FULL SCALE EXPERIMENTAL CAMPAIGN TO DETERMINE THE ACTUAL HEAT FLUX PRODUCED BY FIRE ON COMPOSITE STORAGES - CALIBRATION TESTS ON METALLIC VESSELS

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ABSTRACT

If Hydrogen is expected to be highly valuable, some improvements should be conducted, mainly regarding the storage safety. To prevent from high pressure hydrogen composite tanks bursting, the comprehension of the thermo-mechanics phenomena in the case of fire should be improved. To understand the kinetic of strength loss, the heat flux produced by fire of various intensities should be assessed. This is the objective of this real scale experimental campaign, which will allow studying in future works, the strength loss of composite high-pressure vessels in similar fire conditions to the ones determined in this study. Fire calibration tests were performed on metallic cylinder vessels. These tests with metallic cylinders are critical in the characterization of the thermal load of various fire sources (pool fire, propane gas fire, hydrogen gas fire) so as to evaluate differences related to different thermal load. Radiant panels were also used as thermal source for reference of pure radiation heat transfer. The retained thermal load might be representative of accidental situations in worst case scenarios, and relevant for a standardized testing protocol. The tests performed show that hydrogen gas fires and heptane pool fire allow reaching the target in terms of absorbed energy, regarding the results of risk analysis performed previously. Other considerations can be taken into account that will led to retain an hydrogen gas fire for further works. Firstly, hydrogen gas fire is the more realistic scenario: Hydrogen is the combustible that we every time find near an hydrogen storage. Secondly, as one of the objectives of the project is to make recommendations for standardization issues, it's important to note that gas fires are not too complex to calibrate, control and reproduce. Finally, due to previous considerations, Hydrogen gas fire will be retained for thermal load of composite cylinders in future works.

1.0 INTRODUCTION

1.1 Context

In the context of global warming, research regarding new energy carriers (NEC) is currently active. Among the different topic of NEC, Hydrogen is expected to be highly valuable energy carrier for the 21st century as it should participate in answering main societal and economical concerns. To capitalize on its benefits at large scale, further researches and technological developments are required. Mainly, the storage of hydrogen must be secured. Even if burst in service of pressure vessels in composite material is very unlikely, when exposed to a fire, they present safety challenges imposing to correctly design their means of protection.

The present study is part of a project whose main objective is to better characterize the conditions that are required to prevent from bursting. Following this objective, experimental work is done in order to improve the understanding of heat transfer mechanisms and the loss of strength of composite high-pressure vessels in fire conditions. The thermo-mechanical behaviour modeling of these vessels will then be possible.

In this context, the objectives of the experimental campaign are the following:

- define the best conditions to ensure reliability, reproducibility and safety of the tests,
- check that the tests performed at large scale in laboratory are representative of real fire scenarii and worst case scenarii,
- check the influence of hydrogen release through the wall in case of leakage of H_2 during fire,
- develop and validate the model of thermo mechanical behaviour of a storage in fire,
- optimize the hydrogen release strategy using the cylinder model developed in the project,
- make recommendation for cylinder design to reduce the risk of burst.

The present study deals with the two first items. It corresponds to an experimental campaign, performed on steel cylinders. It allows us to define the parameters of the test to be set-up for composite cylinders in further works. Different applications are to be considered: automotive application, stationary application, transportable cylinders, bundles and tube trailers. A risk analysis has been achieved for each application leading to the definition of optimized safety strategies. The scenarios taken into account in this study are only linked to thermal load of non degraded metallic vessels. It means that were not studied:

- scenarios of thermal load , concomitant with mechanical load,
- scenarios of localized jet fires, where the momentum of gas is very important.

1.2 Objectives and methodology

The objective is to determine one or more fire conditions to test the thermo-mechanical behaviour of real composite vessels. Those conditions have to be representative of accidental situations and represent worst case scenarii with regard to the suspected fire vulnerability of the reservoir. They also need to be instrumented and operated in such a way that valuable comparison with the modeling effort is optimized. A further perspective is to be able to adapt the testing protocol so that new standard testing procedures could be proposed. The following progression was performed:

- Selection of critical fire scenarii with regards to the risk analysis and knowing the reservoir vulnerability.
- Theoretical design of testing conditions thought to cover and represent reasonably the above mentioned critical fire scenarii. The fire protocol (fuel, shield, size...) need to be defined but also the instrumentation judged critical to characterize the fire/reservoir interaction.
- Building the experimental setups and preliminary testing of the performances (attainment of the target flux, duration, temperatures…) using non pressurized tanks. These preliminary tests were performed using a steel cylinder (similar in size to the composite cylinder) in order to calibrate the heat load measurement method and study the reproducibility of the fire. The main advantages of using metallic vessels in this part of the research are that there are not issues related to the thermal decomposition of the specimen and the thermal properties are well known, which up to now, is not the case for composite vessels.

2.0 GENERAL CONCERNS

This chapter is dedicated to the design of the preliminary tests matrix and the presentation of the experimental set up. The methodology that was followed so as to classify the scenarios is also presented.

2.1 Input from risk analysis

The risk analysis performed led to a selection of representative scenarios. Regarding the impact of the scenario on the vessel integrity, and its occurrence probability, an analysis was performed, in order to classify these scenarios. This analysis highlights the fact that all type of combustible can lead to a critical scenario, with a high level of risk. In order to retain the designing thermal load, a classification by thermal load level should be performed.

The experimental approach developed in the following chapter will help meet this aim. The risk analysis performed, helps in determining the primary characteristics that the tests to be performed should have. So, in order to have representative bonfire tests with regards to the fires that the hydrogen systems may be exposed to in accidents, the recommendations made are:

- *"A liquid source of fire generating a heat flux in the surface of the cylinder of 125 kW.m^{-2} should be studied. This fuel covers the majority of fuels considered in the fire scenarios.*
- *A gas fire generating a heat flux in the surface of the cylinder of 280 kW.m^{-2} should be studied.*
- *The fire should be well ventilated. This allows maximizing the power of fire for a given fuel.*
- *The passive barriers such as metallic shields should not be used for the bonfire tests.*
- *The filling piping and the wires of thermocouples in the fire zone should be thermally insulated during test in order to avoid damages.*
- *The ventilation around the vessel should be controlled in order to produce engulfing fire i.e. homogeneous thermal load in the entire surface.*
- *A proper measurement of temperature and heat flux should be done in order to assess the performance to fire of the cylinders."*

As for the value of 280 kW.m^{-2} it has to be noted that it was evaluated considering a flow speed of jet fire around 200 m.s^{-1} at the impact location, which induces momentum higher than the scope of the present study, as mentioned in chapter 1.1. Thereby, regardless of the type of combustible involved, the target incident heat flux to be applied on the external surface of the vessel is 125 kW.m^{-2}.

2.2 Methodology of classification of thermal load

The methodology developed has two main purposes:

- classify by the intensity the different thermal load that will be performed,
- translate a complex thermal load composed of convection conduction and radiation into a simple incident radiative heat flux.

The first issue will help to highlight the designing scenario that will be applied to the composite vessels. The second point will be useful for modeling purpose, knowing that the input data of thermal numerical tool developed in the project is an incident heat flux. To do so, it has been decided to expose the metallic specimen to a pure and calibrated radiation load at different levels as described in chapter 3.1, and to measure the temperature evolution inside the sample. This will lead to series of curve of temperature evolution along time as a function of the incident radiation heat flux. It will then be possible to superimpose to these curves, the evolution of temperature reached during real fire.

As composite material burns, this approach cannot be applied to composite vessels, as it is not possible to dissociate the heat flux due to external thermal load from the heat flux due to composite ignition. This is the reason why steel cylinders described in chapter 2.4.1, with dimensions representative of those of composite vessels, are used during this preliminary test campaign.

2.3 Test matrix

Regarding previous considerations, and results of the risk analysis performed, a preliminary test matrix has been built. It allows studying the behaviour of steel cylinder in various configurations of thermal load, to classify them, and to supply data to apply the “translation” methodology presented previously. The green lines in this table are the reference tests for each sort of thermal load. Yellow boxes highlight the parameters that change regarding the reference case. For radiative tests, F1 to F5 correspond to five levels of emitted heat fluxes. For gas fires, Q1 and Q2 represent two levels of fire energy. This experimental matrix is detailed in Table 1.

Table 1. Preliminary tests matrix with metallic vessel specimen.

No	Sample		Fire condition		
	Volume [L]	Position	Fire source	Distance heat source/cylinder [mm]	impacted surface [%]
1a	36	Horizontal	Radiation F1	300	100
1b	36	Horizontal	Radiation F2	300	100
1c	36	Horizontal	Radiation F3	300	100
1d	36	Horizontal	Radiation F4	300	100
1e	36	Horizontal	Radiation F5	300	100
2	36	Horizontal	Heptane	100	100
3	36	Horizontal	Heptane	600	100
4	36	Horizontal	Radiation	300	100 (soot from 3)
5	36	Horizontal	Heptane	600	50
6	36	Vertical	Heptane	100	100
7	19	Horizontal	Heptane	100	100
8	36	Horizontal	Hydrogen Q2	/	100
9	36	Horizontal	Hydrogen Q1	/	100
10	36	Horizontal	Propane Q1	/	100
11	19	Horizontal	Hydrogen Q2	/	100
12	19	Horizontal + cover	Hydrogen Q2	/	100

2.4 Experimental setup

2.4.1 Steel mock up

As indicated in chapter 2.2, steel cylinders have been used for these preliminary tests of fire calibration. Two cylinders have been built, with representative external dimensions of 19 L and 36 L composite cylinders that will be used in further works, as shown in Figure 1.

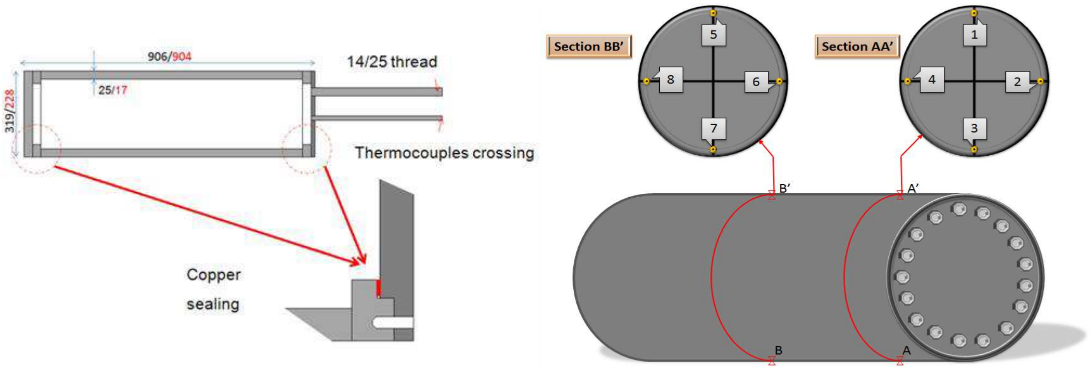

Figure 1. Steel cylinders description for calibration tests.

On this figure dimensions of the fictitious 19 L are written in red, and those of the 36 L in black. The sealing of the cylinders is ensured by copper seals, to enable pressure measurements. Weights of the cylinders are about 107 kg for the 19 L one, and 196 kg for the 36 L one. In addition to the pressure measurement, the evolution of temperature is followed using 8 internal thermocouples localized on Figure 1.

2.4.2 Test facilities

For this preliminary campaign, two facilities are used. The first one, is called 80 m^3 room. It is suitable for fire until 2 MW. This room meets perfectly the needs for the envisioned tests. Moreover, it is linked to a smoke cleaning system that enable to purify smoke before casting it away to atmosphere. When hydrogen is used as fire source, tests cannot be performed in this room anymore, and an outdoor explosion cage is used.

3.0 RADIANT PANEL TESTS

3.1 Test description

The first tests were performed with radiant panels, so as to apply a calibrated and symmetrical thermal load on steel cylinders. The two radiant panels used are composed of 36 infrared halogen lamps; their radiation emitted heat flux is a function of the electrical power input. The electrical power input is then raised from 40 to 100 % of its range. Knowing the received heat flux for each heat fluxmeter and the relative position of fluxmeters and panels, it’s possible to estimate the emitted radiative heat flux of each panel. Results obtained highlight that the two radiant panels have the same behaviour, and will allow performing a symmetric load of the cylinder from 30 to 80 kW.m^{-2}. After these calibration tests, the 36 L steel cylinder was used. As indicated previously, the radiant panels are positioned at 30 cm of the surface of the cylinder, halfway up them as shown in Figure 2.

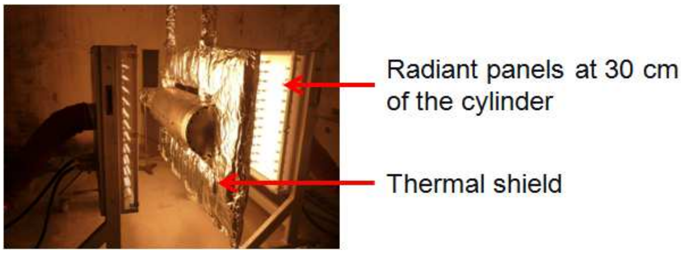

Figure 2. Experimental setup for radiative load of cylinder.

The two panels face, and are too close to each other to be used at full power without damages. A thermal shield is then put in place, in order to protect the apparatus. A 5 cm space is let between the shield and the cylinder, to prevent any disturbing on the top and bottom of the cylinder. Tests are performed with five different emitted heat fluxes, as indicated in the preliminary test matrix, reproduced on Table 2.

Table 2. Radiant panel tests.

No	**Sample**		**Fire condition**		
	Volume [L]	**Position**	**Emitted radiative heat flux [kW.m^{-2}]**	**Distance heat source / cylinder [mm]**	**impacted surface [%]**
1a	36	Horizontal	32	300	100
1b	36	Horizontal	43	300	100
1c	36	Horizontal	55	300	100
1d	36	Horizontal	66	300	100
1e	36	Horizontal	78	300	100

3.2 Results of preliminary tests

As mentioned in chapter 2.4.1, temperature and pressure evolution are considered. The numbering of internal thermocouples is presented in Figure 1. So as to illustrate the thermal behaviour of the cylinder, results are detailed for the medium heat flux, 55 kW.m^{-2}. They are presented on Figure 3.

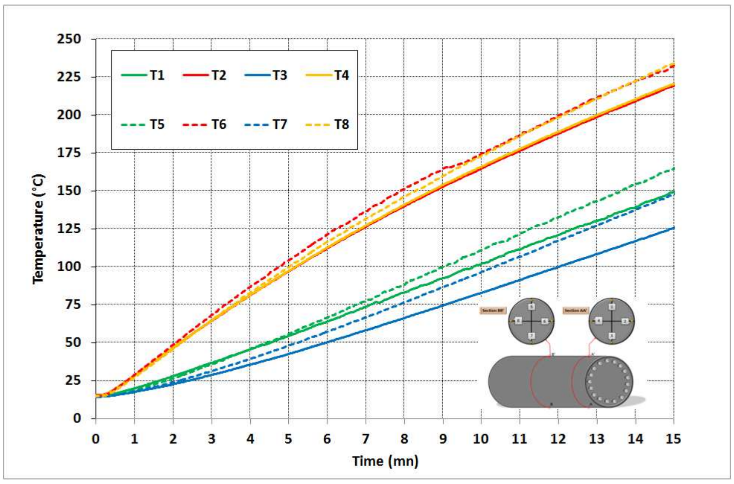

Figure 3. Evolution of temperatures inside the cylinder.

As expected, the thermal load of the cylinder is symmetric, and curves are similar on left and right sides. The temperature is also quite homogeneous along the length of the cylinder, with less than 25 °C difference between one side (section AA') and the center (section BB'). There is however a major difference, around 100 °C, between top and bottom thermocouples, and those located in the horizontal plane. This difference is due to the view factor on the received heat flux. It also appears that the temperature is lower in the bottom parts of the cylinder, than in the top. Similar observations can be made on the other load levels. To compare the behaviour of the cylinder for different scenarios, two ways of temperature evaluation can be used, following the average value of temperature given by inside thermocouples, or evaluating the temperature inside the cylinder thanks to pressure evolution and considering air as a perfect gas. The results for the different radiation loads are presented in Figure 4, with the two ways of temperature determination. In this figure, the average calculations are in full lines, and calculations through pressure are in dotted lines. The emissivity of the external skin of the steel cylinder is taken equal to 0.8. During the 78 kW.m^{-2} test, a pressure sensor malfunction occurred.

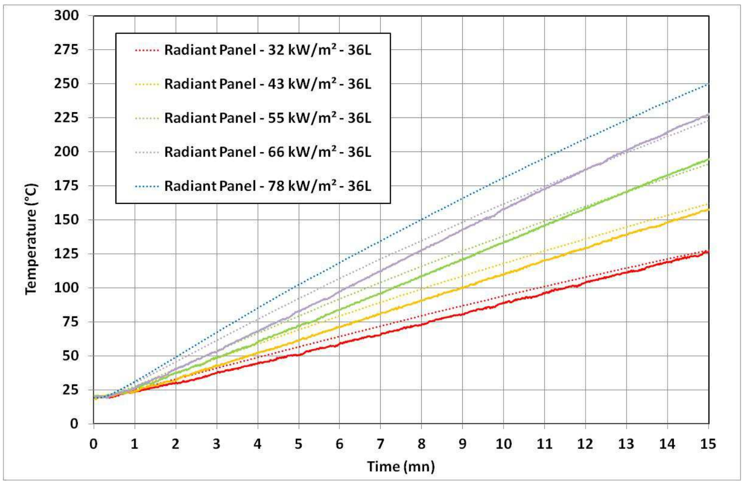

Figure 4. Evolution of temperatures in the cylinder.

It appears that in this configuration, the two ways of evaluation give equivalent results for each load level. The approach through pressure will be convenient for characterization of non engulfing scenarios that will be performed during remaining tests with pool and gas fire, involving punctual temperature measurements irrelevant.

3.3 Extrapolation of experimental results

Previous results also highlight the fact that the radiant panels used are not powerful enough to reach the temperature rising expected during real fire scenarios. As one of the objectives is to superimpose the results of real fire on radiant panel results for "translation" purpose and modeling requirements, an extrapolation of these data has to be achieved. An analytical model has been developed to compute the evolution of temperature inside the cylinder, considering that the radiant panels are fictitiously able to reach greater levels of emitted radiative heat fluxes.

Parameters taken into account into this model are the dimensions of the radiant panels, the dimensions of the cylinder, the evolution of physical characteristics of steel with temperature and the relative positions of radiant panels and cylinder. The comparison of the model with the results of the radiant panel tests is presented in Figure 5. The error obtained is less than 5 °C and remain acceptable.

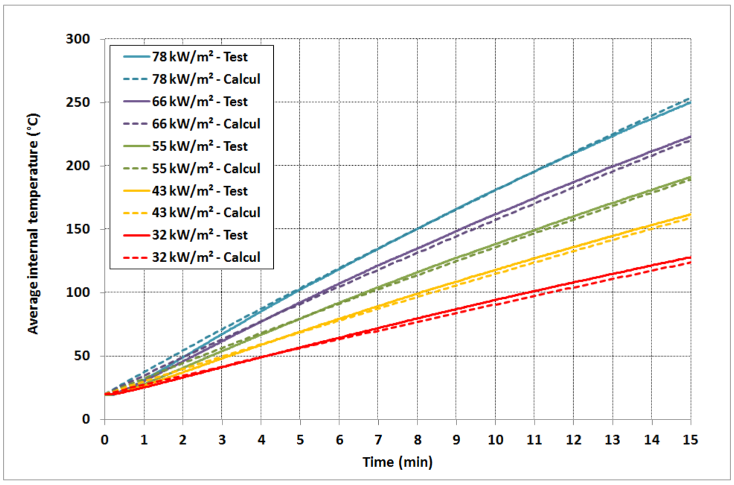

Figure 5. Comparison of experimental results of radiative tests with model.

Results obtained with the model up to a 160 kW.m^{-2} emitted radiative heat flux are presented in Figure 6. In each case, the initial temperature is assumed to be at 20 °C. Regarding the view factor between the radiant panels and the cylinder, the target of 160 kW.m^{-2} for the emission leads to a received heat flux of 125 kW.m^{-2} on the external skin of the 36 L cylinder, which is the representative heat flux define in chapter 2.1.

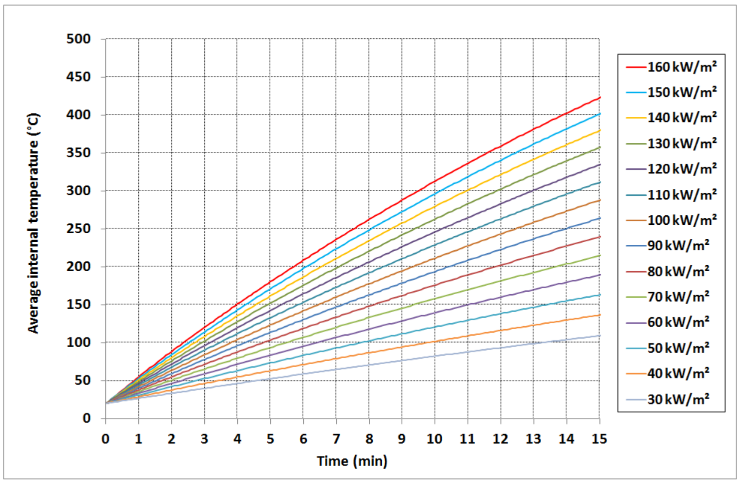

Figure 6. Extrapolation of experimental results of radiative tests.

4.0 REAL FIRE TESTS

This chapter is dedicated to the study of the behaviour of the steel cylinders exposed to real pool and gas fire, in various configurations, as describe in preliminary test matrix presented in Table 1.

4.1 Pool fires

4.1.1 Configurations tested

The different pool fires performed are detailed in Table 3, extracted from preliminary tests matrix. Excepted for scenario 4, the cylinder is cleaned before performing the tests.

Table 3. Pool fire tests.

No	Sample		Fire condition		
	Volume [L]	Position	Fire source	Distance between heat source and cylinder [mm]	impacted surface [%]
2	36	Horizontal	Heptane	100	100
3	36	Horizontal	Heptane	600	100
4	36	Horizontal	Radiation 78 kW.m^{-2} (soot from 3)	300	100
5	36	Horizontal	Heptane	600	50
6	36	Vertical	Heptane	100	100
7	19	Horizontal	Heptane	100	100

In this table, scenario number 2 corresponds to the configuration actually recommended in standards dedicated to characterization of vessels fire resistance (such EN NF 12 245). Scenario number 4 performed with radiant panels is detailed in chapter 3.1. Two types of pan are used during the poll fire tests. The first one used for scenarios 2, 3 and 7 has a 1 m² surface. The pan used for scenarios 5 and 6 has a 0,5 m² surface.

4.1.2 Results of tests

The first observations performed during the tests are that the flame is strongly impacted by ventilation, and that it is hard to maintain an engulfing fire. Considering the value of 45 MJ.kg^{-1} for the heat of combustion of heptane, the Table 4 indicates the theoretical heat release rate obtains for each scenario.

Table 4. Pool fire heat release rates obtained.

No	Distance between heat source and cylinder [mm]	Pool surface [m²]	Heptane mass [kg]	Time of fire [s]	Combustion rate [g.m^{-2}.s^{-1}]	Heat release rate	
						Normalised by pan surface [MW.m^{-2}]	Total [MW]
2	100	1	29,6	660	45	**2.0**	**2.0**
3	600	1	56,3	940	60	**2.7**	**2.7**
5	600	0.5	28,7	890	64	**2.9**	**1.5**
6	100	0.5	28,9	1275	45	**2.0**	**1.0**
7	100	1	30	620	48	**2.2**	**2.2**

It appears that the most impacting parameter is the intrusion of the cylinder in the flame area, which induces perturbation on combustion phenomenon. The power of the fire increases of nearly 1 MW when the cylinder is far away from the pool fire. This does not mean that the fire performs a better engulfment of the cylinder, but that the combustion is better achieved. The evolution of internal temperature during the different tests performed is presented in Figure 7. It is remembered that the temperature is calculated with the increase of pressure.

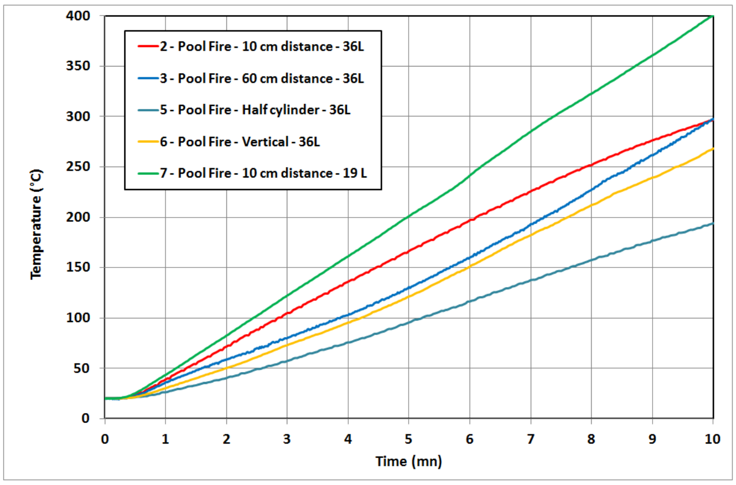

Figure 7. Evolution of temperature during pool fire tests.

The maximal temperature reached regarding the power of the fire helps to determine the efficiency of heating of each configuration. After 10 min, and considering the scenario 2 (red curve) as a reference, it appears that the orientation and the distance of the cylinder to the pool have a quite medium influence, with a temperature below the reference temperature lower than 40 °C. Reducing the impacted surface has on the other hand a huge influence on the energy absorbed by the cylinder, and after 10 min, the temperature is 100 °C below reference. The scale effect is also important, with a 100 °C difference between 19 L and 36 L cylinders, due certainly to a better engulfment of the fire for the smaller cylinder, and a quicker response time due to lower mass of steel to heat up. The best efficiencies are obtained when the cylinder is close to the fuel pan, even if the heat release rate of the fire is lower. So as to characterize the influence of the soot deposit on the thermal behaviour of the cylinder, a radiant panel test is performed on the cylinder after the scenario 3, without cleaning or touching it, but after its natural cooling. With the same experimental setup described in chapter 3.1, the cylinder is exposed to a 78 kW.m^{-2} emitted heat flux. As highlighted in the risk analysis, the soot deposit tends to modify the emissivity of the external skin of the cylinder. After 15 min of test, the difference of 40°C (from 170 °C without soot to 210 °C with soot) observed corresponds to an increase of 0.1 of emissivity. It cannot be excluded that for longer fire, or fire generating more soot, an insulating behaviour of the soot deposit appears, and led to a lower impact of the fire.

4.2 Gas fires

4.2.1 Configurations tested

The different gas fires performed are detailed in Table 5, extracted from preliminary tests matrix.

Table 5. Gas fire tests.

No	Sample		Fire condition		
	Volume [L]	Position	Fire source	Distance heat stress/cylinder [mm]	impacted surface [%]
8	36	Horizontal	Hydrogen Q2	/	100
9	36	Horizontal	Hydrogen Q1	/	100
10	36	Horizontal	Propane Q1	/	100
11	19	Horizontal	Hydrogen Q2	/	100
12	19	Horizontal + cover	Hydrogen Q2	/	100

As mentioned previously, jet fires with a localized impact are out of the present scope, as the mechanical aspect can be majorant regarding the thermal load of the scenario. In the previous table, Q1 and Q2 represent the amount energy developed by the gas fire. It means that energies released during scenario 9 and 10 are equivalent. As for hydrogen, the following data has to be considered: D1 = 2.5 g.s^{-1}, D2 = 6 g.s^{-1} for mass flow rates and ΔHc = 140 MJ.kg^{-1} for the heat of combustion. As for propane gas fire, the following data has to be considered: D1 = 7 g.s^{-1} and ΔHc = 50 MJ.kg^{-1}. Some preliminary tests were performed with only the video, so as to determine visually the best position of the injectors regarding the engulfment of the cylinder. The "cover" mentioned in scenario 12 corresponds to some protections put above the cylinder to maintain as much energy as possible around the cylinder.

4.2.2 Results of tests

Even if the momentum of gas fire is lower than those that could be obtained with jet fire, it remains higher than with a pool fire, implying that the flame is less impacted by ventilation than with pool fire. Figure 8 presents some pictures taken during the tests.

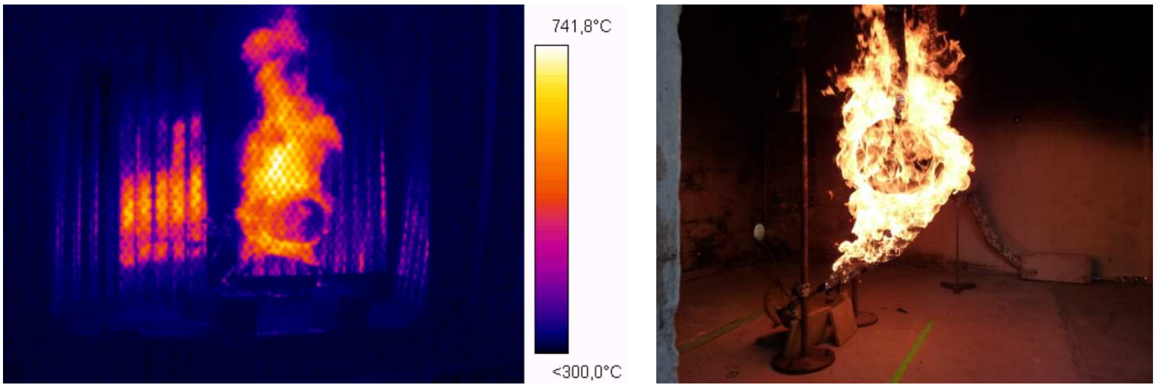

Figure 8. Thermal picture of hydrogen (left) and propane (right) gas fires.

The evolution of internal temperature during the different tests performed is presented in Figure 9.

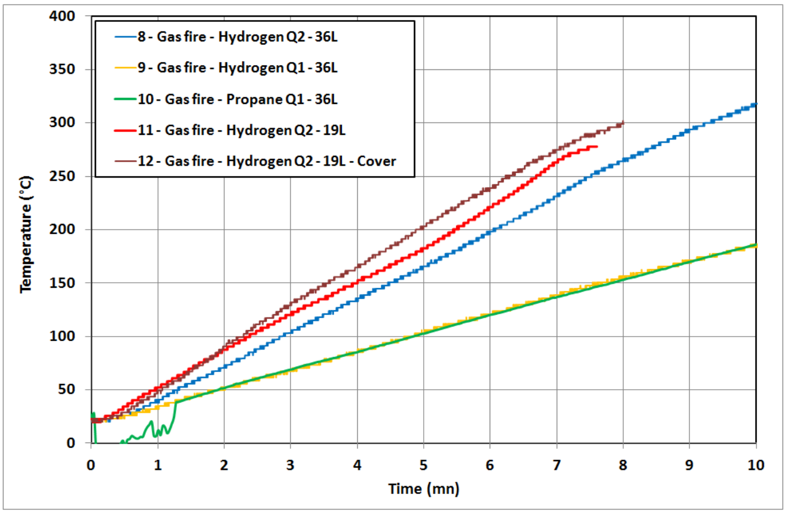

Figure 9. Evolution of temperature during gas fire tests (calculated by the increase of pressure).

The maximal temperature obtained regarding the heat release rate of the fire helps to determine the efficiency of heating of each configuration, as detailed in Table 6. In this table, scenario 8 is considered as the reference scenario. As some tests have not been performed till 10 min, the comparison is done at an earlier time than for pool fire. The impact is low regarding the linearity of the curves.

Table 6. Gas fire power obtained.

No	Number of injectors	Total mass flow rate [g.s^{-1}]	Gas fire heat release rate [kW]	Temperature after 5 min [°C]
8	4	6.0	840	160
9	4	2.5	350	100
10	2	7.0	350	100
11	4	6.0	840	175
12	4	6.0	840	200

Even if the heating efficiency is better with lower gas fire heat release rate, a strong influence of the flow rate of combustible is observed with a difference of nearly 250 °C after 10 min of fire. It also appears that the vessel size has a lower influence on the temperature increase than with pool fire. In the tested conditions, for the same amount of energy provided, evolution of temperature is similar with propane and hydrogen. The cover seems also to improve the energy transmitted to the cylinder.

4.3 Comparison and classifications of thermal load

In this chapter, results for 36 L cylinder and 19 L cylinder are dissociated, so as to allow comparison of thermal load, regardless the impact of heated surface. Concerning the 36 L cylinder, the comparison is done between the majorant scenarios from pool and gas fire tests. The Figure 10 superimposes results of scenarios 2 and 8, to results obtained with the radiant panel tests and their extrapolation.

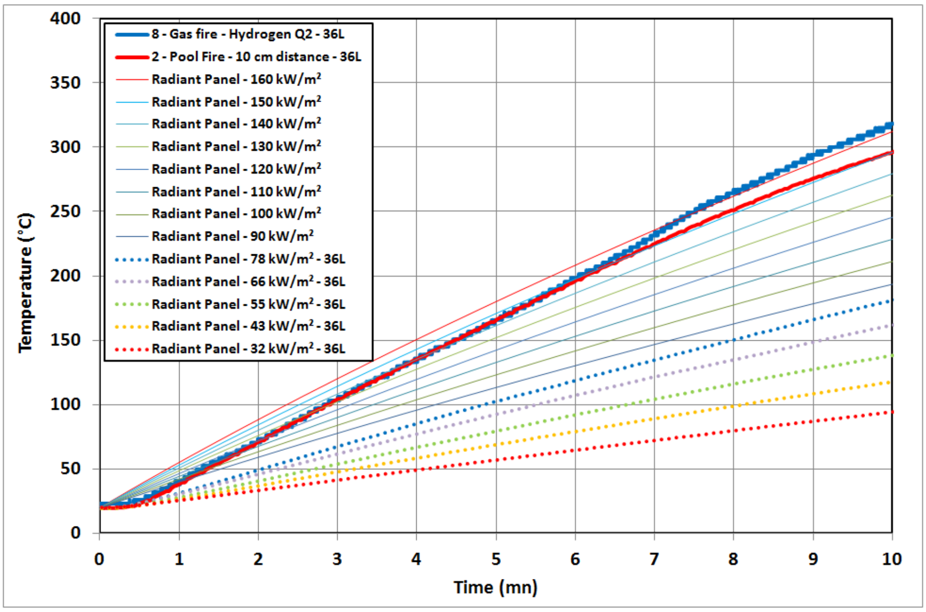

Figure 10. Results for 36 L cylinder.

It appears that even if the amount of energy developed by the fire is lower for the gas fire (0.84 MW) than for the pool fire (2 MW) performed during this experimental campaign, the quantity of energy absorbed by the cylinder is nearly the same in the two configurations. The superimposition also highlights the facts that in these two configurations, the thermal response of the cylinder can be considered equivalent as if the thermal load was performed with the radiant panels set up of chapter 3.1, with a radiation emitted heat flux between 150 and 160 kW.m^{-2}, which is the target proposed on chapter 2.1. Concerning the 19 L cylinder, the comparison is done between the designing scenarios from pool and gas fire tests. As the analytical model has not been validated with experimental results from radiant panels with 19 L cylinder, the superimposition of curves is not relevant. The Figure 11 only superimposes results of scenarios 7, 11 and 12.

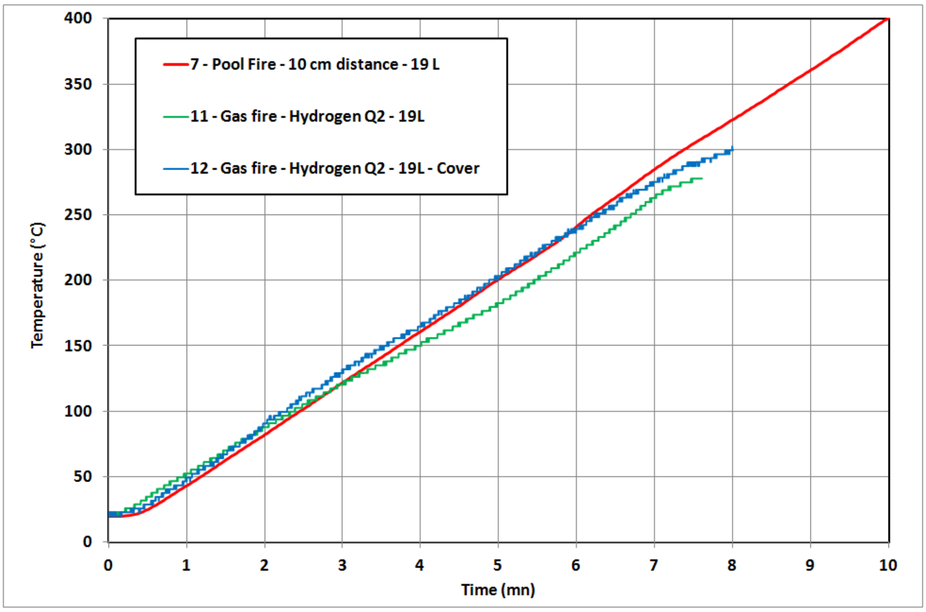

Figure 11. Results for 19 L cylinder.

In the same way than for the 36 L cylinder it appears that even if the amount of energy developed by the fire is lower for the gas fires (0.84 MW) than for the pool fire (2.2 MW) performed during this experimental campaign, the quantity of energy absorbed by the cylinder is nearly the same in the three cases. Nevertheless, even if the evolution of temperature is quite similar for these three scenarios, it can be noted that the use of a cover allow gas fire to be equivalent to pool fire performed. Finally, for 19 L and 36 L cylinders, in the conditions tested, the amount of energy provided by an hydrogen gas fire is at least equivalent to pool bonfires performed during this experimental campaign.

5.0 CONCLUSIONS

The tests performed show that hydrogen gas fires and heptane pool fire allow reaching the target in terms of absorbed energy, regarding the results of risk analysis performed previously. Therefore, the designing aspect of the scenario is not sufficient to decide what type of thermal load is the more relevant for the tests that will be performed on composite cylinders during further works. Other considerations can be taken into account that will led to retain an hydrogen gas fire for further works. Firstly, hydrogen gas fire is the more realistic scenario: Hydrogen is the combustible that we every time find near an hydrogen storage … Secondly, as one of the objective of the project is to make recommendations for standardization issues, it’s important to note that gas fires are not too complex to calibrate, control and reproduce. Finally, due to previous considerations, Hydrogen gas fire will be retained for thermal load of composite cylinders in future works, with the following characteristics:

- Use of 4 injectors, with at least 1.5 $g.s^{-1}$ flow rate per injector.
- Use of confinement so as to increase the energy received by the cylinder.

At the beginning of this further work, an optimization work has to be performed on the experimental setup so as to improve the confinement of the cylinder and the fire and the needed hydrogen flow rate. This optimization will lead to ensure the good repartition of energy around the vessel, and to ensure the majorant aspect of the scenario throughout the duration of the test.