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Domino Effect by Jet Fire Impingement in Pipelines

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Jet fires are often considered to be a “minor” fire accident, as compared to pool or tank fires. However, if there is flames impingement on an equipment very high heat flux densities will be reached, which can originate its failure; thus, jet fires can be the primary step of a domino effect sequence. Diverse circumstances can play an important role in this situation, as the existence and condition of fireproofing or the presence of a liquid or a gas inside the equipment. An interesting case is that of pipelines; often diverse pipes are installed in the same hallway, due to the difficulty and cost of establishing this path. In this case, a high-velocity release in one of the pipes can affect the others by domino effect, essentially through erosion (buried pipes) or thermal effects (aerial and also buried pipes if a crater allows the existence of fire). In the event of a jet fire, flames impingement on another pipe can occur. If there is a thermal insulation, it can be damaged or even can be eroded by the action of a jet. Inside the pipe different conditions can exist: a) continuous flow of a liquid: pipe wall will be cooled and can be considered protected; b) stagnant liquid (for ex., because blocking valves are closed): the liquid can boil, pressure can increase and the wall in contact with vapor can reach high temperatures and fail; c) co flow of a gas or stagnant gas: the wall temperature will increase to dangerous values, a failure is probable. A versatile indoor small size experimental unit has been constructed allowing the testing and analysis of these situations. The case of pipelines is studied, both from the analysis of real cases and experimental tests. Conclusions are obtained concerning the measures that can be applied to decrease the risk of these accidents.

1. Introduction

Jet fires are often smaller than pool fires and in many cases they do not lead to severe effects, as their thermal radiation flux is relatively small and decreases quickly with the distance; furthermore, in certain cases they can be quickly stopped just by closing a valve. So, probably the occurrence of these type of fires is really higher than the one that could be inferred from the data registered in accident databases, as many small jet fires without significant consequences are not included. This is probably also the reason why certain safety measures, as for example, the practices for equipment fireproofing, take into account just the effects of pool fires and do not consider those from jet fires (Badri et al., 2013). However, if there is impingement of the flames on an equipment, heat fluxes can be very high due to the simultaneous effect of both radiative and, even more important, convective heat transfer (Landucci et al., 2013; Scarponi et al., 2018). This, together with the possible erosion effect of the high velocity jet (which can contribute to damaging a fireproofing layer), can originate in a short time the failure of a vessel or a pipe, thus originating the secondary domino effect accident, which can be another fire, an explosion or a toxic release. The size and geometry of a jet fire varies as a function of the fuel flowrate and of the jet direction (vertical, horizontal or inclined).
Jet fires can occur when there is the continuous release of a flammable gas (through a hole, a broken pipe, a safety relief valve) which is ignited; the ignition source can be another fire, an impact, an electrostatic spark, etc. If there is a release of a two-phase fluid of a pressurized liquefied gas, the possibilities are somewhat more complex (Vílchez et al., 2011), but again a jet fire will occur if there is ignition.

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In the case of gas or two-phase release (this second one originated by the flash vaporization of a liquid), it should be taken into account that in most cases the jet will be a high momentum one, with sonic velocity at the outlet (for most gases, sonic velocity will be reached when the pressure inside the vessel or the pipe is equal or higher than approximately 2 bar abs). This is an important fact, as it implies a higher turbulence, a more important air entrainment and a better combustion of the fuel, with higher heat fluxes in the case of flame impingement; it can also imply the aforementioned erosion effect on an insulation layer.
Pipelines are the most important mode for transporting fluids over long distances. Even though this is considered to be generally a safe system, accidents occur from time to time: corrosion, third party activities, mechanical failures and other causes can originate the loss of containment, which, if the released material is flammable, can imply a fire. Often several parallel pipes are installed in the same hallway, because of practical and economical reasons. In this case, if a jet fire occurs in one of them, the probability that it impinges on another one will be a function of the jet direction and length, the diameter of both pipelines and the distance between them (Ramírez-Camacho et al., 2015). In the case of buried pipelines this can also happen when a crater is formed by an explosion or by the pressurized release; if both the primary and the target pipes are inside the crater, jet fire impingement can occur. If the target pipe conveys a gas and it is no thermally insulated or the insulation has been damaged, the pipe wall temperature can reach quickly a high and dangerous value. If it conveys a liquid, its cooling potential will protect the pipe; however, if the action of blocking valves stops the flow, the risk will significantly increase. A few representative examples of these accidents have been included in Table 1; the information on such cases available in the literature is rather scarce.
Therefore, experimental tests can be a very useful tool to analyze the behavior of a pipe conveying or containing a given fluid, or protected by a given fireproofing layer, when subjected to the action of jet fire impingement. A versatile indoor small size experimental unit has been constructed, which can be used to reproduce such situations under different conditions. Data obtained on propane jet fires impinging on a pipe in different conditions are presented.

2. Experimental set-up

An experimental set-up was designed and constructed to obtain data on propane gas medium size jet fires characteristics and effects (Figure 1). It can originate horizontal jet fires with a length up to 3 m, using different gas pressures and outlet orifice diameters. In this communication, jet fires impinged on a carbon steel pipe (11.5 cm outside diameter, 6 mm wall thickness) containing stagnant air or water. An industrial propane bottle was used as the source of gas. For safety purposes, two safety valves, manual and electrical, respectively (plus the one in the bottle) were installed. All these elements were located on a portable structure to increase the operational flexibility during the tests. The flow rate, pressure and temperature of the propane feeding the jet fire were measured. The propane pressure was measured at a point located 12 cm up-stream the release point; the jet temperature at the release point was also measured with a K type thermocouple. A set of K type thermocouples located inside the pipe wall allowed the measurement of the wall temperature during the tests.

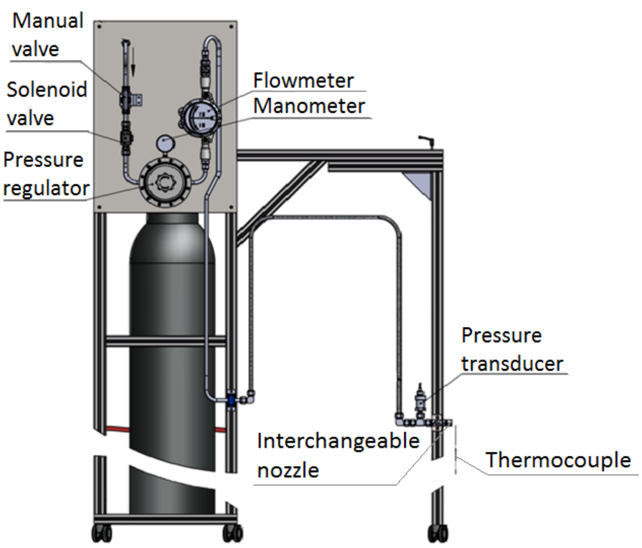

Figure 1: Scheme of the experimental setup

The jet fire was filmed with both a visible and an infrared thermographic camera, located orthogonally to the flame. Two heat flow sensors (Schmidt-Boelter type) were located at different distances from the flame. The values of pressure, temperature and radiant heat flux were continuously registered during the tests through a data acquisition system (Field Point) from the aforementioned measuring devices.

Table 1: Several cases of jet fire domino effect in parallel pipelines

Location, year	System	Source pipe mat./diam.	Target pipe mat./diam.	Accident sequence	Cause	Description
Charleston USA, 1971	Ethanol/ Acetylene pipelines	Ethanol / Not available	Acetylene/ Not available	Fire → →explosion	External event	Railway wagon collided with ethanol pipeline. Ethanol jet fire impinged acetylene pipeline which later on exploded
Las Piedras Venezuela, 1984	Refinery	Oil / 8 inch	NG / 16 inch	Fire → fire→ failure	Welding failure	Oil pipeline failed; jet fire ruptured 16 inch gas pipe: another jet fire led to further pipe ruptures
Rapid City Canada, 1995	Natural gas transmission pipeline	NG / 42 inch	NG / 36 inch	Fire → fire → failure	Stress corrosion cracking	Corrosion ruptured a 42 inch gas pipeline. Jet fire affected a 36 inch gas pipeline: rupture; fire on a third 48 inch gas pipe which did not fail
Uch Sharif Pakistan, 2004	Natural gas transmission pipeline	NG / 24 inch	NG / 18 inch	Explosion → fire→ failure	Sabotage	Sabotage ruptured 24 inch gas pipeline. Jet fire affected a 18 in gas pipeline, which failed
USA Alabama, 2011	Natural gas transmission pipeline	NG / 30 inch	NG / 30 inch	Explosion → fire → damage	External corrosion	Gas pipeline exploded, jet fire burned for hours and damaged a close pipeline
Canada Buick, 2012	Sour gas Gathering system pipeline	Sour gas / 16 inch	Sour gas / 6.62 inch	Explosion → fire → fire → failure	External corrosion	Buried pipeline (16 inch) ruptured: crater, jet fire; in 25 min rupture/ignition of a 6.62 inch pipe in the same hallway (both pipes shut down before rupture)

3. Flames impingement on a pipe

In all but one tests, flames were from a sonic gas jet, as this is the most common situation (chocked flow) in the event of a release (with propane gas, the velocity at the hole is sonic if $P_{gas\ pipe}/P_{atm} > 1.75$); the hole diameter was d = 6 mm. The length of the visible flames (corrected for the curvature) could be predicted with relatively good accuracy by the expression $L_{flame} = d \cdot Re^{0.4}$ (Palacios and Casal, 2011). A typical jet can be seen in Figure 2, together with the infrared image. Because of very high flow velocity and restricted fuel and air mixing just after release, the combustion can only take place further downstream, where lift-off point is marked by a blue combustion annulus flame, at approximately 0.25 m from the hole. From this point, the length of the visible flames was approximately 1.2 m. The flames shape was somewhat disturbed by the presence of the target pipe.

3.1 Gas inside the pipe, sonic jet

The temperature of a pipe subjected to jet fire impingement increases quickly when it conveys or contains a gas. Figure 3 shows the temperature evolution registered by four thermocouples (K type) located (inside the wall) on top, bottom, front and back, respectively, of a perimeter of the pipe (stagnant air inside) receiving the flames of the central section of a sonic jet fire. There was no fireproofing.

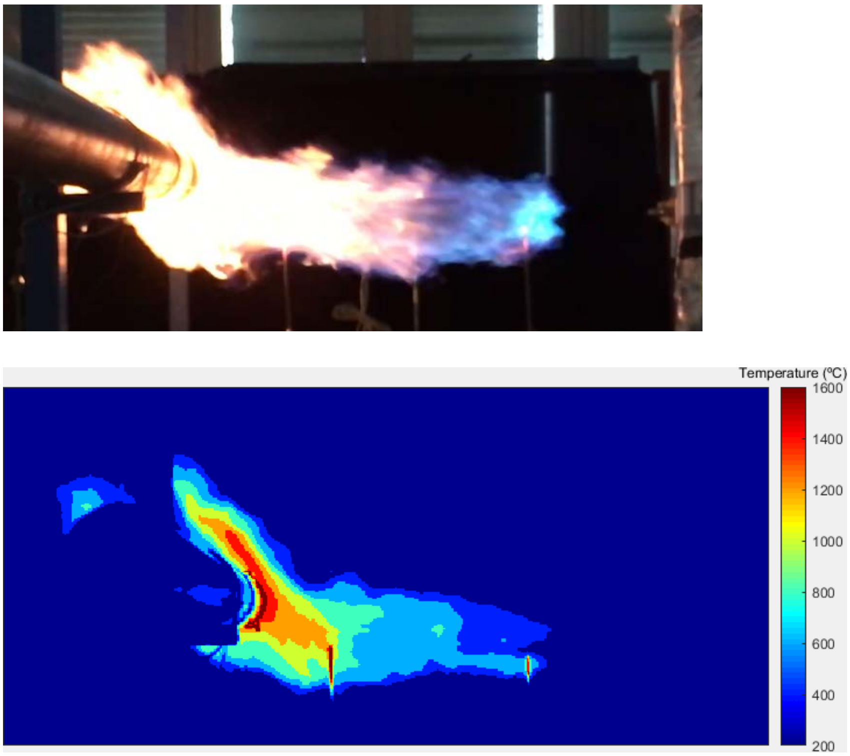

Figure 2: Propane jet fire impinging on a pipe (d = 6 mm; D_{pipe} = 11.5 cm). Top: visible image; bottom: IR image (the wake of a thermocouple modified somewhat the condition just after the lift-off).

The front surface, TC-1, underwent the highest heating, due to the higher turbulence and the more intense convective contribution (heating rates during the first half a minute: 6.5 ºC s^{-1}). The heating velocity decreased afterwards gradually, reaching a temperature of 600 ºC after 2.5 min from the start of the jet fire (this would correspond approximately to a 50 % of the strength ratio of carbon steel at room temperature) and 750 ºC (approximate steel strength ratio: 15 %) after 5.5 minutes. Test duration: 9.8 minutes.

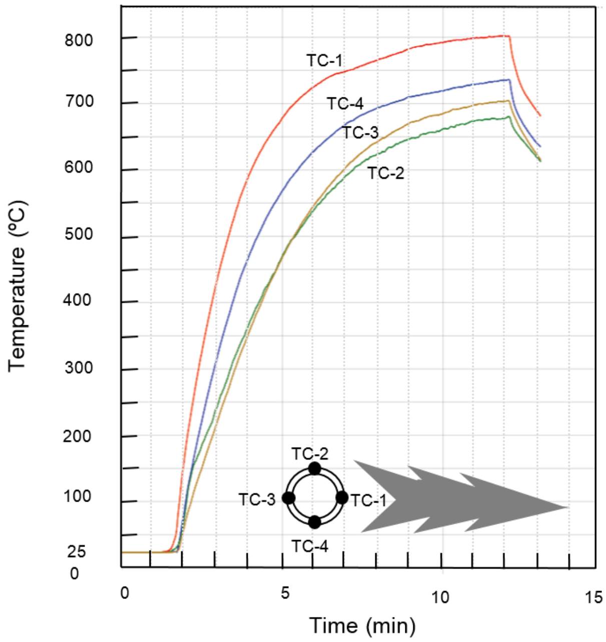

Figure 3: Evolution of pipe wall temperatures as a function of time (stagnant air inside the pipe, sonic jet)

The thermocouple located in the bottom wall (TC-4) of the pipe registered lower -even though very high- temperatures, reaching a maximum temperature of 737 ºC . Somewhat lower temperatures were registered by the top and back wall thermocouples (TC-2, TC-3), even if the pipe wall was in contact with the flames; this could probably be attributed to the lower convective contribution on the pipe external surface originated by the negative influence of the jet fire wake. Taking into account all these temperatures, this must be considered a situation that would lead to the failure of a pipe subjected to internal pressure.

3.2 Liquid inside the pipe, sonic jet

If the pipe contains or conveys a liquid, the surface of the wall in contact with it (i.e., the section of the wall under the liquid level) will be cooled by the liquid, which after a short time will start boiling, and its temperature will reach much lower values. Figure 4 shows the temperature evolution of the different points of a pipe subjected to the impingement of a jet fire (with essentially the same features than that in Figure 2); in this case, stagnant water was contained in the pipe.

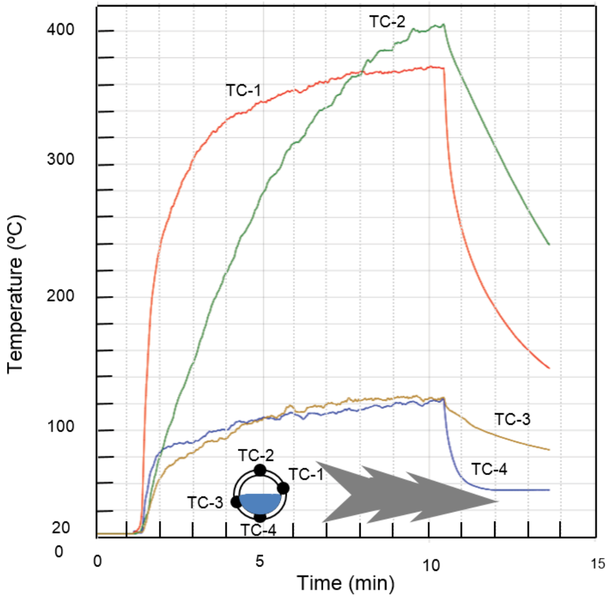

Figure 4: Evolution of pipe wall temperatures as a function of time (stagnant water inside the pipe, sonic jet)

The water level covered the wall at the position of thermocouples TC-4 (bottom) and TC-3 (back). The top surface (TC-2) was not in contact with the liquid, although it was probably cooled by the bubbles erupting from the boiling water; furthermore, in this test, the flame impingement on top of the pipe was rather light, this is why the maximum temperature reached was significantly lower than in the case of Figure 3. Finally, the front thermocouple (TC-1) was just at the height corresponding to water level, reaching an approximately constant and intermediate temperature. Similar results (to TC-2, TC-3 and TC-4) were obtained by Birk et al. (2006), with longer exposure times, when studying the flames impingement on a vessel. A maximum temperature of 375 ºC for the front thermocouple was reached after 9 min of exposure, and 400 ºC for the top one (now the cooling effect of the jet wake was negligible). Instead, thermocouples at the wall under water level reached a maximum temperature of just 120 ºC.

3.3 Liquid inside the pipe, low-velocity jet

If there is a low velocity jet, for example because the pressure in the source pipe has decreased significantly, then the turbulence in the jet and the entrainment of air will decrease; consequently, the combustion in the jet will be poor: the flame will be brighter due to the existence of soot particles, but its temperature will be lower. Therefore, the temperature increase at the pipe wall, even if it will increase quickly at the start of the impingement, will reach lower values than in the case of a sonic jet. Figure 5 shows the temperature evolution in the case of a subsonic jet (u = 40 m/s) impinging on a pipe containing stagnant water. Thermocouples TC-4 (bottom) and TC-3 (back) were on the wall in contact with water, while TC-1 (front) and TC-2 (top) were located in the wall above water level.

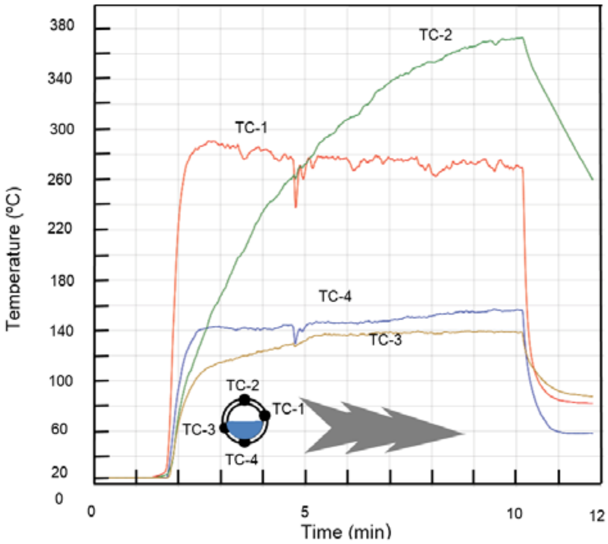

Figure 5: Evolution of pipe wall temperatures as a function of time (stagnant water in the pipe, low-velocity jet)

4. Conclusions

Although jet fire accidents are underrepresented in accidents databases, it is a fact that they have been the origin of important domino effect sequences. In the case of parallel and close pipelines, if a loss of containment of a flammable gas or two-phase flow occurs through a hole –originated by corrosion, excavating machinery or other causes- and it gets ignited, the possibility of flames impingement on a secondary pipe can create a very dangerous situation. The data obtained from an experimental setup, designed for performing indoor tests with small and medium size jet fires, have shown that impingement can imply very high heat fluxes, originating extremely high temperatures in the pipe wall if there is no fire proofing or it has been damaged. With stagnant gas inside the pipe, temperatures of the order of 600 ºC were reached in 2-3 minutes (heating rates of the order of 6.5 ºC s^{-1}), and of 750 ºC in 5-6 min. When the pipe contained a liquid, the wall in contact with it was cooled and the situation was less dangerous. These data emphasize the fact that safety distances must be considered essential in pipelines hallways, together with fire proofing and other safety measures. The analysis of historical cases show that jet fire impingement can occur even in buried pipes if a crater is formed.

Acknowledgments

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References

Badri, N., Rad, A., Kareshki, H., Abdolhamidzadeh, B., Parivizsedghy, R., Rashtchian, D.. 2013, A risk-based decision making approach to determine fireproofing requirements against jet fires, Journal of Loss Prevention in the Process Industries, 26, 771-778.

Birk, A. M., Poirier, D., Davison, C. J., 2006, On the response of 500 gal propane tanks to a 25% engulfing fire, Journal of Loss Prevention in the Process Industries, 19, 527-541.

Landucci, G., Cozzani, V., Birk, M., 2013, Heat radiation effects, Chapter in: G. Reniers and V. Cozzani (Eds.), Domino Effects in the Process Industries, Elsevier, Amsterdam.

Palacios, A., Casal, J., 2011, Assessment of the shape of vertical jet fires, Fuel, 90, 824-833.

Ramírez-Camacho, J. G., Pastor, E., Casal, J., Amaya-Gómez, R., Muñoz-Giraldo, F., 2015, Analysis of domino effect in pipelines, Journal of Hazardous Materials, 298, 210-220.

Scarponi, G. E., Landucci, G., Birk, A. M., Cozzani, V., 2018, LPG vessels exposed to fire: scale effects on pressure build-up, Journal of Loss Prevention in the Process Industries, 56, 342-358.

Vílchez, J. A., Espejo, V., Casal, J., 2011, Generic event trees and probabilities for the release of different types of hazardous materials, Journal of Loss Prevention in the Process Industries, 24, 281-287.