EXPERIMENTAL STUDY OF HYDROGEN RELEASES IN THE PASSENGER COMPARTMENT OF A PIAGGIO PORTER VAN

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ABSTRACT

Hydrogen is currently regarded as an energy carrier for the future, and power generation using fuel cells is a promising technology for next generation vehicles due to their efficiency and zero emissions. Inside the project "H_2 Filiera Idrogeno" funded by "Regione Toscana", a hydrogen power propulsion system will be installed on a light commercial vehicle based on the Piaggio Porter van.

A risk analysis is a primary element in assessing the safety of a new technology, and one of the essential stages is the evaluation of event consequences. A key component of a risk analysis of a hydrogen system is developing an understanding of the behaviour of fuel releases in realistic scenarios. Such knowledge allows the development of measure to minimize the probability of an accident, and of methods to mitigate the consequences if an accident should occur.

In this work the study of different paths for hydrogen released from the system to reach the interior of the vehicle had been carried out and experimental tests had been made to investigate realistic release scenarios.

1.0 INTRODUCTION

Filiera Idrogeno is a project sponsored by MIUR (Ministero dell'Istruzione, dell'Università e della Ricerca) and Regione Toscana, currently under progress. The Project promotes the development and testing of mobility systems based on the use of hydrogen, which is the energy carrier on which many automotive companies have poured their interests recently. It represents a potential choice to produce ZEV (Zero Emission Vehicles) characterised vehicles, which, unlike battery electric vehicles, have ranges not too distant from those of the conventional ones, as well as reduced refuelling time.

The mobility based on hydrogen will require, however, strong changes in vehicles, in the production facilities and in the fuel distribution. In this scenario, Regione Toscana has emphasized the opportunity to test the production, storage and the use on-board vehicles of hydrogen.

The major assets of Tuscany are:

- A good availability of renewable sources, with which it becomes possible to produce hydrogen emission-free: in addition to geothermal, there are wind and solar high energy density areas.
- Presence of chemical companies, for hydrogen production.
- Presence of an extended technical knowledge in this field: Research laboratories (University of Pisa, Scuola Superiore Sant'Anna) and automotive industries (Piaggio).

In Filiera Project two main tasks involve five Departments of the University of Pisa and Scuola Superiore S. Anna. One is related to the development of internal combustion engine converted to operate efficiently using hydrogen (pure or mixed with other gas). The other is related to the fuel-cell based vehicles, that use hydrogen to produce electrical energy; Department of Energy and Systems Engineering is actually involved in the modification of an electric mini-van Piaggio Porter installing a Fuel-Cell based propulsion system. The Project is also characterised by other transversal activities, concerning studies related to hydrogen production and storage, sensors design needed to control the propulsion system and studies of prototypes safety, Well to Wheels studies, development of rules and regulations for the approval of components and systems. In this paper part of a safety study related to the installation of a hydrogen powered system on the Piaggio Porter is presented.

A risk analysis is a primary element in assessing the safety of a new technology, and one of the essential stages is the evaluation of event consequences. A key component of a risk analysis of a hydrogen system is developing an understanding of the behaviour of fuel released in realistic scenarios. Such knowledge allows the development of measures to minimize the probability of an accident, and of methods to mitigate the consequences if an accident should occur. Studies where published which quantified the additional risk related to the operation of a hydrogen powered engine car [1], furthermore several experimental [2, 3, 4] and simulation [5, 6] works concerning the study of hydrogen released from vehicles in garages and in tunnels [7] as well as during the refuelling had been published nowadays; while the only study of the behaviour inside a vehicle compartment has been published by Liu and Schreiber in 2008 [8]. In this scenario this work serves the purpose to contribute to an understanding of the effects inside the passenger compartment of an unintended leak from the hydrogen system. The study of different paths for hydrogen released from the system to reach the interior of the vehicle has been taken into account and the dispersion in the passenger compartment has been studied trough experimental tests.

2.0 VEHICLE DESCRIPTION

Piaggio Porter is a light commercial vehicle, loading capacity $3m^3$ and lifting power 560 kg, available also in electric battery fed version (Figure 1).

Seating capacity	2/4
Number of doors	4
Total length	3370 mm
Total width	1395 mm
Height	1870 mm
Wheel spacing	1810 mm
Loading capacity	3/1,4 m3
Lifting power	540 kg
Loading area	1270x1760
Height of the load area from ground	560 mm
Max speed (electric)	52-57 km/h
Max speed (H2)	80 km/h
Range (electric)	110/137
Range (H2)	180

Figure 1. Piaggio Porter picture and technical characteristics

A new propulsion system architecture characterised by the presence of a Fuel-Cell based generator system combined to an energy storage system has been designed by the Department of Energy and

Systems Engineering [9]. In figure 2 the series-hybrid system architecture is clearly visible: all the needed traction power is first converted into electricity, and the sum of energy between the two power sources is made in terms of electric quantities in an electric node, commonly a DC bus.

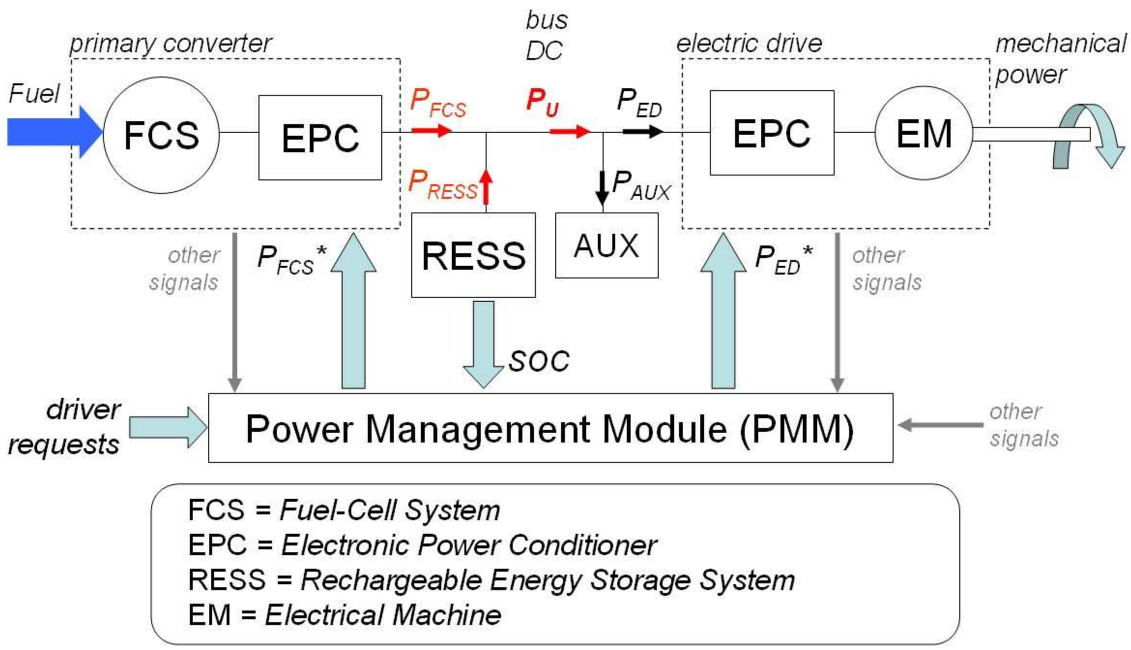

Figure 2. General architecture of the propulsion system

Every sub-system has been sized according to the following performance requirements:

1. Horizontal drive:
   a) *max speed: 80 km/h*
   b) *acceleration 0 – 80 km/h: within 60 s*
   c) *max speed range: 150 km*
2. Slope 25%:
   a) *max speed: 20 km/h*
   b) *start-up acceleration: 0.3 m/s^2*

A strong improvement respect to the electric standard version has been pursued. General characteristics are reported in table 1.

Table 1. Hydrogen powered vehicle characteristics

Vehicle mass (kg) *empty* *full loaded*	 1095 1535
Electric motor power (kW)	22
FCS power (kW)	13.2
Energy stored (kWh)	4.8
Reservoir size (kg H_2)	1.5

The main requirement of the Project was the realisation of a vehicle flexible and usable as the conventional version. Indeed, in addition to the sizing of the different components, several layout studies have been carried on. Finally, all the components have been disposed without influence passenger and luggage compartments of the standard Piaggio Porter.

As shown in Figure 3, the Fuel-Cell System is positioned under the driver seat: a co-design activity with the manufacturer has been defined to dispose all the auxiliaries under the stack module, to have a compact and regular shape for easy installation on existing vehicle frame. The battery pack and electronic converters are disposed on the sides of the vehicle frame. H_2 cylinders are disposed with transversal orientation (one of the storage bottles has been placed in the middle of the vehicle and the second one in its rear): they are provided with valves that isolate the bottles during the stops of the vehicle. Since the first schematic proposal, the company that works on the integration on-board[1] has defined the final disposition of all the components, starting from the CAD model of the Piaggio Porter vehicle. To realise the effective placement of the drive train components, the company designed and built the required mechanical supports. Moreover, the same company worked on the entire hydrogen piping, including valves and pressure regulators that was designed and installed on-board.

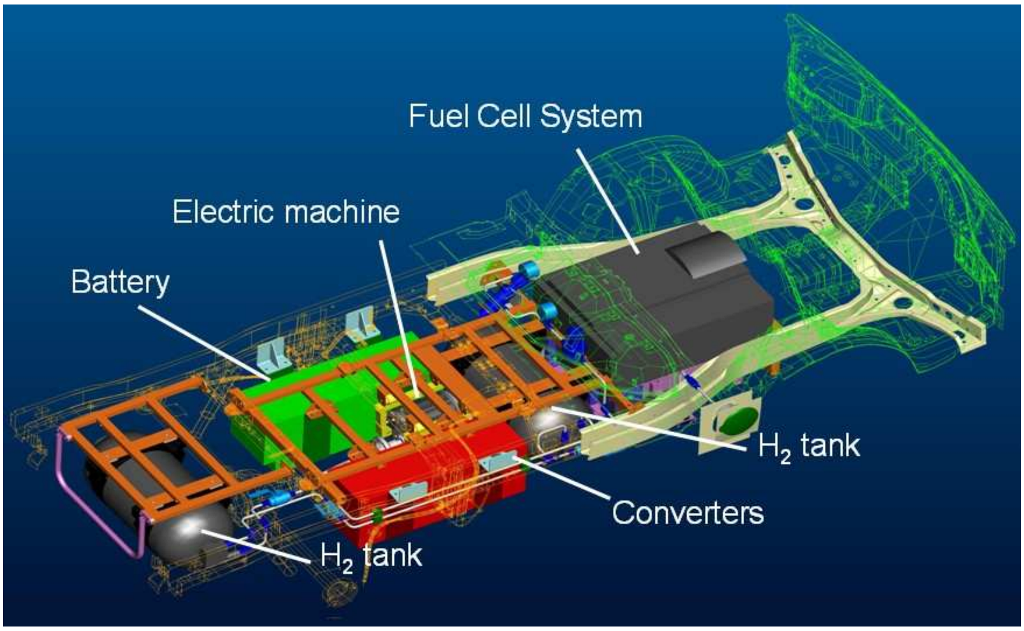

Figure 3. Final layout of the vehicle

Since the vehicle was not originally designed to host the hydrogen system some of its characteristics are not optimal. The passenger compartment is ventilated by a system that sucks air from the lower part of the vehicle in the car front, just above the fuel cell, in an area not directly connected with the outer atmosphere, the maximum air flow rate being 270 Nm^3/h. Furthermore the lower part of the vehicle is surrounded by a vehicle skirt that can reduce the diffusion of hydrogen in radial direction in case of an accidental release from the system. Hydrogen that leaks from the system can accumulate under the vehicle skirt and find its way to reach the passenger compartment, since air circulation openings connect directly the passenger compartment with the lower part of the vehicle, they are considered to represent the easiest way for hydrogen to enter inside the vehicle.

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3.0 SAFETY CONSIDERATION

In order to analyze the additional risks for the driver and the passengers of the vehicle due to the installation of the hydrogen system a brainstorming was conducted by a team composed by safety engineers, designers of the hydrogen system and manufacturers on the installation on board [10]. Considering that with the vehicle in motion hydrogen eventually released cannot accumulate under the vehicle and enter into the passenger compartment, the analysis led to the definition of three main scenarios:

- Hydrogen can accumulate into the passenger compartment during long term stops of the vehicle as a consequence of diffusive leaks.
- Hydrogen can enter into the passenger compartment during the stops of the vehicle as a consequence of major leak from the pipeline, in this scenario insulation valves on top of the hydrogen bottles are closed and the maximum amount of hydrogen released is the content of the pipes. The maximum amount as been calculated to be 1.4 g. A bigger amount of hydrogen has been also considered to take into account a scenario were 5 s are needed for the bottles insulation valve to close after a major leak with the fuel cell in operation.
- During brief stops of the vehicle with operating hydrogen system and operating ventilation system hydrogen released from a leak under the vehicle can be sucked inside the passenger compartment by the operating ventilation system.

4.0 EXPERIMENTAL SET-UP

Preliminary test was performed in aim to check if a diffusive release of hydrogen could accumulate inside the passenger compartment under the ceiling (pavilion). A diffusive leak were simulated producing hydrogen by the mean of a small electrolyser with a rate of 3 10^{-5} g/s. Hydrogen produced was than released under the pavilion close to the ventilation openings of the vehicle, the total duration of the release was more than 3 hours.

After preliminary test, a first series of tests, named Test Series E, where than performed releasing hydrogen with a flow rate of 0.2 g/s under the vehicle: this value matches the mass flow needed by the fuel cell at its maximum power regime. Finally Test Series named V was performed releasing hydrogen with a flow rate ranging between 0.05 and 0.2 g/s directly inside the operating ventilation fan. Release pressure was 4,2 bar upstream the flow meter.

Two different release location under the vehicle were tested in Test Series E, the first one located in the front part of the vehicle close to the fuel cell (named R1) and the second one located between the two hydrogen bottles (named R2), in both configuration the release was directed upwards. Figure 4 shows the location of the release points placed under the vehicle.

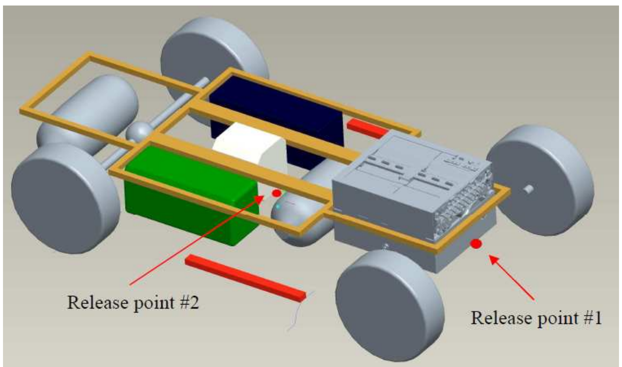


Figure 4. Position of the release points during Tests E

During the release from the operating ventilation system, Test Series V, hydrogen was released inside the ventilation system and than dragged into the vehicle diluted by the stream of air from the “defrost” openings, figure 5 shows the position of the release inside the passenger compartment.

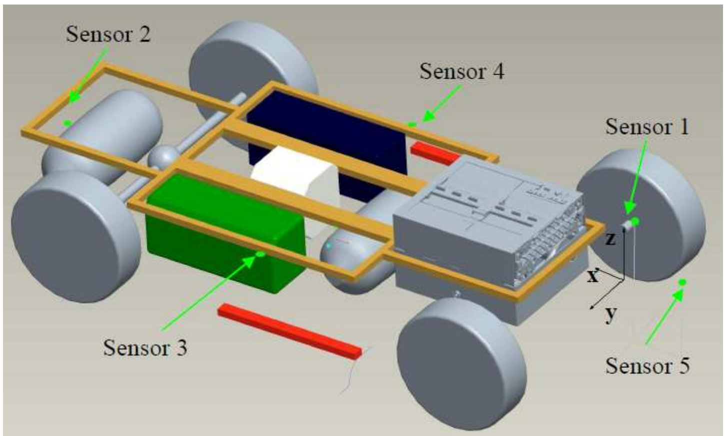
Only one of the two “defrost” ventilation openings was interested by the hydrogen release, the second one, in front of the driver seat, was releasing only air during the experiments.

Figure 5. Position of the release points during Tests V

Hydrogen release rate was measured by a Bronkhorst High-Tech F-202AI-AGD-55-V-MFC mass flow meter.

In both Tests Series E and Series V 13 hydrogen sensor were used, 5 placed in different positions under the vehicle (figure 6) and 8 coupled in 4 different position inside the vehicle (figure 7).

Hydrogen sensors placed under the vehicle were of the type MSA 9010 with a measurement range 0-20%vol.

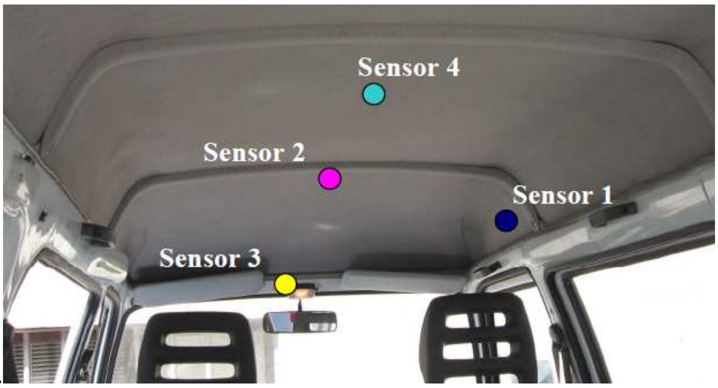


	X [mm]	**Y [mm]**	**Z [mm]**
Sensor 1	-400	540	480
Sensor 2	2410	540	270
Sensor 3	900	1030	410
Sensor 4	900	50	390
Sensor 5	-600	540	270

Figure 6. Position of hydrogen sensors under the vehicle

Inside the vehicle 8 sensors of two different types were coupled in four positions, in each position were placed one sensor of the type KHS-200 MEMS Micro-Pellistor with a measurement range of 0-4% (Lower Flammable Limit of hydrogen), and one of the type Synkera Trace Hydrogen Sensor (P/N 701) with a range 10-1000 ppm.

Trace sensors were used during the preliminary test with the purpose to check the possibility for hydrogen to accumulate and in the other tests in aim to check that no hydrogen was present in the passenger compartment at the beginning of a new test after the atmosphere inside were purged.



	X [mm]	Y [mm]	Z [mm]
Sensor 1	350	1030	1864
Sensor 2	400	530	1854
Sensor 3	-150	540	1868
Sensor 4	900	540	1869

Figure 7. Position of hydrogen sensors inside the vehicle

In order to minimize the effect of the wind on the releases under the vehicle, test were conducted in a site obstructed on three sides by buildings and partially blocked on the fourth side by a wall. Wind was measured to be 6.6 m/s at 10m height, nevertheless most of the tests were performed in a condition of lull in wind in the test area, few tests were affected by wind since the velocity measured during gusts of wind was 33.1 m/s. Temperature was 15°C and humidity was 90%.

5.0 TESTS RESULTS

5.1 Preliminary test.

Preliminary test was conducted with the purpose to check if a diffusive leak of hydrogen could indefinitely accumulate into the passenger compartment during long term stops of the vehicle.

Hydrogen was released 100 mm under the vehicle ceiling in a position close to sensor 1, releasing rate was 3 10^{-5} g/s.

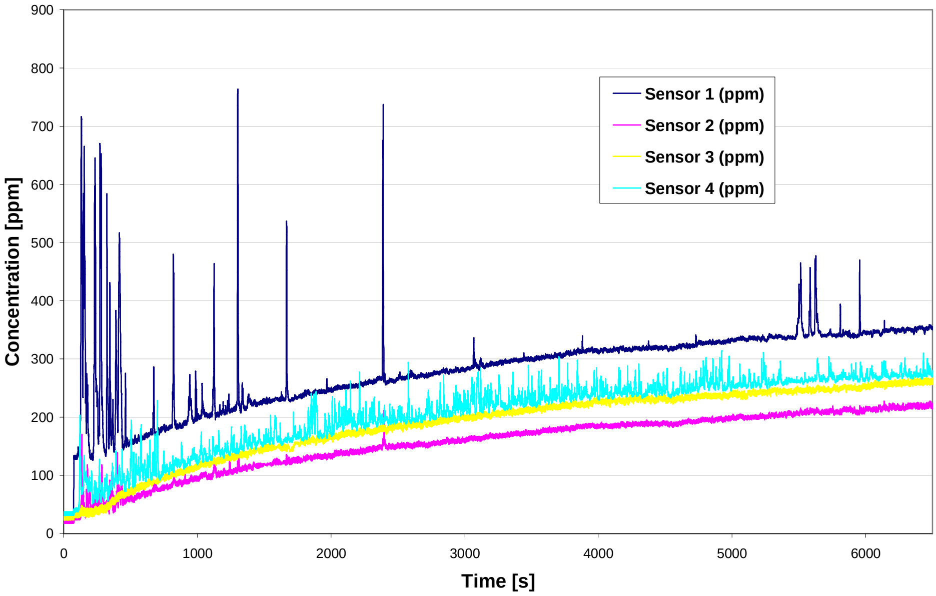


Figure 8. Hydrogen concentration inside the vehicle for preliminary test

The concentration at sensor 3 was 170ppm after 2000 s, 229 ppm after 4000 s and 261 ppm after 6000s. As hydrogen concentration was rising inside the vehicle hydrogen started to leak outside at a higher rate, concentration reached an asymptotic value of 400 ppm inside the passenger compartment. Concentration's time history (figure 8) showed that it tends to an asymptotic value and no unlimited accumulation was found possible for diffusive leaks.

5.2 Test Series E

Tests with release in position R1 were repeated 5 times in each condition, total amount of hydrogen released 1.4g and 2.5g, and a good repeatability was found, nevertheless test 1 8 and 9 where slightly affected by wind. The wind was found to affect the hydrogen distribution and hence the concentrations under the vehicle, but not changes were noticed inside the vehicle and the same amount entered into the passenger compartment.

Table 2. Experimental matrix of Test Series E

TEST SERIES E						
Test #	**Flow rate [g/s]**	**Release time [s]**	**Hydrogen released [g]**	**Max. Conc. under the vehicle**	**Max. Conc. inside the vehicle**	**Air circulation system flow rate**
Release position R1						
1	0.215	6	1.35	2.2%	0.7%	0
2	0.215	10.5	2.41	5.85%	1.6%	0
3	0.215	6	1.33	3.64%	0.6%	0
4	0.215	6	1.44	3.62%	0.65%	0
5	0.215	6	1.37	3.64%	0.6%	0
6	0.215	6	1.46	3.82%	0.6%	0
7	0.215	10.5	2.45	6%	1.7%	0
8	0.215	11	2.5	3.2%	1.7%	0
9	0.215	11	2.43	4.2%	1.8%	0
10	0.215	12	2.84	6.3%	1.8%	0
11	0.215	10.5	2.39	5.5%	0.15%	170 m^3/h
12	0.215	10.5	2.4	5.1%	0.15%	250 m^3/h
Release position R2						
13	0.215	6	1.41	7.4%	none	170 m^3/h
14	0.215	6	1.39	6%	0.2%	
15	0.215	10.5	2.43	8%	0.35%	

Hydrogen released in front of the fuel cell, position R1, were found more prone to leak inside the passenger compartment rather than hydrogen released in position R2. For a total amount of hydrogen released as high as 1.4g the maximum concentration measured under the vehicle in the closest position from the release point was as high as 3.8%vol. and the maximum concentration inside the passenger compartment was 0.6%vol during the release. Hydrogen concentration inside the vehicle after 3 minutes from the release has measured to be less than 0.3%vol.Figure 5 shows hydrogen concentration vs. time for external hydrogen sensor number 1 and internal hydrogen sensors.

For a total amount of hydrogen released of 2.5 g a maximum concentration of 6.3%vol. was measured under the vehicle and a maximum concentration of 1.6% was measured inside the vehicle. Hydrogen concentration inside the vehicle after 3 minutes from the stop of the release was measured to be 0,5%vol.

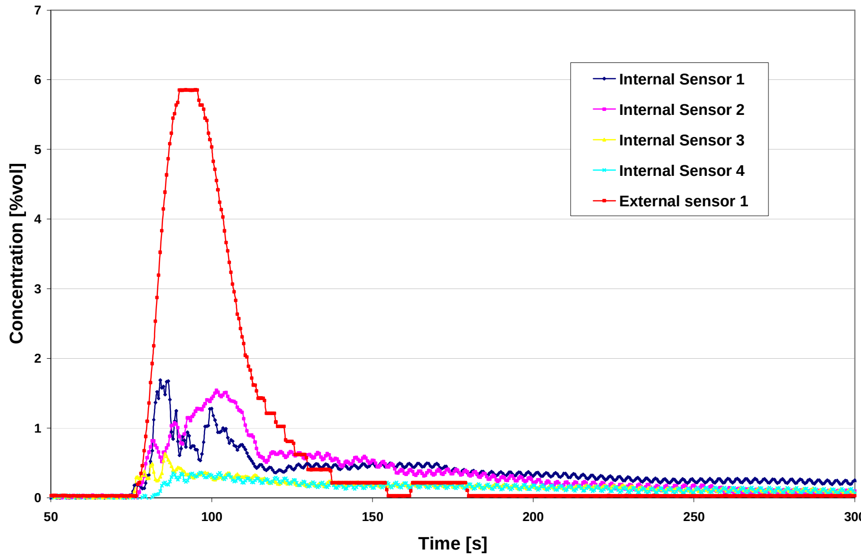


Figure 9. Hydrogen concentration inside and outside the vehicle for test number 2

Whit the ventilation fan in operation the maximum concentration measured outside the vehicle was 5%vol., while inside the vehicle a concentration of 0.15%vol. was measured for a brief period during the release.

Hydrogen released in position R2 led to a concentration under the vehicle of 6%vol and 8%vol for 1.4g and 2.5g released respectively, the maximum concentration was measured by sensor #3.

The maximum concentration inside the vehicle was measured as high as 0.6%vol in case of 2.4g inventory released and 0.2%vol in case of 1.45g of hydrogen released.

Whit the ventilation fan in operation no hydrogen was measured inside the vehicle for position R2.

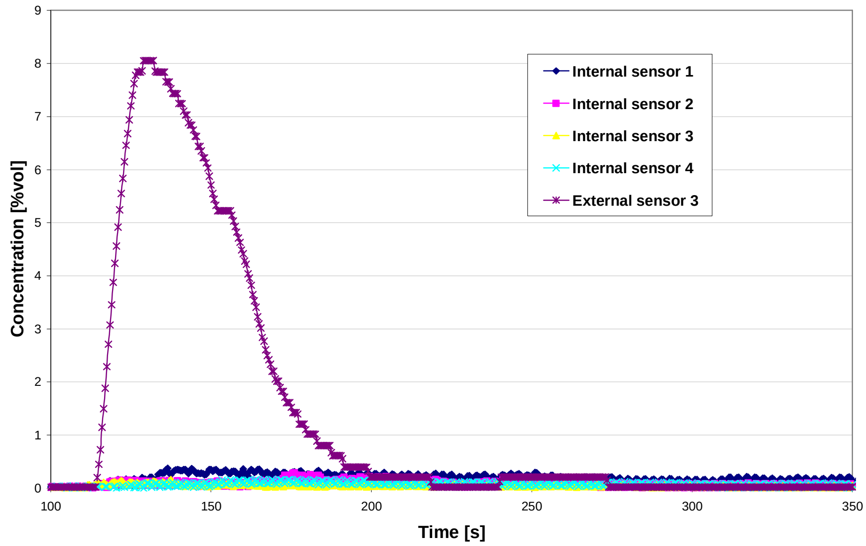


Figure 10. Hydrogen concentration inside and outside the vehicle for test number 15

For all the tests hydrogen concentration inside the vehicle started to decrease immediately after the immission was stopped and reached negligible values without any external intervention.

5.3 Test series V

Even though results from Test E Series showed that hydrogen is not sucked directly inside the vehicle by the air circulation fan, taking into account that no all the possible release point and direction were reproduced in the experiments, this possibility was not excluded and test were performed releasing hydrogen directly inside the air circulation system.

Table 3. Experimental matrix of Test Series V

TEST SERIES V						
Test #	**Flow rate [g/s]**	**Release time [s]**	**Hydrogen released [g]**	**Max. Conc. under the vehicle**	**Max. Conc. inside the vehicle**	**Air circulation system flow rate [m^3/h]**
Release from the left "defrost" air circulation opening						
16	0.215	6	1.29	0.2%	(0.4%)	270
17	0.21	11	2.31	0.4%	4.5% (0.8%)	270
18	0.206	21	4.24	0.8%	4.7% (1.5%)	270
19	0.206	43	8.86	1.4%	5.3% (3%)	270
20	0.206	59.5	12.52	2.2%	5.6% (4%)	270
21	0.104	61	6.33	1.2%	3% (1.1%)	270
22	0.104	150.5	15.72	1.8%	3.8% (2%)	270
23	0.05	61.5	3.08	0.6%	1.4% (0.5%)	270
24	0.05	301.5	15.08	1.4%	1.9% (1%)	270

As mentioned before hydrogen was released directly inside the air circulation system in a point downstream the ventilation fan to prevent any possible ignition. This led to a non uniform distribution of hydrogen in the circulating air, all the flow rate was directed in the "defrost" openings, but only the right part of the openings presented hydrogen dilute in the stream of air. For this reason in table 2 for the maximum concentration inside the vehicle two values are provided. The first value indicates the concentration of hydrogen in the incoming stream, while the bracketed value indicates the concentration reached in the other sensors inside the vehicle. The air circulation flow rate was set at its maximum value (270 Nm^3/h).

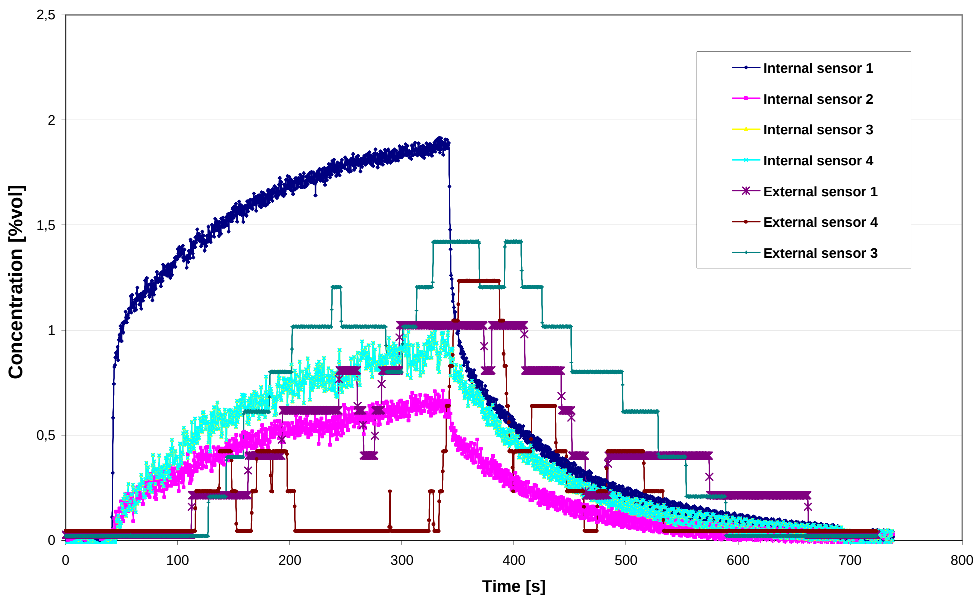


Figure 11. Hydrogen concentration inside and outside the vehicle for test number 24

Figure 11 shows the concentration of hydrogen in the internal and external sensors for test 24 where a release of 0.05 g/s of hydrogen was diluted in the air circulation stream. Internal sensor number 1 shows the concentration in the path of the stream coming from the right side (stream of air – hydrogen mixture), while the rest of the sensors measure the average concentration out of the stream.

Concentration tends to rise up to an asymptotic value that can be calculated taking into account the ventilation and the hydrogen flow rates. Time needed to reach 90% of the asymptotic concentration is 300 s and same time is needed for the air circulation system to wash the inner atmosphere.

Time laps between the rising of concentration inside and outside the vehicle range from 30 to 60 seconds depending on the hydrogen flow rate and it’s smaller for a bigger hydrogen flow rate.

Hydrogen flow rate of 0.2 g/s can lead to a build up of flammable atmosphere on the stream in the front part of the vehicle (driver and passenger seats) immediately after the release of hydrogen take place. Nevertheless if the 0.2 g/s hydrogen flow rate would have been diluted in the entire air circulation stream at its minimum power it could have reached a flammable concentration in 4-5 minutes.

6.0 CONCLUSIONS

Three series of test were performed to study the additional risk for the passenger of a Piaggio Porter vehicle when the original electric propulsion system was replaced by a hydrogen powered fuel cell system.

In a preliminary test a diffusive leak of hydrogen was simulated releasing a flow rate of $3\ 10^{-5}$ g/s close to the vehicle ceiling (pavilion). Concentration inside the vehicle reached an asymptotic value of 400 ppm and no unlimited accumulation inside the passenger compartment was possible for this kind of leaks.

Tests were conducted releasing hydrogen in two different points under the vehicle. The total content of hydrogen present in the pipes, 1.4g, was released and a maximum concentration of 0.7% was measured inside the vehicle close to the ceiling when the release point was placed in the front part of the vehicle. A total amount of hydrogen of 2.5 g was released and a maximum concentration of 1.8% was measured inside the vehicle, in this case concentrations higher than the flammable limit were measured under the vehicle.

Results showed that hydrogen released under the vehicle leaked easily inside the passenger compartment from the ventilation openings, especially when the release point is located in the front part. With the air circulation system in operation hydrogen was prevented to enter the vehicle, even if it was sucked inside the vehicle by the ventilation system when the release location was in the vehicle front the total amount of hydrogen sucked inside was very small and the concentration in the passenger compartment reached a maximum of 0.25% during the release.

Since all the possible releasing points were not studied the possibility for hydrogen to be sucked inside the ventilation system at higher flow rates was not excluded and tests were conducted releasing hydrogen directly inside the air circulation system fan.

Results show that an asymptotic concentration is reached inside the vehicle with a value dependent on both hydrogen and ventilation system flow rates. No possible build up of flammable atmosphere inside the vehicle is possible for hydrogen flow rates smaller than 0.1 g/s, that correspond to 50% of the flow rate needed by the fuel cell at its maximum power regime.

In conclusion no flammable atmosphere is expected in the passenger compartment of the vehicle Piaggio Porter for unintended leaks during the stops of the vehicle when the hydrogen bottles are closed, while the build up of a flammable atmosphere is possible for a continuous leak from the system sucked directly inside the air ventilation system from the fan when the hydrogen sucked flow rate is bigger than 0,1 g/s (coupled with minimum air circulation system flow rate). Since such a flow rate loss from the system should be easily detected by the power control system the conclusion of this work is that no possible arm for the passenger of the vehicle is possible if the unintended leak is the only undesired undergoing event. The conclusion is not valid if the release take place while an independent event is undergoing; for example if the valves don't isolate the storage bottles during the stops of the vehicle or if the control system lose the possibility to shutdown the power and isolate the storage bottles when a flow rate in the pipes bigger than 120% or when no hydrogen reaches the fuel cell while is expected to.

Nevertheless care should be taken anytime a hydrogen system is installed on a vehicle not expressly designed to host it as well as in the design of the air circulation system of a new hydrogen vehicle in order to reduce the possibility for hydrogen to enter inside the passenger compartment.

ACKNOLEDGMENTS

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