EXPERIMENTAL STUDIES ON WIND INFLUENCE ON HYDROGEN RELEASE FROM LOW PRESSURE PIPELINES.

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ABSTRACT

At the DIMNP (Department of Mechanical, Nuclear and Production Engineering) laboratories of University of Pisa (Italy) a pilot plant called HPBT (Hydrogen Pipe Break Test) was built in cooperation with the Italian Department of Fire Brigade. The apparatus consists of a 12 m^3 tank which is fed by high pressure cylinders. A 50 m long pipe moves from the tank to an open space and at the far end has an automatic release system that can be operated from remote. A couple of flanges have been used to house a disc with a hole of the desired diameter, so that it could be changed easily during tests. The plant has been used to carry out experiments of hydrogen release and its ignition. During the experimental activity, data have been acquired about the gas concentration and the length of release as function of internal pressure and release hole diameter. The information obtained by the experimental activity will be the basis for the development of a new specific normative framework arranged to prevent fire and applied to hydrogen. This study is focused on hydrogen concentration as function of wind velocity and direction. Experimental data have been compared with theoretical and computer models (such as CFD simulations).

1.0 INTRODUCTION

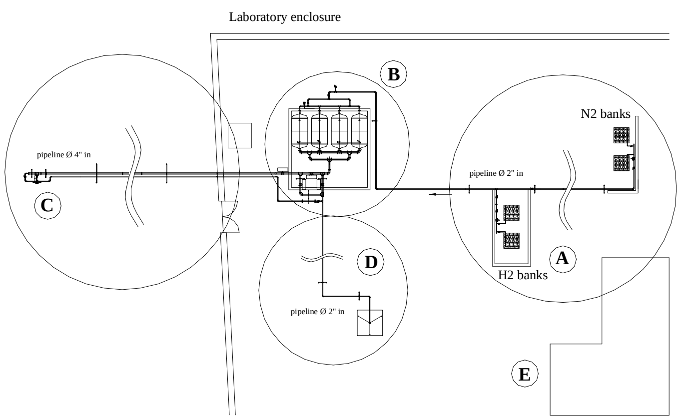
Recently, many studies have been accomplished on hydrogen jet releases [1]. Most of them deals with high pressure releases (up to 1000 bar) [2] referring to hypothetical leakages from high pressure storage tanks. In these studies, the experimental facility reproduces flow rates that undergo to very fast drop-downs, and therefore are very difficult to investigate with measurement instrumentation. The purpose of this experimental study on the HPBT apparatus has been to perform tests that could allow acquiring data of hydrogen concentration, as accurate as possible, into the volume crossed by the jet. To achieve this target, at University of Pisa has been realized an experimental facility that is able to keep quite constant the gas flow rates of releases for a time long enough if related to the hydrogen concentration acquisition system timing. It goes without saying that only low pressure releases from a large volume reservoir could be taken into account. The tests have been executed to have experimental data set that the developers and users of computational codes find useful and, at the same time, to give data that characterize typical leakages from low pressure pipelines that can be used for the Italian regulation for the transport of hydrogen with pipeline [3].

2.0 EXPERIMENTAL APPARATUS

The experimental apparatus named HPBT (Hydrogen Pipe Break Test) was installed within the Laboratory “Scalbatraio” of DIMNP. This apparatus was used to investigate the behaviour of hydrogen leakages from pipelines; it was able to simulate a real, low pressure hydrogen release into free air. The experimental activity was mainly addressed to the acquisition of data, on hydrogen releases from holes at low pressure, that could be useful for computational codes. Another purpose of the activity was to generate data that could help the development of an Italian regulation for the transport of hydrogen with pipeline.

2.1 Experimental apparatus layout

The HPBT apparatus layout is described in detail in [4]. Briefly the apparatus can be divided into four ideal parts: (1) Hydrogen and nitrogen storage (two banks of twenty five cylinders with an initial pressure of 20 MPa); (2) Gas reservoir (test pressure) composed of four large storage tanks (3 m^3 each) with a maximum working pressure of 1 MPa; (3) a pipe of 4 inches (0.102 m) in diameter and 50 m long connects the gas reservoir to an automatic release system (ARS) where the hydrogen leakage takes place in an open field (the release was realized at 0.9 m above ground); (4) a vent line. (Figure 1)



A – Gas storage

B – Gas reservoir

C – Release point

D – Vent line

E – Buildings

Figure 1. HPBT apparatus Layout.

3.0 DATA ACQUISITION SYSTEM

The acquisition system is described in detail in [4]. Only the description of the anemometer and the system used to acquire concentration data are reported below.

3.1 Anemometer

During the tests under study in this paper, wind was monitored at about 3 m from ground and far from obstacles that could create turbulence. The instrument used is an anemometer MODEL N°1086 LTD by Gill Instruments Ltd (Lymington Hampshire – England). The instrument was set at the beginning of the day and acquired data during all the day. This way it was possible to have data about wind not only at the moment of the test, but also before and after.

3.2 Concentration acquisition system

Hydrogen sensors don't work properly in free air when analyzing H_2 concentration in the range between 0 and 100%vol. Therefore in order to have data that could identify hydrogen concentration in free air, oxygen concentration was acquired in nine different points. The sensors used are SMART3 CC-CD (NET/x) by SENSITRON S.r.l. (Milano – Italy). In Table 1 and Figure 4 spatial coordinates of concentration monitor points referring to tests HPBT-JR-3, HPBT-JR-7 and HPBT-JR-8. Coordinates are referred to the release point (center of coordinates) and are right-handed Cartesian coordinates can be found (as written before, the release was realized 0.9 m high from ground). Monitor points are labelled from X4 to X12. In order to connect the points where the samples are taken to the sensors, nine rilsan pipes (6x4 mm) were used. As the samples were up to 4m far from release point, about 6 m long pipes were necessary. A vacuum pump model TIPO BS V3 was used to suck the gas samples in the sensors. The flow rate was regulated through each pipe by flow-meters model TECMA FLUSSIMETRO SERIE 1900.

Table 1. Spatial coordinates of sample points.

	X [mm]	Y [mm]	Z [mm]
X4	290	0	-10
X5	500	0	20
X6	980	0	-10
X7	2000	0	0
X8	2490	0	0
X9	480	0	70
X10	480	0	-50
X11	980	0	100
X12	980	0	-100

4.0 RELEASE EXPERIMENTAL TESTS

During the experimental series a total of 22 release tests were performed. The parameters changed during the tests were: hole diameter (2.5 mm, 5 mm and 11 mm) and internal pressure (from 2 to 10 bar). Three of the tests performed are reported and analyzed in this article: test HPBT-JR-3 (D=2.5 mm and P=2.1 bar), test HPBT-JR-7 (D=2.5 mm and P=5.9 bar), test HPBT-JR-8 (D=2.5 mm and P=10 bar) [5].

4.1 Data acquired

In Table 2 the results of tests are summarized. Mean wind velocity [m/s] and direction [°] are reported as modulus and as clockwise angle starting from release direction. Referring to the maximum mass flow rate G_{max}, the last two columns report how long it was possible to keep the mass flow rate G between the value $G_{max} > G > (0.90)G_{max}$ in the first case and $G_{max} > G > (0.95)G_{max}$ in the second.

4.2 Hydrogen concentration versus time [4]

Due to the concentration measurement system, there is a delay between the time when the release starts (t_0) and the time when hydrogen sensors start to measure a steady value (t_s). To understand how the delay can affect the measure it has been evaluated the time that the gas sample needs to reach the sensor and then the response time of the sensor. The gas measurement system has been described in [4]. Here it is important to underline that once the delay has been defined, it is possible to select a time zone where the concentration values are steady, unless wind turbulence is present (Figure 2).

4.3 Wind behaviour

During the experimental series wind intensity and velocity was monitored. Wind behavior during tests HPBT-JR-3, HPBT-JR-7 and HPBT-JR-8 is shown in the following Figure 3. In Figure 3 (a), (d) and (e) is shown wind velocity as modulus (time dependent) in the plane XY and the two horizontal components v_x and v_y, respectively along the axis of the jet and along the orthogonal direction; component v_z is also shown. In Figure 3 (b), (c) and (f) is shown the anti-clockwise angle α (time dependent) that wind vector forms with X-axis on plane XY moving away from the center of coordinates.

It can be noticed that v_z contribution to overall wind intensity is negligible in the three tests under study. The angle vs. time plot shows that during most part of tests HPBT-JR-3 and HPBT-JR-8 wind direction was definitely constant. During test HPBT-JR-7 the angle shows fast and large changes: in about 20 s undergoes up to a 90° variation, starting from 130° it drops to 40° and grows back to 120°.

Table 2. Experimental data referring to wind and jet parameters.

	P_j	d_j	***Wind modulus***	***Wind angle (anti-clockwise from release direction)***	***Time before G drops under 90%***	***Time before G drops under 95%***
	[bar]	[m]	[m/s]	[°]	[s]	[s]
HPBT-JR-3	2.1	$2.5 \cdot 10^{-3}$	1.68	79.4	> 155	> 155
HPBT-JR-7	5.9	$2.5 \cdot 10^{-3}$	1.24	87.5	> 180	> 180
HPBT-JR-8	10	$2.5 \cdot 10^{-3}$	2.10	55.4	> 249	175

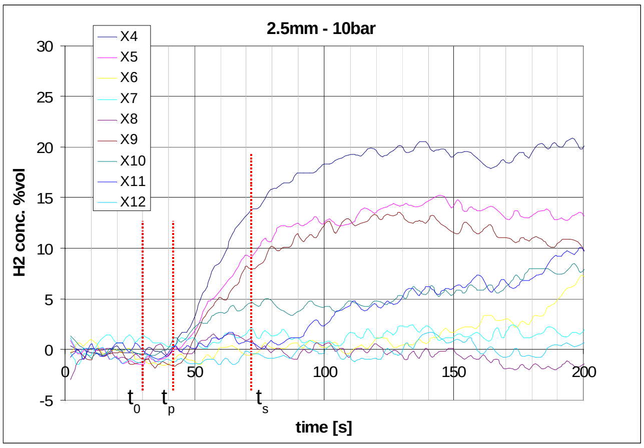


Figure 2. Test HPBT-JR-8: hydrogen concentration versus time.

It is hard to identify the influence of changes in wind direction on hydrogen diffusion because they are too fast and correspond to variation in wind modulus. On the contrary, it is easy to find a time region during which wind modulus changes while the angle is constant. Starting from this remark, wind speed and hydrogen concentration were plotted versus time and some interaction has been noticed. Eventually each test could be analyzed on the basis of a series of data that can be summarized as shown in Figure 4.

5.0 WIND INFLUENCE ON CONCENTRATION BEHAVIOUR

Looking at the concentration vs. time graph for test HPBT-JR-3 it is evident that there is some influence due to wind. Furthermore in Figure 5 it is possible to see that sensors X5, X7, X10 and X11 show a direct reaction to wind velocity. This paper was intended for the study of this phenomenon. In fact overlapping the two graphs representing wind velocity (vs. time) and hydrogen concentration (vs. time), it is possible to investigate if changes in wind speed mirror changes in hydrogen concentration. To achieve this purpose in every test two or three time intervals have been chosen. Every time interval has a different wind intensity and a corresponding variation in hydrogen concentration. Figure 6 shows the intervals chosen and Table 5 reports all concentration and data referring to the time intervals defined in Figure 6. Three tests have been chosen as example in this article, because each of them has a different configuration of wind intensity and direction. In test HPBT-JR-3 wind changes its speed from about 3 m/s to 0.8 m/s and Y component is dominant, while direction holds steady. In test HPBT-JR-7 wind changes its speed from about 0.7 m/s to 2.1 m/s and X component is dominant, while direction holds steady. In test HPBT-JR-8 wind changes its speed from about 3.8 m/s to 1.7 m/s and no component is really dominant, while direction holds steady.

5.1 Wind speed and jet speed

In the following paragraphs the variation of hydrogen concentration as function of wind velocity will be discussed in detail. What is important to underline here is that in all the tests under study the sample points are inside the momentum dominated region of the jet [6, 7].

Therefore the influence of wind speed is theoretically negligible because it is much smaller than jet velocity. So it is interesting to evaluate the velocity of jet corresponding to the points where samples are taken, following theoretical approach [6, 7, 8, 14, 15] and then to compare it to wind velocity evaluated at the altitude of release point (about 0.9 m) [9, 10].

As the pressure inside the apparatus was always more than 2 bar, a second expansion of the gas outside the release must be expected [7, 9]. The final velocity of the gas can be valuated by the equation:

$$u_f = u_j - \frac{(P_\infty - P_j)}{\rho_j u_j}, \tag{1}$$

where u_j – velocity at exit hole, m/s; P_j – pressure at exit hole, bar; P_∞ – atmospheric pressure, bar; ρ_j – hydrogen density at release hole, kg/m^3.

The notional diameter is given by:

$$d_{eff} = d_j \sqrt{\frac{\rho_j u_j}{\rho_{H\infty} u_f}}, \tag{2}$$

where d_j – release hole diameter, m; $\rho_{H\infty}$ – hydrogen density at atmospheric conditions, kg/m^3.

Froude number has been evaluated as follow [7]:

$$Fr = \frac{u_f}{\sqrt{g d_{eff}\left(\frac{\rho_\infty - \rho_{H\infty}}{\rho_{H\infty}}\right)}}, \tag{3}$$

where g – acceleration due to gravity, m/s^2; ρ_∞ – air density at atmospheric conditions, kg/m^3.

Moreover Chen & Rodi [6] give an expression that can be used to evaluate jet velocity along jet axis:

$$u_j(x) = u_f \frac{d_{eff}}{x} A_{u1} \sqrt{\frac{\rho_j}{\rho_\infty}}, \tag{4}$$

where x – distance from release hole, m; A_{u1} – non-dimensional coefficient (= 6.2 [6]).

The speed change of wind due to the difference in altitude of the anemometer and the release point has been taken into account as follow [9, 10]:

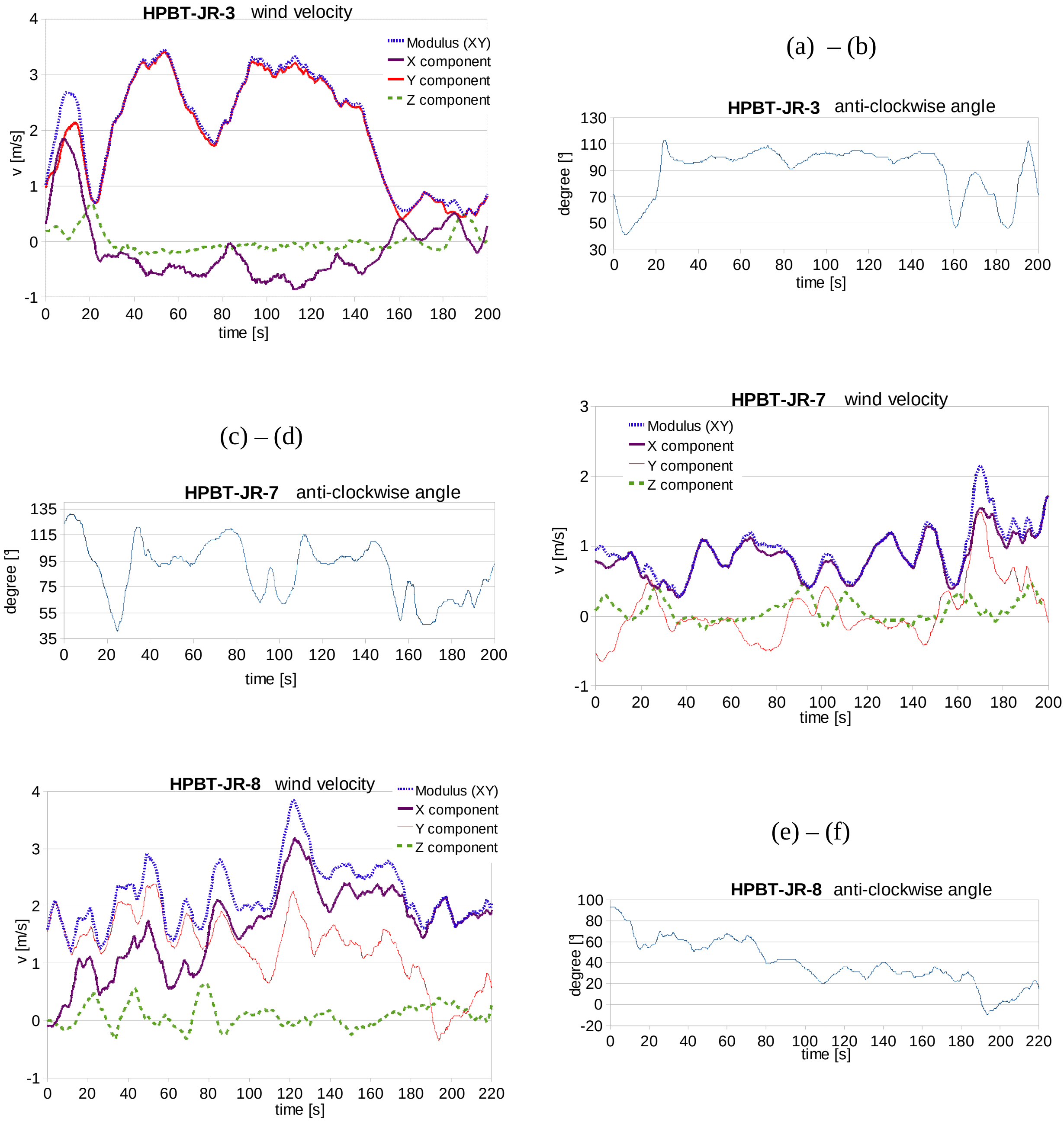


Figure 3. (a), (d) and (e) wind modulus and wind components; (b), (c) and (f) wind anticlockwise angle (see Figure 4)

$$u_w(z) = u_w^{ref} \frac{\ln\left(\frac{z - z_0}{z_0}\right)}{\ln\left(\frac{z_{ref}}{z_0}\right)}, \tag{5}$$

where u_w^{ref} – wind velocity measured by anemometer, m/s; z – height of release, m; z_{ref} – height of anemometer, m; z_0 – atmospheric roughness length, m (= 0.03; [9, 10]).

By means of expression (5), wind modulus on plane XY is lowered to 76.8% of measured value. As this correction is proportional to the measured velocity, Figures 3 are still a valid reference for wind fluctuation.

Table 3 and Table 4 show the coordinates of sample points and the value of u_f, $u_j(x)$, Fr and Re. In order to evaluate $Fr(x)$ and $Re(x)$ it was necessary to calculate $\rho(x)$ as suggested by Chen & Rodi [6]:

$$\rho(x) = \rho_\infty - 5\left(\frac{\rho_j}{\rho_\infty}\right)^{-\frac{1}{2}} \frac{d_{eff}}{x}\left(\rho_\infty - \rho_j\right), \tag{6}$$

Table 3. Data referring to gas exit conditions before and after second expansion.

	P_j [bar]	d_j [m]	D_{eff} [m]	u_j [m/s]	u_f [m/s]	Fr	Re
HPBT-JR-3	2.1	$2.5\cdot10^{-3}$	$3.2\cdot10^{-3}$	1345	$1.84\cdot10^{3}$	4155	$1.08\cdot10^{5}$
HPBT-JR-7	5.9	$2.5\cdot10^{-3}$	$4.98\cdot10^{-3}$	1348	$2.13\cdot10^{3}$	7682	$5.49\cdot10^{5}$
HPBT-JR-8	10	$2.5\cdot10^{-3}$	$6.35\cdot10^{-3}$	1350	$2.20\cdot10^{3}$	12040	$1.21\cdot10^{6}$

Table 4. Data referring to centerline sample points. All values are calculated by means of Chen and Rodi equations [6].

	HPBT-JR-3				HPBT-JR-7				HPBT-JR-8			
	$U_j(x)$	ρ(x)	Fr(x)	Re(x)	$U_j(x)$	ρ(x)	Fr(x)	Re(x)	$U_j(x)$	ρ(x)	Fr(x)	Re(x)
	m/s	kg/m^3	-	-	m/s	kg/m^3	-	-	m/s	kg/m^3	-	-
X4	34.0	1.05	502	$1.26\cdot10^{4}$	89.3	1.10	1330	$5.43\cdot10^{4}$	148	1.14	2650	$1.19\cdot10^{5}$
X5	19.7	1.11	394	$7.78\cdot10^{3}$	51.8	1.14	1033	$3.27\cdot10^{4}$	85.7	1.17	2039	$7.06\cdot10^{4}$
X6	10.1	1.15	287	$4.12\cdot10^{3}$	26.4	1.17	747	$1.71\cdot10^{4}$	43.7	1.18	1467	$3.65\cdot10^{4}$
X7	4.93	1.18	203	$2.06\cdot10^{3}$	12.9	1.18	526	$8.49\cdot10^{3}$	21.4	1.19	1030	$1.80\cdot10^{4}$
X8	3.96	1.18	182	$1.66\cdot10^{3}$	10.4	1.19	472	$6.84\cdot10^{3}$	17.2	1.19	924	$1.45\cdot10^{4}$

Table 5. H_2 concentration: experimental data.

	HPBT-JR-3			HPBT-JR-7		HPBT-JR-8		
	Δt1	Δt2	Δt3	Δt1	Δt2	Δt1	Δt2	Δt3
	H2 %vol.			H2 %vol.		H2 %vol.		
X4	8	8.1	6.2	18	15.7	19.3	19.4	20
X5	4.5	1.7	3	14.7	11	13.5	14	13.3
X6	(0)	(0)	(0)	(2.6)	(3.2)	(1)	(2)	(4.2)
X7	0.7	0	1.4	0	0	1.3	1.5	1.9
X8	0	0	0	0	0	0	0	0
X9	2.7	2	0	6.3	4.2	13.1	11.9	10.3
X10	3.2	2.5	4.4	9.3	7.6	4.6	6	7.8
X11	2.3	0.7	1.1	5.4	1.3	4.4	6.6	8.3
X12	0.6	0.9	1.3	2	1	0	0	0

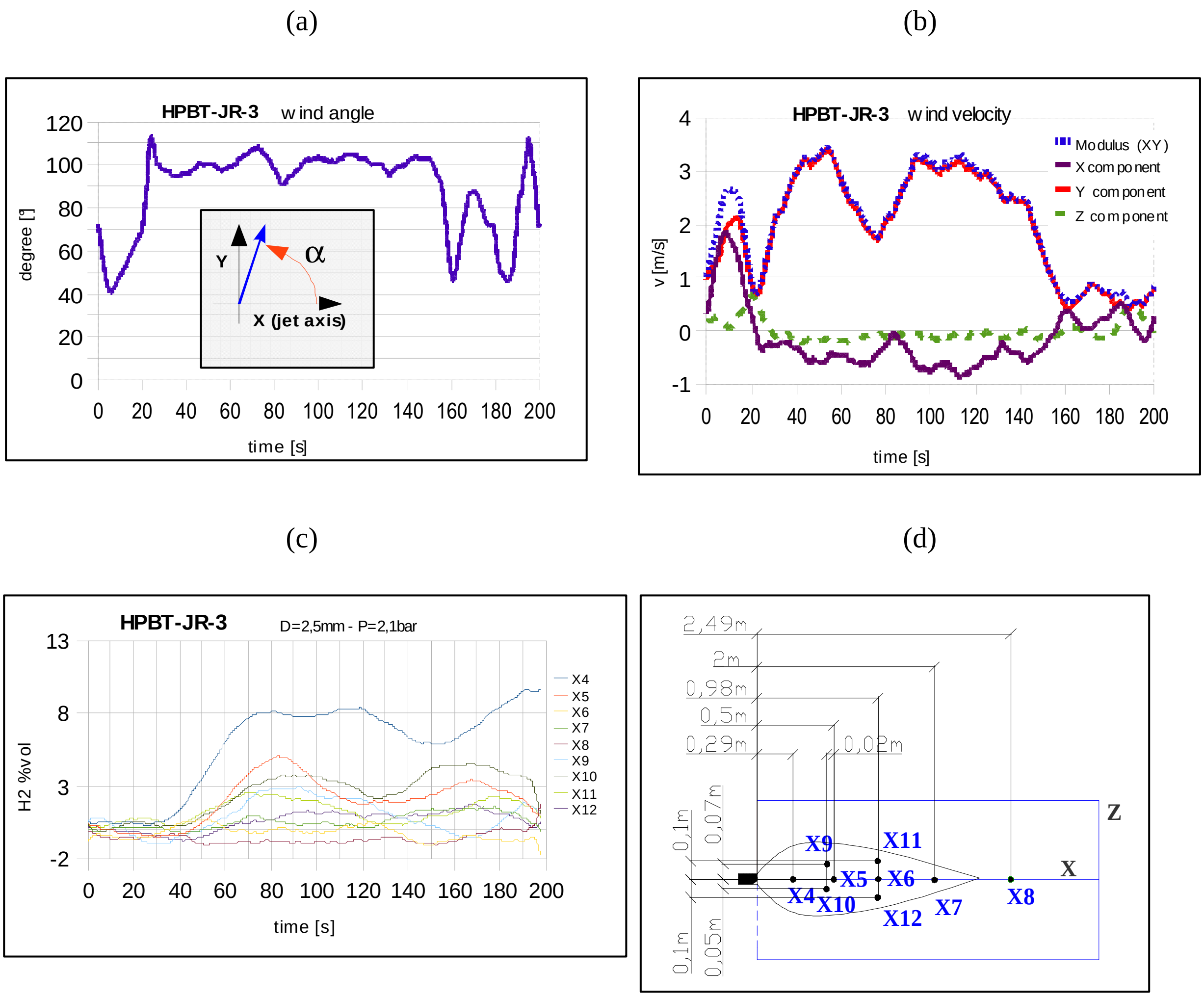


Figure 4. (a) wind anticlockwise angle from jet axis on plane XY; (b) wind velocity; (c) hydrogen concentration versus time and (d) spatial position of monitor points.

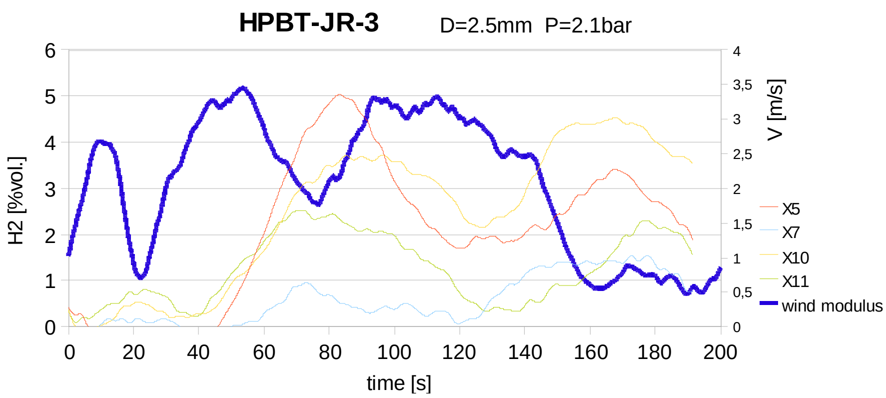


Figure 5. Hydrogen concentration variations and corresponding wind velocity.

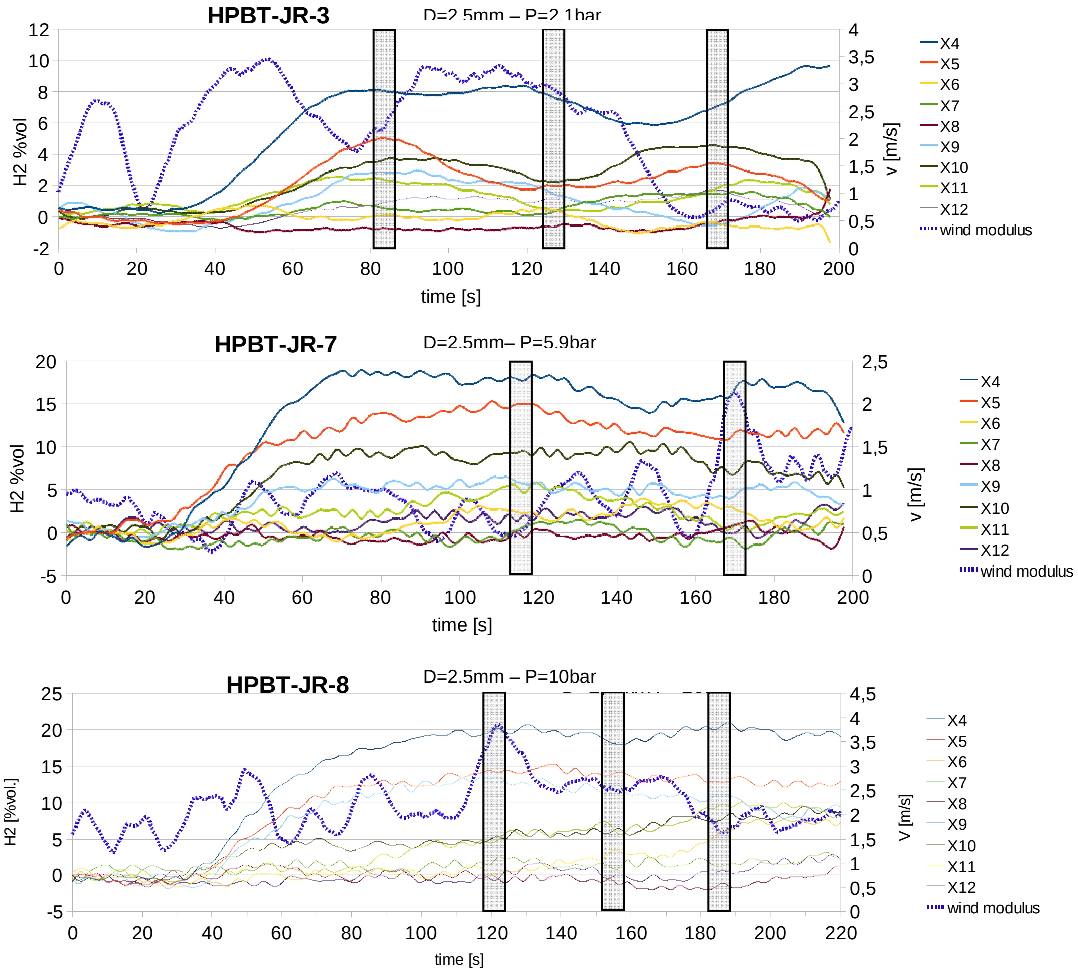


Figure 6. Hydrogen concentration versus time and time intervals.

6.0 MODELS USED BY COMPUTER CODES

Computational codes use has undergone large developments lately and many programs can be found on commerce. For this work three of them have been used, but the results of only two of them are available. Every code has been developed on the basis of a theoretical model: in this paragraph a brief review of the different approach will be shown, anyway a discussion about the physical models of the codes is beyond the purpose of this article.

EFFECTS 7.6.1 is a commercial program by TNO which can perform calculations to predict the physical effects (gas concentrations, heat radiation levels, peak overpressures etc.) of the escape of hazardous materials. Models in EFFECTS are based upon the Yellow Book [9]. FLACS V9.0 is a commercial program by GexCon AS and is based on CFD (computational fluid dynamics), a branch of fluid mechanics that uses numerical methods to solve and analyze problems that involve fluid flow, with or without chemical reactions [10]. The program allows to create a 3D representation of the scenario. Afterwards it is necessary to create a grid of discrete cells (the mesh). When the program is started it solves iteratively fluodynamic equations for every cell and can print a visualization of the results or at a definite time or can visualize time dependant phenomena as a video. SPRAY is a program under development in Italy by CNR-ISAC (in Turin) and ARIANET (in Milan); it is a Lagrangian particle dispersion model that considers the buoyancy effects and is based on evaluating the behaviour of a large number of small particles [11, 12]. Unfortunately the results of the simulations performed by SPRAY are not still available.

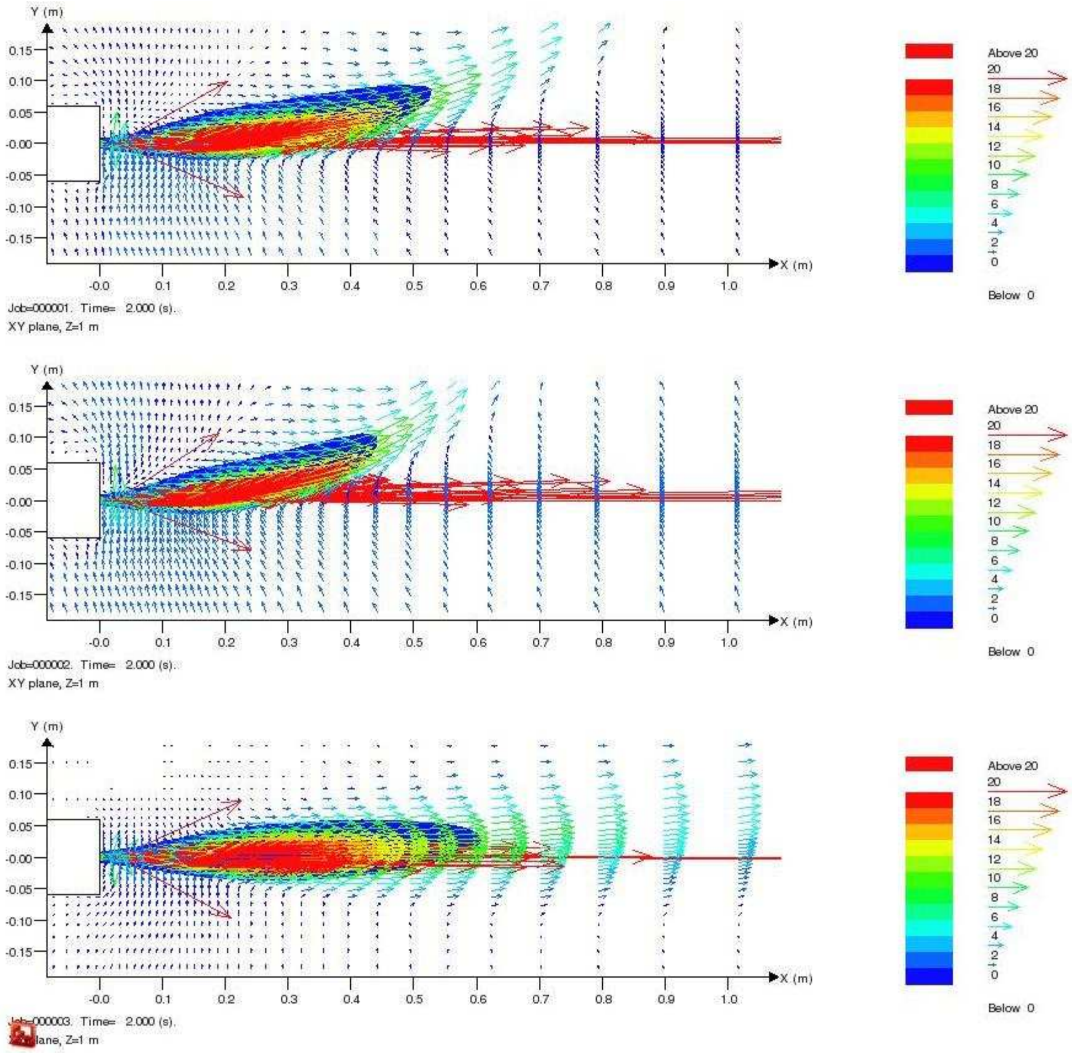


Figure 7. Simulation of wind effect on jet direction by FLACS

7.0 EXPERIMENTAL RESULTS AND COMPUTATIONAL VALUES

As mentioned before, only FLACS and SPRAY code allows to introduce wind parameters, while EFFECTS model for turbulent jets doesn't allow to assign wind velocity, but only a direction that is used by the code to define jet direction. SPRAY results are not available at present, as it has been used to investigate different tests [12, 13]. FLACS code can simulate "fluctuating wind" [10] and allows to define two different frequencies in horizontal direction and one in vertical direction. Anyway for the purpose of this paper FLACS code has been used to simulate jets in presence of a constant wind velocity and direction, and the corresponding value of H_2 concentration are reported in Table 5. The time interval has been chosen as large as wind parameters could be considered steady, therefore it includes about 10 s.

7.1 Wind influence on jet direction as result of FLACS simulations

In Figures 7 is shown the result of FLACS simulations of time intervals $\Delta t1$, $\Delta t2$ and $\Delta t3$ of test HPBT-JR-3. The Figure shows how the code simulates wind on plane XY (wind along Z-axis has been neglected) and the influence of wind in the three cases under study.

7.2 Wind influence on hydrogen concentration

It is usual assumption that wind helps gas dispersion. Therefore for fixed monitor points higher wind speed should yield lower gas concentrations. This work tries to show if experimental data support this theory.

A comparison of hydrogen concentration as function of distance from hole release at different wind speed can be seen in Figures from 8 to 11. In the Figures experimental data are reported as triangles, FLACS data are reported as balls and EFFECTS data are reported as squares.

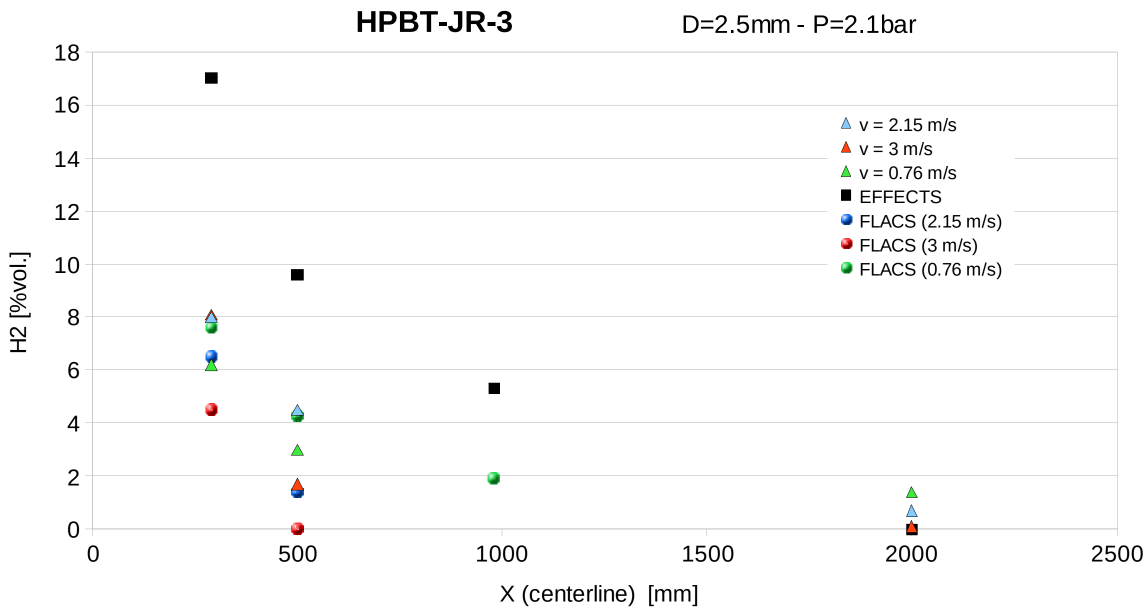


Figure 8. HPBT-JR-3: Hydrogen concentration vs. X axis (jet centreline)

In general both codes report a similar trend which is also shown by the experiments. Along X axis EFFECTS overestimates real values in every test and only when evaluating concentration along Z axis, it calculates values comparable to experimental ones. On the opposite FLACS offers a more realistic series of values. Test HPBT-JR-8 does not shows a considerable variation of hydrogen concentration due to wind fluctuation. Experimental data results quite completely overlapped in good accordance to wind intensity. In regards to this a remark is necessary.

Looking at Table 6 is possible to see that wind modulus has decreased with increasing time. At the same time internal pressure has decreased with increasing time, so in complete lack of wind hydrogen concentration is expected to drop with time. This means that any increase of hydrogen concentration has to be attributed to wind fluctuation. Furthermore the first two sensors (X4 and X5) in Table 7 refer to high jet velocity and the corresponding Froude and Reynolds numbers, as reported in Table 4, suggest that small influence has to be expected from wind speed. Unfortunately sensor X6 has given underestimated values and can be considered only as trend, but both X6 and X7 sensors have reported a change in values that is in good accordance with theory.

With regard to test HPBT-JR-7, a more evident difference between concentrations at different wind speed can be pointed out. The difference is shown also by FLACS values and the gap between the two values remains quite constant along X axis. Experimental data are higher than those calculated by the code with a difference that is quite large and that keeps constant along X axis.

Table 6. Data referring to wind at 3m above the ground at different time

test	HPBT-JR-3		HPBT-JR-7		HPBT-JR-8	
Wind	**Speed [m/s]**	**Angle [°]**	**Speed [m/s]**	**Angle [°]**	**Speed [m/s]**	**Angle [°]**
Δt1	2.15	91	0.68	95	3.8	35
Δt2	3	100	2.1	47	2.5	28.4
Δt3	0.76	82			1.68	18.5

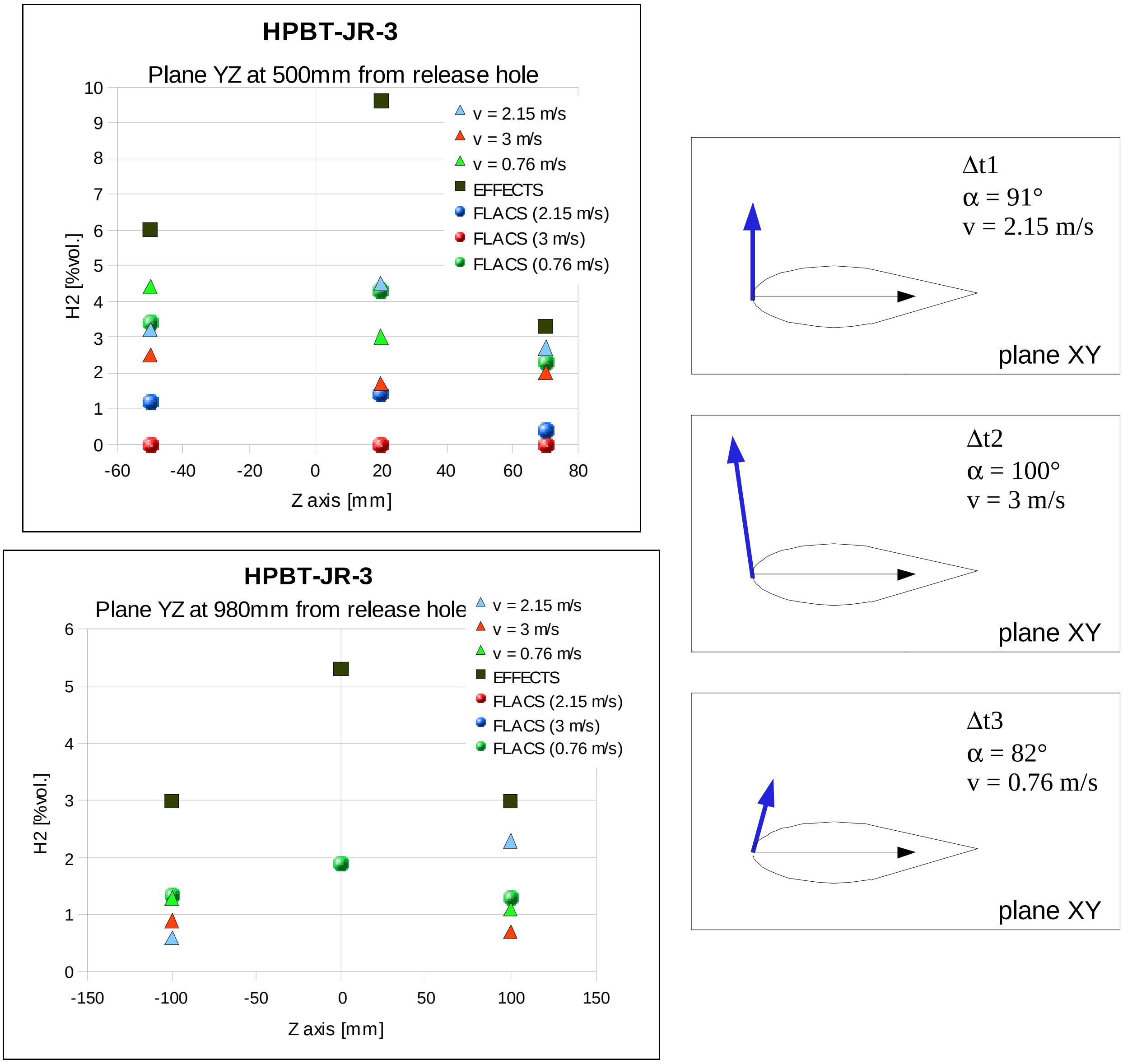


Figure 9. HPBT-JR-3: Hydrogen concentration along Z axis and wind parameters.

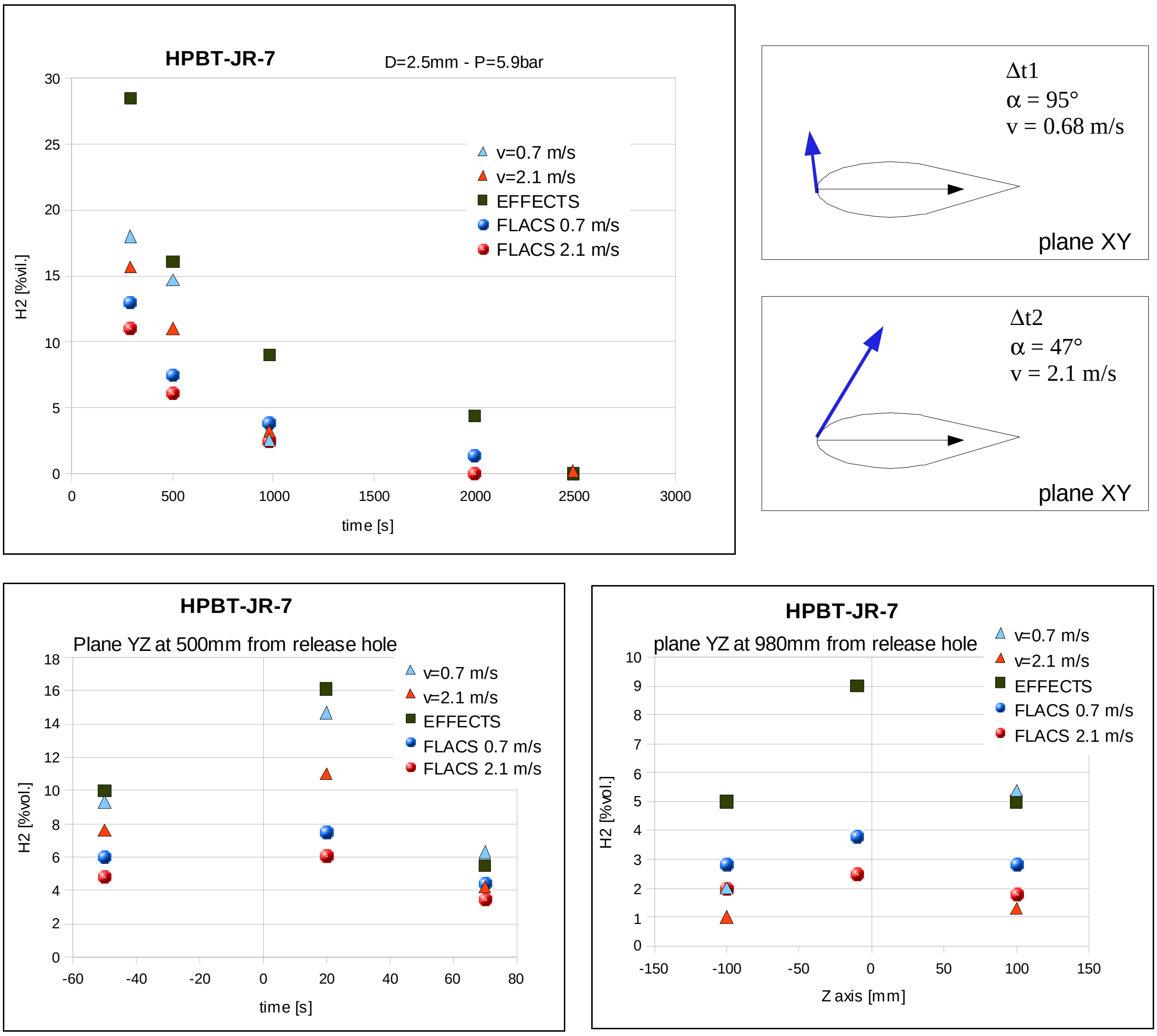


Figure 10. HPBT-JR-7: Hydrogen concentration along Z axis and wind parameters.

Test HPBT-JR-3 requires a more accurate analysis. Low internal pressure and small hole diameter make so that wind influence affects much more hydrogen concentration than it does in tests discussed before. To understand how wind speed interferes with jet speed it can be useful to evaluate the ratio of jet speed to the vector that comes out from the vector sum of wind vector and jet vector versus axial distance (Figure 12). Furthermore the corresponding hydrogen concentration has been reported on plots. In these plots wind velocity has been calculated at the height of hole release by means of equation (5).

In Figure 12 it can be noticed that a higher speed of wind does not translate into a higher velocity vector, because wind component along X axis can have a direction that is opposite to jet direction (Δt3). So it can be said that a higher increase in speed modulus (due to vector sum of wind and jet speed) leads to a lower value of hydrogen concentration. In Figure 12 it is also possible to notice that the curves overlaps more than once before they clearly separate. The second measurement (X5) is made where the curves overlaps and this is supposed to be the reason why the values of concentration are apparently in disagreement with the curves, while in the other case a higher velocity corresponds to a lower concentration as expected.

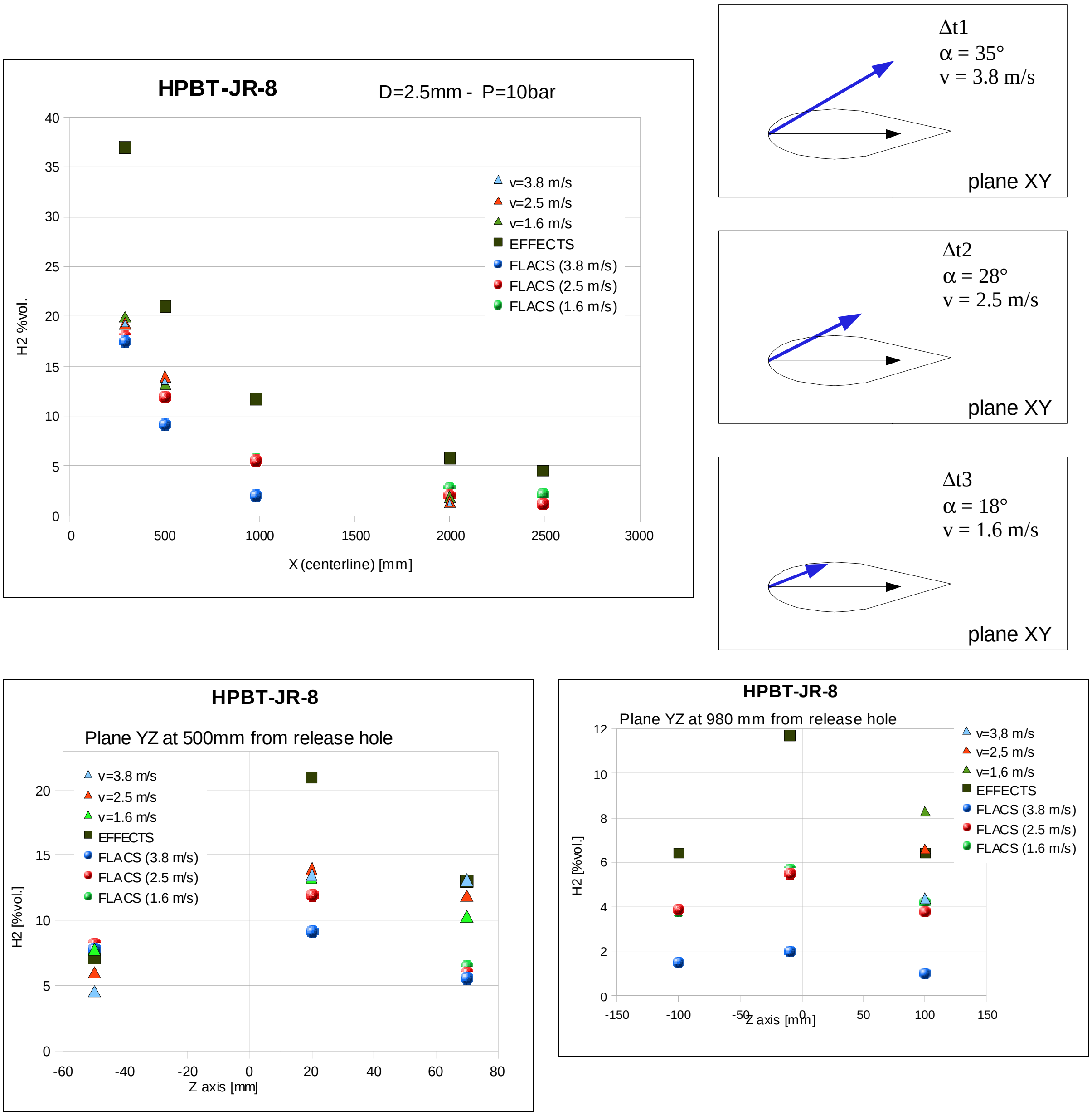


Figure 11. HPBT-JR-8: Hydrogen concentration along Z axis and wind parameters.

The same plots for test HPBT-JR-7 (Figure 12) shows the same results as described before, but no overlapping of the curves can be observed. So there is a direct correlation between total velocity modulus and hydrogen concentration: the higher is the first value and the lower is the second value. With regard to test HPBT-JR-8, there is no evident difference in hydrogen concentration so as there is no evident difference in total velocity modulus. In Figure 13 H_2 concentration along X axis is compared for the same point at decreasing wind velocity. Values far from release point show a trend that agrees with theory.

About FLACS data, it is evident that they are in really good agreement with experimental data in test HBPT-JR-8, when considering the points along centerline. Along Z axis they are very symmetrical while test data are not. The higher velocity of the jet can explain the most correct values along centerline, while the higher turbulence may explain the lack of agreement along Z axis. In fact the real phenomenon is affected by higher turbulence than the model can simulate, because of the fast variations of wind velocity and direction that have been measured (Figure 2).

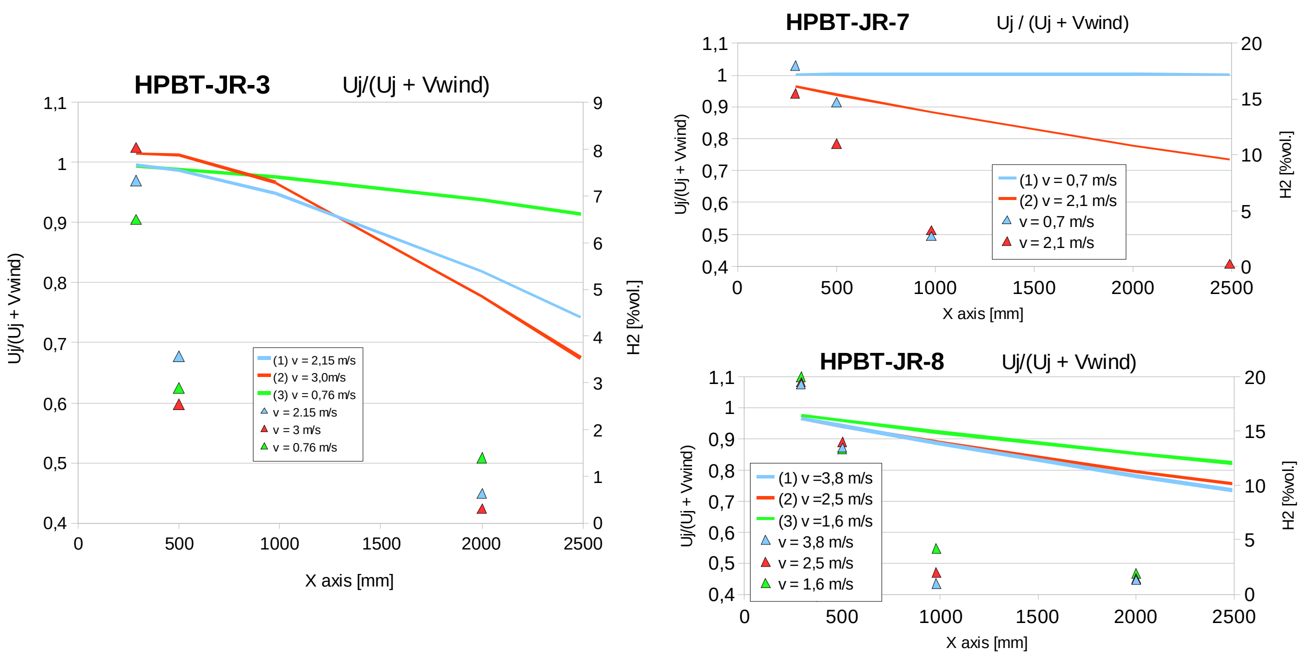


Figure 12. Ratio of jet velocity to vector sum of wind velocity and jet velocity compared to H2 concentration along X axis as function of wind velocity

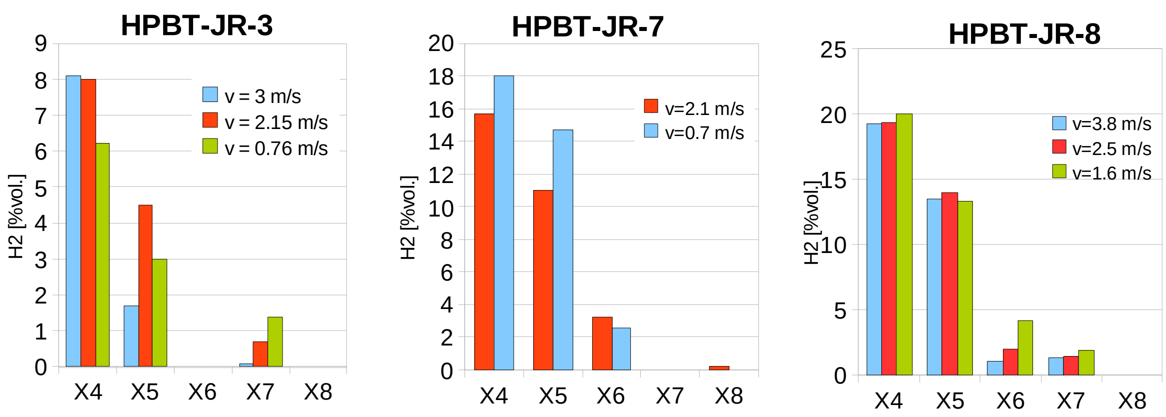


Figure 13. Comparison of H_2 concentration measured in a specific point at different wind velocity

In test HPBT-JR-7 FLACS values along X axis are underestimated but have a good coherence both as overall trend and as drop due to increased wind. For values along Z axis the same remarks as for test HPBT-JR-8 are valid.

The same considerations can be made for test HPBT-JR-3: good agreement can be noticed along X axis, but along Z axis experimental data differs from those given by code.

8.0 CONCLUSIONS

When considering wind influence on gas dispersion, a better dilution is expected by higher values of wind speed. Experimental data show a good agreement with theory along X axis and far enough from release hole to have a jet velocity that is comparable to wind velocity. When internal pressure is low a higher influence on gas concentration is recorded. When internal pressure is high, experimental values show very little variation due to wind influence.

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