Review of knowledge and recent works on the influence of initial turbulence in methane explosion

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Abstract

GDF SUEZ, as a gas and LNG company, operates onshore and offshore facilities where accidental high pressure releases of natural gas are likely to occur. To study this hazard, experiments have been performed in uncongested areas, focusing on fires and heat flux. In parallel, trials were carried out to assess overpressures generated by a gas explosion in a congested area. Most experiments were done with a quiescent stoichiometric gas cloud and not with a real turbulent release of methane or natural gas. The same assumption of stoichiometric gas cloud is then followed for quantitative risk assessment and influence land use planning, occupational safety, safety gaps definition and design. The following review endeavours to collect existing knowledge and recent experimental and numerical works on the influence of initial turbulence on methane explosions severity and to highlight the differences between explosions with initial turbulence and explosions with quiescent stoichiometric mixtures. Small-scale experiments of methane explosions carried out by INERIS and GDF SUEZ in 2011-2013 are presented. These are 0.8 kg/s methane jets dispersion and explosion tests, in open field and within various congested areas. According to those tests, maximum overpressure is multiplied by 5 for turbulent jets ignitions compared to tests with quiescent stoichiometric mixtures of same volume. The influence of gas jet turbulence on explosion is confirmed by FLACS simulations performed by GDF SUEZ for large scale configurations. In addition, sensitivity studies on FLACS simulations show uncertainties on the CFD modelling of gas jets explosions. In order to further increase knowledge and to validate models and CFD codes, as FLACS, GDF SUEZ Research Center is currently setting up a JIP for a campaign to pursue large-scale explosion tests with pressurized natural gas releases into both congested and uncongested areas.

Keywords: *Turbulence, industrial explosions, natural gas, methane*

1. Introduction and context

GDF SUEZ, as a gas and LNG company, operates onshore and offshore facilities where accidental high pressure releases of natural gas are likely to occur. To study this hazard, experiments have been performed in uncongested areas, focusing on fires and heat flux. In parallel, trials were carried out to assess overpressures generated by a gas explosion in a congested area. Most experiments were done with a quiescent stoichiometric gas cloud and not with a real turbulent release of methane or natural gas.

The same assumption of stoichiometric gas cloud is then followed for quantitative risk assessment and influence land use planning, occupational safety, safety gaps definition and design. It is an accepted practice but there is a consensus on the need to investigate deeper this question of explosion in "real release" with pre-ignition turbulence. For instance, HSE and NORSOK (2001) indicate that explosion of real releases is a pending issue, for which experimental knowledge is necessary. Experiments and numerical simulations have demonstrated that pre-ignition turbulence within the air/fuel mixture enhances strongly the flame acceleration, flame speed and explosion violence. Experimental studies (Ahmed & Mastorakos, 2006) have also demonstrated that ignition within a turbulent methane jet between UFL and stoichiometry on jet axis is possible and must be considered for risk assessment despite high momentum and turbulence.

The following review endeavours to collect existing knowledge and recent experimental and numerical works on the influence of initial turbulence on methane explosions severity and to highlight the differences between explosions with initial turbulence and explosions with quiescent stoichiometric mixtures. Section 2 reviews the knowledge on the influence of initial turbulence on flame acceleration and overpressures in configurations without obstacles. Subsection 2.1 is a literature review of experiments of free methane jets ignitions. Subsection 2.2 presents the new experiments of free methane jets ignition carried out by GDF SUEZ and INERIS in 2011-2013. Subsection 2.3 compares results of these free methane jets ignitions with the results of past experiments with quiescent stoichiometric air/methane mixtures without obstacles. Subsection 2.4 presents models which have been developed for simulating free methane jets ignitions and subsection 2.5 compares the results of these models with experiments presented in subsection 2.2.

Section 3 reviews the knowledge on the influence of initial turbulence on flame acceleration and overpressures in configurations with obstacles. Subsection 3.1 is a literature review of experiments of methane and natural gas explosions with initial turbulence within obstacles. Subsection 3.2 presents the new experiments of methane jets ignition within obstacles carried out by GDF SUEZ and INERIS in 2011-2013. Subsection 3.3 presents models which can be used for simulating methane jets ignitions within obstacles. Subsection 3.4 is a sensitivity study on FLACS simulations which highlights some uncertainties on the CFD modelling of gas jets explosions within congested areas. Finally subsection 3.5 presents a comparison between a FLACS simulation of a large-scale methane jet explosion within a congested area, and a FLACS simulation of the explosion of an equivalent volume of quiescent stoichiometric air/methane mixture.

Section 4 concludes on the influence of initial turbulence on methane explosion effects and presents a proposal of large-scale experiments to further improve knowledge.

2. Influence of initial turbulence on flame acceleration without obstacles

2.1 Literature review of experiments of free methane jets ignitions

At least, four tests series have been performed to study overpressure generated by the ignition of a pressurized jet of natural gas in open field:

- Tests "Shell-Hoff" (Hoff, 1983). These are vertical steady-state jet releases of natural gas (14 tests, release rate between 11 and 88 kg/s, 27 pressure measurements),
- Tests of Chémery by GDF and ENSMA (Bruguier et al 1991; Arnaud et al, 1992). These are vertical steady-state jet releases of natural gas (17 tests, release rate between 2 and 11 kg/s, 31 pressure measurements),

- Tests “MERGE-INERIS” (Chaineaux, 1993). These are transient horizontal jet releases at five meters high of methane (12 tests, release rate between 3 and 15 kg/s at ignition time, 12 pressure measurements),
- Tests “EXPLOJET-INERIS” (Guibert-Duplantier, 1997). These are transient horizontal jet releases at five m high (38 tests, release rate around 5 kg/s, 227 pressure measurements).

The first two tests series only measured low overpressure around the gas jet at ground level (pressure under 5 mbar). Indeed, the gas release was vertical with ignition at four to eight meters high on the jet axis, whereas the pressure sensors were at ground level around the release orifice, which means that the pressure sensors were upstream and cross-stream compared to the ignition point. The two other tests series, “MERGE-INERIS” and “EXPLOJET-INERIS”, proved that overpressures are significantly higher downstream of the ignition point. For “MERGE-INERIS” tests campaign, the measures of overpressure reached 84 mbar at 11 m downstream of the ignition source, for a release rate around 110 kg/s at the start of the release and 15 kg/s at the ignition time, generating by a 150 mm diameter orifice fuelled by a 40 bar methane tank. The measures of overpressure reached 65 mbar at 11 m downstream of the ignition source, for a release rate between around 40 kg/s at the start of the release and 20 kg/s at the ignition time, generating by a 100 mm diameter orifice fuelled by a 40 bar methane tank. For “EXPLOJET-INERIS” tests campaign, the measures of overpressure reached 50 mbar at 4 m downstream of the ignition source, for a release rate of around 5 kg/s in the first seconds of the release, generating by a 30 mm diameter orifice fuelled by a 40 bar methane tank.

These experiments enable a first understanding of flame propagation inside the jet. When ignited on the jet axis, the flame first accelerates due to the turbulence of the jet and generates an overpressure. A low energy ignition source may be blown out by the gas flow, and if ignition occurs, the fireball will be translated downstream. After this first phase of acceleration, the flame front decelerates because it reaches zones of the jet where the turbulence and reactivity are lower. In consequence, the overpressure is generated by a small part of the flammable jet. Overpressures are higher downstream of the ignition point on jet axis, and they are lower cross-stream and much lower upstream. “MERGE-INERIS” tests and “EXPLOJET-INERIS” tests also confirmed that initial turbulence enhances the explosion. The explosion strength of a free jet was concluded to be greater than the explosion strength of a quiescent stoichiometric cloud of corresponding volume, which generates only a few mbars of maximum overpressure. In addition, highest overpressures are reached if the jet is ignited in the fuel rich region along jet axis, upstream of stoichiometry.

2.2 Experiments of free methane jets ignitions by INERIS and GDF SUEZ : 2011-2013

The experiments mentioned in section 2.1 generally suffered from:

- a lack of measurements of turbulence characteristics of the gas jet
- a lack of flame propagation visualizations with high-speed cameras
- non-exhaustive gas concentration measurements, which for example prevents from knowing the gas concentration at the ignition point and size of the flammable volume.
- the decrease of the mass release rate during the tests due to the decompression of the gas tank.

To solve these issues, INERIS and GDF SUEZ carried out in 2011-2013 new experiments of pressurized methane releases in combining:

- Velocity probes developed by INERIS and Fraunhofer ICT (Schneider and Proust, 2007) based on McCaffrey probes (McCaffrey, 1976) to measure mean and turbulent velocities in the jet direction before ignition (Figure 2),
- Oxygen meters (paramagnetic cells) to deduce methane concentration,
- High-speed cameras (3000 images/s) located on the side of the jet and above the jet,
- Pressure sensors (piezo-resistive gauges) to measure overpressure within and outside the flame.

The first part of the trials was dedicated to gas concentration and velocity measurements within the gas jet (without ignition) with repeated tests in order to have a whole cartography of the gas jet. Then ignition tests were performed in varying the ignition location inside the jet, with a particular focus on the zone between UFL and stoichiometry on jet axis. The release was produced by a 12 mm diameter orifice fuelled by a 38-39 bar gauge reservoir. This ensures a low decrease of the 5 m^3 tank pressure and a low decrease of the mass release rate during the tests (the tests last around 30 seconds for non ignited tests and only a few seconds for ignited tests). The mass release rate decreased from 0.78 kg/s to 0.69 kg/s in 30 seconds. The test bench used by INERIS and GDF SUEZ is presented in figure 1.

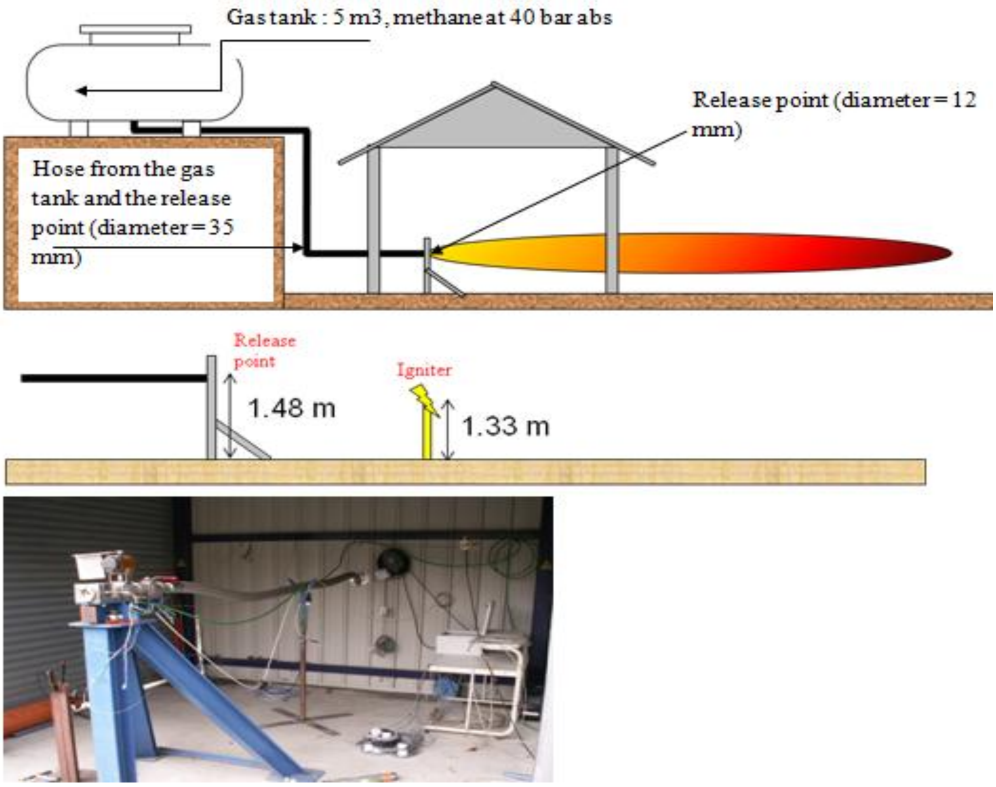


Figure 1 : test bench used by INERIS and GDF SUEZ for free methane jets

First experiments have been done with an horizontal free jet at 1.5 meters high to calibrate the measurement devices and ease the interpretation of the flame propagation. The bidirectional Pitot probes with differential pressure sensors based on McCaffrey concept used to measure mean and root-mean-square (rms) velocities in the direction of the jet are shown in figures 2, 3 and 4.

Figure 2 : measurement devices : 11 oxygen sensors and 14 velocity probes (probes developed by INERIS based on McCaffrey probes)

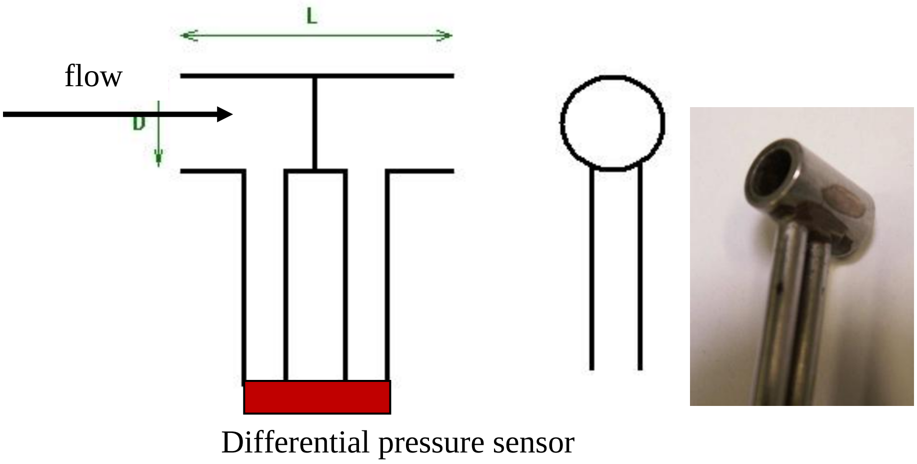


Figure 3 : velocity probe : Bidirectional Pitot probe

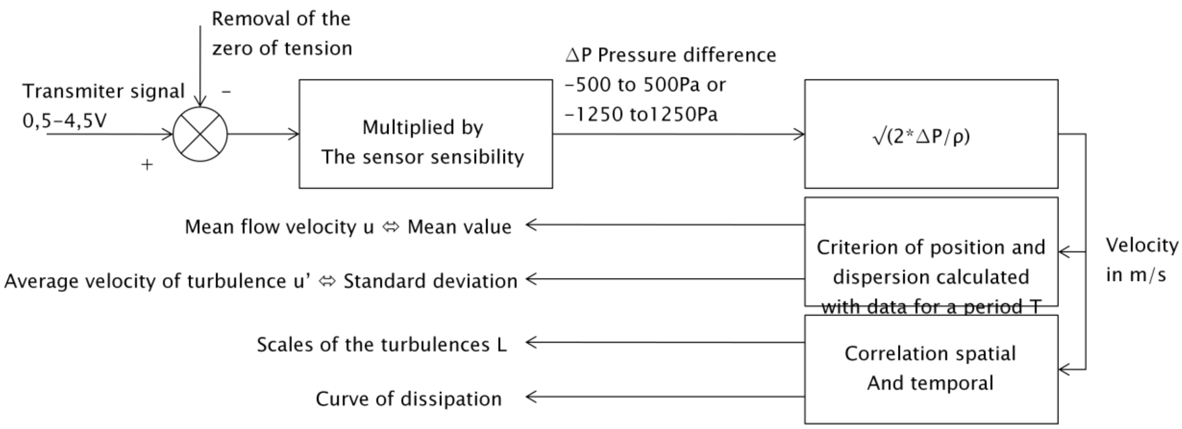


Figure 4: assessment of mean velocity, rms velocity and integral scale of turbulence from the signals of the differential pressure sensor mounted in the bidirectional Pitot probes

Three ranges of differential pressure sensors mounted in the bidirectional Pitot probes are used : -5 to +5 mbar; -12.5 to +12.5 mbar and +/-70 mbar, depending on the maximum velocity to measure. They have been well-compared with hot wire anemometers in a wind tunnel for mean velocities up to 15 m/s.

Bidirectional Pitot probes have also been tested in a shock tube and showed good behaviour for pressure fluctuations up to 200 Hz which limits the use of the probes for measuring rms velocity to a maximum corresponding mean velocity of 40 to 50 m/s. Measures of methane concentration, axial mean velocity and axial turbulent velocity have been compared well with correlations developed by Birch (1984) and Birch (1987) with free jets of methane and air (figure 5).

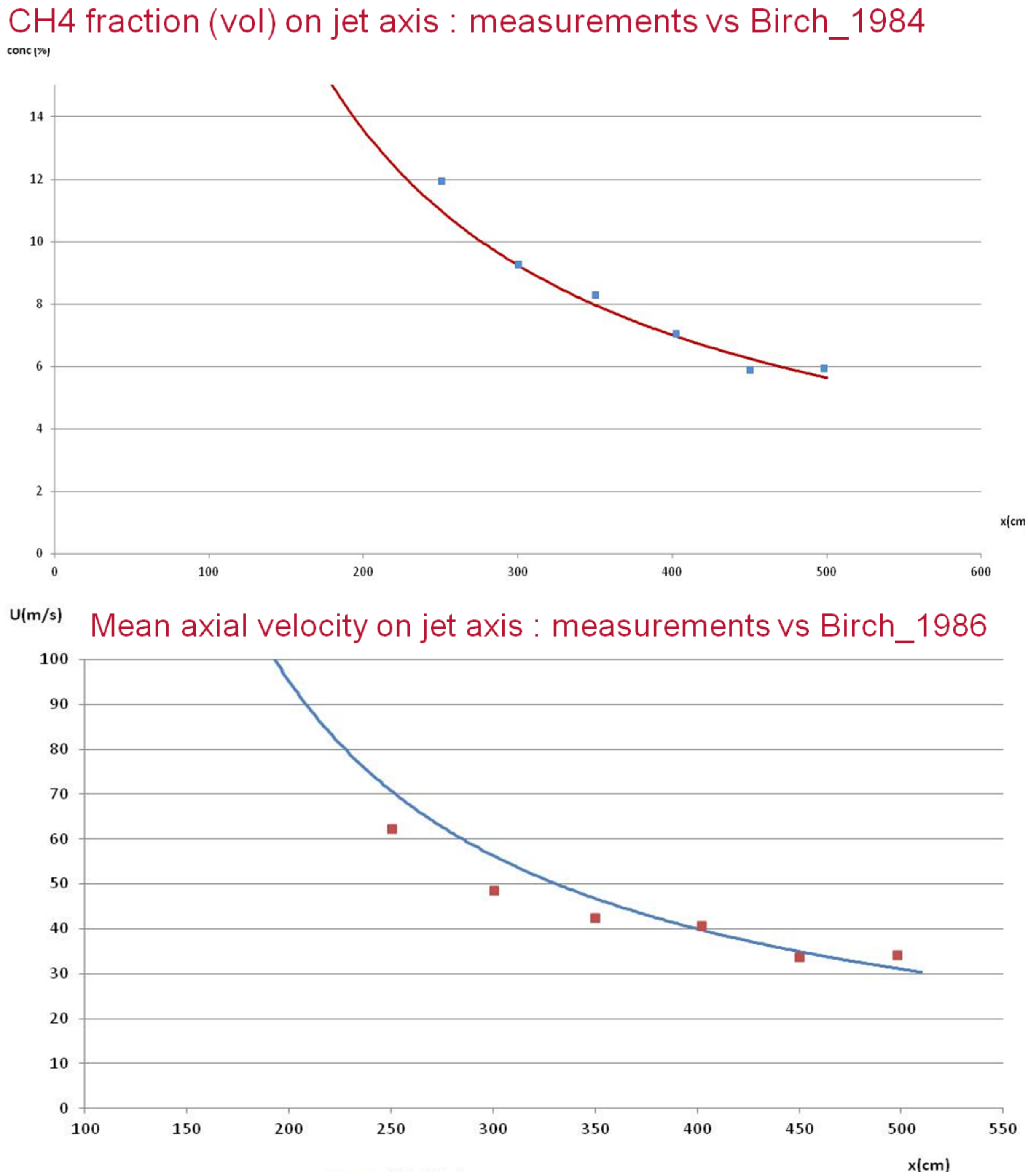


Figure 5 : Axial decays of methane concentration and mean velocity axial for free jets tests carried out by INERIS and GDF SUEZ in 2011, compared to Birch correlations: (Birch, 1984); (Birch, 1987)

Figure 6 shows the set-up of the pressure sensors for the tests of ignition of the free methane jet. Several tests with several positions of the igniter have been done (table 1).

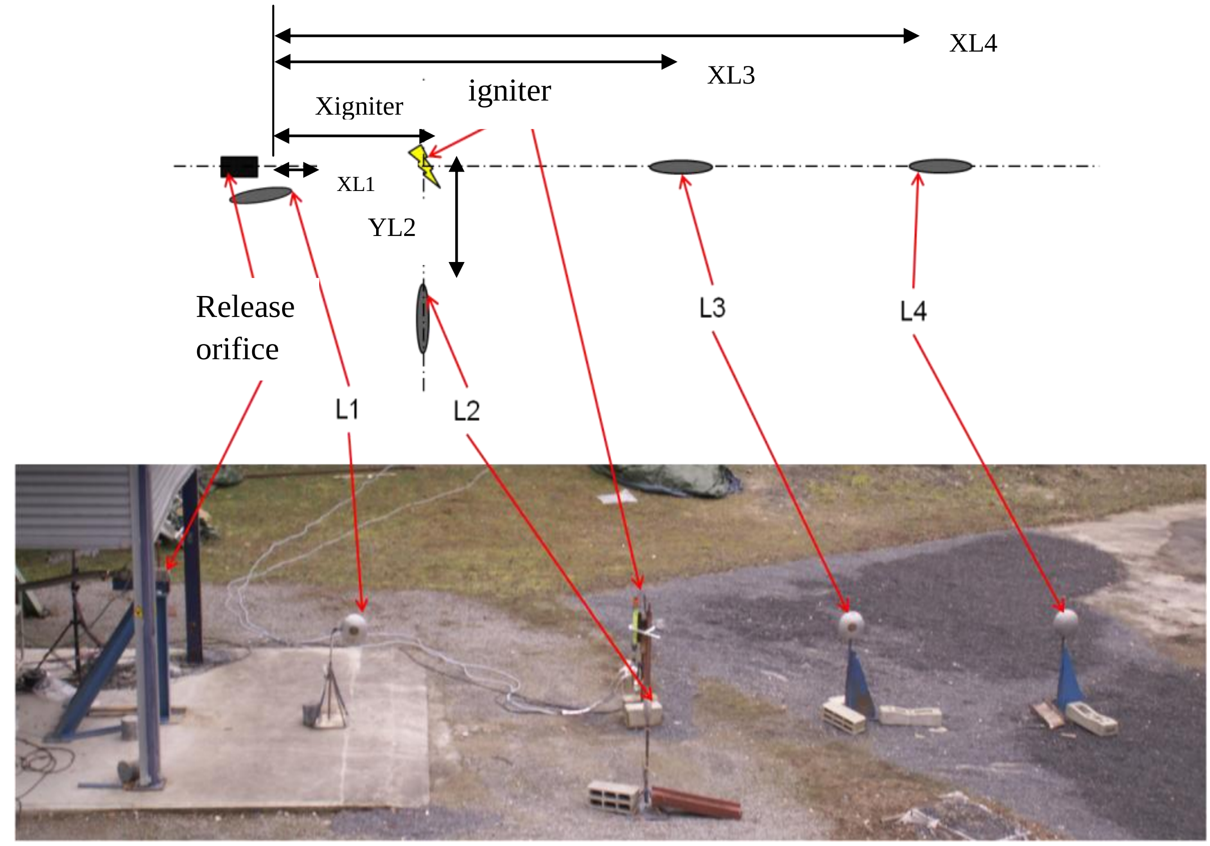


Figure 6: set-up of pressure sensors

Table 1. Correlations for the turbulent burning velocity

Test configuration	**Xigniter (m)**	**XL1(m)**	**YL2(m)**	**XL3(m)**	**XL4(m)**	**methane volumetric fraction at ignition point**
C1	2.1	0.25	2.5	5.1	8.0	13,0%
C2	2.6	0.25	2.5	5.1	8.5	10,6%
C3	3	0.25	2.5	5.0	8.0	9,2%
C4	5	2.0	2.5	7.5	10.0	5,6%

Figure 7 shows the signals of pressure measured by the four pressure sensors L1, L2, L3, L4 for one test of ignition of the free methane jet done in configuration C2 (table 1).

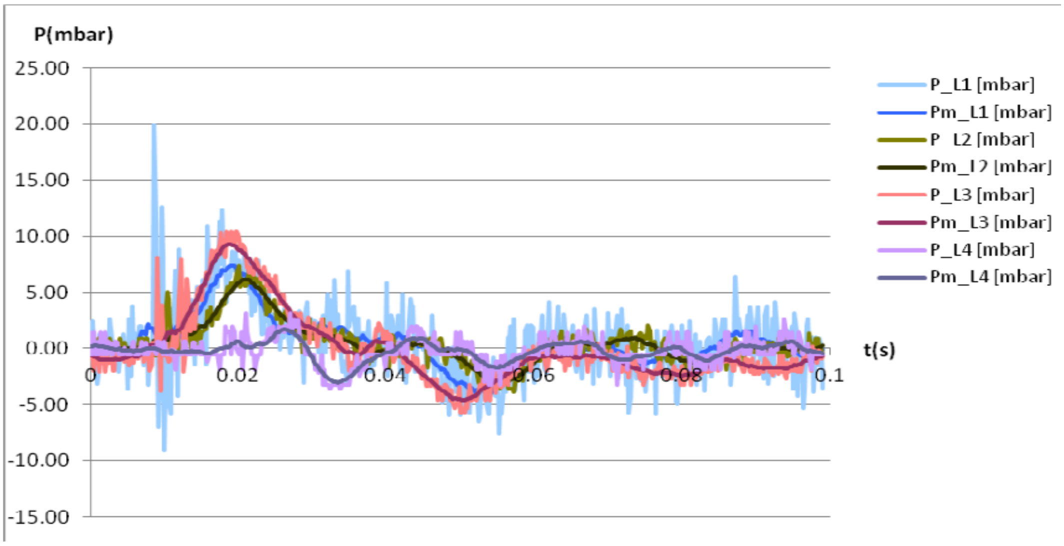


Figure 7 : overpressure signals for 1 test of free jet

To follow the flame propagation and estimate the flame speed over time 2 high-speed cameras were used with 3000 images/s. Post-treatment is used to improve the visualization of the effective flame front. Figure 8 shows the side view of the flame during one test of ignition within a gas jet, with post-treatment.

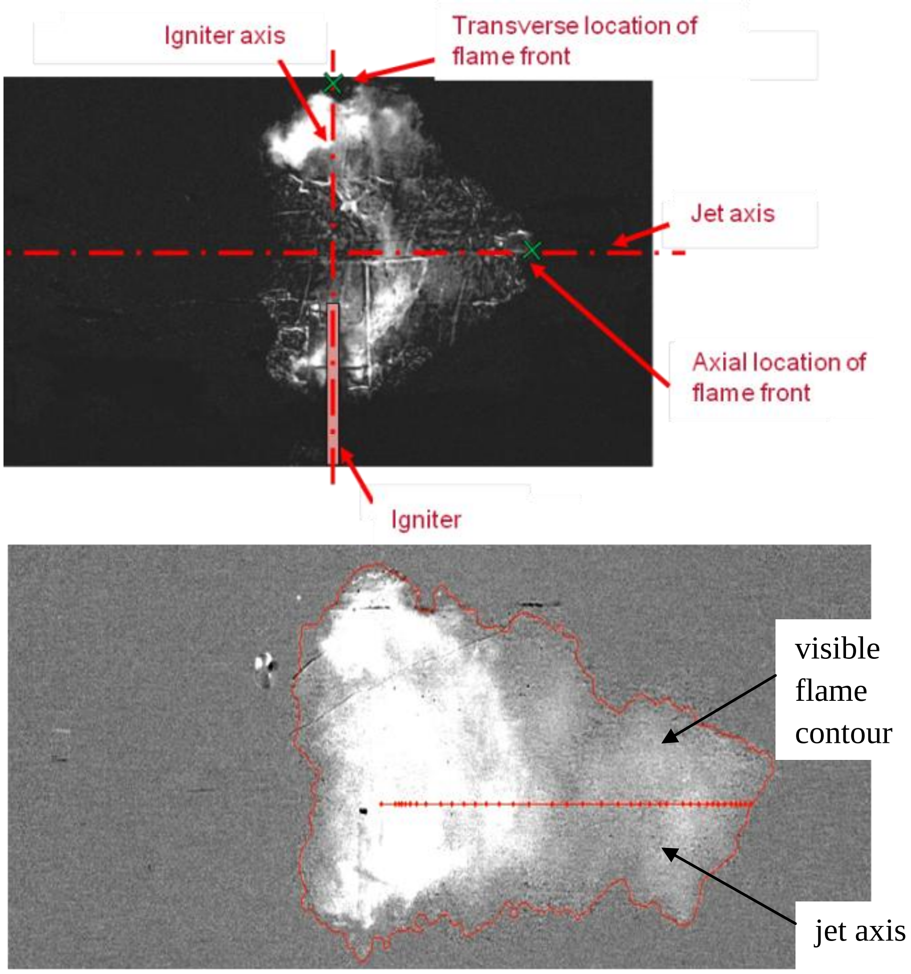


Figure 8 : flame front visualizations of one ignition test (side views), post-treated images

The high speed images must be refined with further post-treatment to confirm maximal flame velocity. For all the tests, the pressure sensor L3, located downstream of the ignition point measured the maximum overpressure (figure 7). The maximum overpressure measured for tests in configuration C2 and C3, with the igniter on jet axis close to stoichiometry, is around 10 mbar. The maximum overpressure measured for tests in configuration C1, with the igniter at a methane concentration of 13%vol, is around 11 mbar, although the distance between the pressure sensor L3 and the igniter is higher: 3 m for C1 configuration, 2.5 m for C2 configuration and 2 m for C3 configuration (table 1). For C1 configuration, the mean velocity at ignition point is around 80 m/s and the turbulent rms velocity is around 22 m/s, higher than for C3 configuration (around 50 m/s for mean velocity and 14 m/s for rms velocity). For configuration C4, with a methane fraction of 5.6% vol at ignition point, no overpressure is observed. Similar experiments were done with a grounded jet (jet orifice at 0.2 m high). The experimental methane concentration field is significantly modified with a spreading of the flammable plume and an increase of the LFL distance by 50%. The pressure sensors array is based on the one presented in figure 6 and table 1, except that the release orifice, the igniter and the pressure sensors are 0.2 meters high, and that there are two additional pressure sensors: one at ground level 0.6 m downstream of the igniter, and one above the igniter at 1.05 m high. The maximum overpressure measured 2.5 m downstream of the ignition point is only slightly increased from 11 mbar to 13 mbar compared to the test of ignition of the free jet. The maximum overpressure measured by the pressure sensor at ground level 0.6 m downstream of the igniter varies between 30 and 35 mbar.

2.3 Comparisons between experiments of methane jets ignitions and experiments with quiescent stoichiometric air/methane mixtures

The experiments of methane jet ignitions presented in section 2.2 are compared in this section to other experiments performed with quiescent stoichiometric methane/air mixtures. Experiments done by Pfortner and Schneider (1988), show that the ignition of a pancake-shaped free cloud of 6400 m^3 filled with a methane/air mixture at a methane concentration of 11,3%vol (close to stoichiometry), with no obstacles and no initial turbulence generated a maximum flame speed of 8 m/s and a maximum overpressure of 1.3 mbar. This result can be compared with the maximum overpressure of 11 mbar measured the tests of configuration C1 presented in section 2.2 where the flammable volume is only 1.9 m^3. Pfortner and Schneider (1988) also performed tests with turbulence generated by 1 fan within the stoichiometric gas volume. With a 10000 m^3 gas volume, the flame speed is between 20 and 45 m/s and the maximum overpressures are between 6.9 and 18.5 mbar, which is comparable to the gas jet explosions presented in section 2.2 but with a volume 5000 times higher. Initial turbulence generated by pressurized methane jets enhances the flame acceleration and leads to higher overpressures.

2.4 Existing models of free gas jet explosions and limitations

The Baker Strehlow-Tang (BST) method (Pierorazio et al, 2004) and the Multi-Energy method (Committee for the prevention of disasters, Yellow book, 1995) by TNO[1], are difficult to use to quantify the violence of gas jet explosions.

[1] TNO : Netherlands Organisation for Applied Scientific Research

They would need a large set of experiments to calibrate severity index or flame speed, depending on the jet size and the ignition location. Dedicated phenomenological models have been developed to simulate gas jet explosions.

First, these models assess the axial decays of gas concentration, mean velocity and turbulent (rms) velocity, with exponential laws or with a 1D integral model. Then the radial profiles of concentration, mean and turbulent velocities are generally given by Gaussian profiles based on the axial values. For example EXORIS and EXPLOJET models by INERIS are built with exponential laws for axial decays of gas concentration and velocity and Gaussian radial profiles. The model used by GDF SUEZ (included in its in-house risk assessment software called PERSEE) uses an adapted version of the 1D integral model by Ooms (1972) for calculating the gas concentration field and the mean velocity field. Turbulent (rms) velocity field is then deduced based on the empirical correlations by Hinze (1975). Once the concentration and turbulence fields have been estimated, a turbulent burning velocity correlation is used to calculate the speed of the flame front over time. In the jet explosion model developed by GDF SUEZ in PERSEE software with CMR[2] and ENSMA[3], the flame front is supposed to propagate spherically with a turbulent burning velocity functions of the local mean concentration and local rms velocity. Numerous correlations are available to calculate the turbulent burning velocity based on laboratory experiments. The turbulent burning velocity is given by a correlation as in equation 1 :

$$S_T = A \cdot u'^b \cdot S_L{}^c \cdot \upsilon^d \cdot L_t{}^e \quad \text{or} \quad S_T = A \cdot u'^b \cdot S_L{}^c \cdot \upsilon^d \cdot L_t{}^e + S_L \tag{1}$$

with :

- SL : Laminar burning velocity (tabulated) [m.s-1]
- u' : turbulent velocity (rms) [m.s-1],
- Lt : integral scale of turbulence [m],
- ν : cinematic viscosity of fluid (tabulated) [m2.s-1]

Lots of correlations with different coefficients A, b, c, d, e, have been developed (table 2).

Table 2. Correlations for the turbulent burning velocity

	A	b	C	D	e	
Bray (1990)	1.81	0.412	0.784	-0.196	0.196	
Bray	0.96	0.912	0.284	-0.196	0.196	$+S_L$
Bradley	1.53	0.55	0.6	-0.15	0.15	
Abdel-Gayed (1987)	1.5	0.275	0.6	-0.15	0.15	
Gülder – Omer (1990)	0.6	0.75	0.5	-0.25	0.25	$+S_L$

GDF SUEZ uses the correlation by Bray (1990) for its in-house model in the software PERSEE whereas INERIS uses Gülder correlation, with differences in the assessment of explosion effects. The instantaneous flame front velocity is then deduced by $V_F = S_T \times \beta$ with β the ratio between the density of burnt gas and unburnt gas.

[2] CMR : Christian Michelsen Research, research institute in Bergen, Norway
[3] ENSMA : Ecole Nationale Supérieure de Mécanique et d'Aérotechnique

Finally, based on incompressible assumption, the overpressure over time around the ignition point is estimated, according to Deshaies and Leyer (1981), by equation 2 :

$$\Delta p(r,t) = \frac{\rho_0}{r}\left(1-\frac{1}{\beta}\right)\left[2r_F(\tau)\left(\frac{dr_F(\tau)}{dt}\right)^2 + r_F^2(\tau)\left(\frac{d^2 r_F(\tau)}{dt^2}\right)\right] \tag{2}$$

With r_F the flame radius, r the distance from the ignition point, t the duration, ρ_0 the air density, and $\tau = 1 - r/c_0$ where c_0 is the sonic velocity in air. The model allows to calculate and display the overpressure over time for each point of interest (figure 9). The negative part of the pressure signal is an empirical function of the positive pressure signal which has been calculated by the model.

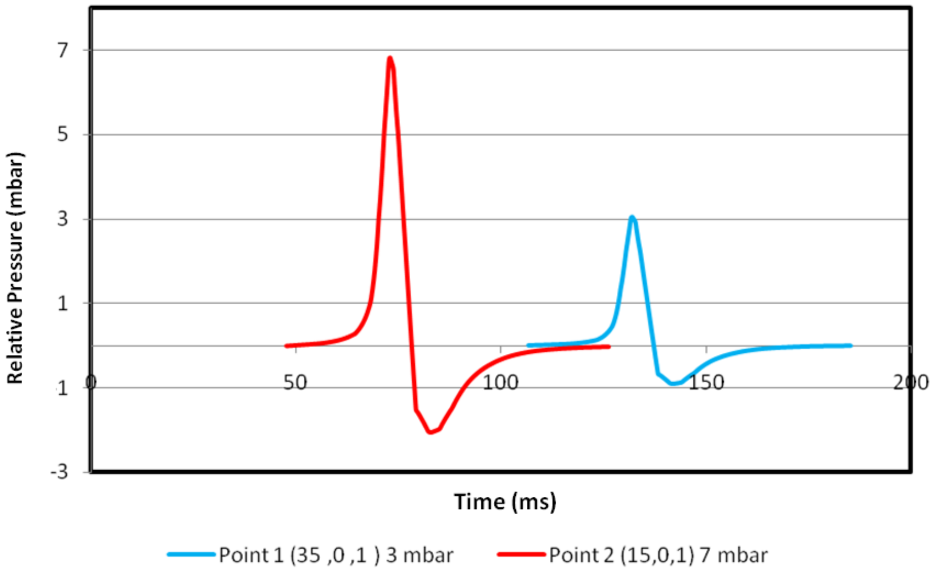


Figure 9 : overpressure signals for 1 ignition test of a free methane jet

This model is limited to incompressible cases, and thus to small flame Mach numbers (Mf < 0.35), corresponding to maximum flame speed around 120 to 150 m/s. Cleaver and Robinson (1996) developed a similar model and added a drag force in the momentum equation to consider effects due to various obstacles. Some effects of compressibility have also been taken into account in order to extend the domain of validity of the model. However, this model remains limited for taking into account the interaction between congested area and the jet and flame propagation, and it is still limited to quite slow flame speed : lower than 250 m/s. CFD codes can also be used for modelling such gas jets explosions. RANS (Reynolds Averaged Navier Stokes) models dedicated to gas explosions have been developed: ANSYS® AutoReaGas™ (ANSYS and TNO), EXSIM (Telemark Technological R&D center, Porsgrunn, Norway, supported by Shell Research Ltd. And a European excellence program), FLACS (Gexcon, CMR). Other commercial CFD codes like CFX and Fluent (ANSYS), STARCCM+ (Cd-Adapco) can also be used for simple configurations. More academic models like LES (Large-Eddy Simulation) models of transient turbulent combustion can also be used but are not necessary for simple free jet configurations in open field.

2.5 Comparisons between models and experiments of methane jets ignitions

Comparisons of gas concentrations and velocities between the INERIS/GDF SUEZ experiments presented in section 2.2 and the model of GDF SUEZ (PERSEE) are sum up in the tables 3, 4 and 5.

Table 3. Relative deviations of the axial distances to several thresholds of volume fraction of methane between the simulation and the experiment

Volume fraction of CH4 (%vol)	**12%**	**9%**	**7%**	**6%**
Distance on jet axis : Difference between model and experiments	+18%	+31%	+27%	+24%

Table 4. Comparison of the maximum measured and predicted overpressures for the test in C2 configuration (with igniter at 10.6% vol. on jet axis)

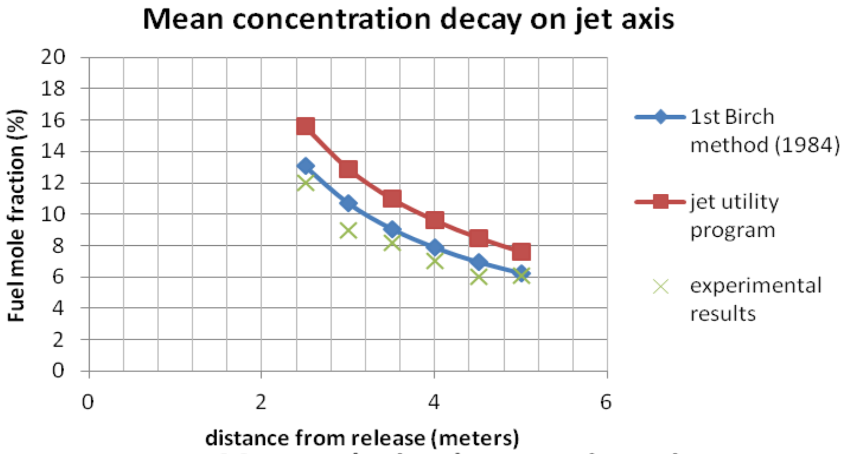
Igniter at 10.6 % vol on jet axis	**Maximum Pressure : measurement (mbar)**	**Maximum pressure calculated by PERSEE model (mbar)**
Sensor downstream the igniter	10	15
Far field sensor downstream	2	5
Cross-stream sensor	6.5	9
Sensor upstream the igniter	7	8

Table 5. Comparison of the maximum measured and predicted overpressures for the test in C1 configuration (with igniter at 13.0% vol. on jet axis)

Igniter at 13.0 % vol on jet axis	**Maximum Pressure : measurement (mbar)**	**Maximum pressure calculated by PERSEE model (mbar)**
Sensor downstream the igniter	12	14
Far field sensor downstream	2	6
Cross-stream sensor	7	13.5
Sensor upstream the igniter	8	14

The results of the model (PERSEE) by GDF SUEZ compare quite well with the experiments presented in section 2.2, and the spatial distribution of overpressure is similar. Simulations with FLACS code were also compared to the experiments of section 2.2. Two FLACS simulations with two different pseudo-source methods were tested. The first simulation was done with a pseudo-source calculated with the method by Birch (1984) which leads to the following characteristics for the pseudo-source : area of 0.002417 m² (diameter = 0.0555 m), velocity of 481 m/s, temperature of 288 K (assumed to be equal to temperature of gas in the reservoir), mass release rate of 0.78 kg/s. The leak is a point source leak located in a cell of 0.06 m diameter, which follows the FLACS grid guidelines by Gexcon (2014) (area leak < area control volume < 2 area leak). The domain volume is 60 m x 40 m x 20 m. The grid is stretched from the leak cell in cross-stream, upstream, downstream and vertical directions, with a 1.19 stretch factor. The grid contains $1{,}7.10^6$ cells. The second simulation was done with the jet utility program of FLACS as a pseudo-source calculator (Gexcon, 2014), which leads to the following characteristics for the pseudo-source : area of 0.0047564 m² (diameter = 0.07782 m), velocity of 236 m/s, temperature of 277 K, mass release rate of 0.78 kg/s. The leak is a point source leak located in a cell of 0.1 m diameter, which follows the FLACS grid guidelines (area leak < area control volume < 2 area leak). The domain volume has been reduced to 50 m x 30 m x 15 m, in order to limit the number of cells. The grid is stretched from the leak cell in cross-stream, upstream, downstream and vertical directions, with a 1.194 stretch factor. The grid contains 309000 cells. In any case, the explosion calculation is done using as a starting point the dispersion simulation. The ignition location is the same as the one used in the experiments. The jet is ignited once established.

The dispersion results with FLACS appear to be sensitive to the pseudo-source method used (other RANS CFD codes show similar trends). It can be seen on the decay on jet axis of concentration and axial mean velocity (figure 10, table 6).



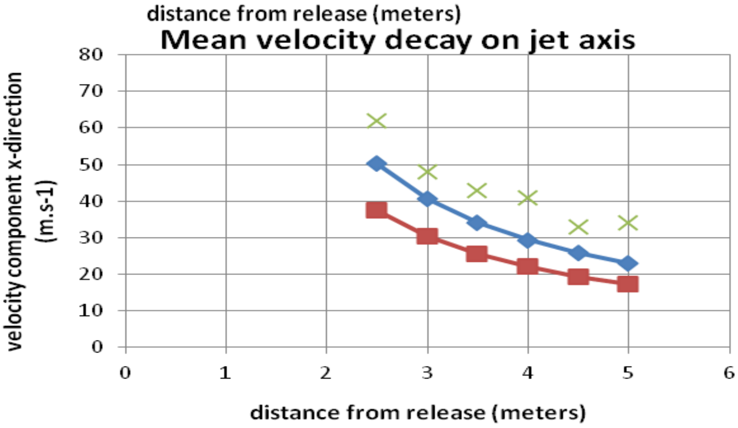


Figure 10 : centreline axial concentration (top) and axial mean velocity(bottom) decays estimated with FLACS using 2 pseudo-source methods. Compared to experimental measures (GDF SUEZ/INERIS tests, 2011-2013)

Table 6. deviation between centerline axial concentration (left) and axial mean velocity (right) decays estimated with FLACS using 2 pseudo-source methods, and experimental measures (GDF SUEZ/INERIS, 2011-2013)

Deviation: experimental results - FLACS	**Fuel mole Fraction**	**Velocity**
(Birch, 1984)	+12%	-23%
jet utility program: FLACS pseudo-source method (Gexcon, 2014)	+35%	-42%

Explosion calculations show that FLACS represents correctly the dynamics of pressure but pressure level are underestimated (between 30 and 60% depending on the sensor locations). On figure 11, the measured pressures over time are represented on top, and the pressures over time calculated with FLACS are presented at the bottom. The FLACS pressure points P5, P6, P7, P8 correspond respectively to the pressure sensors L1, L2, L3 and L4.

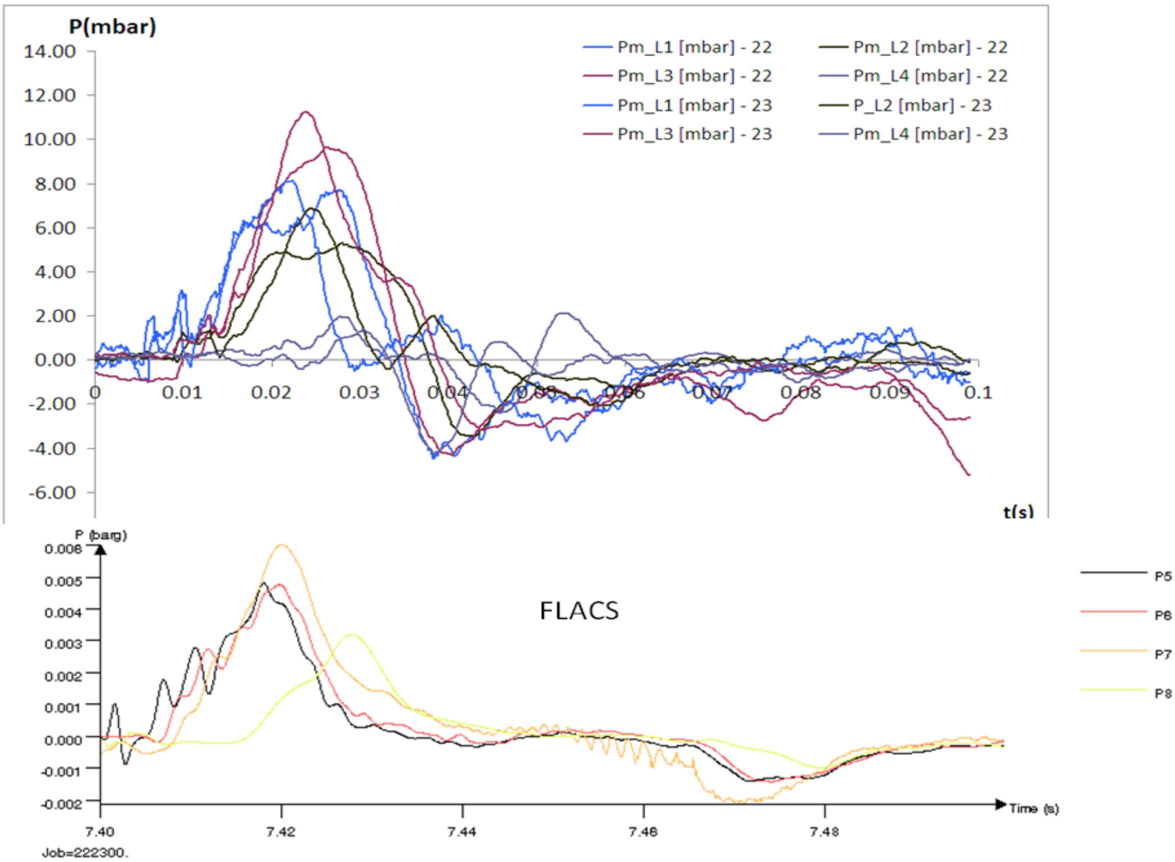


Figure 11 : pressure signal over time for different sensors positions, measured in the free gas jet ignition test (top) and calculated by FLACS (bottom)

3. Pre-ignition turbulence coupled with turbulence induced by obstacles

3.1 Literature review of experiments of methane explosions with initial turbulence and obstacles

Pfortner and Schneider (1988) carried out tests of ignitions of homogeneous stoichiometric mixtures of natural gas and air and propane and air, with low turbulence artificially produced by fans. These tests showed that, in particular for a low congestion level, initial turbulence produced by fans increases the overpressure and the flame speed (table 7).

Table 7. tests program of small-scale gas explosions with pre-ignition turbulence generated by fans (Fraunhofer ICT,1988)

Test N°	**Flammable mixture**	**Number of obstacles (box, cylinders)**	**Volume blockage ratio**	**Initial turbulence**	**Pmax (mbar)**
8	NG : 90%CH_4, 10%C_2H_6	34	1%	No	2.6
9		35	1%	Low (1 fan)	7.7 to 30
10	Near-stoichiometric air/NG mixture	20	5%	Low (1 fan)	8.7 to 25.6
14		18	4%	Medium (4 fans)	30
17		13	3%	Medium (4 fans)	20.9 to 78.5
15	Propane/air near-stoichiometric mixture	20	5%	Medium (4 fans)	72 to 76.7

Furthermore, several experiments of methane/air explosions within congested areas with initial turbulence were performed in the framework of the EMERGE project (EMERGE project, 1996) by CMR, TNO and British Gas Research.

TNO performed small-scale tests (Mercx et al, 1996) and BG performed medium and large-scale tests (Shale et al, 1996) within 3D regular obstacle arrays which have been used prior in the MERGE project[4]. CMR (Linga et al, 1995) performed tests in a model of the M24 platform, scale 1:5 ($50m^3$), as well as in a 62.5 m^3 tent with no internal obstacles. For all these tests, the congested area was filled by a homogeneous stoichiometric mixture of air/methane and initial turbulence was created by means of stoichiometric fuel/air jets emerging from four lances pointing at the ignition point. In consequence the turbulence field was generated only locally around the ignition point, with different levels of turbulence (turbulent rms velocity estimated between 1 and 20 m/s).

Tests by CMR in the 62.5 m^3 tent with no obstacle showed that the initial turbulence causes a high flame speed, but as the turbulence is not sustained by the combustion itself outside the region with initial turbulence, the flame speed drops at greater distances from the ignition location. Tests in regular obstacles arrays by TNO and BG showed that the maximum overpressure was not increased in comparison with the results of the MERGE project performed with the same obstacles but with quiescent stoichiometric mixtures. An explanation given in the final summary report of the EMERGE project (EMERGE project, 1996) was that the turbulent region in the vicinity of the ignition location was too small to have a lasting effect on flame acceleration. The turbulence must have accelerated the flame in the very early stages but outside the initial turbulence region, the turbulence induced by the expansion flow was not of sufficient strong to accelerate the flame any further after it left the initial turbulence region. Tests performed by CMR (Linga et al, 1995) in the M24 module, -scaled version of an offshore platform module-, showed that the location of the ignition point was important.

According to the final summary report of EMERGE project (EMERGE project, 1996), only when the ignition location was in the focus of the four turbulence generating jets did the overpressure increase. Then, contrary to the TNO and BG tests, the overpressures increased by 50 to 80% and the pressure impulse increased by 40-60% compared to the tests without initial turbulence. According to the final summary report of EMERGE project, as the BG and CMR jet pipes configurations are similar, the difference in influence of overpressure due to the initial turbulence field must be attributed to the differences in obstacle types and obstacle dimensions. In addition, although the measurements show that the turbulent velocities before ignition were comparable in the BG and CMR tests, the turbulent length scales perhaps were not, leading to a large initial turbulence region in the CMR case. Additional tests with low turbulence generated by fans performed by Linga et al (1995) yield to only minor increase in explosion violence contrary to jet flows.

[4] MERGE project : Modelling and Experimental Research into Gas Explosions: CEC contract

The final summary report of EMERGE project concluded that pre-ignition turbulence leads to an increase in overpressure provided this turbulence is relevant (u' and turbulent scales large enough) compared to the turbulence generated by the flame front across obstacles. These tests also showed that the influence of pre-ignition turbulence on explosion violence is lower for higher congestion, which is confirmed by the tests carried out by British Gas (Shale et al, 1996) in the more congested EMERGE geometry F and C*.

In addition, in the framework of the MERGE project, Battelle Institute carried out experiments of ignitions of propane jets within congested area (Schumann et al, 1993). These tests showed that the results are comparable with the data obtained by British Gas for a quiescent stoichiometric mixture inside similar obstacles. This can be explained by the fact that these tests were done in a high congestion level obstacles module and by the fact that the blast load-enhancing effect of initial turbulence was offset by reactivity decrease inside the module (non-uniform fuel concentration in these experiments). Hansen et al (1998) performed ignited jet releases inside the 50m^3 M24 module. Some tests showed low pressures, when gas build-up was not filling the rig, while some tests showed pressures higher than tests with quiescent mixtures at stoichiometry.

In addition, large-scale experiments of natural gas explosion inside several realistic offshore modules were carried out between 1998 and 2002:

- BFETS phase 2 JIP[5] consisted in explosions tests of quiescent stoichiometric methane/air mixtures filling the entire volume of a 1600 m^3 semi-confined module with low to high congestion, with and without water deluges.
- HSE phase 3A JIP consisted in explosions tests of quiescent stoichiometric methane/air mixtures filling the entire volume of a 2600 m^3 congested module with low confinement.
- HSE Phase 3B JIP consisted in explosions tests of natural gas/air mixtures generated by natural gas injection (release rate between 2 and 12 kg/s) within a 2600 m^3 congested module. 6 different gas cloud sizes were generated from 10% to 100% filled module. The objectives of these tests were to address realistic release cases and to measure methane dispersion in a naturally ventilated module (wind speed around 1 to 9 m/s).

The phase 3B tests showed that in most cases the flammable volume was lower than the congested module and thus the overpressures were lower than for the tests with ignition of a quiescent natural gas/air mixture at stoichiometry filling the whole congested module. However, in some cases the congested module has been filled with a natural gas/air mixture cloud at a concentration close to stoichiometry and localized high overpressure and flame speed were produced, higher than for the tests with ignition of a quiescent natural gas/air mixture at stoichiometry. According to GDF SUEZ and INERIS, all these tests showed that when the flammable part of a pressurized methane jet fills a significant part of a congested area, the overpressure generated can be larger than the overpressure generated with a quiescent stoichiometric mixture filling the module, provided that the initial generated turbulence is comparable to the turbulence due to the propagation of the flame front across obstacles.

[5] JIP = Joint Industry Project

3.2 Experiments of methane jets ignitions within obstacles by INERIS and GDF SUEZ : 2011-2013

3.2.1 INERIS/GDF SUEZ experiments of methane jets ignitions within a series of pipelines in parallel

GDF SUEZ and INERIS have carried out medium scale experiments of ignition of a horizontal methane jet impinging a series of pipes. This configuration comes from a partial scaling of a low congestion onshore site (figure 12) with same pitch, same area blockage ratio, lower release rate and smaller flammable jet.

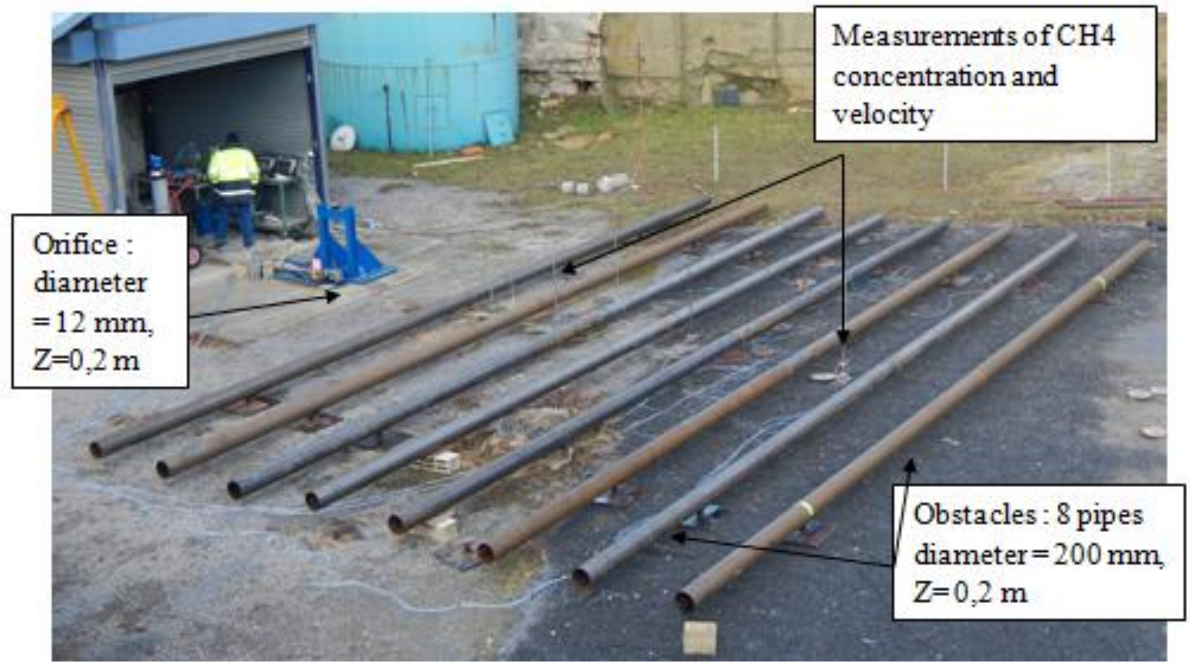


Figure 12 : test bench used by INERIS and GDF SUEZ for free methane jets

The pressure sensors array is presented in figure 13. Compared to the one presented in table 1 and figure 6 in section 2.2, the release orifice, the igniter and the pressure sensors are 0.2 meters high, and there are three additional pressure sensors : one at ground level 0.6 m downstream of the igniter, one above the igniter at 1.05 m high, and one at ground level 1.3m downstream of the igniter.

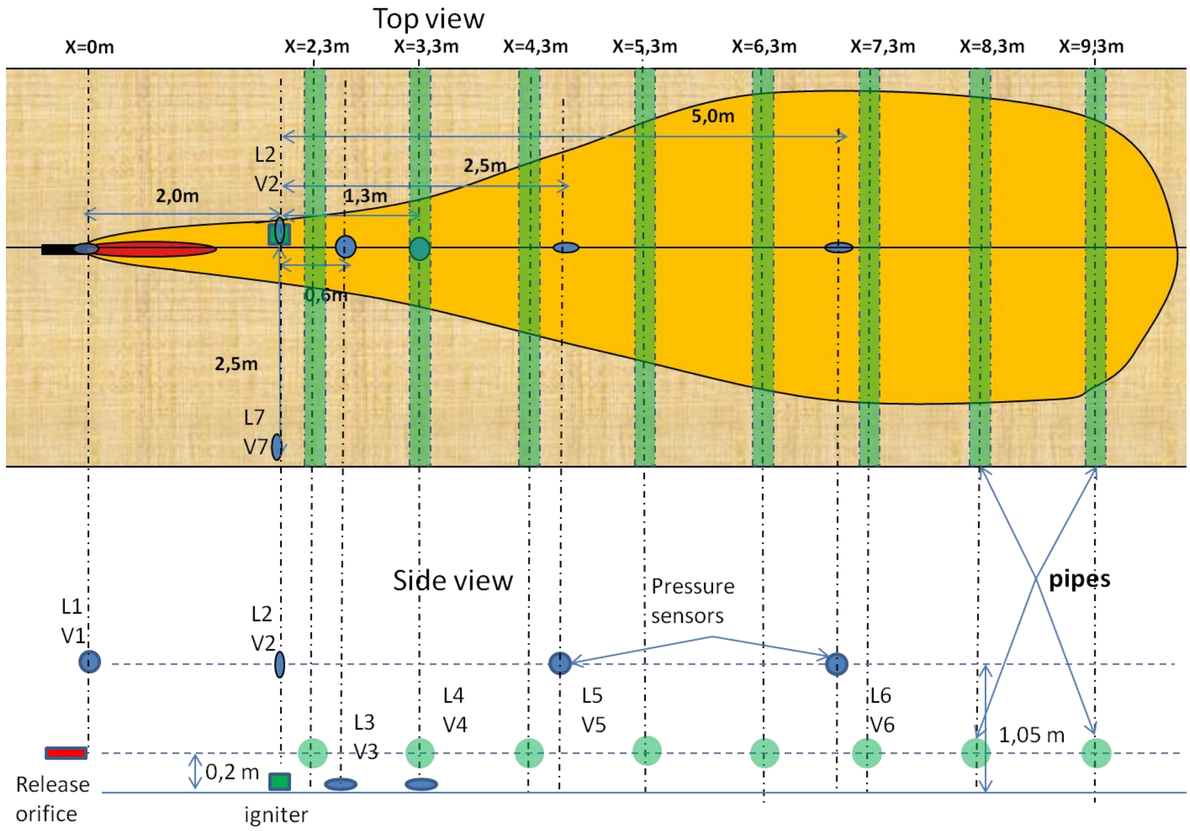


Figure 13 : locations of the release orifice, pipes, igniter and pressure sensors used by INERIS and GDF SUEZ for methane jets within a series of pipelines in parallel

The maximum overpressure measured 2.5 m downstream of the ignition point is slightly decreased compared to the test of ignition of the grounded jet without obstacles, from 13 mbar to 8 mbar. This is due to the fact that the concentration field is modified by the obstacles (pipes) and that the methane concentration close to the pressure sensor is lower for the case with obstacles. The maximum overpressure measured by the pressure sensor at ground level 0.6 m downstream of the igniter is similar to the one measured for the grounded jet without obstacle, it varies between 30 and 35 mbar. Further analysis of the flammable volumes, distributions of methane concentration and flame propagation recordings (high-speed cameras) for each configuration of experiments (free jet, grounded jet and grounded jet with obstacles) will allow to better understand the contribution of the initial turbulence, the turbulence due to obstacles and the heterogeneity of the methane/air mixture to the flame speed and explosion violence.

3.2.2 INERIS/GDF SUEZ experiments of methane jets ignitions within a medium congestion module (2014)

GDF SUEZ and INERIS have carried out tests of methane jets explosions filling a medium congestion module constituted by a 3D array of 20 mm diameter tubes at 140 mm intervals (figure 14). The module is 3 m x 1 m x 0.5 m, which tends to be representative for a 1:10 offshore module (V=1.5 m^3 vs. 1500 m^3 for an example of offshore module).

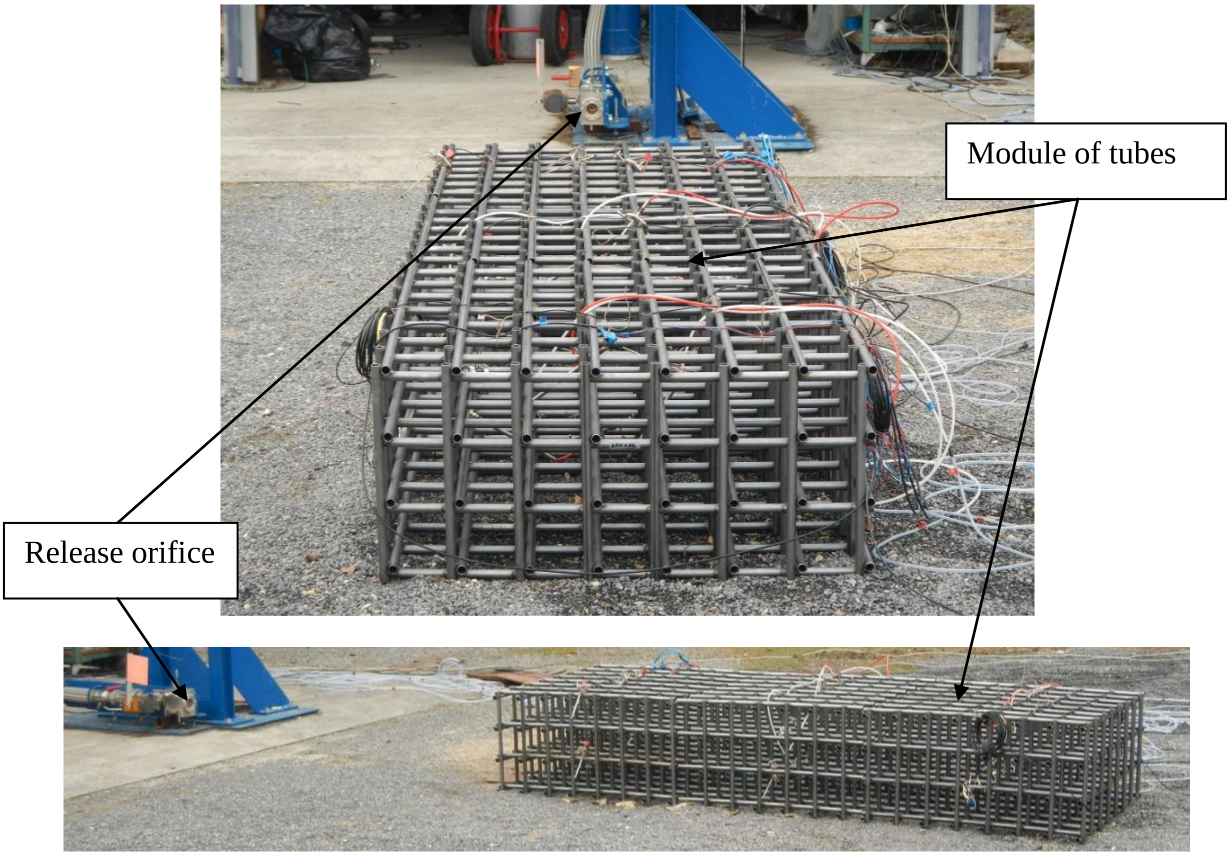


Figure 14 : 3D array of 20 mm diameter tubes used by GDF SUEZ and INERIS

The area blockage ratio (ABR) in the vertical transverse plane is 36%, the volume blockage ratio (VBR) is 6%. Past reduced scale experiments of gas explosions within congested areas (for example MERGE-British Gas tests) showed that the pressures (when above 20 kPa) to some extent would scale with the parameter S x A/V, where S is the linear scale, A/V is the congested object surface area per volume. In that case, S x A/V = 1.3 (with S=1/10), which is estimated to be representative for an offshore process area. The distance between the jet orifice and the module is 2.35 m in order to have a methane concentration around 11%vol at the entrance of the module and in order to fill completely the module with gas at concentration between 11%vol and 9%vol (and with velocities between few decades of m/s to few m/s and significant turbulence). Figure 15 shows the locations of the release orifice, the module of obstacles, the igniter and the pressure sensors.

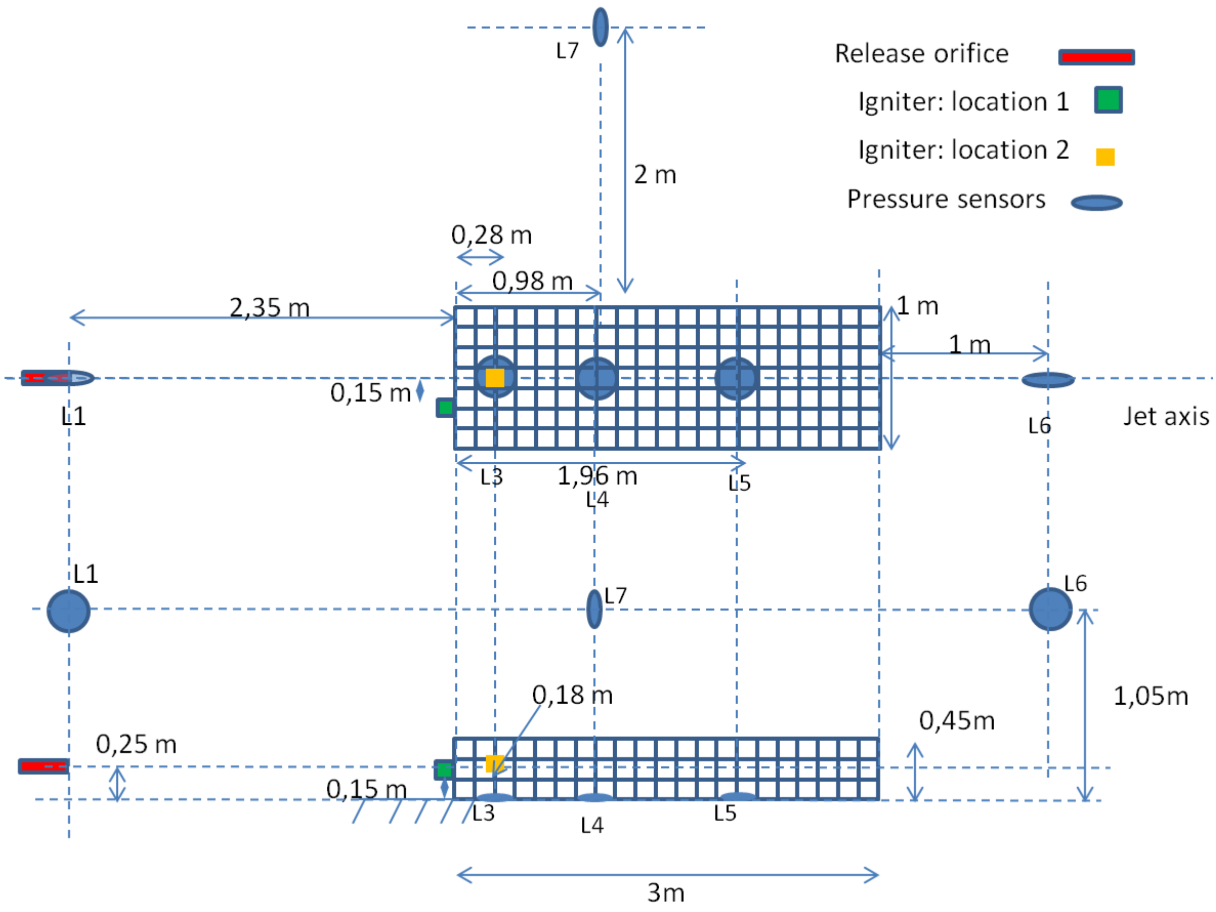


Figure 15 : locations of the release orifice, pipes, igniter and pressure sensors used by INERIS and GDF SUEZ for methane jets within a 3D array of 20 mm diameter tubes

The test program was:

- 2 tests of unignited jet within the module of tubes: measurements of concentration, mean velocity and turbulent velocity in various locations within the module.
- 3 tests of ignition of the jet within the module of obstacles: 2 tests with ignition location 1 and 1 test with ignition location 2 (figure 15)
- 3 tests of ignition of a quiescent stoichiometric air/methane mixture filling a tent slightly larger than the covered module of obstacles: 2 tests with ignition location 1 and 1 test with ignition location 2 (figure 15).

The tent is a light plastic sheet fixed on a steel frame (the fixing magnets are not resistant to the flame propagation). The steel frame is 20 cm larger and higher than the module of obstacles which is covered (figure 16). A few seconds before the ignition, the gas concentration has been measured in 3 points within the module to check the stoichiometric methane concentration.

Figure 16 : steel frame which supports the plastic sheet, covering the module of tubes

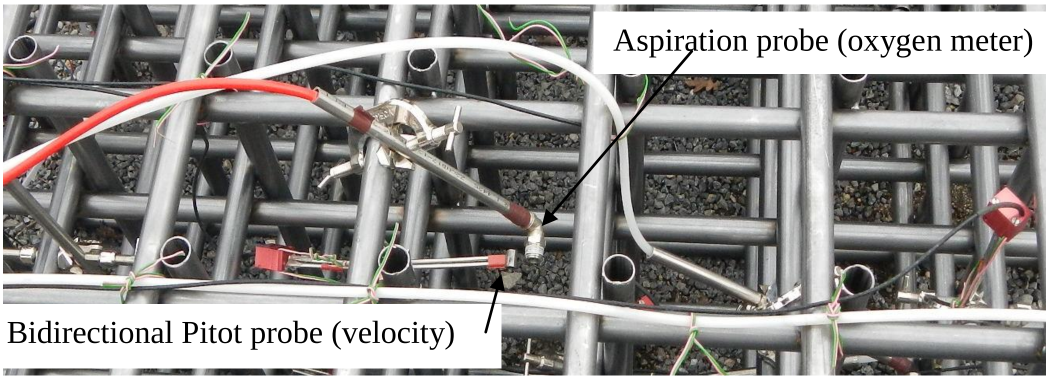


Figure 17 : aspiration probes and bidirectional Pitot probes used for the dispersion tests with the medium congestion module

For the dispersion tests with the jet, nine aspiration probes linked to oxygen meters have been implemented inside and outside the module of tubes in order to measure the methane concentration field and fourteen bidirectional Pitot probes have been implemented inside and outside the module of tubes in order to measure the mean and turbulent velocities (figure 17). The dispersion tests with the jet have showed that the methane concentration is between 8,5% vol and 10.5% vol, close to the stoichiometry. The mean velocity is around 30 m/s at the entrance of the module at ground level, around 15 m/s at the middle of the module and around 10 m/s at the exit of the module (in the direction of the jet).

For the ignition tests, 6 pressure sensors inside and outside the module have been implemented and 2 high-speed cameras. Table 8 summarizes the measures of overpressures during the tests. For the tests with the quiescent air/methane mixture, the concentration is between 9.5% vol and 10% vol of methane within the whole volume (close to stoichiometry) except in one corner of the module where the concentration drops to 6-7% vol due to a opening of the plastic sheet which contains the gas.

Table 8 summarizes the overpressure measurements obtained during the ignition tests of jets and stoichiometric air/methane mixture filling the congestion module.

Table 8. overpressure measurements for ignition tests of jets and quiescent stoichiometric air/methane mixtures within the congestion module, by INERIS and GDF SUEZ

		Maximum overpressure in mbar					
Test configuration	**Test number**	**Pressure sensor L1**	**Pressure sensor L3**	**Pressure sensor L4**	**Pressure sensor L5**	**Pressure sensor L6**	**Pressure sensor L7**
Explosion of the jet with ignition location 1	1	12	52	41	26	8	14
	1bis	13	56	40	27	9	14
Explosion of the jet with ignition location 2	2	10	42	34	30	9	11
Explosion of the quiescent stoichiometric air/methane mixture filling the congestion module, ignition location 1	3	3.5	8	8	13	3	4
	3bis	2	4	4	6.5	1.5	2.5
Explosion of the quiescent stoichiometric air/methane mixture filling the congestion module, ignition location 2	3ter	1.5	4.5	6	6	1	1.5

These tests show that, for the same positions of the igniter and same positions of the pressure sensors and for similar methane concentration fields, the peak of pressure measured by each sensor is multiplied by 3 to 7 for the tests with the turbulent jet filling the congestion module compared to the tests with a quiescent air/methane mixture. These differences are more important than those obtained for past experiments. According to GDF SUEZ, this is because in the present experiments the size of the jet is comparable with the size of the congestion module, the jet fills totally the congestion module, the methane concentration is close to stoichiometry in the whole congestion module, and the velocity (and thus the turbulence) stays important in the whole congestion module. It is representative for possible major accidents on Oil&Gas facilities.

3.3 Modelling of gas explosions with initial turbulence and obstacles

CFD models are well-adapted to represent effects of both obstacles and initial turbulence due to jet momentum on gas explosions. Phenomenological models like those described in section 2.4 can also be developed but they are limited to specific congestion/confinement configurations.

RANS models (Reynolds Averaged Navier Stokes) do not solve the full equations of fluid mechanics, they use several sub-models, in particular a turbulence model (the 2 transport equations models such as the k-ε standard model are widely-used). They also generally use a simplified combustion reaction scheme and a correlation for the turbulent burning velocity. RANS models can be used with a fine mesh and no sub-grid obstacles. But the required calculation capacities are important in that case and industrial applications are not reachable with standard numerical means. Some RANS models have been developed for industrial applications, they use sub-models which have been tuned to allow a good approximation of the effects of obstacles which are smaller than the computational grid size. These are porosity models with drag forces as functions of the sub-grid obstacles.

Moreover, the flame front cannot be modelled in details due to the grid resolution which is limited in order to deal with large size industrial configurations. So a numerical simplification, such as an artificial thickened flame zone increasing the diffusion with a factor β and reducing the reaction rate with a factor $1/\beta$ as it is used in FLACS (β–model), is necessary. All these models limit the solving of the physics of the flame propagation across obstacles. These CFD codes widely used in oil & gas industry are for examples ANSYS® AutoReaGas™, (ANSYS & TNO), EXSIM (Telemark Technological R&D center, Porsgrunn, Norway, supported by Shell Research Ltd. And a European excellence program), FLACS (Gexcon,).

LES (Large-eddy simulation) limits the sub-models used for solving the Navier-Stokes equations compared to RANS models and increases the level of physics which is solved. As an example, AVBP (developed by CERFACS and EM2C research laboratories) is a CFD code for unsteady turbulent combustion calculations. It is currently tested by CERFACS on gas explosions scenarios. However, the calculation capacity required for such calculations is much higher than the one needed for RANS porosity models. For now, these models are only used for small-size gas explosions (a few m^3).

DNS (Direct Numerical Simulations) solves the Navier-Stokes equations with no simplification, and requires high calculation capacity. DNS can be used for simulating academic configurations, with large calculation effort, but are not suitable for medium-scale and large-scale simulations.

3.4 Modelling of the explosion of a natural gas jet filling a congested area with FLACS: relevant sensitivity to the mesh and source-term

GDF SUEZ has performed a sensitivity study on the input parameters of FLACS, based on a real scenario of a natural gas pipe failure within a pipe work at high pressure (figure 18) :

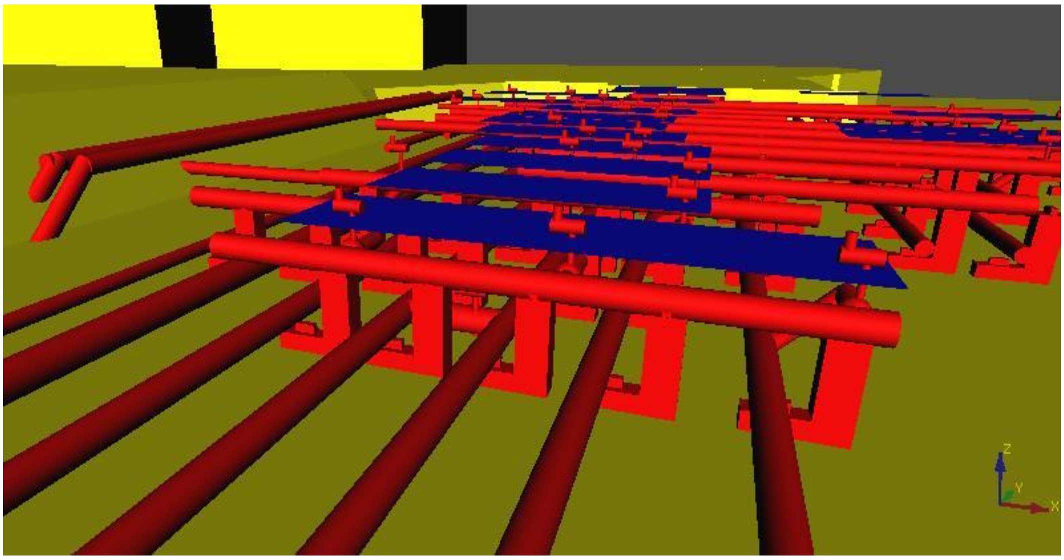


Figure 18 : example of large-size FLACS geometry

The source-term is classically defined with a pseudo-source (downstream of the zone of flow establishment which is present close to the release orifice for under-expanded gas jets), estimated by the "jet utility program" of FLACS (Gexcon, 2014).

The mesh is defined according to FLACS guidelines :

- In the area of the gas release, the cells are cubical, with a diameter equal to the diameter of the pseudo-source.
- Cells are cubical in all the combustion zone and stretched outside the combustion zone.
- For the explosion calculation, the mesh within the flammable cloud contains 16 cells in the smaller direction (vertical direction Z), whether FLACS guidelines impose 10 cells at least.

These guidelines lead to 700 000 cells whose diameter is 25 cm in the area of the flammable plume and flame propagation.

A sensitivity study on the pseudo-source has been done. The pseudo-source method by Birch (1984) has been tested in addition to the pseudo-source by the "jet utility program" of FLACS. Figure 19 shows the horizontal cut views at the height of the release orifice of the molar fraction of methane calculated by FLACS, with the two different pseudo-source methods. The methane concentration fields are different, as well as the flammable volume and the Q9 equivalent cloud volume, considering the same mass release rate, the same mesh (and thus the same porosity levels) and the same boundary conditions (table 9).
As a reminder, according to FLACS manual, the Q9 equivalent volume is defined as:
$Q9 = \sum V \times LBV \times E/(LBV \times E)_{stoich}$
Here, V is the flammable volume, LBV is the laminar burning velocity (corrected for flame wrinkling/Lewis number effects), E is volume expansion caused by burning at constant pressure in air, and the summation is over all control volumes.
Thus, Q9 cloud is a scaling of the non-homogeneous gas cloud to a smaller stoichiometric gas cloud that is expected to give similar explosion loads as the original cloud (provided conservative shape and position of cloud, and conservative ignition point). This concept is useful for QRA studies with many simulations, and has been found to work reasonably well for safety studies involving natural gas releases (NORSOK,2001).

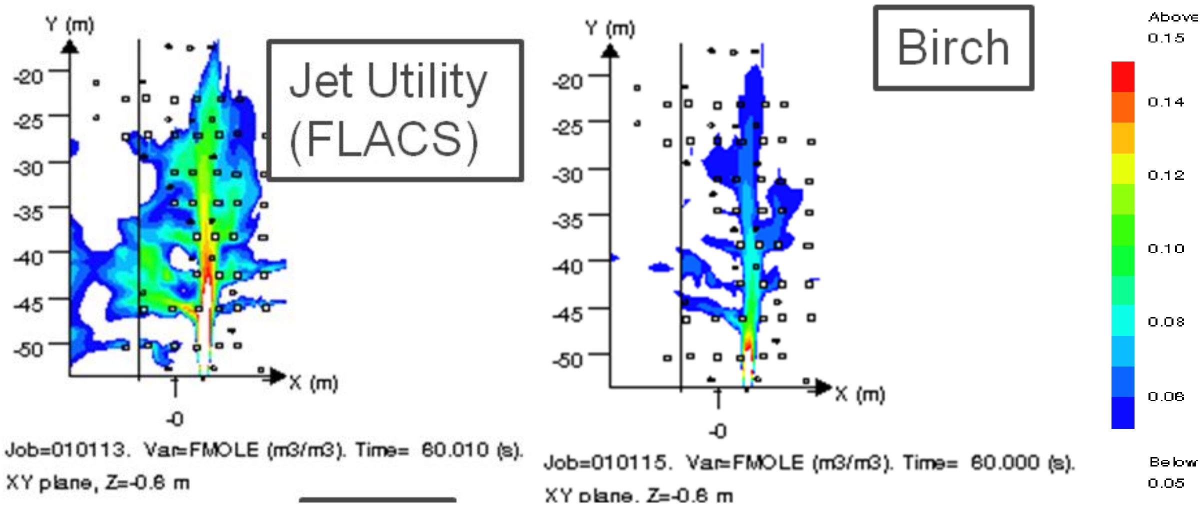


Figure 19 : comparisons of mean concentration fields for different source-term methods.

Table 9. Q9 and flammable volumes calculated with FLACS using different pseudo-source methods

	Q9 equivalent cloud volume	**Flammable volume**
Birch pseudo source: (Birch 1984)	70 m^3	400 m^3
Jet utility program (Gexcon, 2014)	460 m^3	980 m^3

Gas dispersion appears to significantly depends on the pseudo-source method for this configuration. FLACS simulations of free jets experiments (section 2.4) show that for configurations without obstacle, there are also differences on the dispersion results functions of the pseudo-source method which is used but the differences are lower than for the scenario with obstacles.

A sensitivity study on the meshing has been done. A mesh with 3 millions cells (minimum size : 12.5 cm) was used in addition to the first mesh with 700000 cells (minimum size : 25 cm). Figure 20 shows the horizontal cut views at the height of the release orifice of the molar fraction of methane calculated by FLACS, with the two meshes. The methane concentration fields are significantly different, as well as the flammable volume and the Q9 equivalent cloud volume, considering the same mass release rate, the same source-term, and the same boundary conditions (table 10).

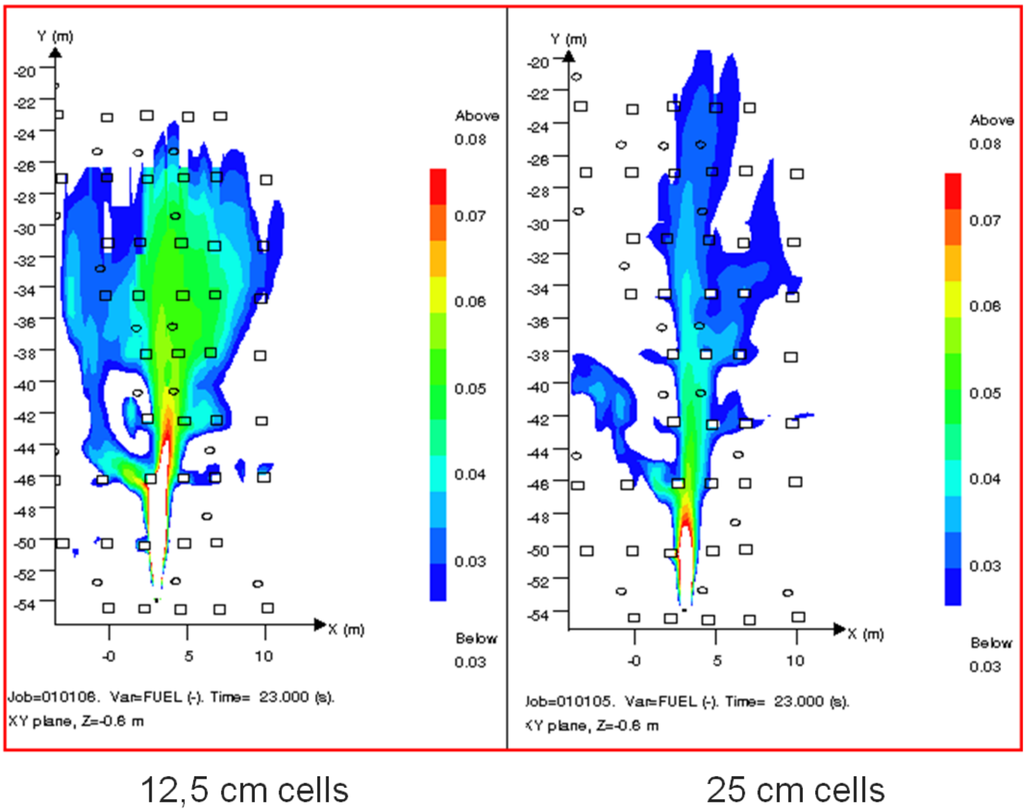


Figure 20 : dispersion calculation: comparisons of mean concentration fields for different meshes

Table 10. Q9 and flammable volumes calculated with FLACS using different meshes

	Q9	Flammable volume
Cell 25cm	70 m^3	400 m^3
Cell 12.5 cm	302 m^3	795 m^3

Although, both simulations respect the FLACS guidelines for meshing, there is still a grid effect on dispersion with obstacles. The grid sensitivity to dispersion calculation is very low for free jets (section 2.4). On the contrary, the influence of the grid size on the modelling of the obstacles (sub-grid obstacles vs. resolved obstacles) is not negligible and make difficult the choice of the most accurate results.

Figure 21 compares the pressure fields calculated with FLACS with two meshes (cells of 12.5 cm diameter on the left, cells of 25 cm diameter on the right). The maximum pressure is 60 mbar on the left and 52 mbar on the right. Differences are not important in that case (15%).

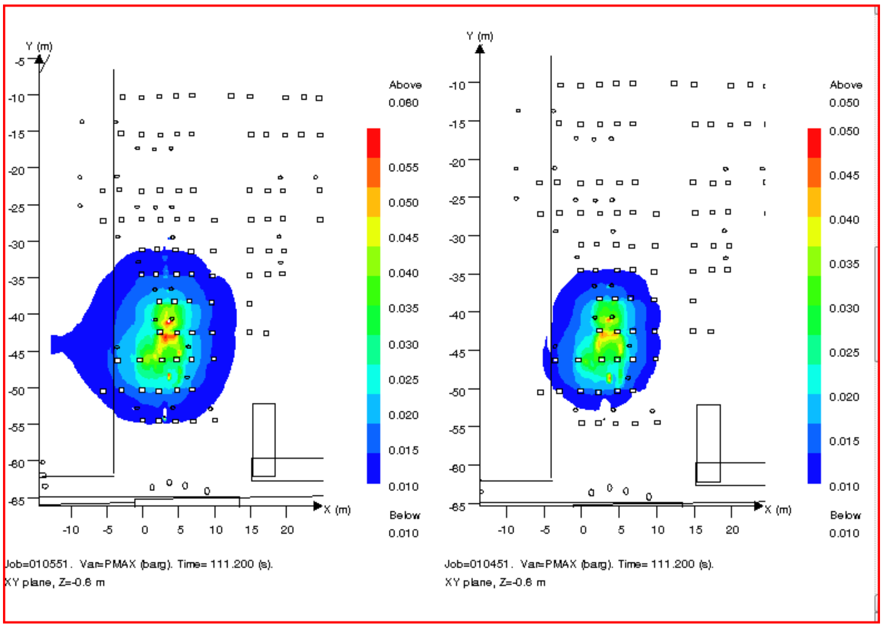


Figure 21 : dispersion calculation: comparisons of mean concentration fields for different

GDF SUEZ has also compared FLACS calculations with the experimental data of methane jets ignitions tests carried out by INERIS for MERGE project (Chaineaux, 1993). The test of MERGE-INERIS project which has been simulated with FLACS is a methane jet generated by a 150 mm diameter release orifice fuelled by a 5 m^3 methane tank, initially at 40 bar. The release orifice is located at 5 meters high. During the gas release, the pressure within the tank decreases and the mass release rate decreases also. The discharge coefficient at the orifice is 0.85. The ignition is done at 2.8 s after the opening of the release orifice, and it is located on release axis, at 5 meters high, at 15 meters downstream of the release orifice.

The pseudo-source is calculated by the FLACS "jet utility program" (Gexcon, 2014). The decrease of the mass release rate over time is calculated by the FLACS "jet utility program" and the surface of the pseudo-source is decreased over time to take into account the decrease of the mass release rate. Between the start of the release and the time of ignition the mass release rate comes from 107 kg/s to 13.5 kg/s and the pseudo-source surface comes from 0.62 m^2 to 0.056 m^2. The dispersion has been calculated first with a cubical mesh of 80 cm diameter cells and one pseudo-source in one cell, and second with a cubical mesh of 40 cm diameter cells and a pseudo-source divided in four cells.

Dispersion results are similar, except close to the release orifice where the turbulent kinetic energy K and the dissipation of the turbulent kinetic energy ε are increased for the FLACS simulation with 40 cm diameter cells.

Explosion simulation starts from the results of the dispersion simulation taken at 2.7 seconds, and with the ignition occurring at 2.8 seconds. Three different meshes have been used: a cubical mesh with 80 cm diameter cells, a cubical mesh with 40 cm diameter cells and a cubical mesh with 20 cm diameter cells. All these meshes respect the guidelines defined in FLACS' manual by Gexcon (Gexcon, 2014) for explosions simulations, these guidelines having been validated for explosions of quiescent stoichiometric mixtures. These explosion simulations show that overpressures are modified by a factor 2 to 4 between the three different meshes tested (table 11). During the MERGE-INERIS tests, the maximum overpressure was 84 mbar, which had been measured by the pressure sensor located at 1 meter high, 25 meters downstream of the release point.

Table 11 : Overpressures calculated with FLACS using different meshes

Diameter of the cells	Calculated maximum pressure	Calculated maximum pressure at 1 meter high, 25 meters downstream of the release point
80 cm	25 mbar	20 mbar
40 cm	50 mbar	40 mbar
20 cm	130 mbar	90 mbar

These simulations show that the simulation with FLACS of the dispersion and explosion of a pressurized gas jet is depending on mesh definition.

3.5 Comparison of the explosion effects calculated by FLACS for a large-scale methane jet explosion within a congested area, simulated with a real turbulent release and with an "equivalent" quiescent stoichiometric mixture

GDF SUEZ have run and compared FLACS simulations of methane explosions inside 2 different types of congested module, first with a quiescent stoichiometric mixture filling the whole congested module and second with a real release of 150 kg/s of pressurized methane entering the congested module. These simulations are representative for an accidental scenario of a large size leak on a high pressure natural gas pipeline located close to a congested area, which leads to the flammable part of the generated methane jet filling the congested area. The congested modules which have been tested are two 100 m^3 modules similar to those used by Baker Risk for its experiments, with two different levels of congestion: Low Congestion and Medium Congestion. For the tests with a quiescent air/methane mixture at stoichiometry, the congested module is totally filled with the mixture.

The real release is completely covering the congested area and the methane volumetric fraction in the module is close to 10% vol (figure 22, figure 23).

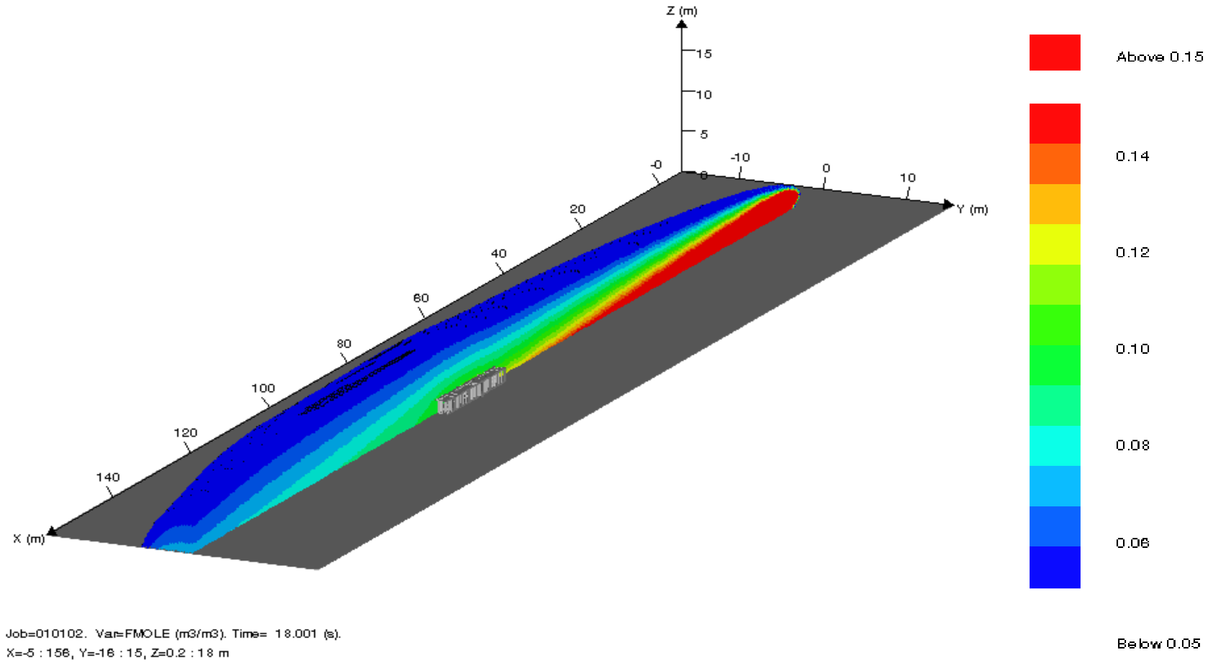


Figure 22 : 3D cut plane of the jet release covering the congested area (volume concentration)

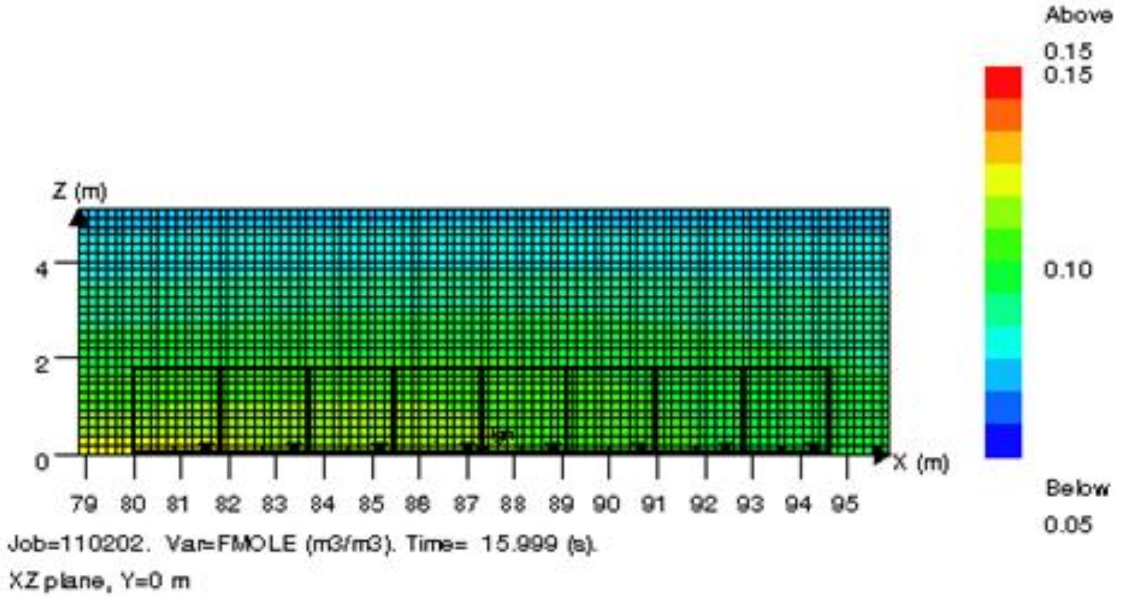


Figure 23 : 2D cut plane of the gas concentration along the jet axis

The ignition source is located at the centre of the congested area at ground level. A second ignition position was tested for the simulation of the "real release" explosion: at the entrance of the congested module at 1 m high. The simulations are consistent with the grid guidelines defined in FLACS' manual by Gexcon (Gexcon, 2014). The same mesh is applied for the quiescent mixture and the real releases. The cells are cubic (0.183 m) in the congested area and also 10 meters around the congested are in every directions. Beyond this area, the grid is stretched in every direction with a stretch factor of 1.2.

Table 12 compares the distances to several overpressure thresholds for the FLACS calculation performed with the low congested module of Baker Risk.

Table 12 Overpressures calculated with FLACS using quiescent mixture and a real release (150 kg/s of CH4) – low congestion module

Case	**Position of the ignition source**	**Pmax**	**Distance between the module exit (X= 94.4m) and the overpressure threshold (meters)**			
			200 mbar	**140 mbar**	**50 mbar**	**20 mbar**
Quiescent mixture	Centre	50 mbar	Not reached	Not reached	In module	~1 m
Real release	Centre	150 mbar	Not reached	In module	26 m	~ 65 m
Real release	Entrance	250 mbar	In module	5 m	~ 30 m	~ 70 m

Table 13 compares the distances to overpressure thresholds for the FLACS calculation performed with the medium congestion module of Baker Risk.

Table 13 Overpressures calculated with FLACS using quiescent mixture and a real release (150 kg/s of CH4) – medium congestion module

Case	**Position of the ignition source**	**Pmax**	**Distance between the module exit (X= 94.4m) and the overpressure threshold (meters) m)**			
			200 mbar	**140 mbar**	**50 mbar**	**20 mbar**
Quiescent mixture	Center	220 mbar	In module	In module	6 m	8 m
Real release	Center	260 mbar	In module	3 m	~ 32 m	~ 78 m
Real release	Entrance	500 mbar	3 m	8 m	~ 36 m	~ 75 m

The FLACS simulations give significant differences between the maximal overpressures calculated with the quiescent mixture and with the real release. For the low congestion module, the maximum overpressure is multiplied by 3 for the real release case compared to the quiescent stoichiometric mixture case. For the medium congestion case, the difference is lower: the maximum overpressure is increased by 20% for the real release case compared to the quiescent stoichiometric mixture case.

In open field with no obstacle, the FLACS simulation of a 150 kg/s grounded jet (with a release orifice at one meter high) gives a maximal overpressure inside the jet of 100 mbar for a flammable volume of 11200 m^3 and a Q9 volume of 4300 m^3, which is also very important compared with the maximum overpressure of 3 mbar which has been measured by (Pfortner & Schneider, 1988) for the ignition of a air/methane quiescent soichiometric volume of 12800 m^3.

4. Conclusions and discussion on the need for large-scale explosion tests of real releases within congested areas

The reduced scale experiments carried out by INERIS and GDF SUEZ in 2013 and the simulations performed by GDF SUEZ using FLACS show that initial turbulence of a real jet can have a significant impact on explosion and resulting overpressure compared to the ignition of an equivalent quiescent stoichiometric mixture. The effect of the initial turbulence is higher for low congestion areas than for medium or high congestion areas, as it was already demonstrated in the EMERGE project and the Phase 3B JIP. To observe a significant influence of initial turbulence on the explosion effects, the size of the gas release must be of the same order of magnitude as the congested module, in order to fill it totally with concentrations close to stoichiometry in the whole congested module and in order to have turbulent velocities and turbulent length scales comparable to the turbulence levels reached during the flame propagation. At that condition, the ignition of a flammable air/methane mixture produced by a pressurized jet with a high release rate might be significantly more severe than the ignition of a flammable air/methane mixture of equivalent volume produced by the passive dispersion of a dense gas (ex: LNG vapour, LPG, etc.).

The test bench set up by GDF SUEZ and INERIS allows to carry out various reduced scale tests of gas jets explosions with different releases locations and different congested areas and provide reliable measurements on the flammable cloud (concentration, velocity, turbulence) to understand the involved phenomena. However, as the level of turbulence is characterized by the turbulent velocity but also by the size of the turbulent structures (generally represented by the integral scale of turbulence) which is proportional with the size of the jet itself, scales factors are relevant. Flame speed and explosion consequences are in addition proportional to the flame path, and thus to the scale of the tests.

In consequence, as there are not enough large scale experimental data for gas jet explosion, and given the uncertainty of existing models including CFD models, according to GDF SUEZ, there is a need for a full-scale validation of the existing explosion models by achieving large-scale experiments of explosions of real large-size pressurized fuel releases. For this purpose, GDF SUEZ is setting up a project of large-scale tests which should allow to assess the levels of flame acceleration and overpressures that can be reached by the ignition of a real large-size jet that can be generated by a large puncture on a high pressure natural gas pipeline (release rate around 100 kg/s). A full-scale grounded jet with no obstacle will be first tested to study separately the effect of initial turbulence on the explosion effects. Then, the test will be repeated in adding congested modules to study the influence of obstacles on the explosion effects. The fuel jet (natural gas) will fill completely or at least most part of the congested area, and the congested areas to be used will be representative for gas sites, both in onshore environment and offshore environments.

These tests might enable to:

- Assess the influence of initial turbulence generated by large size real releases on explosion effects and estimate the scale effects.
- Verify if the classical assumption of using an “equivalent” quiescent stoichiometric mixture is still conservative for large size jets explosions in various congested areas.
- Verify the accuracy of CFD models (i.e FLACS) for similar scenarios, define good modelling practices associated to this phenomenon and eventually identify the potential need for further developments of the models.

References

Abdel Gayed, R.G.; Bradldey, D & Lawes, M. (1987). *Turbulent burning velocities : a general correlation in terms of straining rates*.

Ahmed, S.F & Mastorakos, E. (2006). *Spark ignition of lifted turbulent jet flames*. Combustion and Flame 146: 215–231.

Arnaud, R. (1992). *The overpressures generated by the inflammation of a large-scale free natural gas jet*. Proceedings of the 7th international loss prevention and safety promotion in the process industries symposium, Taormina Italy vol 3: 113-1 – 113-14.

Birch, A.D; Brown,D.R; Dodson, M.G. & Swaffield, F. (1984). *The structure and concentration decay of high pressure jets of natural gas*. Combustion Science and Technology.

Birch, A.D; Hughes, D.J. & Swaffield, F. (1987).*Velocity decay of high pressure jets*. Combustion Science and Technology, vol. 52: 161-171.

Bray, K.N.C. (1990). *Studies of the Turbulent Burning Velocity*. Proc. R. Soc. Lond. A 431: 315-335.

Brugier, J.L. ; Desbordes, D. ; Guerraud, C. ; Leyer, J.C. ; & Ruttun, B. (1991). *Caractéristiques de l'explosion aérienne produite par l'inflammation d'un rejet accidentel de gaz naturel sous pression dans l'atmosphère*. GDF/ENSMA contract.

Chaineaux, J. (1993). *Rapport final du projet MERGE,* Rapport INERIS.

Cleaver, R.P. & Robinson, C. (1996). *An analysis of the mechanisms of overpressure generation in vapour cloud explosions*. Journal of Hazardous materials, 45: 27-44.

Committee for the prevention of disasters (1995). *Methods for the calculation of physical effects.* Yellow book. Third edition. Chap 5, 5.31-5.72.

Deshaies & Leyer. (1981). *Flow field induced by unconfined spherical accelerating flames*. Combustion and flame, 40: 141-153 B.

EMERGE project (1996). *Final summary report for the project EMERGE*. EC contract EV5V-CT93-0274

Gexcon AS.(2014). *FLACS v10.2 User's Manual*. Copyright ©GexCon AS

Guibert-Duplantier, C. & Elzière, A. (1997). *Explojet, Campagne d'essais Avril 97-Décembre 97*. INERIS: EXI/CDu 16FA26 EXPLOJET.

Hansen, O.R., Van Wingerden, K., Pedersen, G.H. & Wilkins, B.A. (1998). *Studying Gas Leak, Dispersion and Following Explosion after ignition in a Congested Environment Subject to a Predefined Wind-Field, Experiments and FLACS-simulations are Compared*. Proceedings of: 7th Annual Conference on Offshore Installations; Fire and Explosion Engineering, At London, Volume: ERA-report 98-0958

Hinze, J.O. (1975). *Second Edition Turbulence*. 547.

Hoff. (1983). *Experimental study of the ignition of natural gas in a simulated pipeline rupture.* Combustion and Flame 49: 51-58.

HSE. *Fire and explosion strategy issue 1*. Hazardous installations directorate, offshore division.

Linga, H.; Pedersen, G.H.; Wilkins, B.A. & Wingerden, K. van (1995). *Gas explosions with initial turbulence, large-scale experiments in a 62,5m3 tent and a 50m3 module*. Report of Christian Michelsen Institute for the EMERGE project, ref: CMR-95-F20022, Bergen, Norway.

McCaffrey, B.J. & Heskestad, G. (1976). *A Robust Bidirectional Low-Velocity Probe for Flame and Fire Application.* Combustion and flame 26: 125-127.

Mercx, W.P.M.; Bruijn, P.C.J de & Wijchers,T. (1996). *Extended modelling and experimental research into Gas Explosions,* Contribution of TNO Prins Maurits Laboratory, Annex A : experiments to investigate the influence of initial turbulence on gas explosions, report of TNO Prins Maurits Laboratory for the EMERGE project, PML 1996-C16.

NORSOK standard. (2001). *Risk and emergency preparedness analysis. Z-013*

Omer, L. & Gulder. (1990). *Turbulent premixed flame propagation models for different combustion regimes*. 23rd Symposium on Combustion/The Combustion institute: 743-750

Ooms, G. (1972). *A new method for the calculation of the plume path of gases emitted by a stack.* Atmospheric environment, vol 6 pp 899-909.

Pfortner, H. & Schneider, H. (1988). *Experimental investigations into the deflagration of flat, premixed hydrocarbon/air gas clouds.* American institute of aeronautics and astronautics.

Pierorazio, J.A.; Thomas, J.K.; Baker, Q.A. & Ketchum, D.E. (2004). *An update to the Baker-Strehlow-Tang vapour cloud explosion prediction methodology flame speed table*. Process Safety Progress, 24 (1).

Schneider, H. & Proust, C. (2007). *Determination of turbulent burning velocities of dust air mixtures with the open tube method.* Journal of Loss Prevention in the Process Industries 20: 470–476

Schumann, St.; Rastogi, A.K.; Haas, W. & Schmittberger. H. (1993). *MERGE: Modelling and Experimental Research into Gas Explosions, Final report*. Battelle R40.061-E4

Shale, G.A. & Walker, D.G. (1996). *Extended Modelling and Experimental Research into Gas Explosions. Final report for medium and large-scale explosions experiments* (EC contract number: EV5V-CT93-0274), British Gas plc, GRC R 1327, Loughborough, United Kingdom.