe, except in case 1 (V1s; Av = 0.35 m^2). Regarding the leak of 90 l/min the NV is effective only in case 10 (V1b – V2 – V3 – V4 ; Av = 1.33 m^2), on the contrary the NV is always not effective considering a leak of 180n/min. In order to elicit an useful model from the experiments and simulation made till now, it is opportune to consider the following parameters:

Q_{aw} = air flow circulating inside the enclosure;

Q_{H2} = H_2 flow from the leakage;

H_2%vol = homogenous concentration of hydrogen;

A_{aw} = vent area;

Δc_p = index of difficult ventilation, angle on incidence of the wind direction with the Av plane;

W = wind intensity [m/s].

The correct ventilation in an enclosure in order to not overtake the concentration of 2% depends some main factors. These factors are the geometry of the vents, their size, the strength of the wind, the gradient of temperature between the internal part of the enclosure and the external one.

In NV experiments the worst conditions of ventilation were considered concerning the wind and the temperature. In fact most of the tests have been carried on with wind ≈ 3 m/s or less and internal temperature ≈ 25°C. Where specified a small number of tests have been performed with wind 5 – 6 m/s and gradient of temperature of 10°C (internal 40°C external 30°C).

Concerning the geometry and size of the vent areas, it is possible distinguish two cases, the first where the areas are located on the same wall, the second where the vents are on two opposite walls. Starting from the geometry the second step is the calculus of the air-flow Q_{aw} necessary to evacuate the hydrogen. To calculate Q_{aw} it is possible to use a steady state equation:

$$H_2\%vol = 100\frac{Q_{H2}}{Q_{aw} + Q_{H2}}$$

That equation considers the whole volume of enclosure with homogenous H_2 concentration, in the experimental cases the homogenous volume is a fraction of the whole one. For this reason the partial volume is $V_E^{(P)} = K_v V_E ;\quad 0 < K_v < 1$

Considering the definition in steady state conditions [4] of $H_2\%vol = 100\frac{V_{H2}}{V_E}$ we can define the homogenous concentration in the partial volume in steady state conditions as:

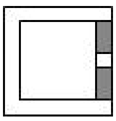
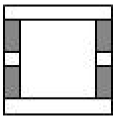
$$H_2^{(P)}\%vol = 100\frac{V_{H2}}{V_E^{(P)}}$$

Considering the definition of $V_E^{(P)}$ and $H_2\%vol$: $H_2^{(P)}\%vol = 100\frac{V_{H2}}{V_E^{(P)}} = 100\frac{V_{H2}}{K_v\, V_E} = \frac{H_2\%vol}{K_v}$;

$$H_2^{(P)}\%vol = 100\frac{Q_{H2}}{Q_{aw} + Q_{H2}} K_v^{-1}.$$

In this simple model the $H_2^{(P)}\%vol$ and Q_{H2} are measured during the experiments. The steady state condition is quickly reached (in 3, 4 minutes) due to the H_2 buoyancy. The final step is the calculation of the vent area size Av from the ATEX formulas as shown in the next table.

Table 6. Natural Ventilation Model steps.

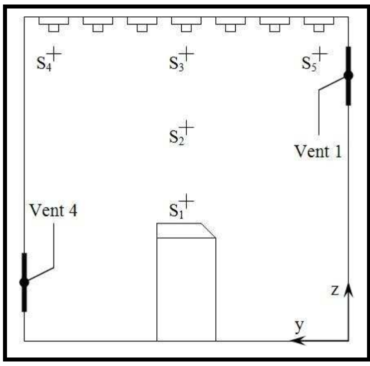
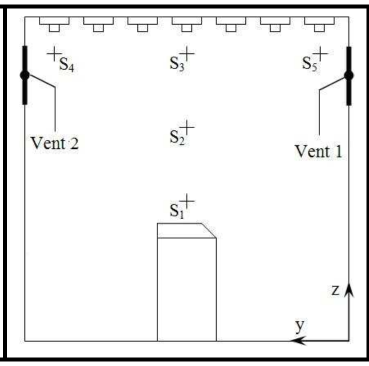
Step 1: Choose of the NV Geometry	Step 2: calculus of Q_{aw} using Steady state equation	Step 3: Calculation of A_{aw} using the ATEX [1] Correlation between Q_{aw} and A_{aw}
	$H_2^{(P)}\%vol = 100\frac{Q_{H2}}{Q_{aw} + Q_{H2}} K_v^{-1}$	$Q_{aw} = 0.025\ Av\ W$
		$Q_{aw} = c_s\ A_{aw}\ W\ (\Delta c_p)^{0.5}$ $\frac{1}{A_{aw}^2} = \frac{1}{(V1+V3)^2} + \frac{1}{(V2+V4)^2}$

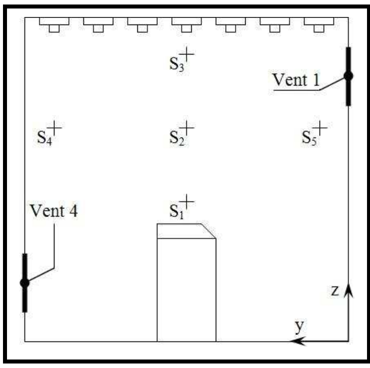
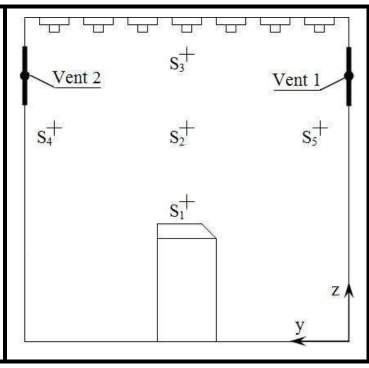
In order to evaluate the factor K_v eight experiments have been performed, the geometry and other information are shown in the next figure. The geometry case 2 and case 8 has been analysed for two values of H_2-flow, 40 l/min and 90 l/min.

Table 7. Data input of the Kv-factor tests.

Plan A (K_v)		Plan B (K_v)	
H_2 Flow [l/min]	40	H_2 Flow [l/min]	90
Vent Area [m^2]	0.35 + 0.14	Vent Area [m^2]	0.35 + 0.14
Duration of the leakage [s]	1200	Duration of the leakage [s]	1200
Direction of the leakage	Z	Direction of the leakage	Z
Coordinates (x ; y ; z)	1070 ; 1480 ; 925	Coordinates (x ; y ; z)	1070 ; 1480 ; 925
Diameter of the pipe [mm]	6	Diameter of the pipe [mm]	6
Nozzle diameter [mm]	6	Nozzle diameter [mm]	6

Table 8. Geometries and new sensors coordinates for Kv-factor tests.

Geometry - Case 2 -	Geometry - Case 8 -	Sensors coordinates in mm
		S1 ≡ 1375; 1630; 1110 S2 ≡ 1375; 1630; 1960 S3 ≡ 1375; 1630; 2800 S4 ≡ 1375; 2830; 2800 S5 ≡ 1375; 400; 2800

Geometry - Case 2 -	Geometry - Case 8 -	Sensors coordinates in mm
		S1 ≡ 1375; 1630; 1110 S2 ≡ 1375; 1630; 1960 S3 ≡ 1375; 1630; 2800 S4 ≡ 1375; 2830; 1960 S5 ≡ 1375; 400; 1960

The calculus of K_v factor is necessary to evaluate the volume involved in the steady state equation step 2. In fact the hypothesis is that in the volume the gas concentration is homogenous and that is not true in the whole CVE volume but only in a fraction (K_v) of that.

The correlation of the experimental data gives the concentration of the H_2-air layer in terms of Q_{H2}, Q_{aw} and the stratification factor K_v. The model is realised by NCSRD (National Centre for Scientific Research Democritos – Athens - Greece) using the experimental data. The stratification factor K_v expresses the ratio between the volume of the H_2-air layer divided by the volume of the whole enclosure (where $K_v=1$ means that H_2 is homogeneously distributed in the whole enclosure), that the correlation $K_v=1/3$ represents the best fit of the of data (NCSRD best fit). This result refers to a real situation, as performed during the experiments, with weak variable external wind value (less then 4 m/s) and internal temperature around 28°C.

10. Forced ventilation, experimental asset and conclusion

The forced ventilation (FV) tests are conceived to complete the evidence referring to the natural ventilation experiments. FV is carried on the CVE facility using two industrial fans, their general characteristics are shown in the table 9. The fans are located on the vent 1 (central) and vent 4. The area of those two vents is coincident with the area of the fan (Af = 0.05 m^2).

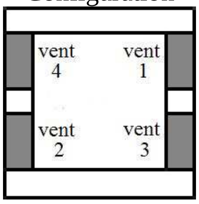
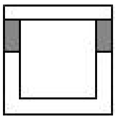
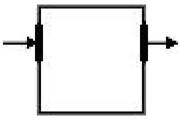
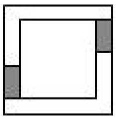
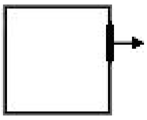
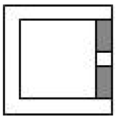
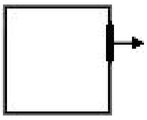
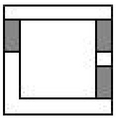
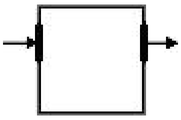
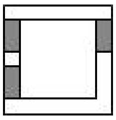
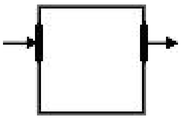
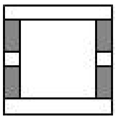
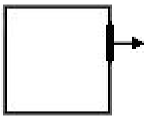
Table 9.Characteristics of the fan AXEX254T used during the tests.

Fan Model AX	rpm	Power [kW]	Voltage [V]	current intensity [A]	Diameter [mm]	Air – flow [m^3/s]	Coordinates fan centre [x; y; z]
254T	1500	0,04	220/380	0,25	260	0.33	Fan 1 (1375; 0; 2670)
							Fan 2 (1375; 3220;2670)

The results of FV tests are shown in table 10, as we can see the use of one fan in aspiration is enough to ensure the evacuation of the hydrogen maintaining the concentration below 2% considering leakage flow till 90 l/min.

The consumption of the fan is 0.04 kW, the production of the fuel cell is 5 kW, the installation of a fan is convenient both from a safety and energetic point of view. The results of FV tests are summarized in table 10. For each tests the direction and type of FV is shown.

Table 10. Results of forced ventilation tests.

Geometrical Configuration 	Direction of air-flow Fan area Af = 0.05 m^2	Free vent area Av	Fan air-flow, Internal value of Q_{aw}	NV 40 l/min Efficient Y/N	NV 90 l/min Efficient Y/N	NV 180 l/min Efficient Y/N
		Av = 0.14 m^2	Q_{aw} = 0.66 m^3/s	Y	Y	N
		Av = 0.14 m^2	Q_{aw} = 0.33 m^3/s	Y	Y	N
		Av = 0.35 m^2	Q_{aw} = 0.33 m^3/s	Y	Y	N
		Av = 0.49 m^2	Q_{aw} = 0.66 m^3/s	Y	Y	N
		Av = 0.28 m^2	Q_{aw} = 0.66 m^3/s	Y	Y	Y
		Av = 0.89 m^2	Q_{aw} = 0.33 m^3/s	Y	Y	Y

11. General conclusions and recommendations

The analysis of the natural and forced ventilation efficiency makes it necessary to use this safety system in all the enclosures where a credible non-catastrophic leakage can occur.

To calculate the vent area it is convenient to choose the geometry first, then the leak size and consequently the size of vent areas which are shown in the table 5.

The result is the minimum vent area in that geometry for which the enclosure respects the ATEX limit of zone 2 (H_2 concentration less then 2%vol).

Where it is possible, it is convenient to use one or more suitable solutions like:

- To reasonably increase the vent areas beyond the minimum value in table 5;
- To consider the vent areas for a leak flow reasonably bigger then the minimum;
- To incline the roof making the NV easy and efficient;
- To install a small fan able to remove the internal mixture from the enclosure.

The limit of 40 l/min of the leakage is relevant for every kind of fuel cell suitable for civil use. leaks beyond 90 l/min would refer to catastrophic leakage and therefore should not be considered with the assumptions made.

12. References

[1] ATEX guide of reference CEI EN 60079-17 ; CEI 31-35:2001-01 (ITA).

[2] NFPA 68: *Guide for Venting of Deflagrations* , National Fire Protection Association ed. 2007.

[3] Barley, C.D. et al. “*Analysis of buoyancy-driven ventilation of hydrogen from building* ”, Second International Conference of Hydrogen Systems - ICHS, San Sebastian - Spain 11-13 September 2007.

[4] R.J. Harris, *The investigation* and control of gas explosion in buildings and heating plants, , printed in Great Britain by Eyre & Spottiswoode, Grosvenor press, Portsmouth, in association with British Gas Corporation 1983 – ISBN 0 419 13220 1.