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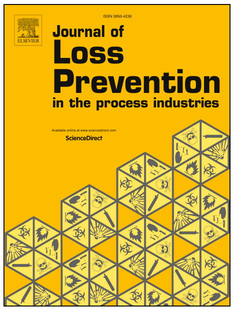

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PII: S0950-4230(21)00060-7

DOI: https://doi.org/10.1016/j.jlp.2021.104449

Reference: JLPP 104449

To appear in: *Journal of Loss Prevention in the Process Industries*

Received Date: 30 September 2020

Revised Date: 20 February 2021

Accepted Date: 25 February 2021

Thermal effects of a sonic jet fire impingement on a pipe

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Abstract

Although the effects of jet fires are often limited to rather short distances, if their flames impinge on a pipe or a vessel collapse can occur in very short times. In such cases, the heat flux on the affected equipment is very high and wall temperature can increase very rapidly. This can happen in parallel pipelines, if a release occurs and impinges on another one. Nevertheless, jet fire impingement has been scarcely studied. In this communication the results obtained from an experimental set-up are presented. Sonic jet fires impinged on a pipe containing stagnant air or water. The temperatures of the flames impinging on it were measured for the worst case (flame front-bright zone), as well as the evolution with time of the pipe wall temperature at different locations. Initial temperature increases up to around twenty ºC/s were registered for the air inside, with maximum values of up to 600 ºC reached in 2.5 minutes, and 800 ºC in approximately 9 minutes. In the case of pipe containing water, in the zone of the wall in contact with the liquid the heating rates were much lower, the maximum temperature reached being up to approximately 150 ºC. From the temperatures of the jet flames and of the pipe, the heat fluxes reaching the pipe and the corresponding heat transfer coefficients were obtained. The results obtained emphasized that safe distances are essential in pipelines, together with fire proofing and other safety measures.

Keywords: jet fire; flame impingement; domino effect, heat flux; heat transfer coefficient.

1. Introduction

Historical surveys show that, among the fire accidents, the most common ones are pool and tank fires, with approximately 65% of cases, followed by flash fires with 30% and by jet fires, with a much smaller occurrence (4.5%) (Planas et al., 1997). Of course, these values can change somewhat from one survey to another one, but jet fires seem to be always much less frequent. However, jet fires are often much 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 types 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 really not known and therefore not included in these databases.

When considering the major accidents, fires have often a damage radius significantly shorter than those reached by explosions or toxic releases, but in this relatively short radius there can be other equipment (piping, vessels) that can undergo a domino effect, thus being incorporated to the accident (Gomez-Mares et al., 2008). And this is especially important in the case of jet fires as, if there is flame impingement, the heat fluxes on the affected equipment 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. A case in which this occurred was probably the severe accident of San Juan Ixhuatepec (México, 1984), where the first BLEVE occurred just 69 s after the initial vapor cloud explosion which probably originated several jet fires (Casal, 2018).

If there is the continuous release (through a hole, a broken pipe, a safety relief valve) at a very high speed of a flammable liquid, gas or two-phase mixture which is ignited, a jet fire will appear (Figure 1) (Vílchez et al., 2011). The ignition source can be another fire, an impact, an electrostatic spark, etc. If there is no ignition, due to the high momentum of the jet the released fuel will probably be dispersed; however, in the case of low speed jets, the situation would be more complex, with also the possibility of delayed ignition of a flammable cloud (flash fire) followed by a jet fire.

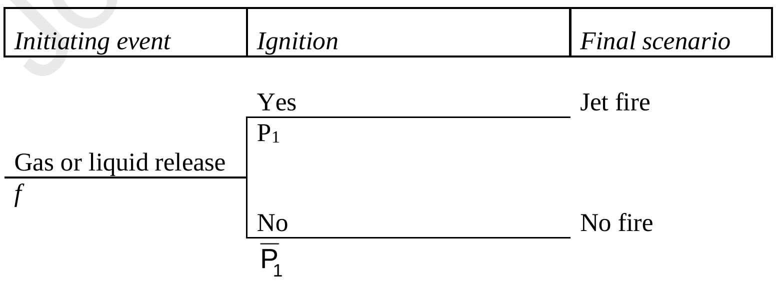

Fig. 1. Event tree for a continuous release of flammable gases or pressurized liquefied gases. Probabilities depend on the mass flow rate.

If there is a release of a two-phase fluid of a pressurized liquefied gas, the possibilities are somewhat more complex but again a jet fire can occur if there is ignition, as shown in Figure 2 (Vílchez et al., 2011).

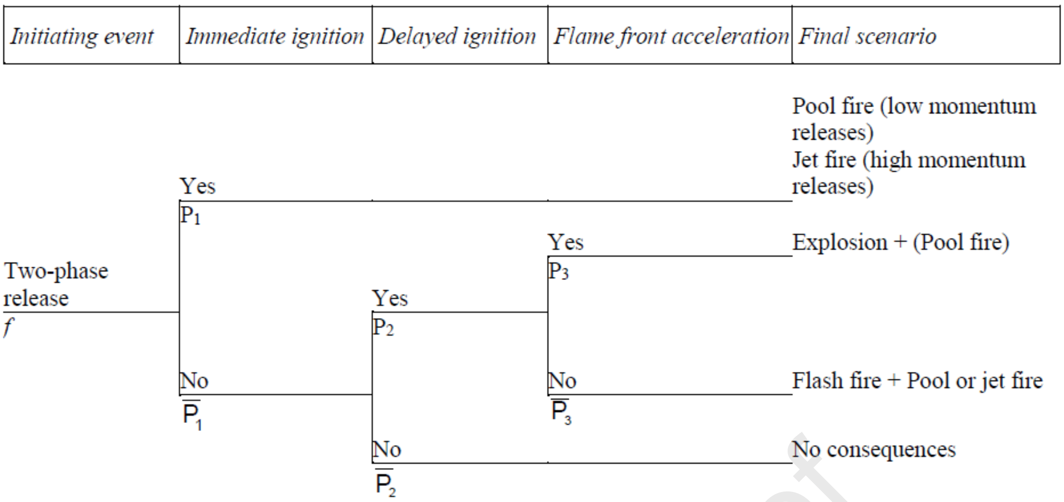

Fig. 2. Event tree for a continuous release of two-phase flammable pressurized liquefied gas. Probabilities depend on the mass flow rate.

In the case of gas or two-phase release (the latter 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.

There are still rather scarce data on the values of heat flux densities during jet flames impingement, even though they have originated severe accidents in fixed plants and in the transportation of flammable materials by rail, road and pipelines.

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 economic 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 not 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 of pipe failure will significantly increase. A few representative examples of these accidents have been included in Table 1.

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

Location, year	**System**	**Source pipe Material / OD**	**Target pipe Material / OD**	**Accident sequence**	**Cause**	**Brief 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 on acetylene pipeline, which later on exploded (MHIDAS, 2007)
Las Piedras Venezuela, 1984	Refinery	Oil / 8 in	NG / 16 in	Fire → →fire→ →failure	Welding failure	Oil pipeline failed; jet fire ruptured 16 in gas pipe: another jet fire led to further pipe ruptures (MHIDAS, 2007)
Gulf of Mexico, USA 1989	Natural gas transmission pipeline in platform	NG / 18 in	Six nearby pipelines	Explosion→ →fire→ →rupture	External event	18 in sales gas pipeline on the platform failed during installing a pig trap on it. Released hydrocarbons ignited. The explosion and fire burned the main structure and caused subsequent explosions when six other pipelines ruptured due to the intense heat (USDI, 1989)
Rapid City Canada, 1995	Natural gas transmission pipeline	NG / 42 in	NG / 36 in	Fire → →fire → →failure	Stress corrosion cracking	Corrosion ruptured a gas pipeline. Jet fire affected another gas pipeline: rupture; fire on a third 48 in gas pipe which did not fail (TSBC, 1995)
Uch Sharif Pakistan, 2004	Natural gas transmission pipeline	NG / 24 in	NG / 18 in	Explosion→ → fire→ →failure	Sabotage	Sabotage ruptured a gas pipeline. Jet fire affected a 18 in gas pipeline, which failed (Hassan and Ahmed, 2007)

Table 1. Several cases of jet fire domino effect in parallel pipelines (continue).

Location, year	System	Source pipe Material / OD	Target pipe Material / OD	Accident sequence	Cause	Brief description
Ontario Canada, 2011	Natural gas transmission pipeline	NG / 46 in	NG / 36 in	Explosion→ →fire → →failure	Stress corrosion cracking	Corrosion ruptured a gas pipeline. Explosion created a large crater →jet fire. The 36 in pipeline was shut down due to leakage from cross-over shut-off valve between both pipelines (TSBC, 2011)
Alabama USA, 2011	Natural gas transmission pipeline	NG / 30 in	NG / 30 in	Explosion→ → fire → →failure	External corrosion	Gas pipeline exploded, jet fire burned for hours and damaged a close pipeline. (USDT, 2011)
Buick Canada, 2012	Sour gas gathering system pipeline	Sour gas / 16 in	Sour gas / 6.62 in	Explosion→ → fire → → failure → → fire	External corrosion	Buried pipeline ruptured: crater, jet fire; in 25 min rupture/ignition of a 6.62 in pipe in the same hallway (both pipes shut down before rupture) (TSBC, 2012)
Manitoba Canada, 2014	Natural gas transmission pipeline	NG/ 30 in	NG/ 36 in NG/ 48 in	Explosion→ → failure → → fire	Welding failure	Natural gas released from the pipeline ignited, the resulting fire burned for approx. 12 h. Two adjacent pipelines were shut down before rupture (TSBC, 2014)

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. In the present study, a versatile indoor small size experimental unit has been constructed, which can be used to reproduce such situations under different conditions. Data obtained on sonic propane jet fires impinging on a pipe in different conditions are presented.

2. Literature review on jet flames impingement

Most of the experimental works published over the last four decades were mainly undertaken in order to investigate the behaviour of pressurized vessels engulfed in flames, while scarce attention has been dedicated to the experimental analysis of other types of equipment such as atmospheric tanks and pipelines, which are commonly used in industries and in the transportation of certain fluids (Landucci et al., 2013). The target equipment usually consisted of small-scale cylindrical or spherical vessels filled up to different levels, and the fuels were propane or methane. Table 2 summarizes some of the experimental set ups found in the literature.

Table 2. Experimental studies conducted on thermal effects by jet fire impingement*

Data source	Fuel	Mass flow rate (kg/s)	Release diameter (mm)	Release pressure (bar)	Gas exit velocity (m/s)	Convective heat transfer coefficient (kW/m^2·°C)	Total heat flux (kW/m^2)	Heat rate (kW)	Flame direction	Type of target	Surface specifications	Exposure mode
Kuntikana and Prabhu, 2018	Methane	1.12×10^{-5}	13, 15, 17.25, 20.25	2	NA	7.8×10^{-3} - 1.1×10^{-2}	up to 6	NA	Vertical	Semi-cylindrical surfaces	quartz half-cut tube, *d*=100 mm, *L*=150 mm, thickness=2.5 mm	Direct
Morad et al., 2016	Methane	1 ×10^{-6} to 2.8 ×10^{-6}	3.5 mm × 25 mm	1	0.74 to 2.26	NA	up to 90	0.05-0.16	Vertical	Flat surface	Copper. 250 mm x 130 mm x 10 mm	Direct
Bradley, 2017	Propane	0.21 to 22	20 to 50	60-113	50-250	NA	50-250	NA	Vertical and Horizontal	Cylindrical/ Flat/Vessel	Copper plate (7 m x 10 m), Pipe (*d*=0.9 m), 13 tonne LPG tank, 2 tonne vessel (*d*=1.2 m x 15 m)	Direct. Engulfed
Virk, 2015	Propane	NA	70	NA	NA	0.048 - 0.094	68-110	NA	Horizontal	Flat	Aluminium, 0.61 m x 0.61 m	Direct
Patej and Durussel, 2007	Propane	1.23 to 5.31	10.9	NA	11-47	NA	NA	62-296	Vertical	Cylindrical	Steel pipe, *d*= 22 mm, *OD*=34 mm,	Direct
Lowesmith et al., 2007	Propane	NA	NA	NA	NA	0.08	240	NA	Horizontal	Cylinder	NA	Engulfed
Birk et al., 2006a	Propane	NA	15	2.05	NA	NA	NA	NA	Horizontal	Cylindrical vessel	Steel, *d*=0.953 m, *L*=3.07 m	25% engulfed
Birk et al., 2006b	Propane	NA	15	2.07	NA	NA	NA	NA	Horizontal	Horizontal cylinder	Steel, *d*=0.953 m, *L*=3.07 m	25% engulfed
Birk and Vander Steen, 2006	Propane	NA	21	NA	NA	NA	NA	NA	Horizontal	Cylindrical vessel	Steel, *d*=0.96 m, *L*=3.07 m	Partially engulfed

Table 2. Experimental studies conducted on thermal effects by fire impingement *(continue)*.

Data source	**Fuel**	**Mass flow rate (kg/s)**	**Release diameter (mm)**	**Release pressure (bar)**	**Gas exit velocity (m/s)**	**Convective heat transfer coefficient ($kW/m^2 \cdot °C$)**	**Total heat flux (kW/m^2)**	**Heat rate (kW)**	**Flame direction**	**Type of target**	**Surface specifications**	**Exposure mode**
Birk et al., 2006b	Propane	NA	15	2.07	NA	NA	NA	NA	Horizontal	Horizontal cylinder	Steel, *d*=0.953 m, *L*=3.07 m	25% engulfed
Birk and Vander Steen, 2006	Propane	NA	21	NA	NA	NA	NA	NA	Horizontal	Cylindrical vessel	Steel, *d*=0.96 m, *L*=3.07 m	Partially engulfed
Persaud et al., 2001	Propane	1.5	12.7	NA	NA	NA	180-200	NA	Horizontal	Horizontal cylinder	Steel, *d*=1.2 m, *L*=4 m	Fully engulfed
Malikov et al., 2001	Methane/ Natural gas	NA	4, 6	0.5	up to 230	NA	up to 500	NA	Vertical	Cylindrical	Water-cooled, cylindrical calorimeter (0.108 m in diameter)	Direct
Droste and Schoen, 1998	Propane	NA	NA	5.5-9.8	NA	NA	NA	NA	NA	Horizontal cylinder	Steel, *d*=1.25 m, *L*=4.3 m	Engulfed
Wighus and Drangsholt, 1993	Propane	0.3	17.8	1-2.3	40-150	NA	190-340	14000	Horizontal	Cylindrical/Flat (Box-like)	Steel	Direct
Hustad and Sonju, 1991	Propane	NA	5, 8.6, 10, 40	NA	5-200	NA	up to 200	33.3	Vertical	Cylindrical	Steel pipe, *d*= 50 mm	Fully engulfed
Hustad and Sonju, 1991	Methane	NA	5, 8.6, 10, 40	NA	10-125	NA	up to 125	37	Vertical	Cylindrical	Steel pipe, *d*= 50 mm	Fully engulfed
Townsend et al., 1974	Propane	NA	NA	18.6	NA	NA	NA	NA	NA	Horizontal cylinder	*d*=3.05 m, *L*=18.3 m	Fully engulfed

**Note: Premixed jet fires not included*

Wighus and Drangsholt (1993) studied the thermal features of horizontal sonic jet fires of propane (0.3 kg/s) impinging perpendicularly on a vertical surface. They observed that both the velocity and the temperature at the different points of the jet have an important influence on the heat transfer, with the highest velocities being associated to the lowest temperatures. Therefore, the highest values of convective heat flux density were found when the combustion products had reached a high temperature and the entrained air had not cooled yet the mixture. Maximum values of heat flux density (including both contributions, radiative and convective) of up to 340 kW/m^2 for a flat plate and 290 kW/m^2 for a pipe located in front of the flame were registered.

Somewhat different values were obtained by Bennet et al. (1991) from methane and propane jet fires impinging on a pipe (0.9 m diameter) and a 13 tons vessel. Their results varied significantly with the fuel flowrate and the distance between the jet source and the target; in the case of the pipe: propane: 240-250 kW/m^2, methane: 200-325 kW/m^2; and with the vessel: propane, 150-250 kW/m^2; methane: 140-250 kW/m^2.

It can be observed from these examples that the published data on the heat flux density show an important scattering and uncertainty. One experimental campaign was performed by Patej and Durussel (2007) aiming at the analysis of heat transfer to a pipe impinged by a jet fire. Within this framework, the thermal impacts of fires on industrial pipes and tanks were studied. The measurements from the experiments made it possible to define the dimensions of jet fires, its surface emissive power and the hot gas velocities for then deducing from them the heat received by the pipe; these authors analysed as well the response of a pipe transporting water subjected to the jet fires, by monitoring the pipe with thermocouples.

3. Experimental set-up

In order to obtain data on the main features and effects of propane gas medium size sonic jet fires, an experimental set-up was designed and constructed (Figure 3). Horizontal jet fires with different lengths could be obtained by using different gas pressures and outlet orifice diameters; in this work a nozzle with a diameter of 6 mm was used. The jet flames impinged on a carbon steel pipe (API 5L X60, 11.5 cm outside diameter, 6 mm wall thickness, 3 m length) containing stagnant air or water. A 35 kg 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 upstream 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 (4 mm inside pipe wall thickness) allowed the measurement of the wall temperature at different positions during the tests. Additionally, another set of four B-type thermocouples were located outside the pipe (at 1 cm distance from the pipe wall), to measure the flame temperature at the same above-mentioned positions.

CCD and IR cameras were used to record the experiments. The Optris PI 640® IR used camera had a spectral range of 8–14 µm. From observations of visible and infrared images, the flame boundary was defined as that corresponding to a temperature of 800 K (Palacios and Casal, 2011) and an emissivity value 0.35 was used (Palacios et al., 2012).

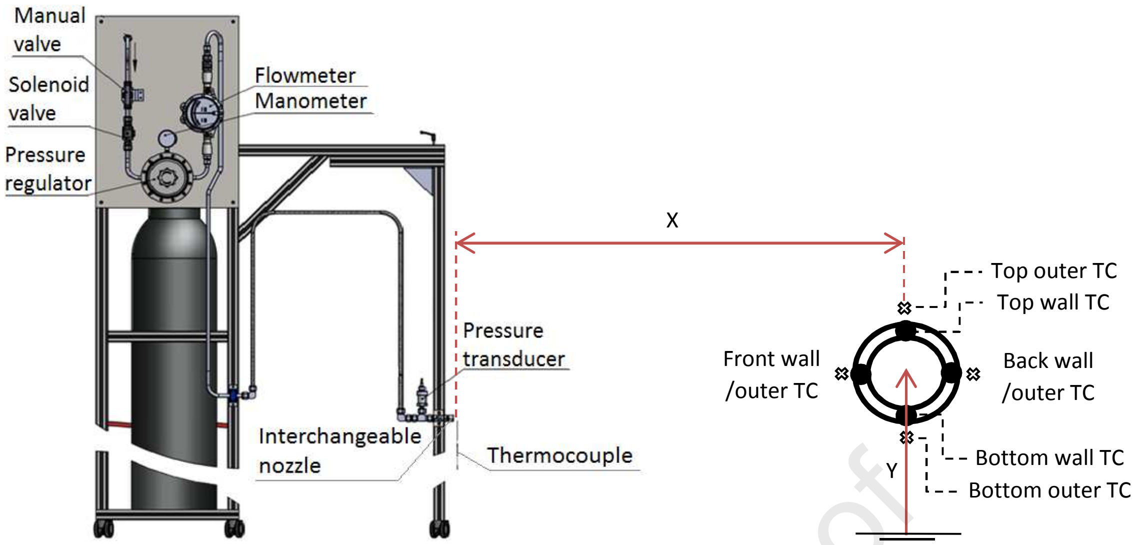

Fig. 3. Scheme of the experimental set-up and cross section of the pipe.

During the tests, the gas release nozzle was located 105 cm (horizontal distance) from the target pipe centre and the pipe centre line was elevated 115 cm from the ground level. The position of the experimental test equipment is shown in Table 3.

Table 3. Position of experimental test equipment.

X: Horizontal distance from nozzle to pipe centreline (cm)	Y: Elevation distance from level ground to pipe centre line (cm)	Location of thermocouples (cm)				
		Position	**Front**	**Top**	**Back**	**Bottom**
105	115	Wall TC	X: 100 Y: 115	X: 105 Y: 120	X: 110 Y: 115	X: 105 Y: 110
		Flame TC	X: 99 Y: 115	X: 105 Y: 121	X: 111 Y: 115	X: 105 Y: 109

The jet fires were filmed with both a visible and an infrared thermographic camera, located orthogonally to the flames. The values of pressure, temperature and release mass flow rate were continuously registered during the tests through a data acquisition system (Field Point) from the aforementioned measuring devices.

4. Flames impingement on a pipe

All the tests were performed with sonic gas jets, as this is the most common situation (chocked flow) in the event of a release. Sonic velocity is reached if the ratio between the pressure inside the pipe or the vessel and the pressure outside (usually the atmospheric one) is:

$$\frac{P_{in}}{P_{out}} \geq [\frac{\gamma+1}{2}]^{\frac{\gamma}{\gamma-1}} \quad (1)$$

For propane at 25 ºC, sonic velocity exists if $P_{in}/P_{out} > 1.74$. The image of one of the horizontal jet fires, not in contact with any obstacle, can be seen in Figure 4.

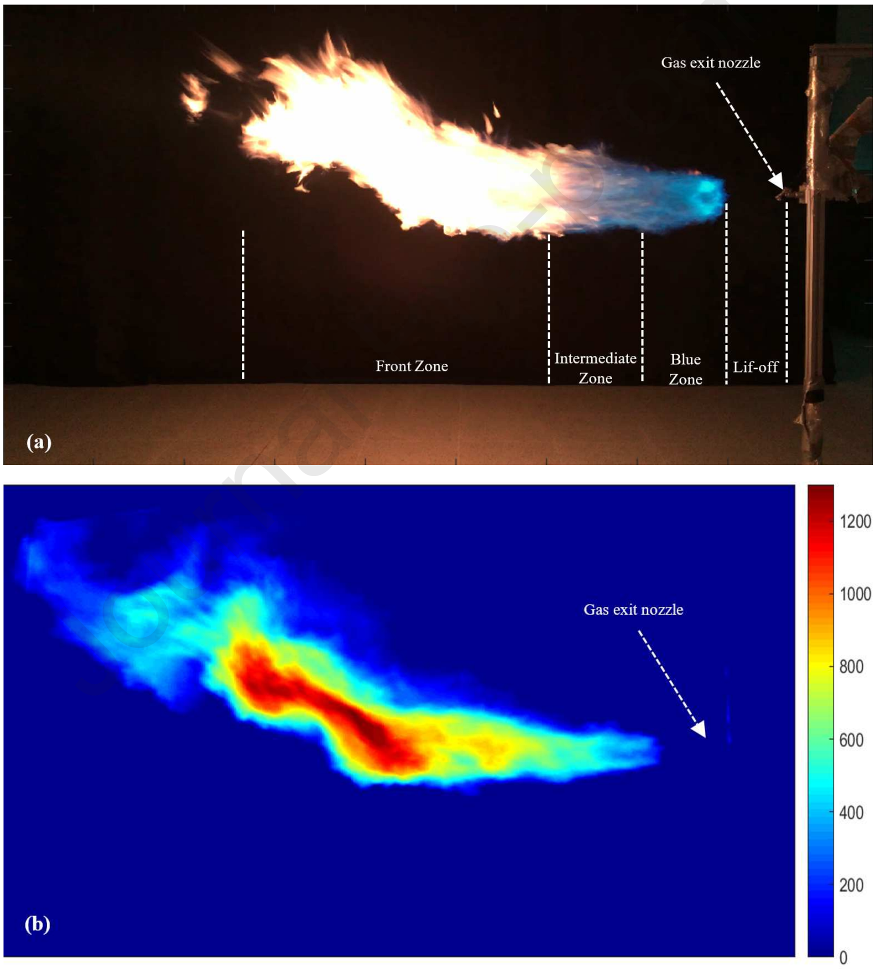

Fig. 4. Sonic propane free jet fire: (a) Visible image; (b) Infrared image (temperature in °C).

Three zones can be seen: the blue one just after the lift-off (i.e. no ignition zone between the base of the flame and the nozzle), an intermediate one, and the front one, very bright and undergoing the buoyancy effect. The variation of the temperature along these three zones -lower in the blue one, higher in the intermediate and with the highest values in front one- is clearly shown in the infrared image. The length of the visible flames could be predicted with relatively good accuracy —when there was no impingement— by the expression $L_{flame} = d \cdot Re^{0.4}$ (Palacios and Casal, 2011), although due to the high turbulence it experienced an important oscillation.

However, the existence of an obstacle —a pipe, a vessel— has a certain influence on both the shape of the flame and on its turbulence. A typical impinging jet can be seen in Figure 5, together with the corresponding image of the impacted area —heated to red— of the target pipe.

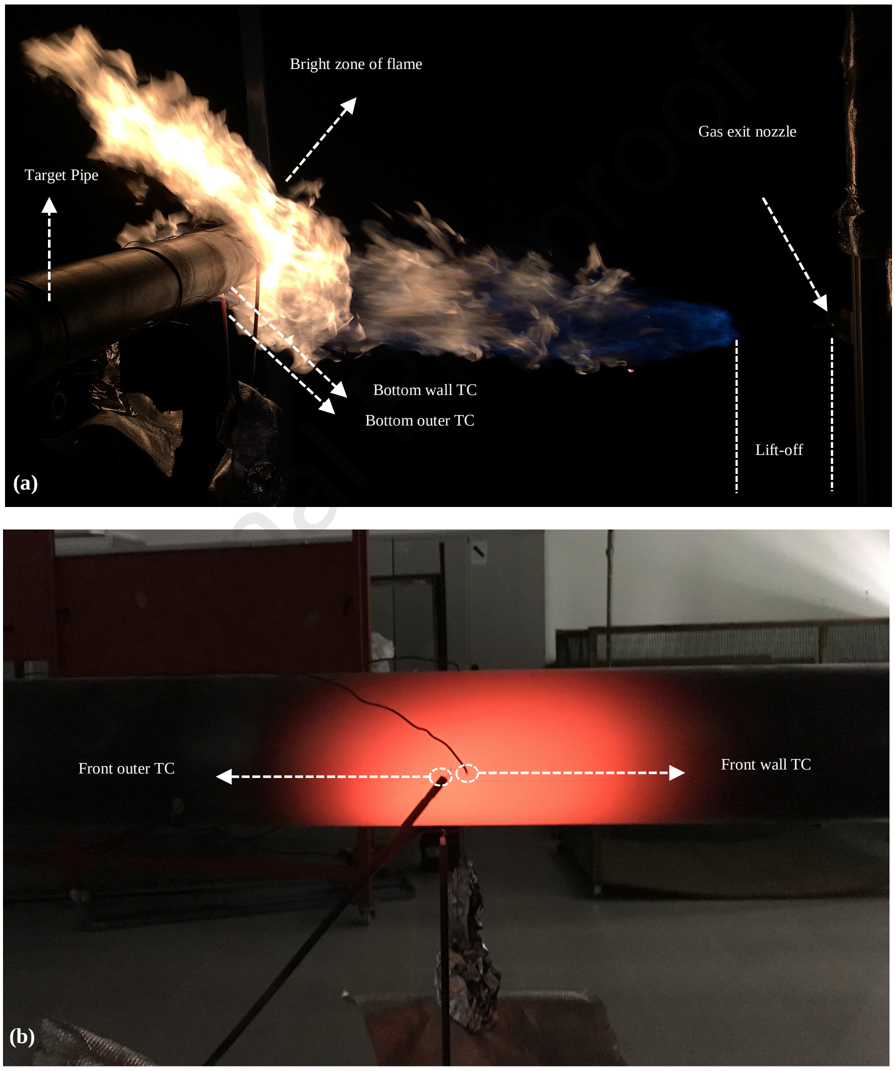

Fig. 5. (a) Propane jet fire impinging on a pipe. (b) Impacted area of the target pipe just after impingement.

Because of very high flow velocity and restricted fuel and air mixing just after release, the combustion could only take place further downstream, where lift-off point was marked by a blue combustion annulus flame, at approximately 0.2 m from the hole. From this point, the length of the visible flames was approximately 1.7 m. The shape of the highly turbulent flames was of course somewhat disturbed by the presence of the target pipe in the impinging zone. Very light modifications in the respective positions of the flame and the pipe implied significant changes in the flame contact with the bottom, top and back surfaces of the pipe wall, with the consequent influence on the heat transfer in those zones.

4.1 Gas inside the pipe

The temperature of a pipe subjected to jet fire impingement increases quickly when it conveys or contains a gas. Figure 6 shows the temperature evolution registered by the 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. Additionally, four B-type thermocouples were located out of the pipe, in front of the thermocouples in the pipe wall, at 1 cm from the wall (Figure 3) to measure the flame temperature. There was no fireproofing around the pipe.

In the first step of the impingement the heating rate of the pipe wall was very intense due to the high temperature difference between it and the flames; for example, between the initial pipe temperature of 25 ºC and 100 ºC, the following heating rates were registered: 19.5 ºC/s for front TC, 5.5 ºC/s for the bottom TC, 3.7 ºC/s for the top one and 2.2 ºC/s for the back one. The front zone of the pipe wall (TC-1) underwent the highest heating, due to the higher turbulence and the more intense convective contribution. The heating velocity decreased afterwards gradually as the pipe wall temperature increased. Thus, the front zone of the pipe wall (TC-1) reached a temperature of 600 ºC after 2.4 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 4.8 minutes. These very high heating rates are the reason why, in certain accidents, the failure of a pressurized pipe or vessel has occurred after a very short time from the start of the jet fire.

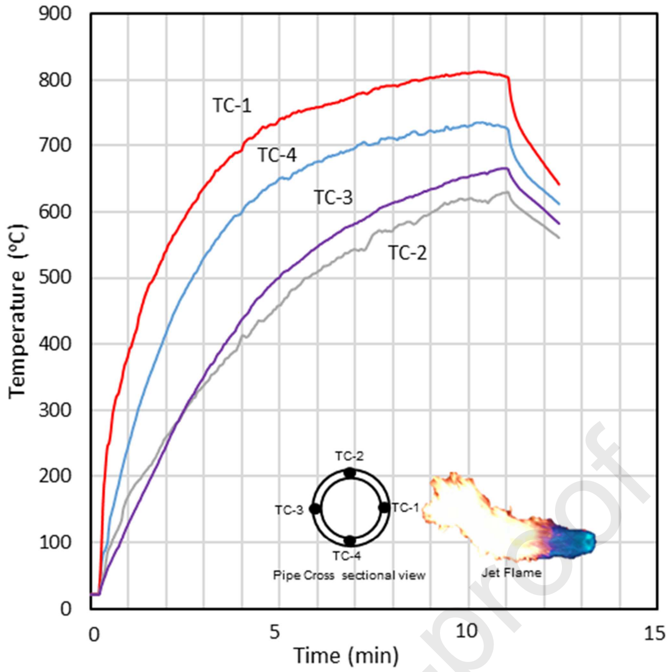

Fig. 6. Evolution of pipe wall temperatures as a function of time (stagnant air inside the pipe, sonic jet).

The thermocouple located in the bottom wall (TC-4) of the pipe registered somewhat lower —even though also very high— temperatures, reaching a maximum value of 737 ºC. Lower temperatures were registered by the top and back wall thermocouples (TC-2, TC-3, respectively), even if the pipe wall was in contact with the flames. This should be attributed to a much lower contribution of the radiation on the back pipe surface originated by the flame features in this zone (see Fig. 5a), and to a significantly lower contribution of the convection mechanism in the top pipe surface due to the tangential contact of the flames.

4.2 Liquid inside the pipe

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 the wall temperature will reach much lower values than in the previous case due to the corresponding cooling effect. Figure 7 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 those in Figure 6). In this case, stagnant water was contained in the pipe.

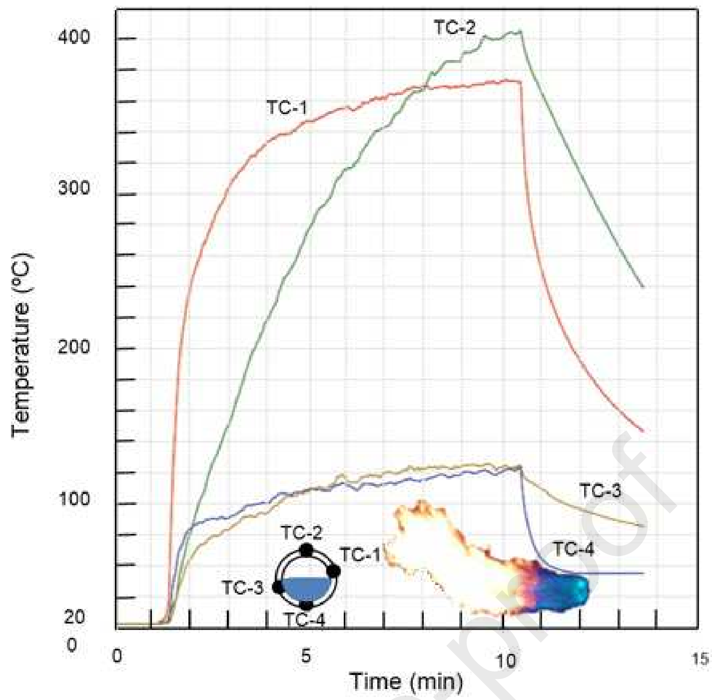

Fig. 7. Evolution of pipe wall temperatures as a function of time (stagnant water inside the pipe, sonic jet).

The temperatures registered by the thermocouples located at the front and top zones, TC-1 and TC-2, respectively, where relatively high (a maximum temperature of 375 ºC for the front thermocouple was reached after 9 min of exposure, and 400 ºC for the top one) but much lower than those found when the pipe contained air, due to the action of the water droplets ejected by the boiling liquid; and the temperatures measured by the thermocouples located at the zones of the wall in contact with the water measured significantly lower values, lightly higher than the water boiling temperature. Of course, if water was flowing at a certain speed, the cooling effect would be higher. Similar results (to those from TC-2, TC-3 and TC-4) were obtained by Birk et al. (2006a) with longer exposure times, when studying the flames impingement on a vessel.

5. Heat transfer fluxes and heat transfer coefficients

The analysis of both the pipe wall temperature and the jet flame temperature at any position of the pipe wall (i.e. front, bottom, back and top) allowed to obtain the approximate values of the flame-to-wall heat transfer fluxes and heat transfer coefficients corresponding to each case (Figure 8).

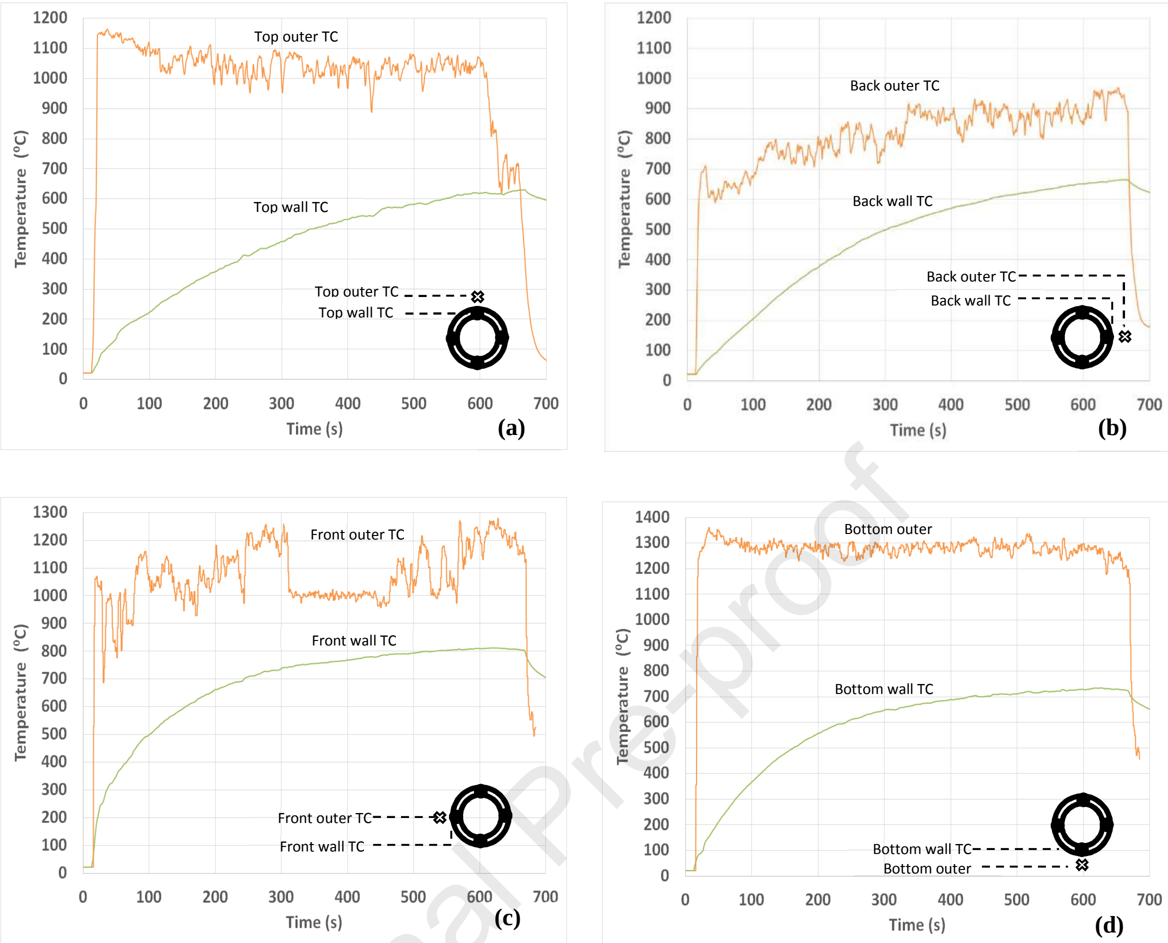

Fig. 8. Evolution of flames and temperature together with the corresponding flames temperature by a sonic flames impingement at the bright zone in (a) the top wall, (b) the back wall, (c) the front wall, and (d) the bottom wall.

The heat fluxes reaching the pipe wall were calculated during the first step of the test (i.e. within the first 40 s, although the time lapse varied with the pipe wall position), when the still relatively low temperature of the pipe (between 25 ºC and 100 °C) implied negligible heat losses from it. In this condition, all the heat received through a given external surface area (i.e. for a given steel mass), during a certain time by both radiation and convection mechanisms, were invested in heating the pipe wall, as follows:

$$Q = \frac{m_p . C_p}{A_p} \cdot \frac{dT_{wall}}{dt} \quad (2)$$

And the flames-to-wall heat transfer coefficient was estimated by:

$$Q = h \cdot A_p \cdot (T_{flame} - T_{wall}) \quad (3)$$

Due to the strong turbulence, in some cases the flame temperature underwent important oscillations and an average value was taken. The flame-to-wall heat transfer coefficients were calculated from the value of the heat flux reaching the pipe wall, and by knowing both the pipe wall temperature at a given point and the flame temperature at that location (measured by the thermocouples located quite close to that wall point). This coefficient was associated to all the net heat flux reaching and entering the pipe wall, thus including the net contributions of both conductive and radiative phenomena. Afterwards, as the pipe wall progressively increased and the temperature difference driving force decreased, the pipe heating rate decreased and the heat losses from it to the environment increased. Finally, an essentially constant temperature was reached when the heat received by the pipe was equal to the heat lost from it. These values corresponding to one representative experimental case have been included in Table 4. In other tests, with the propane source at higher pressure, higher values of the flames-to-wall heat transfer coefficient (up to 0.43 $kW \cdot m^{-2} \cdot °C$) were registered.

Table 4. Heat fluxes and heat transfer coefficients for a representative experimental case (sonic jet fire, flames bright zone impingement).

Stagnation pressure (bar)	**Mass flow rate (kg/s)**	**Gas exit velocity (m/s)**	**Impingement position**	**Heat flux ($kW \cdot m^{-2}$)**	**Flames-to-wall heat transfer coefficient ($kW \cdot m^{-2} \cdot °C^{-1}$)**
1.75	0.07	250.1	Front wall	170	0.16
			Bottom wall	126	0.112
			Top wall	95	0.125
			Back wall	90	0.114

The bright, fully developed zone of the jet fires was the one (i.e. compared to the intermediate one and the blue one) which gave the highest heating rates. The evolution of the pipe wall temperatures in the four positions of the thermocouples (front, bottom, back and top) for this situation have been shown in Figure 8 for a sonic jet fire**.**

The highest heat fluxes, reaching values of up to 275 $kW \cdot m^{-2}$, were registered for the higher propane release pressures at the front position, where the flames impinged against the pipe wall, with a very high turbulence and an intense convective contribution. These values were higher than those measured by most of other authors, also with propane jet fires (except some tests by Wighus and Drangsholt, see Table 5). At the other positions (bottom, back and top), the heat fluxes were significantly lower.

Table 5. Heat flux and convective heat transfer coefficient obtained by other authors.

Reference	Heat flux			Convective heat transfer coefficient
	Total (kW/m^2)	Radiative (kW/m^2)	Convective (kW/m^2)	($kW\cdot m^{-2}\cdot °C^{-1}$)
Bradley, 2017	50-250	NA	NA	NA
Virk, 2015	68-110	NA	NA	0.048 -0.094
Lowesmith et al., 2007	240	160	80	0.08
Persaud et al., 2001	180-200	NA	NA	NA
Wighus and Drangsholt, 1993	190-340	NA	NA	NA

Several authors have experimentally found that both radiation and convection parts can dominate the total heat flux, depending on the circumstances (Kilham, 1948; Hustad and Sonju, 1991; Lowesmith et al., 2007). In the current experiments, convection heat transfer was determined to be always the more dominant part in the front wall of the pipe, followed by the back and bottom walls. This can be explained as the consequence of direct contact with the highly turbulent jet flame for the front zone, and the influence of the formation of jet fire wake on the pipe's back surface and of a contribution of the flame buoyancy convection in the bottom zone. However, light differences in the position of the flames with respect to the pipe could have significant influence on the heat fluxes received by the bottom, back and top zones of the pipe wall.

It is also interesting to note the possible influence of soot deposits on the pipe wall, a phenomenon that was detected in the diverse developed tests, which according to some authors (Patej and Durussel, 2007) could have a thermal insulating effect. Nevertheless, in the present tests the soot deposition was not important, being probably eroded by the jet action.

6. 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 even in the case of relatively small jet fires. 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 (up to 275 kW/m^2 in the worst case), originating extremely high temperatures in the pipe wall when there is a gas inside, 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 (initial heating rates of up to 19.5 ºC/s were registered), 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 much 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

This research was funded by the Institut d'Estudis Catalans (project PRO2021-SO3) and the Spanish Ministry of Economy and Competitiveness (project CTQ2017-85990, co-financed with FEDER funds). A.P. gratefully acknowledges financial support of the Royal Society as a Postdoctoral Newton International Fellowship.

Nomenclature

A_p	surface area of the pipe wall taken for the heat flux calculation (m^2)
C_p	specific heat of the pipe wall ($kJ\cdot kg^{-1}\cdot °C^{-1}$)
d	pipe diameter (m or mm)
dt	duration of initial heating measurement (s)
dT_{wall}	temperature increase in the pipe wall (°C)
f	frequency of occurrence ($year^{-1}$)
h	flames-to-wall heat transfer coefficient ($kW\cdot m^{-2}\cdot °C^{-1}$)
L	length of the surface or pipe (m or mm)
L_{flame}	length of the jet flame (m)
m_p	mass of the pipe wall taken for the heat flux calculation (kg)
OD	outer diameter of pipeline (in, cm or mm)
P	probability of occurrence (-)
P_{in}	stagnant pressure inside the pipe or the vessel (Pa)
P_{out}	pressure downstream the outlet orifice (Pa)
$\bar{P}$	probability of occurrence of the complementary event (-)
Q	flame to wall total heat flux (kW)
Re	Reynolds number ($d\cdot u\cdot \rho/\mu$)
T_{flame}	average temperature of flame at a given location (°C)
T_{wall}	temperature of pipe wall at a given location (°C)
u	release speed of the jet ($m\cdot s^{-1}$)
X	horizontal distance from nozzle to pipe centre line (cm)
Y	elevation distance from level ground to pipe centre line (cm)

Greek symbols

γ	ratio of specific heats (-)
μ	dynamic viscosity at the outlet orifice ($kg/m\cdot s$)
ρ	density at the outlet orifice (kg/m^3)

Acronyms

TC	thermocouple

References

Baukal, C.E., Gebhart, B., 1995. A review of flame impingement heat transfer studies part 1: experimental conditions. Combustion Science and Technology, 104:4-6, 339-357. https://doi.org/10.1080/00102209508907727

Bennett, J.F., Cowley, LT., Davenport J.N., Rowson, J.J., 1991. Large scale natural gas and LPG jet fires - final report to the CEC, TNER.91.022; Shell Research Limited.

Birk, A.M., Poirier, D., Davison, C.J., 2006a. On the response of 500 gal propane tanks to a 25% engulfing fire. J. of Loss Prevention in the Process Industries. 19, 527-541. https://doi.org/10.1016/j.jlp.2005.12.008

Birk, A.M., Poirier, D., Davison, C.J., 2006b. On the thermal rupture of 1.9 m^3 propane pressure vessels with defects in their thermal protection system. J. of Loss Prevention in the Process Industries. 19, 582-597.

Birk, A.M., VanderSteen, J.D.J., 2006. The effect of pressure relief valve blowdown and fire conditions on the thermo-hydraulics within a pressure vessel. J. of Pressure Vessel Technology. 128, 467-475.

Bradley, I., 2017. A review of the applicability of the jet fire resistance test method to severe release scenarios. Health and Safety Executive. Report RR1120.

Casal, J. 2018. Evaluation of the effects and consequences of major accidents in industrial plants, 2nd edition. Elsevier, Amsterdam.

Droste, B., Schoen, W., 1998. Full scale fires test with unprotected and thermal insulated LPG storage tanks. J. of Hazardous Materials. 20, 41-53.

Foroughi, V., Cavini, A., Palacios, A., Albó, K., Àgueda, A., Pastor, E., Casal, J., 2019. Domino effect by jet fire impingement in pipelines. Chem. Eng. Trans. 75. https://doi.org/10.3303/CET1977156

Gómez-Mares, M., Zárate, L., Casal, J., 2008. Jet fires and the domino effect. Fire Saf. j. 43, 583-588. https://doi.org/10.1016/j.firesaf.2008.01.002

Hassan, F., Ahmed, F., 2007. Metallurgical analysis of high pressure gas pipelines rupture, Pak. J. Eng. Appl. Sci. 1, 14-23.

Hustad, J. E., Sonju, O.K., 1986. Radiation and size scaling of large gas and gas/oil diffusion flames. Dynamic of reactive systems, Part I, Flames and configurations. AIAA Progress in Astronautics and Aeronautics, New York, 105, 365-387.

Hustad, J. E., Sonju, O.K., 1991. Heat transfer to pipes submerged in turbulent jet diffusion flames. In: da Graça Carvalho M., Lockwood F.C., Taine J. (EDS) Heat Transfer in Radiating and

Combusting Systems. EUROTHERM Seminars, vol 17. pp. 474-490. Springer, Berlin, Heidelberg. https://doi.org/10.1007/978-3-642-84637-3_30

Kilham J.K., 1948. Energy transfer from flame gases to solids. Combustion Flame and Explosion Phenomena. 3(1), 733-740. https://doi.org/10.1016/S1062-2896(49)80102-4

Kuntikana, P., Prabhu, S.V., 2018. Heat transfer investigations on methane-air premixed flame jet exiting from a circular nozzle and impinging over semi-cylindrical surfaces. International J. of Thermal Sciences. 128, 105–123. https://doi.org/10.1016/j.ijthermalsci.2018.02.016

Landucci, G., Cozzani, V., Birk, M., 2013. Heat radiation effects, in: G. Reniers and V. Cozzani (Eds.), Domino Effects in the Process Industries: Modelling, Prevention and Managing, 70-115.

Lowesmith, B. J., Hankinson, G., Acton, M. R., Chamberlain, G., 2007. An overview of the nature of hydrocarbon jet fire hazards in the oil and gas industry and a simplified approach to assessing the hazards. Process Safety and Environmental Protection. 85(3), 207-220. https://doi.org/10.1205/psep06038

Malikov, G.K., Lobanov, D.L, Malikov, K.Y., Lisienko, V.G., Viskanta, R., Federov, A.G., 2001. Direct flame impingement heating for rapid thermal materials processing. International J. of Heat and Mass Transfer. 44, 1751-1758. https://doi.org/10.1016/S0017-9310(00)00204-0

MHIDAS (Major Hazardous Incident Data Service) 2007, in AEA Technology, London: HSE-Health and Safety Executive (United Kingdom).

Morad, M.R., Momeni, A., Ebrahimi Fordoei, E., Ashjaee, M., 2016. Experimental and numerical study on heat transfer characteristics for methane/air flame impinging on a flat surface. International J. of Thermal Sciences. 110, 229-240. http://dx.doi.org/10.1016/j.ijthermalsci.2016.07.005

Palacios, A., Casal, J., 2011. Assessment of the shape of vertical jet fires. Fuel, 90, 824-833. https://doi.org/10.1016/j.fuel.2010.09.048

Palacios A, Muñoz M, Darbra RM, Casal J., 2012. Thermal Radiation from Vertical Jet Fires. Fire Safety Journal. 51, 93-101. https://doi.org/10.1016/j.firesaf.2012.03.006

Patej, S., Durussel, T., 2007. Domino effect: thermal impact of jet fires on industrial pipes. IChemE. Symposium Series no. 153, 1-6.

Persaud, M.A., Butler, C.J., Roberts, T.A., Shirvill, L.C., Wright, S., 2001. Heat-up and failure of liquefied petroleum gas storage vessels exposed to a jet fire. Proceedings of the 10th International Symposium, 19–21 June 2001, Stockholm, Sweden. pp. 1069-1106.

Planas, E., Montiel, H., Casal, J, 1997. A survey of the origin, type and consequences of fire accidents in process plants and in the transportation of hazardous materials. Trans IChemE. 75, Part B, 3-8. https://doi.org/10.1205/095758297528706

Ramírez-Camacho, J. G., Pastor, E., Casal, J., Amaya-Gómez, R., Muñoz-Giraldo, F., 2015. Analysis of domino effect in pipelines. J. of Hazardous Mater. 298, 210-220. https://doi.org/10.1016/j.jhazmat.2015.05.033

of the requirements for the degree of Master of Science.

Scarponi, G. E., Landucci, G., Birk, A. M., Cozzani, V., 2018. LPG vessels exposed to fire: scale effects on pressure build-up. J. of Loss Prevention in the Process Industries. 56, 342-358. https://doi.org/10.1016/j.jlp.2018.09.015

Sonju, O.K., Hustad, J. E., 1984. An experimental study of turbulent jet diffusion flames and react systems, AIAA Progress in Astronautics and Aeronautics, New York, 95, 320-339.

Townsend, W., Anderson, C., Zook, J., Cowgill, G., 1974. Comparison of thermally coated an uninsulated rail tank filled with LPG subjected to a fire environment. (Report No. FRA-OR&D 75-32). US Department of Transportation Federal Railroad Administration Office of Research Development, and Demonstrations.

TSBC, Transportation Safety Board of Canada. Commodity Pipeline Occurrence Report P95H0036, Natural gas pipeline ruptures, TSB. (Transportation Safety Board of Canada), Rapid City, Manitoba, Canada, July 29, 1995.

https://www.bst-tsb.gc.ca/eng/rapports-reports/pipeline/1995/p95h0036/p95h0036.html (consulted 09/2020)

TSBC, Transportation Safety Board of Canada. Commodity Pipeline Occurrence Report P95H0036, Natural gas pipeline ruptures, TSB. (Transportation Safety Board of Canada), Near Beardmore, Ontario, Canada, February 19, 2011.

https://www.tsb.gc.ca/eng/rapports-reports/pipeline/2011/p11h0011/p11h0011.html (consulted 09/2020)

TSBC, Transportation Safety Board of Canada. Commodity Pipeline Occurrence Report P95H0036, Natural gas pipeline ruptures, TSB. (Transportation Safety Board of Canada Near Buick, British Columbia, Canada, June 28, 2012.

https://www.bst-tsb.gc.ca/eng/rapports-reports/pipeline/2012/p12h0105/p12h0105.html (consulted 09/2020)

TSBC. Transportation Safety Board of Canada. Commodity Pipeline Occurrence Report P95H0036, Natural gas pipeline ruptures, TSB. (Transportation Safety Board of Canada, Near Otterburne, Manitoba, Canada, January 25, 2014.

https://www.bst-tsb.gc.ca/eng/enquetes-investigations/pipeline/2014/p14h0011/p14h0011.html (consulted 09/2020)

USDI, US Department of the Interior Minerals Management Service, Gulf of Mexico OCS Region, OCS Report Investigation of March 19, 1989, Fire South Pass Block 60 Platform B, Lease OCS-G

1608, https://www.bsee.gov/sites/bsee.gov/files/incident-statisticssummaries-fire-explosions/reports/90-0016-pdf.pdf (consulted 09/2020)

USDT. Department of Transportation, Pipeline and Hazardous Materials Safety Administration, Natural gas pipeline ruptures, Marengo County, Alabama, US, December 3, 2011.

Vílchez, J. A., Espejo, V., Casal, J., 2011. Generic event trees and probabilities for the release of different types of hazardous materials. J. of Loss Prevention in the Process Industries. 24, 281-287. https://doi.org/10.1016/j.jlp.2011.01.005

Virk, A.S., 2015. Heat Transfer Characterization in Jet Flames Impinging on Flat Plates. Thesis submitted to the faculty of the Virginia Polytechnic Institute and State University in partial fulfilment

Wang, Z., Zhou, K., Liu, M., Wang, Y., Qin, X., Jiang, J., 2019. Lift-off behavior of horizontal subsonic jet flames impinging on a cylindrical surface. Proceedings of the 9 International Seminar on Fire and Explosion Hazards (ISFEH9). 831-842. https://doi.org/10.18720/SPBPU/2/k19-79

Wighus, R., Drangsholt, G., 1993. Impinging jet fire experiments - propane 14 MW laboratory tests. SINTEF NBL – Norwegian Fire Research Laboratory. Report STF25 A92026.

Zhang, B., Liu, Y., Laboureur, D., Mannan, S., 2015. Experimental study of propane jet fire hazards; thermal radiation. Industrial & Engineering Chemistry Research. 54, 9251-9256. https://doi.org/10.1021/acs.iecr.5b02064

Highlights

Jet fires have been the origin of severe domino effect sequences

Jet flames impingement have originated serious accidents in parallel pipelines

An experimental set-up has allowed the study of jet fire flames impingement on a pipe

Flames impingement imply very high heat fluxes, heating the pipe wall very quickly up to high and dangerous temperatures

The results obtained have shown the importance of safety measures (distance, fire proofing) in pipelines hallways

Author statement

New version and response to reviewers attached, as well as the rest of information required

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

There are no conflicts to declare.