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SAFETY OF HYDROGEN/NATURAL GAS MIXTURES BY PIPELINES: ANR FRENCH PROJECT HYDROMEL

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ABSTRACT

In order to gain a better understanding of hazards linked with Hydrogen/Natural gas mixtures transport by pipeline, the National Institute of Industrial Environment and Risks (INERIS) alongside with the Atomic Energy Commission (CEA), the industrial companies Air Liquide and GDF SUEZ, and the French Research Institutes ICARE and PPRIME (CNRS) have been involved in a project called HYDROMEL. This project was partially funded by the French National Research Agency (ANR) in the framework of its PAN-H program aimed at promoting the R&D activities related to the hydrogen deployment.

Firstly, the project partners investigated how a NG/H_2 mixture may influence the modeling of a hazard scenario, i.e. how the addition of a quantity of hydrogen in natural gas can increase the potential of danger. Therefore it was necessary to build an experimental database of physics properties for mixtures.

Secondly, effect distances in accidental scenarios that could happen on pipelines have been calculated with existing models adapted to the mixtures. This part was preceded by a benchmark exercise between all partners' models and experimental results found in the literature. Finally the consortium wrote a "good practice guideline for modeling the effects related to the release of natural gas /hydrogen mixture".

The selected models and their comparison with data collected in the literature as well as the experimental results of this project, and the main conclusions of the guidelines are presented in this paper.

1.0 INTRODUCTION

The development of hydrogen as energy carrier in our society raises issues (storage, production, transportation ...).

Within the project HYDROMEL, the partners Air Liquide, GDF SUEZ, CEA, two CNRS laboratories ICARE and PPRIME and INERIS focused on assessing the risks associated with transport of hydrogen, pure or mixed with natural gas.

Indeed, the most cost effective solution for large-scale distribution of hydrogen as energy seems now to be the pipeline transport. Either by adding a larger or smaller fraction of hydrogen in existing natural gas networks or specific networks dedicated to hydrogen. For each scenario, the safety and the finding of an economic optimum are key elements for the design of future hydrogen transport systems.

It is therefore necessary to assess all risks during transportation and distribution of this gas, particularly related to accidental leakage.

In the HYDROMEL project, two main objectives were:

- Study the constraints associated with the addition of hydrogen in natural gas pipelines and the impact on the safety of a high content of hydrogen
- Realization of experiments in order to obtain data for the validation of computational models of the hazardous consequences while advancing these models.

In the first step, the consortium has achieved a full state of the art in order to identify plausible scenarios. INERIS, GDF SUEZ, Air Liquide and CEA compared their models.

In the experimental part of the project, the Institute ICARE focused on the characterization of the inflammation and explosion for different blends of hydrogen and natural gas. LCD worked on a specific issue concerning the risk of self-ignition in case of high pressure leakage of hydrogen in air.

2.0 RISK ANALYSIS

The use of hydrogen as energy carrier requires its transport and distribution by pipelines.

Two sorts of transport solution by pipeline have been considered:

- The use of the existing natural gas pipeline network with modifications, by which the hydrogen will be transported mixed with the natural gas or pure in some parts of the network
- A new network dedicated to pure hydrogen with some specific characteristics of diameters, pressure and materials.

The production capacities of hydrogen will condition the possible mass flow into the natural gas network or dedicated hydrogen network, and the injections conditions. The production rate of hydrogen by high temperature electrolysis linked with a nuclear reactor would be in the order of 350 000 m^3 / h. Considering this hypothesis hydrogen would be injected at high pressure (100 bar) into the network (Diameter: 500 mm) dedicated to the transport of hydrogen.

.Hydrogen can be produce by:

- Steam Methane Reforming (SMR) with CCS[1]
- Gasification (biomass or coal + CCS[1])
- Water electrolysis (coupled with wind or photovoltaic power).

Concerning the transport of natural gas/hydrogen mixtures by pipeline two configurations are envisaged:

- Injection of hydrogen in the small local NG networks. The hydrogen content in this case is lower than 20% .
- Injection of hydrogen in the national NG network. The hydrogen content will be lower than 10% in this case.

Summary of scenarios used in the Safety Studies for transport of hydrogen and natural gas

In order to determine realistic leak scenarios we referenced our work to the methodology used in the French guide GESIP 96/08[2] . Three types of breach are taken into account:

- a small breach by corrosion,
- a medium size breach,
- and the full bore rupture.

The orientation of the leak flow in the case of full bore rupture has a vertical direction. For small breaches, the release can be inclined or horizontal in the case of overhead pipelines and jets can disturbed by an obstacle.

The studied hazardous phenomena in this work are dispersion, thermal radiations, and overpressures following the inflammation of the release.

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[1] CCS = CO_2 Capture and Storage

[2] le Guide GESIP 96/08 « Méthodologie pour la réalisation d'une étude de sécurité concernant une installation de transport (hydrocarbures, gaz, produits chimiques) »

In general, the impact of these hazardous phenomena on humans is, considering overpressure, worse for hydrogen and, considering thermal radiations, worse for natural gas. The methodologies used for the pipeline transport safety studies are relatively similar for hydrogen and natural gas. Differences concern the definition of the breach size and the consideration of overhead pipelines or equipments. Another difference is the consideration of the influence of a crater formation on the direction of the gas release. The models used for the estimation of effects distances are also, of course, different.

The geometry of the breach was chosen circular (overestimation of the mass flow rate).

The following transport equipments have been taken into account:

- Pipeline
- Switching stations
- Crossing rivers, roads ...
- Compressor stations online.

The chosen “top events”:

- the full bore rupture of the pipeline (aggression by a powerful vehicle or by ground movement including earthquakes),
- medium size breach of 70 mm diameter, corresponding mainly to the attack on the pipeline by a tool used for construction,
- a small 12 mm diameter breach of , corresponding mainly to a crack or corrosion,

From this analysis, and this choice of scenarios, the partners managed to reach an agreement that resulted in the writing of a “good practice guideline for modeling the effects of a gas natural/hydrogen mixtures release”.

3.0 GUIDELINE

The main objective of this guideline is to provide some indications for users of the different modeling methods used in HYDROMEL project to calculate H_2/CH_4 pipelines transport hazard scenario consequences.

We will discuss:

- The physical models developed in the different software used by the project partners (PHAST, PERSEE, CAST3M, ALDEA et EXPLOJET)
- The input parameters (weather, pressure, temperature…)
- The initial assumptions (homogeneous mixtures methane / hydrogen, perfect gas…).

The models used by the partners (the list presented in the following table is not exhaustive) have been tested on few experimental configurations with data found in literature.

Each partner used its own internally developed model and sometimes also commercial software. GDF-SUEZ used its own Persee platform, Air Liquide used Phast 6.53 software and the internally developed ALDEA. INERIS used also Phast 6.53 and its own EXPLOJET model and CEA used the internal CAST3M platform. The detailed models [1] are presented on the following table:

Partner	**Code**	**Model**	**Description**
GDF SUEZ	Persee	Dispersion Over-pressure Jet fires	Integral model [2] or pseudo source model (CATS) Deshaies [3] Chamberlain [4, 5]
	Flacs	*Building explosion*	*CFD*
	CALDEIRA 3.0	Mass flow rate	Real gas EOS for CH_4 and Perfect gas EOS for H_2
Air Liquide	Phast (DNV)	Dispersion Jet fires Over-pressure	Unified Dispersion model (Gaussian) Chamberlain [4,5] TNO multi-energy
	ALDEA	Dispersion Jet fires	Birch [6] Schefer [7]
	Flacs (H_2 version)	*Building explosion*	*CFD*
INERIS	Phast (DNV)	Dispersion Jet fires Over-pressure	Unified Dispersion model Chamberlain [4,5] TNO multi-energy
	Explojet	Dispersion	Analytical formulas for gas concentration decay
		Over-pressure	*In-house method (constant volume explosion and acoustic wave source)*
CEA	CAST3M	Dispersion Jet fires Over-pressure *Building explosion*	Integral model [8] Pseudo source model [6] Schefer [7] *Dorofeev [9]* *CFD*

Table 1: Presentation of the software and models used by partners

Some of the models have been used out of their validation domain given by their editor. This stresses the need of further developing and validating models for use in new configurations. All models have been developed for pure gases. For example Persee is for natural gas only, Explojet can accept pure hydrogen or pure methane. For commercial softwares (Flacs, Phast), mixing laws are already integrated.

Source term calculations: this aspect is relatively well controlled for high pressure gas releases (pure or mixtures). The two main difficulties are:

1. The choice of the state equation: it is advisable to choose a real gas equation (Abel Noble and Van der Waals for example) when the pressure reaches 70-80 bar. For lower pressures, the assumption of perfect gas gives satisfactory results, especially for methane.

2. Pressures losses evaluation in the network (choice of the discharge coefficient for example). In some cases, all the inputs are unavailable, so it is of course advisable to take a small loss in order to increase results (taking a Cd around 0.8 for the release scenarios of gas through an orifice for example).

For mixtures, properties are balanced by ideal laws or Le Chatelier laws with masses or molar fractions of each pure gas.

NB: the software Persee has not been used for the calculation of mixtures.

When the breach is small compared with the pipe diameter, the mass flow rate is considered as constant. All partners found very similar results because the calculation then depends principally on the equation of state and the choice of the discharge coefficient.

For the full bore rupture of a pipeline, the pipeline depressurization can be modeled (this is not necessary for the other breaches). Experiments [10] have been run by Shell to measure the mass flow-rate from a pressurized air pipe suddenly open at one end. The test conditions are summarized in **Figure 1** (left), the mass flow rate evolution is plotted in **Figure 1** (right). All models used by the partners gave results very close to experimental observations, particularly for the 20 first seconds. For later times, some models tend to underestimate mass flow rate. For consequences analysis mean values over one or two periods are usually considered. The mean mass flow rate for duration of 60 s is assumed to be very close for all models. These models can be used for pure gases and mixtures.

Test 23 [10]	
Gas	Air
Pipe diameter	305 mm
Pipe length	3438 m
Initial pressure	68.1 bar
Initial temperature	278 K
Pipe rugosity	0.107 mm
Duration	180 s

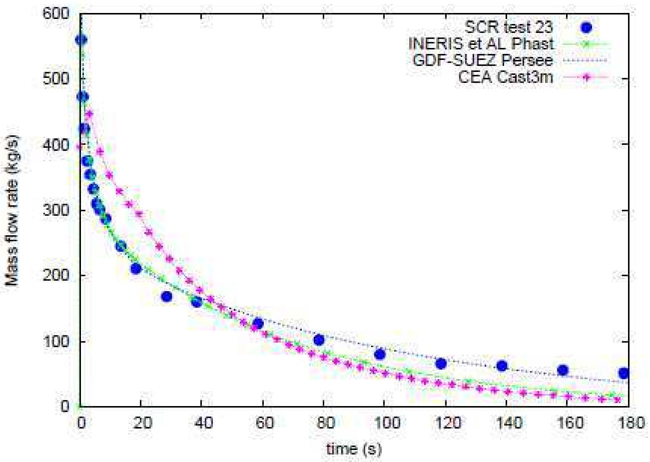

Figure 1: Comparison between all pipeline decompression models

The dispersion: The high pressure release of gas is quite well known in general. A comparison has been made in [1] between the experiments of [12] for hydrogen and [6] for methane, and the model predictions. For the hydrogen experiments [12], an upstream pressure of 31 bar was used associated with an exit diameter of 2.7 mm. For methane experiments [6], the pressure was 100 bar with a diameter of 3 mm. Both experiments have been run at room temperature. The resulting axial center line gas concentrations are plotted in Figure 2. The results are within an accuracy of 30 %, which is reasonable for dispersion modeling.

Experiments	[6]	[12]
Gas	CH_4	H_2
Pressure (bar)	31	100
Orifice diameter	2.7	3

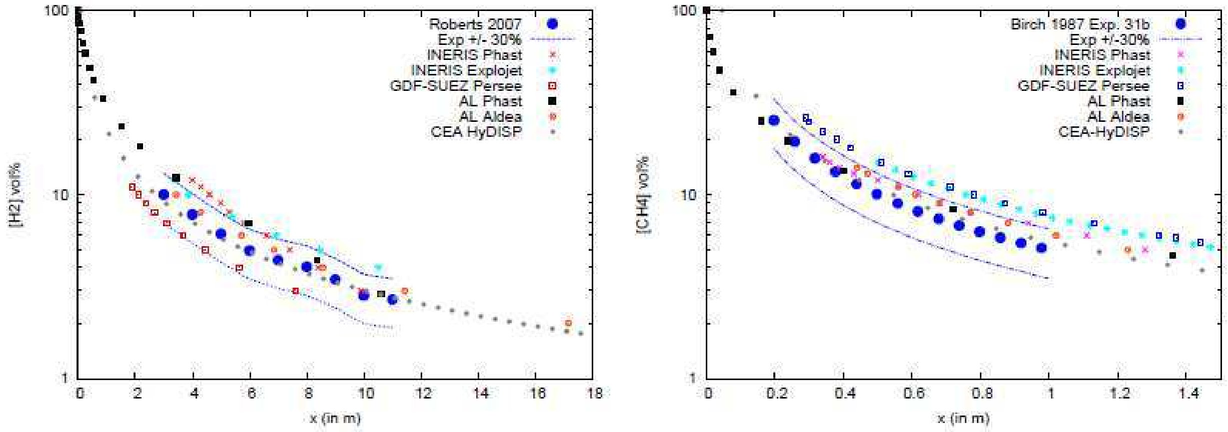

Figure 2 : Gas concentration along the center line of the cloud: top – inputs, bottom left: hydrogen jet [12], right: methane jet [6]

Another safety information is the mass of fuel in the flammable cloud. The results presented in [1] shows for hydrogen jet an explosive mass varying by a factor five. However, the associated overpressures are proportional to the cubic root of this quantity and a factor less than two is expected for the overpressure at a certain distance from the ignition point.

The pseudo-source models seem particularly adapted for the dispersion of high pressure releases for pure gas and even for mixtures. Even if sometimes this model allows to slightly increasing results. The balance laws allowed keeping coherence between results obtained from pure gas to mixtures.

To take into account the atmospheric conditions in integral models seems superfluous regarding the high rate of establishment of a cloud of light gas at high pressure. However, in the case of large jets oriented vertically, taking into account the effects of a strong side wind and buoyancy phenomena may allow a more accurate simulation.

It should be noted that the software PERSEE was developed specifically for natural gas, the results for hydrogen are then not relevant.

Thermal radiation calculations: natural gas safety is mainly driven by thermal radiations from large scale jet fires. Exclusion distances are usually determined for worst case scenario by explosion phenomenon in hydrogen related accidents. Safety properties of the mixtures should then include each as the above explained features and it is a challenging issue to determine the exact location of the transition between thermal effects is worst or explosion effect is worst. Regarding this important issue, experiments have been conducted within the HYDROMEL project to address properties of large scale H2/CH4 jet fires. A short description of the INERIS test facilities is presented on figure 3. Heat fluxes, temperature and flame lengths have been recorded using thermocouples, thermal and speed cameras. These experimental results with validations of numerical models are presented by [13]

Practically, the Chamberlain model implemented in PHAST, ALDEA or PERSEE give good results. They are validated on a lot of cases and are considered dependable. PERSEE has been validated on natural gas. The model of [7] (CAST3M, ALDEA) is limited to small jet fires. Its use should be limited to flame length lower than 50 m. The mixture composition should be based on mass weighted properties. It was justified by comparing them with test data.

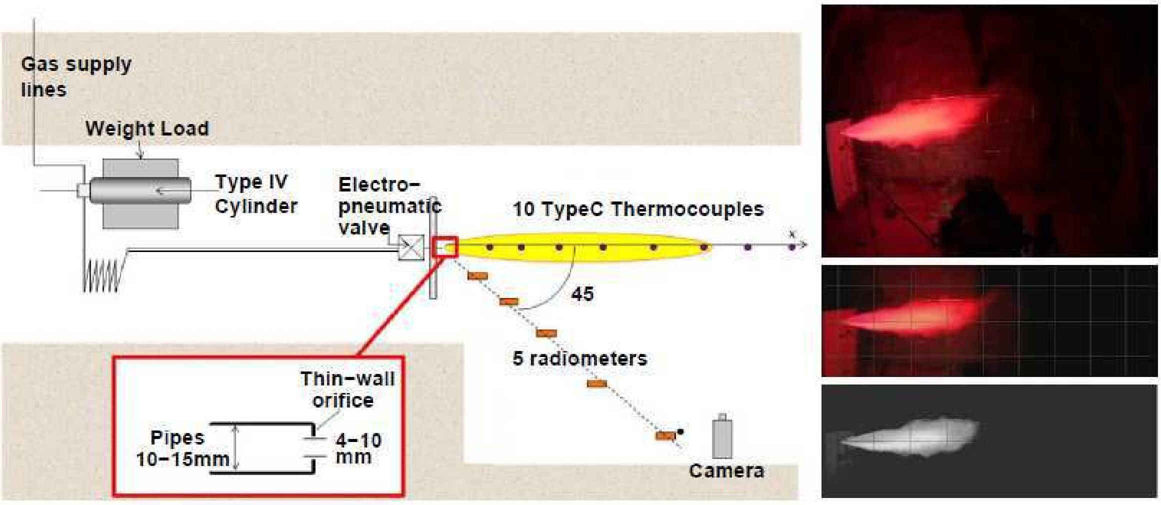

Figure 3: Facility design and example of measured and post-processed flame shape

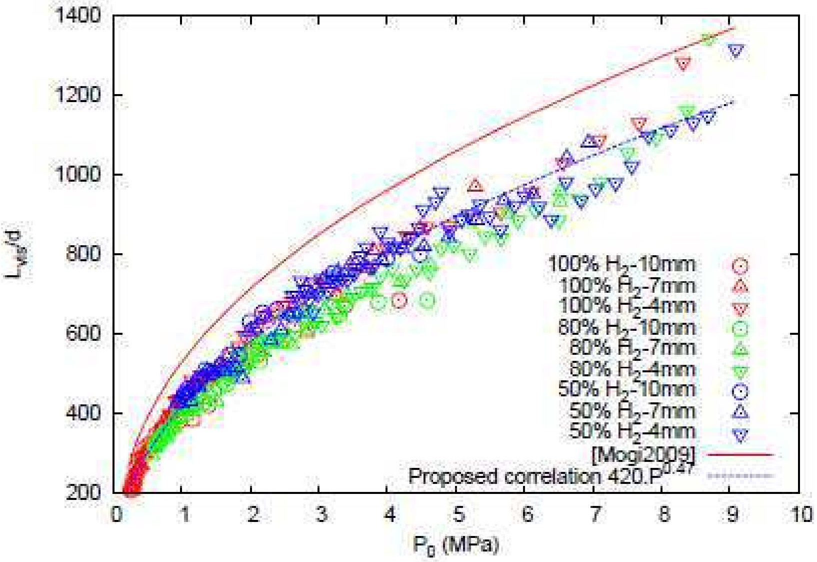

Figure 4: Visible flame length function of the upstream pressure P_0

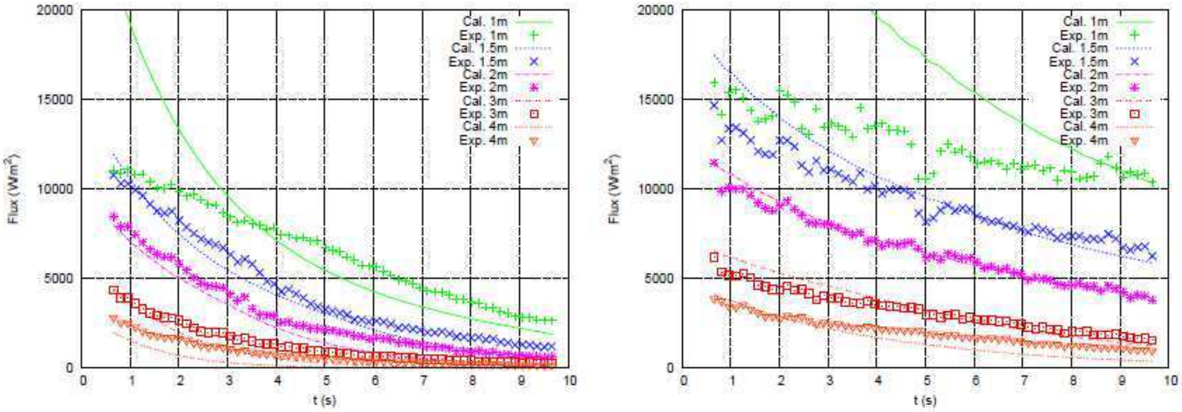

Figure 5: Example of computed and measured transient heat fluxes at different locations for a 4 mm diameter release – Left: hydrogen – Right: 50:50 mixture – Axial distances refer to the radiometer axial location in figure presenting the setup facility

The experiment results [13] show the non dimensional flame length in the momentum dominated regime is affected by the composition of the released gas. Pure hydrogen is very close to the results obtained by [7] for vertical jet fire. Visible flame length (figure 4) compares well with the already available results, and engineer correlations have been proposed. Blow-out characteristics are in agreement with the properties predicted by [14] model. Radiative properties of H_2/CH_4 jet fires scale with the parameter proposed by [15] $\tau_f T^4_f a_p$. Finally, the phenomenological model developed within the project [13] has shown great capabilities to predict the main characteristics of the jet fires: flame length, blow-out velocities and radiant fluxes.

Over pressure calculations: the modeling of the blast effects showed several differences between all partners' calculation methods. This can be explained by the initial assumptions concerning the flame propagation and not really by the dispersion calculations. The pseudo-source models used to calculate the inflammable mass are good and provide very comparable results. The differences come from the over pressure calculations. The three methods are presented below; the partner did not find any agreement to use one of them:

1) The first method consists in considering the entire flammable mass dispersed (i.e. the part of the cloud between LFL and UFL). Then a multi energy strength number of 3 for natural gas or 4 for hydrogen and mixtures are applied.

2) The second method seems to take into account the physical phenomena more accurately. A combustion (variable velocity) model is applied to a spherical volume (the sphere radius equal the jet radius at the ignition point). This modeling method has been validated on experimental data [16] for pressure up to 40 bar and breach diameters up to 100 mm for natural gas. Beyond this limit, the turbulence levels in the jet may be large enough to induce very high flame velocities, which would tend to make models out of there validation domain.

3) If the flame velocity model is out of there validation domain, a multi energy strength number of 6 could be used but on a reduced spherical volume able to accelerate the flame (i.e more than 11% for H2) [17]. This method is generally conservative.

NB : From [18] it was found that the introduction of a small amount of CH4 ($x \geq 0.8$, i.e. ratio of CH4 less than 20% in the fuel) desensitizes the mixture compared to H2 - Air mixture and increases the run-up distance L_{DDT} to obtain transition to detonation.

The poor number of experimental data on the blast effects did not allow the partners to conclude. Therefore, the models cannot be validated and further experimental work is needed to conclude on the appropriate approach for modelling H_2-CH_4 mixture explosion.

4.0 CONCLUSIONS

The two main objectives of the HYDROMEL project were to:

- Study the constraints associated with the addition of hydrogen in natural gas pipelines and the impact on the safety of a high content of hydrogen
- Produce experimental data to validate computational models of the hazardous consequences while advancing these models.

In this work a practical modeling guideline has been realized which identifies a few methods and models for calculating effects (thermal and over pressure) following a breach on pipelines using hydrogen/natural gas mixture.

The different dispersion models showed a good accordance with experimental data found in the literature. The experimental set-up allowed partners to validate their radiation models on H_2/CH_4 mixtures. Finally, all the partners agreed on the modeling methods, even for mixtures; except for blast effects. Indeed, no database is being available for blast effects that would have allowed partners to validate their models. It is necessary to undertake additional experimental work to reach an agreement on modeling these effects.

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