High pressure hydrogen fires

Christophe PROUST[1], Didier JAMOIS[1], Etienne STUDER[2]

[1]INERIS, Parc Technologique Alata - BP 2 - 60550 Verneuil en Halatte (France), e-mail: christophe.proust@ineris.fr , Phone: +33.(0)3.44.55.65.28, Fax : +33.(0)3.44.55.62.00
[2]CEA, CEA Saclay, DANS/DM2S/SFME bat. 454 - Point Courrier 47 - 91191 Gif-sur-Yvette (France), e-mail : etienne.studer@cea.fr, Phone: +33.(0)1.69.08.35.21

Abstract

In the scope of the french national project DRIVE and european project HyPER, high pressure jet flame of hydrogen were produced and instrumented.

The experimental technique and measurement strategy will be presented. Many points are original developments like the direct measurement of the mass flowrate by weighing continuously the hydrogen container, the imaging processing to extract the flame geometry, the heat flux measurement device, the thermocouples…

Flame have been produced from 900 bar down to 1 bar through orifices ranging from 1 to 10 mm. Thus an original set of data is now available not only about the flame but also about the thermodynamic properties of high pressure hydrogen (since the pressure and the temperature in the container were continously monitored during the release).

A comparison with other published data is proposed and a discussion of some available models .

Introduction

A number of hydrogen fuelled applications are envisioned using the fuel cell technology. One great challenge is to be capable of storing a large enough amount of hydrogen for the system to have a reasonable autonomy. It is crucial for hydrogen vehicles. High pressure gaseous storages are regarded as a promising route provided the storage pressure could be large enough and, at least for vehicles, not less than 70 MPa (Perrette et al., 2007).

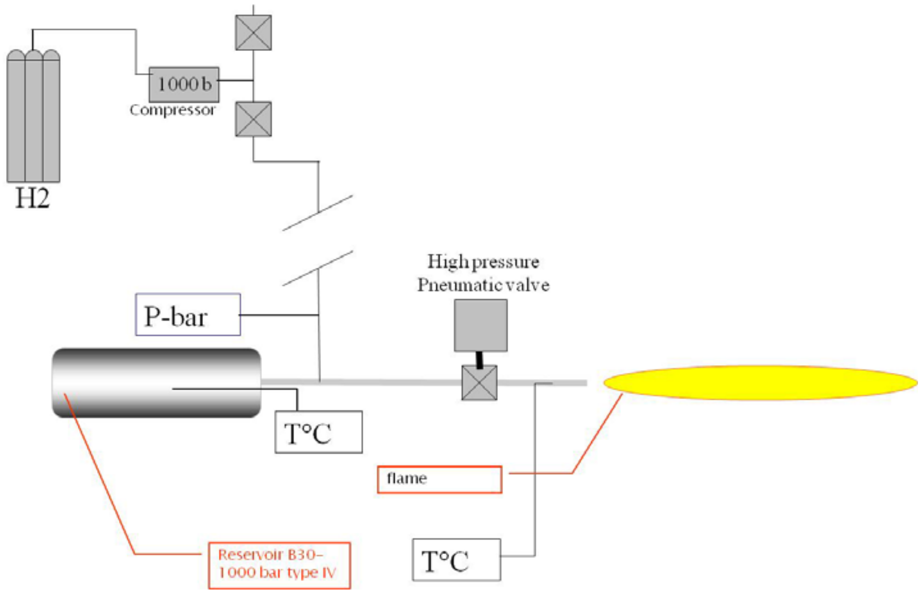
Several technical issues need to be solved. In particular, the consequences of a leakage due a mechanical failure of the piping of the activation of the safety pressure relief device of the reservoir (PRD) need to be assessed. Although, the question of the spontaneous ignition is still open (Asbury and Hawksworth, 2007), it is generally admitted that the release will ignite.

From the pioneering work of Houf and Shefer (Shefer et al., 2006; Houf et al., 2007), it is known that very large jet flames may be produced (up to 10 m for a 5 mm orifice under 30-45 MPa). Further evidence was provided by Mogi and Horiguchi (Mogi and Horiguchi, 2009) with smaller diameters and similar pressure range. Data not available in the international literature are mentioned in the latter paper and some experimental information concerning blowout and lift-off is given.

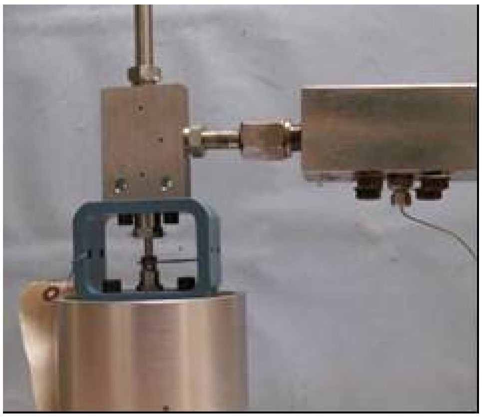
In this paper, an original set of data is presented about the blowout of a high pressure hydrogen reservoir (from 90 MPa down) through orifices ranging from 1 to 3 mm. The jets were ignited and the flame geometry and radiative properties were investigated. This work was performed within the frame of the French national project DRIVE and E.U. sponsored programme HyPER.

Experimental system

The facility is a type-IV reservoir with an internal volume of 25 L (figure 1). It is connected to the orifice nozzle (1 to 3 mm bore hole) via a 10 m pipe with a constant internal diameter of 10 mm in order to minimize head losses. A high pressure valve just upstream of the orifice triggers the blow down (opening time 0.1 s). The jet is directed horizontally at approximately 1.5 m above the ground level. The igniter is a continuous propane air Maecker burner.



- Sketch of the facility -



- valve -

- reservoir -

- orifices -

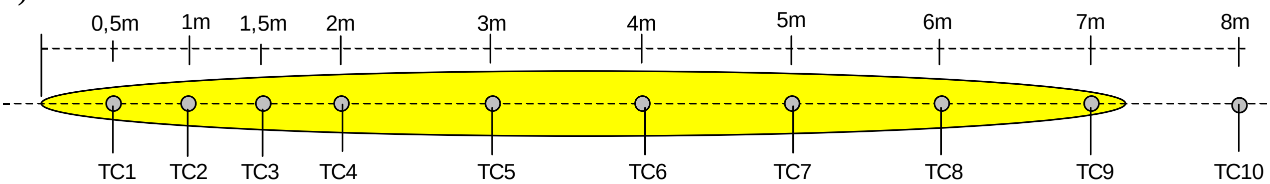
- igniter (burner)-

Figure 1 : experimental device

The device is installed in a dark 12 m^2-80 m long open gallery in order to favour the visualisation of the flame. High pressure hydrogen is supplied to the reservoir from 20 MPa standard bottles after compression up to 90 MPa.

The pressure is measured on the head of the bottle (figure 1) using a piezoresistive sensor (FGP, 0-1000 bar, 0-1000 Hz). The temperature is measured with K-thermocouples inside the bottle and just upstream of the orifice. The reservoir is installed on a numerical weighing device (+/- 10 g) to deduce directly the mass flow rate.

On the jet axis, 10 C-type thermocouples are aligned (2 mm bead diameter, response time 2 s: figure 2) and, on a line forming a 45° angle with the jet axis, 5 fluxmeters are installed (CAPTEC: sensing element of 20 × 20 mm, view angle 180°, response time 100 ms : figure 3).



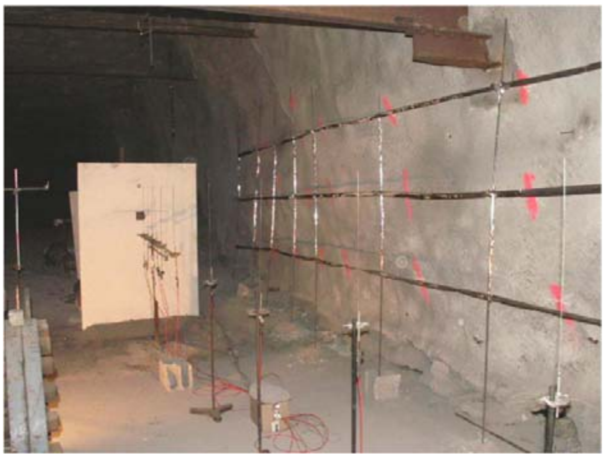


Figure 2 thermocouple arrangement

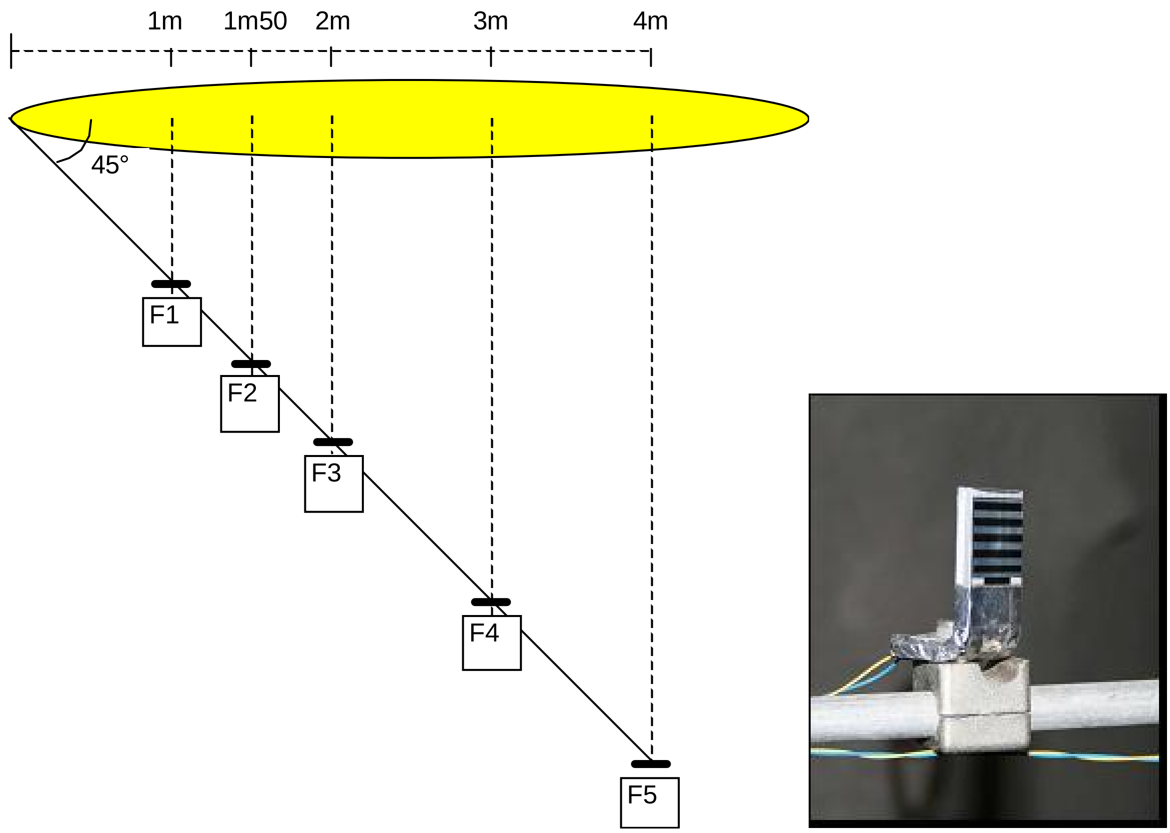


Figure 3: fluxmeter arrangement

A video camera is installed within the gallery at about 5 m from the jet centreline so as to visualise the flame (Sony HVR, 25 pictures/s).

Flow rate

Typical blow down curves are presented in figure 4 (pressure in the reservoir and temperature just upstream of the orifice) for the discharge of 90 MPa of hydrogen through a 2 mm orifice. The initial temperature peak is attributed to the compression of the little air column between the valve and the orifice. After, the temperature decreases with the pressure as expected down to typically -40°C. If the expansion of the gas were adiabatic and the gas ideal, a much larger temperature decrease would have been observed (down to -200°C). It follows that neither is the discharge adiabatic nor the gas ideal. Apart from the peak, temperatures in the reservoir and just upstream of the orifice are similar.

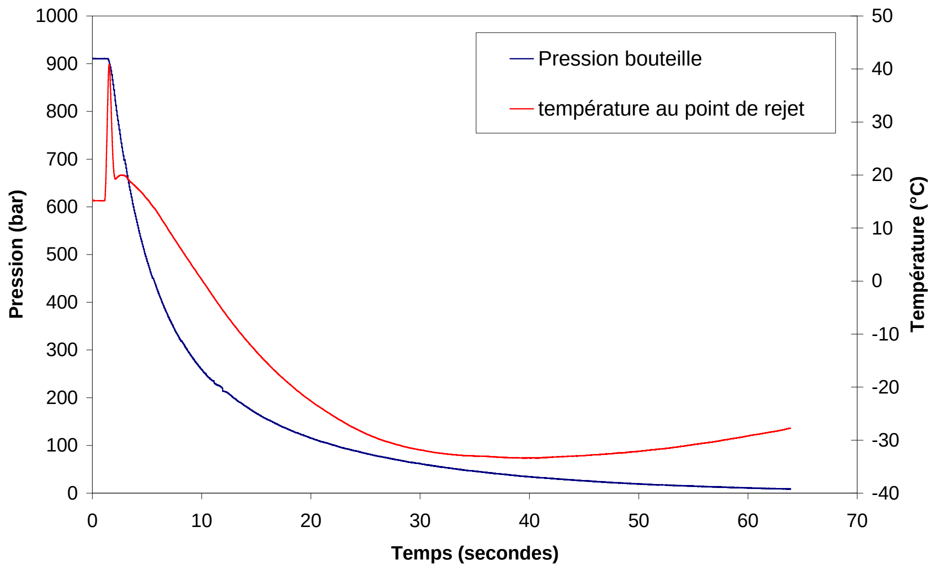


Figure 4 : Pressure (blue) in the reservoir and temperature (red) just upstream of the orifice (blow down 900bar/2mm)

The evolution of the mass flow rate as function of the pressure in the reservoir and size of the orifice is shown on figure 5. If hydrogen would behave as a perfect gas, the curves would have been close to linear.

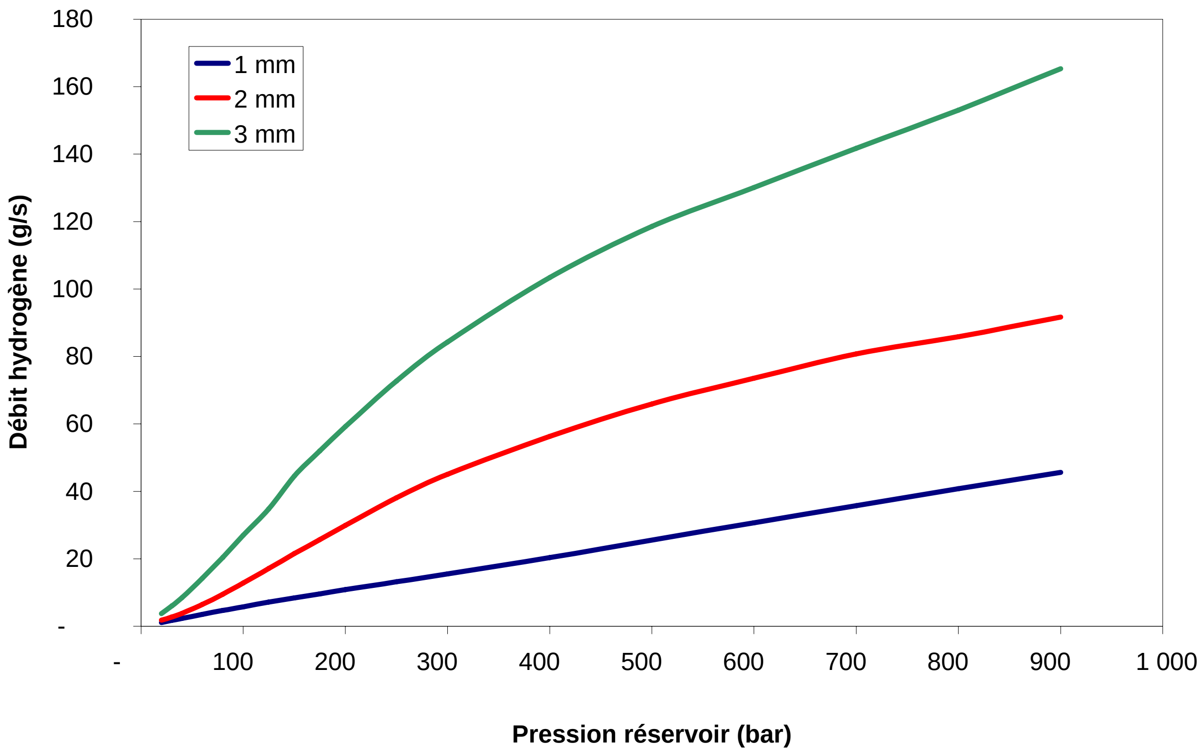


Figure 5 : mass flow rate as function the pressure in the reservoir for the 3 orifices

Since the volume of the reservoir is known and the mass of hydrogen is measured during the blow down, it is possible to derive the specific mass of the gas and associate this parameter to the instantaneous values of the measured temperature and pressure in the reservoir (table 1). As an example the estimated value of the specific mass is compared to the predicted one obtained using the perfect gas law (with the measured temperature and pressure in the reservoir) on figure 6. As soon as the pressure is above 20 MPa, hydrogen may not be considered as a perfect gas and the discrepancy is commensurate above 60 MPa.

1mm				2mm			3mm		
pression	température	masse volumique (Kg/m3)		température	masse volumique (Kg/m3)		température	masse volumique (Kg/m3)	
		mesure	gaz parfait		mesure	gaz parfait		mesure	gaz parfait
900	42	42	70	42	40	70	46	42	69
800	40	40	62	40	37	62	44	39	61
700	36	37	55	38	35	55	42	37	54
600	27	34	49	34	32	48	39	34	46
500	15	31	42	27	29	41	35	31	40
400	-2	27	36	15	26	34	28	28	32
300	-18	23	29	-4	21	27	15	23	26
250	-25	20	25	-20	18	24	4	21	22
200	-31	17	20	-39	15	21	-11	17	19
175	-34	15	18	-47	13	19	-20	15	17
150	-37	13	16	-54	11	17	-30	14	15
125	-38	11	13	-58	9	14	-47	11	13
100	-39	9	10	-62	7	12	-61	9	12
80	-39	8	8	-64	6	9	-70	7	10
60	-37	6	6	-64	4	7	-77	5	7
40	-34	4	4	-62	3	5	-80	3	5
30	-32	3	3	-60	2	3	-78	3	4
20	-28	2	2	-56	2	2	-76	2	2

Table 1 : specific mass, temperature and pressure in the reservoir during blow down (an estimation of the specific mass using the perfect gas law is also presented)

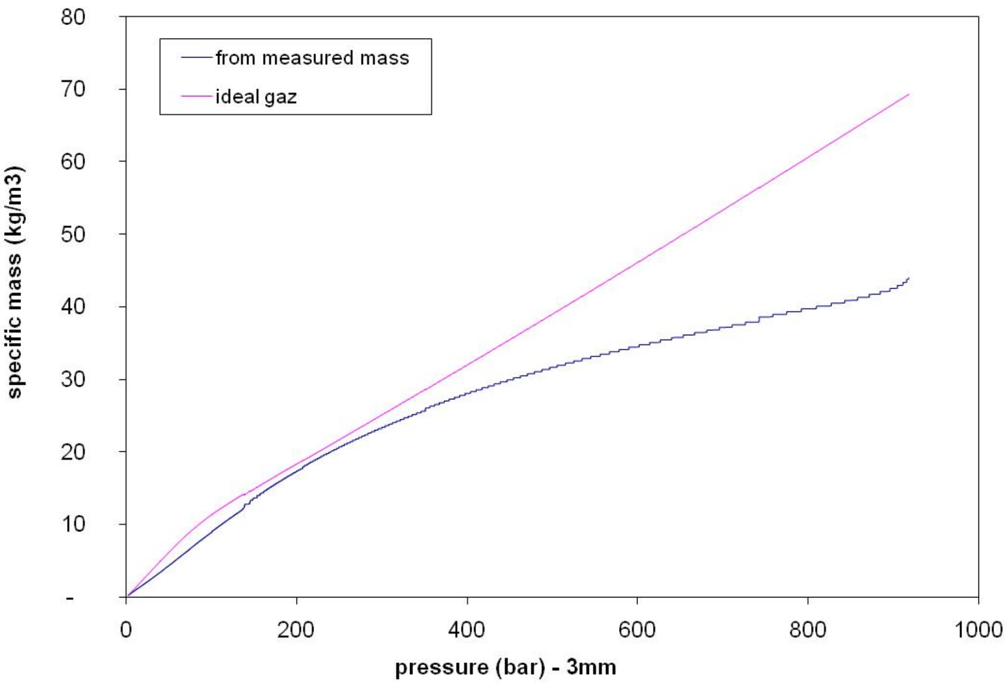


Figure 6 : measured specific mass during blow down compared to the predicted value using the perfect gas law (with the measured temperature and pressure in the reservoir)

Flame geometry

An example of flame geometry extracted from the video records is presented on figure 7. The largest diameter (D) is closer to the extremity of the flame than from the middle of the flame length (L). The ratio L/D is 1/6 for all the flames.

Figure 7 : view extracted from the video record of the blow down through a 3 mm orifice

A video reduction technique was used to determine the flame length. The uncertainty is about +/- 20 cm. The evolutions of the flame length as function of the orifice size and pressure in the reservoir are shown on figure 8. It never exceeded 7 m and the slope of the curve is reduced above 30 MPa.

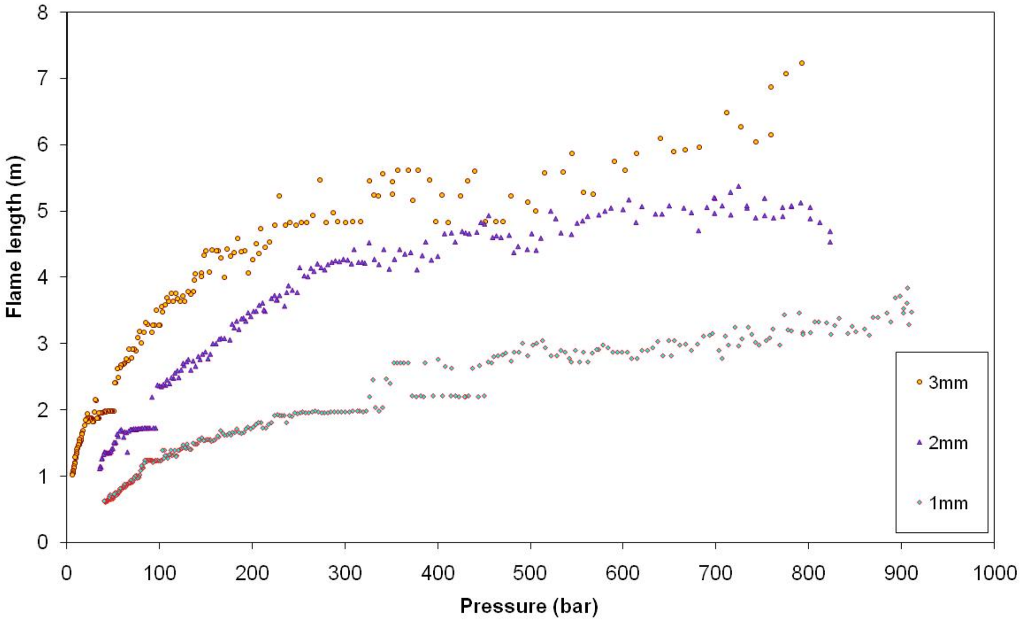


Figure 8: flame lengths as function of the pressure and size of the orifice

Thermal properties of the flame

The temperature inside the plume can be as high as 1400 °C (figure 9) and can be reached only by the thermocouple remaining long enough embedded into the flame (so the closest from the orifice). This temperature is higher than for standard hydrocarbons.

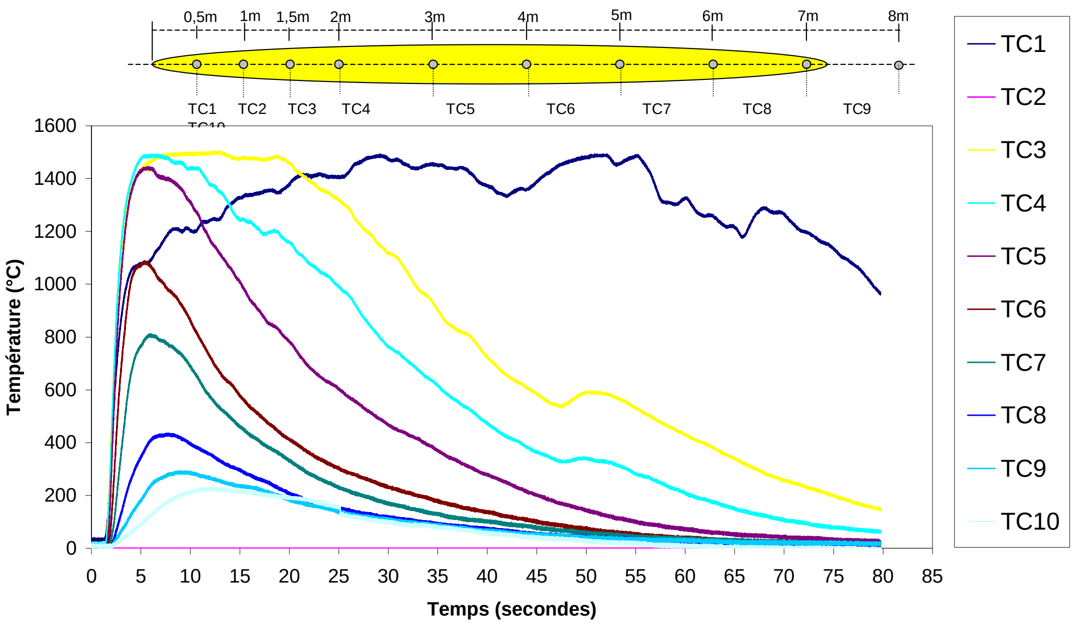


Figure 9 : temperature on the axis of the flame (orifice 3 mm)

Heat fluxes are presented on figure 10. The decrease is simply due to the reduction of the size of the flame.

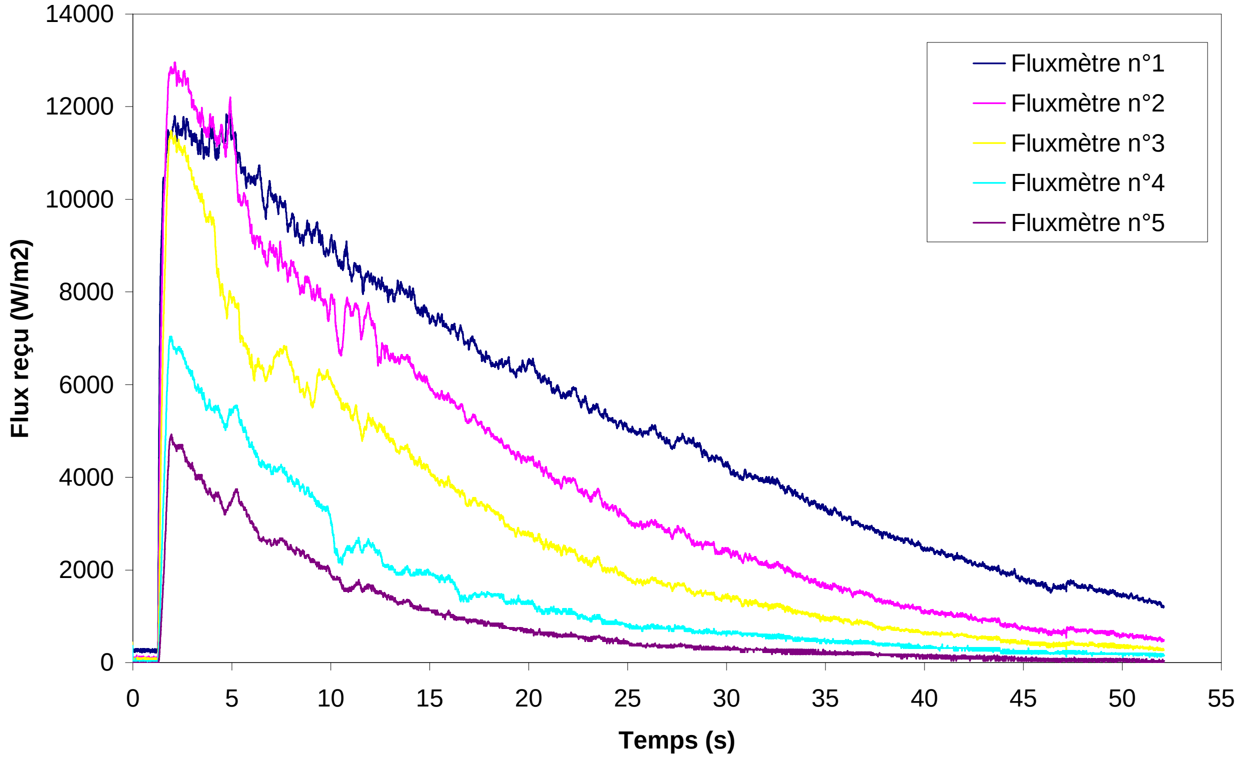


Figure 10 : Heat fluxes as function of time (900bar/2mm)

Considering the flame as a solid surface (a cylinder), it is possible to calculate the view factor for each sensor and deduce the irradiance of the flame (figure 11). The irradiance does not depend only from the geometry of the flame but also, seemingly, of the jet conditions.

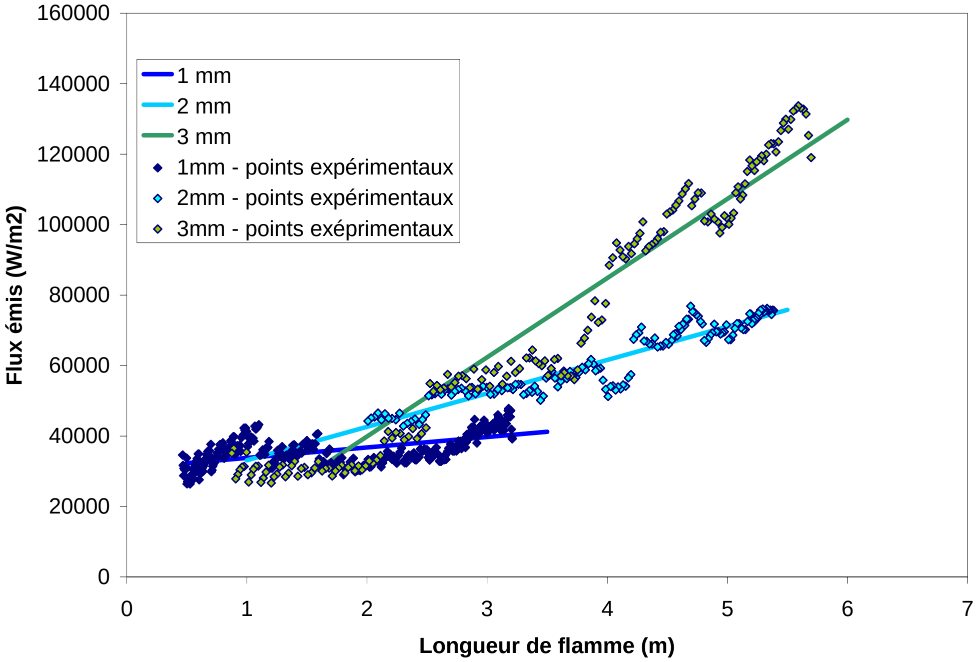


Figure 11 : irradiance of the flame as function of the length of the flame and orifice size

Finally, the radiative fraction depends on the orifice size (figure 12).

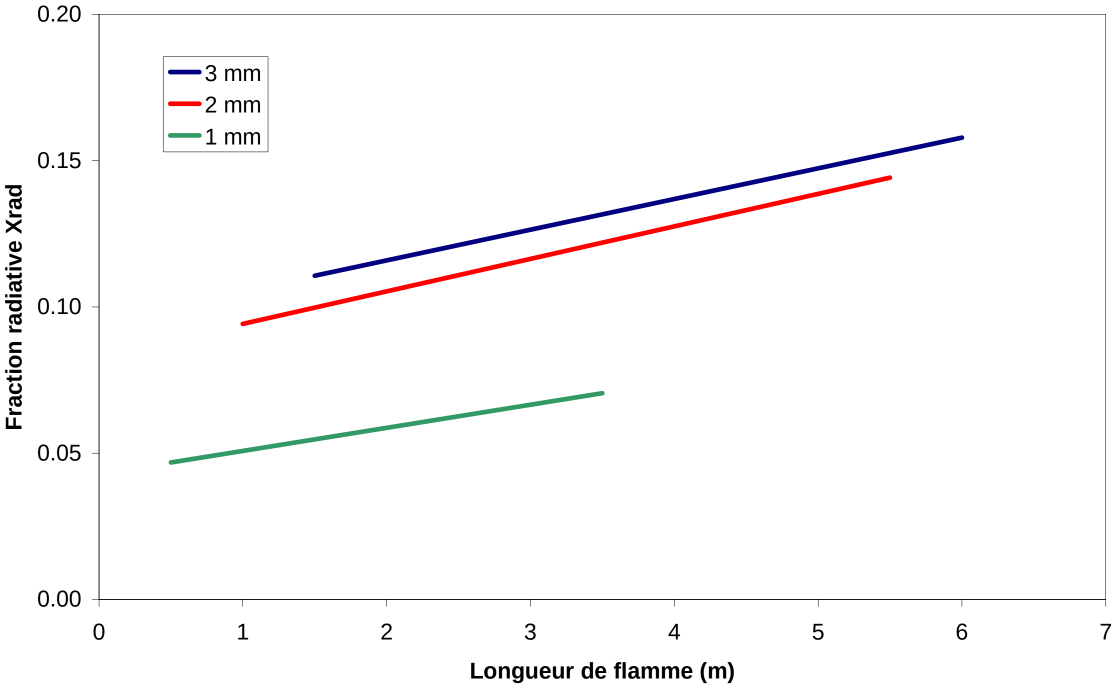


Figure 12 : radiative fractions

Discussion

About the equation of state of high pressure hydrogen the Abel Nobel equation is sometimes advocated (Shefer et al., 2007). But, in the present situation, it does not seem to work properly.

About the geometry of the flame, the ratio L/D is exactly the same than found by Shefer's team and Mori and Horiguchi. The flame lengths seem to follow correctly the correlations proposed by Chamberlain or Shefer but is not consistent with the empirical law of Mori and Horiguchi.

Radiative fraction seem in the range of the values given by Shefer but the dependency with the orifice size seems significant in the present situation.

Acknowledgments

The authors are grateful to the E.U. and the French Government to have funded this research.
Many thanks to the technicians who performed the experiments and to the colleagues of the project DRIVE and HyPER.

Literature

L. Perrette, H. Paillère, G. Joncquet, "Presentation of the French national project DRIVE: Experimental Data for the Evaluation of hydrogen Risks onboard vehicles, the Validation of numerical tools and the Edition of guidelines", SAE 2007.

Asbury G., Hawksworth S. (2007), « spontaneous ignition of hydrogen leaks : a review of postulated mechanisms » - Int. J. Hydrogen Energy - 2007

Shefer R.W., Houf W.G., Bourne B., Colton J. (2006), "Spatial and radiative properties of an open flame hydrogen plume", Int. J. of Hydrogen Energy, vol. 31, pp 1332-1340

Houf W.G., Shefer R.W., (2007), "Predicting radiative heat fluxes and flammability envelope of unintended release of hydrogen", Int. J. of Hydrogen Energy, vol. 32, pp 136-151

Shefer R.W., Houf W.G., Williams T.C., Bourne B., Colton J. (2007), "Characterisation of high pressure, underexpanded hydrogen,-jet flames", Int. J. of Hydrogen Energy, vol. 32, pp 2081-2093

Mori T., Horiguchi S. (2009), "Experimental study of the hazards of high-pressure hydrogen jet diffusion flame", J. of Loss Prev. Process Industries, vol. 22, pp 45-51

Chamberlain G.A. (1987), "Developments in design methods for predicting thermal radiation from flares", Chem. Eng. Res. Des., Vol. 65, pp. 299-309