Domino effects : thermal impact of jet fires on industrial pipes

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DOMINO EFFECTS: THERMAL IMPACT OF JET FIRES ON INDUSTRIAL PIPES

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Due to accidental thermal attacks, industrial plants can be damaged or more seriously become themselves the centre of major accidents (domino effects). At the origin of these attacks, it is advisable to mention the "classical" fires such as pool fires, jet fires, but also more exceptional phenomena which generate fire balls with an intense radiation as BLEVE or Boil-Over.
Therefore, as part of hazard surveys and more particularly survey of domino effects, some questions are asked about, for example:

- the relevance to consider the explosion of such or such tank as a result of the contribution of heat since a close fire considered besides,
- or again the quantitative earnings expected by the implementation of materials of heat insulation or the implementation of means of cooling.

Now it concerns typical structures as pipes or tanks, there are not or few tools which are enough fine to answer the previous asked questions and at the same time there is not enough quick implementation to be compatible with the deadline constraints of usual studies.

Thus a research programme focuses on the thermal impact of different fires on industrial pipes and tanks. Its objective is to develop, to validate and to produce one or several tools of calculation satisfying needs mentioned above in order to approach in a most realistic possible way the thermal impact of fires on equipment such as the industrial pipes and tanks.

This paper presents an experimental campaign aiming to the analysis of the heat transfers being exerted on a pipe submitted at a fire jet. Thus, an experimental apparatus was set up making it possible to determine on the one hand, precisely the characteristics of jet fire and on the other hand, the thermal response of the pipe crossed by water.

To characterise jet fire, measurements of gas temperatures, gas velocities and heat fluxes are realised for three gases that are the methane, propane and ethylene and for various gas release rates. Additionally, test monitoring has also been done, making use of both infrared camera and conventional video camera. These measurements make it possible to define dimensions of jet fires, its surface emissive power as well as the hot gas velocities for then deducing from them the heat transfers received by the pipe. In the second time, the pipe crossed by water is subjected to these various jet fires and the thermal response of pipe is quantified by monitoring the pipe with thermocouples.
The experimental apparatus makes it possible to vary various parameters such as:

- the presence or not of an heat insulator like rockwool,
- the thermal attack (various gases and heat release rates),
- the flow velocity in the pipe going from 0,1 to 1 m/s.

This test campaign aims to validate the physical models concerning the thermal response of a structure to a thermal attack and to quantify the influence of the hot soots conduction in the heat transfers by testing jet fires of gas producing soots more or less.

KEYWORDS: domino effects, jet fire impingement, experiment, radiation, soot concentration

INTRODUCTION

Due to accidental thermal attacks, industrial plants can be damaged and become themselves the centre of major accidents (domino effects). At the origin of these attacks, it is advisable to mention the "classical" fires such as pool fires, jet fires, but also more exceptional phenomena which generate fire balls with an intense radiation as BLEVE or Boil-Over.

To better characterise thermal domino effects, the French Ministry for Ecology and Sustainable Development supports INERIS for the performance of a research program named "FREDRIC". This program focuses on the thermal impact of fires on industrial pipes and tanks. Its main objective is to develop, to validate and to produce one or several tools in order to calculate the thermal response of industrial structures submitted to major fires accidents.

Within this framework, this paper presents an experimental campaign aiming to the analysis of heat transfers being exerted on a pipe impinged by a jet fire. Ultimately,

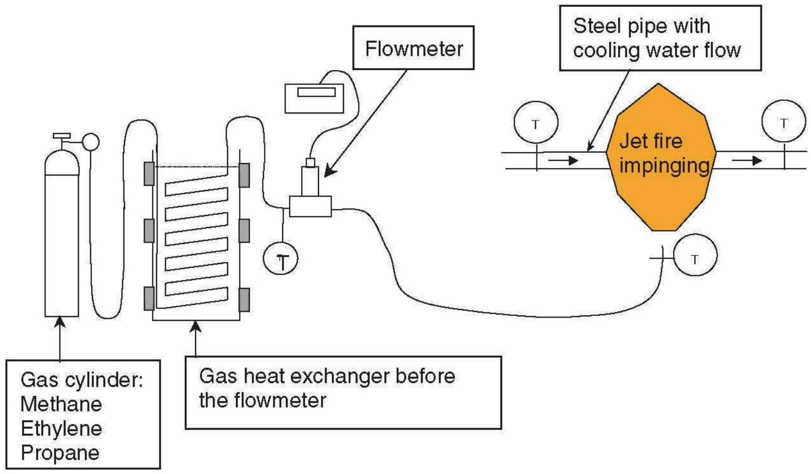

Figure 1. Sketch of the experimental apparatus

this test campaign aims to quantify the influence of the hot soot in the heat transfers by testing jet fires of gas producing soot more or less.

EXPERIMENTAL APPARATUS

A first experimental campaign consisted in determining precisely the characteristics of jet fire and a second campaign made it possible to define the thermal response of the pipe impinged by a jet fire. Figure 1 presents a sketch of the global experimental apparatus. The experimental campaigns were realised within the closed INERIS fire gallery that provides a confined medium. Thus, there is no influence of meteorological conditions such as wind.

A first experimental apparatus was set up making it possible to characterise initially the phenomenon of jet fire for three various gases chosen for their different propensity to produce soot which are methane, propane and ethylene. Figure 1 presents this apparatus which is made up of a gas cylinder and a warming device of gas to allow the flowmeter to work in its range of operation. This flowmeter is used to control the exit gas velocity (nozzle diameter d_j being unchanged during all the tests) in order to obtain a jet fire in stationary regime.

A mass flow rate and an exit temperature define the gas jet. Then, in order to characterise jet fire in term of geometry (lift off, flame length …) but also radiative power, various instruments of measurements are used such as:

- thermocouples placed in the axis of the jet fire to measure the hot gas temperatures Tg along the flame,
- an anemometric bi-directional probe being able to be moved along the axis of the flame to measure the hot gases velocity Ug,
- radiative fluxmeters located on the sides and above the flame measuring the radiative flux,
- a video camera system to measure dimensions of the flame (by visualisation).

The plan of tests is presented in Table 1 which indicates for all gases, the ranges of the gas mass flow rate $\dot{m}_f$, of the heat release rate $\dot{Q}$, of the exit gas velocity Uj, of the Reynolds number Re_s, of the Froude number Fr and the effective diameter of the jet D_s. The Froude number is often considered to define the characteristics of jet fire.

For the second experimental campaign, the steel pipe is subjected to these various jet fires and the thermal response of pipe is quantified by monitoring the pipe with thermocouples (Figure 2).

It should be noted that measurements are done on the part of the pipe directly impinged by jet fire and symmetrically on the part located in the drag of the flame. The pipe has the following characteristics: internal diameter 22 mm and external diameter 34 m, that is to say a 6 mm thickness. The installation is made of three sections of measurements, the section B located in the axis of jet fire, section A 10 cm upstream and section C 10 cm downstream. The

Table 1. Characteristics of jet fires tests

Gas	$\dot{m}_f$ (g/s)	$\dot{Q}$ (kW)	U_j (m/s)	D_s^1 (mm)	$Re_s = \frac{U_j D_s}{\nu_f}(-)$	$Fr = \frac{U_j^2}{g D_s}(-)$
Methane (CH_4) $f_s^2 = 18{,}9\%$	1,02–3,81	51–191	25–93	6,6	10000–37330	9600–134030
Propane (C_3H_8) $f_s = 17{,}6\%$	1,23–5,31	62–296	11–47	10,9	27150–117200	1130–21060
Ethylene (C_2H_4) $f_s = 17\%$	1,32–6,27	57–246	18–87	8,7	18790–89260	3970–89530

[1] D_s: Effective diameter of the gas jet such as: $D_S = d_j \sqrt{\frac{\rho_{fuel}}{\rho_{air}}}$.

[2] f_s: Fraction which represents the fuel mass fraction at which carbon particles begin to form (Beyler, 2002).

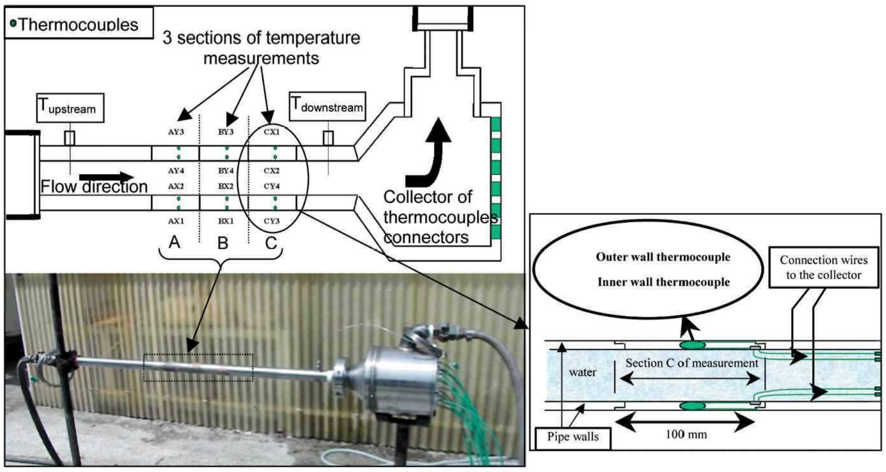

Figure 2. Sketches and picture of the steel pipe monitored with thermocouples and the collector of connectors

thermocouples directly impacted by jet fire are noted AX1, AX2, BX1, BX2, CY3 and CY4 and those in drag noted AY3, AY4, BY3, BY4, CX1 and CX2 (Figure 2). In addition, a collector was also necessary to place the whole of the connectors, and also to ensure the clearing of the extension cables towards outside (Figure 2). An internal fluid that is water at ambient temperature flows in the pipe. This water flow can be modulated until obtaining a maximum mass flow rate of 12 kg/min, that is to say a velocity of 0,5 m/s. The temperature in water is measured using thermocouples upstream and downstream from the sections of measurements. Measurements are done with a rate of 2 seconds acquisition and make it possible to obtain an evolution of the steel pipe temperatures as well as the water temperatures. The variable parameters are as follows:

- the jet fire (various gases and the variation of heat release rate),
- the water flow within the pipe (water velocity going from 0 to 0,5 m/s),
- the presence or not of an heat insulator like rock wool.

EFFECT OF SOOT ON RADIANT ENERGY

Whatever the gas tested, the visualisation by video camera shows that jet fire takes a general form of cone (Figure 3) which characterises fully turbulent jet flames whose the Reynolds number is greater than 2000 (Table 1). But the structure of flame differs according to gas. Indeed, the methane flame compared to the propane and ethylene flames has a blue aspect and is very lifted off from the nozzle. The blue color of this flame is characteristic of the radiation in the field of visible of the carbon dioxide and the water vapor. The methane flame is generally considered as a nonluminous flame and soot radiation can be neglected (Marracino, 1997). The soot production in a methane flame is very weak even null under our conditions of tests. At the opposite, the propane and ethylene flames known as luminous are characterised by their yellow color because of their important soot concentration. Indeed, the ethylene and propane have a greater propensity to produce soot (see the f_s fraction in Table 1).

The fraction of combustion energy radiated η_r is important in the calculation of the radiative flux received by a target. To estimate it in experiments, a calculation is carried out while being based on the values of radiative flux given by the fluxmeters.

Figure 4 shows the fraction of combustion energy radiated η_r and the radiative power $\dot{Q}_r(\dot{Q}_r = \eta_r\dot{Q})$ according to the Froude number Fr.

In a general way, the radiative fraction tends to decrease when the gas jet velocity increases. This observation proves to be a recognized characteristic of the turbulent jet fires rather controlled by the forced convection induced by the gas jet. Even if the fraction of combustion energy radiated η_r is reduced, the radiative power $\dot{Q}_r$ increases with the exit gas velocity. Indeed, more the mass flow rate grows and more the flame is going to radiate.

In addition, the radiative fraction of the methane flame is systematically lower than the radiative fractions

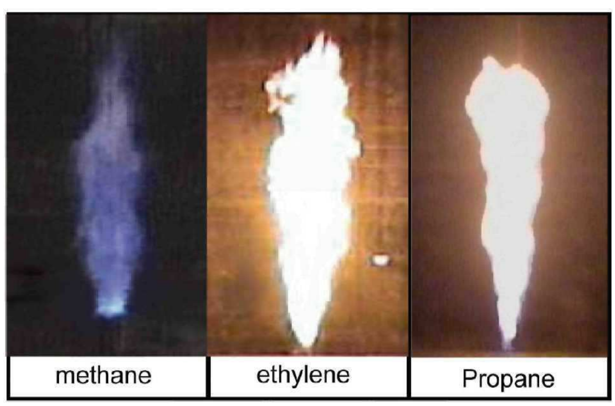

Figure 3. Photos of different gas flames

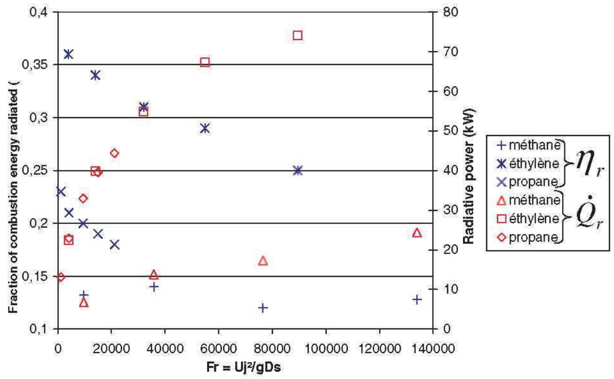

Figure 4. Fraction of combustion energy radiated η_r and radiative power $\dot{Q}_r$

of propane and ethylene. Indeed, the radiation of a methane jet fire comes exclusively from the water vapor and carbon dioxide which are bodies known as "semi-transparent". Their emission is very weak compared to the emission of a black body. Conversely, ethylene and propane jet fires have important concentrations of soot, particles radiating as black bodies.

Moreover, ethylene jet fire has a radiative fraction more raised than propane one. The radiation of the propane and ethylene flames is due mainly to their consequent soot concentration. The alkenes (ethylene) have a greater disposition to produce soot than the alkanes (propane) (Rasbah, 1982). The more the flames are concentrated out of soot and the more they tend to radiate until they are saturated with particles. It is completely logical to obtain a radiative fraction of propane flame weaker than ethylene one.

EFFECT OF SOOT ON HEAT TRANSFERS TO THE PIPE

The first tests realised with jet fires put forward the differences existing between tested gases in term of soot concentrations. The second experimental campaign based on the jet fire impingement of the steel pipe apprehended how jet fire interacts with the engulfed equipment.

With this intention, Figure 5 presents the thermal response of the pipe impinged by the flames of three gases (methane, propane and ethylene). The pipe is located at the centre of jet fire and has a water flow of 12 kg/min. The methane mass flow rate is of 3,81 g/s, that of the propane of 4,48 g/s and that of ethylene of 2,48 g/s (Froude number is the same for propane and ethylene).

First of all, an observation can be made as the temperature of the pipe rises very fast. This is caused by its thermal inertia which is very weak. This weak thermal inertia is due mainly to the thermal diffusivity of the steel which is high and about $1{,}55.10^{-5}$ m^2/s. Consequently, in less than one minute, the pipe subjected to the methane fire reaches a thermal equilibrium characterised by an asymptotic temperature of 120°C. This thermal response is logical since with thermal equilibrium, absorbed (contributions by radiation and forced convection) and evacuated (losses by forced convection of water) heat fluxes by the pipe are compensated. It should be noted that this is valid only if absorbed and evacuated heat fluxes remain constant. The pipe impinged by propane and ethylene flame does not reach a thermal equilibrium. Indeed, after having reached a temperature peak, the thermocouple returns a temperature which decreases during time instead of stagnating. The forced convection induced by the water flow remaining unchanged during the test, only a modification of the heat absorbed by the pipe can be at the origin of such a phenomenon. The photographs taken after tests showed that the methane fire had caused an oxidation of steel due to the condensation of the combustion steam coupled with the high temperature in the flame. The formation of this ferric oxide residue did not have any impact on the thermal response of steel. On the other hand, after the propane and ethylene tests, it appeared on the pipe a consequent soot deposit. Thus, we deduced from it that this deposit was at the origin of the temperature decrease. This phenomenon is called "thermophoresis" and corresponds to a laminar transport by which the particles (soot) go upstream a temperature gradient. Indeed, the opaque particles (strongly

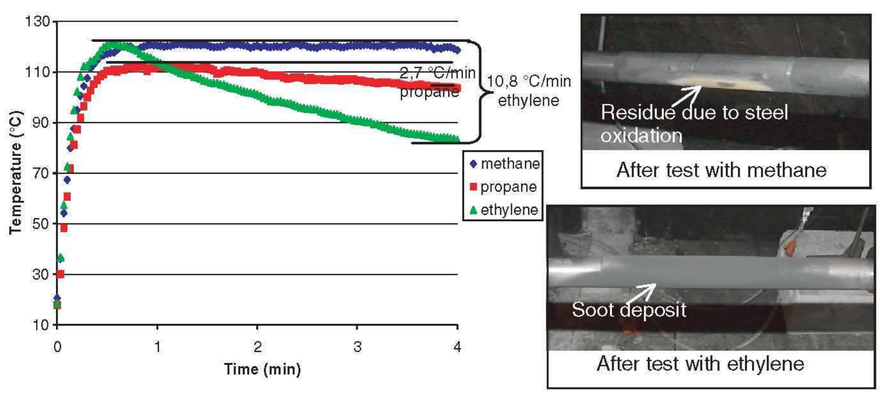

Figure 5. Evolution of the thermocouple directly impinged by jet fire and photos showing the consequences of jet fire

absorbing) follow usually the heat gradient while escaping from the hot zones to go towards the cold zones. Soot would come to deposit preferentially on the cold pipe and to insulate the pipe thermally as the deposit thickness evolves in the course of time. A test carried out over one forty minutes duration showed that the pipe could go down until a temperature of 40°C after having reached a temperature peak of more than 140°C. The soot particles always remain in place condensing and agglomerating on the pipe in thin layer then in the form of aggregates.

How soot can create such a protection? The pipe emissivity changes while passing from 0,2 to 0,95 because of the formation of the soot deposit which radiates roughly as a black body (McEnally, 1997). This modification generates an increased heat loss. In same time, soot absorbs heat due to the radiation and the forced convection but restore only a part with the pipe by conduction. An interstitial medium must remain between soot and the pipe inducing an imperfect contact and thus a thermal resistance of contact, the heat transfer by conduction is carried out less better. Moreover, this soot deposit plays the same role in the long term as a heat insulator because of a very low thermal conductivity.

In addition, this phenomenon which can be characterized by the relationship between the temperature decrease and the time over which it is carried out noted $\frac{\Delta T_{soots}}{\Delta t}$ must be related to the soot quantity produced by jet fire. Figure 5 shows that for propane, $\frac{\Delta T_{soots}}{\Delta t} = 2{,}7°\mathrm{C/min}$ and for ethylene, $\frac{\Delta T_{soots}}{\Delta t} = 10{,}8°\mathrm{C/min}$. However, for these two tests, the gas velocity and gas temperature are identical (Ug = 8,5 m/s and Tg = 1000°C) as well as the radiative power which is 40 kW. If the radiative power is equivalent, the quantities of soot provided by the two flames are about equal. Therefore, the thermal decrease should be similar between two gases and yet, there is a factor 4 between the two $\frac{\Delta T_{soots}}{\Delta t}$. This can be explained by the fact of a different granulometry between ethylene and propane soots that implies a more or less insulator soot deposit.

EFFECT OF HEAT INSULATOR ON THE THERMAL RESPONSE OF THE PIPE

The system of heat insulator is tested in order to consider its effect of fire protection on the pipe. The heat insulator used for the tests consists of a rock wool layer 3 cm thickness. Figure 6 presents two tests carried out, one concerning the impact of the methane fire ($\dot{m}_f = 3{,}81$ g/s) on the insulated pipe and the other the impact of the ethylene fire ($\dot{m}_f = 4{,}91$ g/s). The insulated pipe is placed in the centre of jet fire and is crossed by a water flow of 2 kg/min.

First of all, it should be noted that thermal equilibrium is reached at the end of 3–4 minutes whereas without heat insulator, less than one minute is enough. This additional time is due to the high thermal inertia of the heat insulator caused by a low thermal diffusivity of about 8.10^{-7} m^2/s. Indeed, the heat insulator tends to diffuse heat more slowly. Then, the very low thermal conductivity of the heat insulator of 0,08 W/mK makes it possible to maintain a maximum temperature of the pipe of 40°C when the methane jet fire impinges this one. The same test carried out without heat insulator shows that the pipe reaches a maximum temperature of 140°C. The heat insulator decreases the temperature of 100°C that is to say a reduction in the heat transmitted to the pipe of 70%. Consequently, a system of heat insulator is completely eligible as fire passive protection of the equipment. Thus, it can be considered like a means of reducing the risk of rupture in the survey of domino effects.

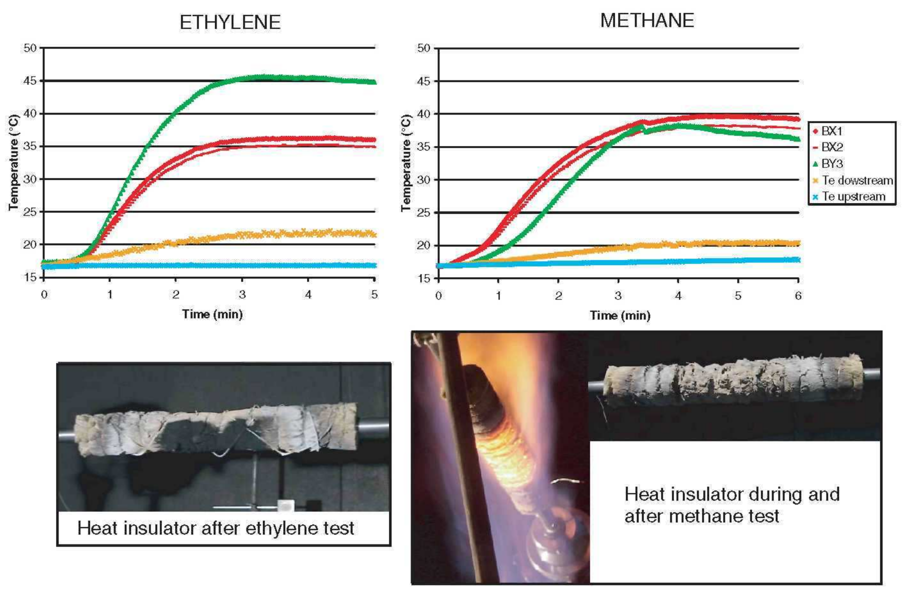

Figure 6. Tests carried out with the insulated pipe impinged by methane and ethylene jet fire

On the other hand, this heat insulator can undergo deterioration during the thermal aggression. Indeed, the photographs show it, during the test with methane, the binder constituting the heat insulator started to burn. With the end of the test, this binder being partly consumed, the structure of the heat insulator is found somewhat faded on the surface. At the opposite, while looking at the photo of the heat insulator after ethylene jet fire, one realises that the rock wool was not degraded and that a soot deposit came to be formed with the flame impingement. And yet, the heat release rate of the ethylene fire ($\dot{Q} = 232$ kW) as well as the temperature in the flame ($Tg = 1100°C$) are higher than those of the methane fire ($\dot{Q} = 191$ kW; $Tg = 900°C$).

Thus, soot condensation on the heat insulator by thermophoresis could be at the origin of this different rate of deterioration. The graph of the temperatures shows that with thermal equilibrium, the temperature located in the jet fire drag is more consequent than at the impingement. In the case of the methane fire, these temperatures are identical with a few degrees because, under normal conditions, the heat insulator must restore heat towards the pipe in a more homogeneous way. Soot would act like an additional insulator protecting a part of the heat insulator from the thermal aggression. The phenomenon that appears with the soot deposit is the same one as observed with the pipe without heat insulator. Except any decrease of temperature is not observed, because of the heat insulator thermal inertia which is stronger than steel one.

CONCLUSION AND FUTURE WORK

Two tests campaigns were carried out. One related to the characterization of jet fires and the other the thermal response of a pipe subjected to these jet fires. In this paper, only the effect of soot was investigated.

The tests about jet fires showed that a high molar mass of fuel did not grant a better propensity to produce soot. Propensity is related to the chemical nature of fuel such as alkenes have a better propensity than alkanes. The alkenes flames tend to radiate more than alkanes ones. Thus, the radiative fraction model will have to take into account the soot concentration of the flame. To supplement these investigations, the experimental data will be compared with the existing models of jet fires calculation which are the SHELL model (Chamberlain, 1987) and the API RP 521 model (API, 1997).

Concerning the thermal response of the pipe subjected jet fire, it appears that soot comes to insulate the pipe by a phenomenon of "thermophoresis". The soot deposit plays the same role than a heat insulator. When the pipe is insulated by rockwool, the soot deposit protects rockwool from the jet fire heat. Soot acts as a second heat insulator. Ultimately, this second tests campaign aims to modify the physical models concerning the thermal response of a structure subjected to fires. It will be necessary to determine the thermophoretic soot mass flux settling on the equipment as well as the increase thickness of insulating soot in the course of time. The modification of the physical models will be the subject of the other papers.

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