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Jet Fires: An Experimental Study of the Main Geometrical Features of the Flame in Subsonic and Sonic Regimes

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Although jet fires are usually smaller than other fires, they may lead to a destructive chain of events that can increase the scale of an accident. Therefore, their size should be predicted for accurate risk assessment. In the literature, most of the proposals for estimating jet fire size concern small jet fires (up to 2.5 m in length) or subsonic flames. In this study, experiments on relatively large propane jet fires in still air were performed. Vertical turbulent diffusion flames up to 10 m in length, with sonic and subsonic mass flow rates, were obtained using six different orifice exit diameters. The experiments were filmed with video and thermographic cameras and the resulting visible and infrared images were used to determine flame length and lift-off distance. Expressions for estimating jet length as a function of several variables (mass flow rate, orifice exit diameter, Froude and Reynolds numbers) are also proposed. *AIChE J,* 55: 256–263, 2009
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Introduction

Among the accidental fires that can occur in processing plants or in the transportation of hazardous materials (due to leaks caused by ruptures in equipment or pipelines), jet fires are of particular interest. They are characterized by a high momentum jet flame lifted above the mouth of the duct from which the fuel (often a gas) is flowing, generally at a relatively high pressure.

Jet fires are diffusion flames (i.e., the fuel and the air are initially separated and mixing occurs after the fuel release). For hydrocarbon turbulent jet diffusion flames, two dominant regimes can be found: buoyancy and momentum. For flames with a very high velocity at a very high Froude number, the jet momentum dominates the mixing process. Thus, the momentum of the fuel vapor largely determines the behavior of these types of flames. This will be typically the case of an accidental jet fire. In contrast, at lower velocities, buoyancy becomes important in flames, because of the density differences that combustion generates (i.e., the density decreases from the density at the outlet orifice diameter to the density located at the top of the flame).[1,2] This is often the case of a flare.

Although the direct effects of a jet fire are among the least severe of those found in fire accidents, they can often provoke a chain of events that ultimately amplifies the scale of the destruction caused by a single jet fire. For example, a single jet fire might damage a piece of equipment (i.e., a pipeline or a tank) and cause it to fail, which may then have more severe consequences still. This has been commonly described as the domino effect. In fact, jet fires have repeatedly been reported as being the first stage in severe accidents involving explosions, large fires, and serious damage to equipment because of thermal radiation and flame impingement.

A historical survey recently carried out by Gómez-Mares et al.[3] reports that in 50% of the jet fire events registered in accident databases, the domino effect has led to a subsequent

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explosion, large fire, or other events with severe effects; the consequences for equipment are particularly severe if flame impingement occurs. Thus, to assess the risk of such a situation it is essential to be able to predict the size of a possible jet fire.

Although several authors have published experimental data on jet fire size, most of them concern relatively small jet fires (of up to 2.5 m in length) or involve only subsonic exit velocities. However, in the event of an accidental release of a flammable gas (i.e., through a safety relief valve or a hole), sonic exit velocity (i.e., the velocity of sound in the gas in exit gas conditions) is often reached. In fact, for most gases sonic velocity is reached if the pressure at the fuel source is greater than 1.9 bar (absolute), which is common in many storage tanks and pipelines.[4] Because of the lack of research in this area the main aspects of accidental jet fires are still poorly understood.

Thus, the prediction of the flame length in the event of a subsonic or sonic jet fire is important because it is closely related to the possibility that flames impinge on other equipment, giving rise to a domino effect. Besides, from the point of view of flame length, vertical upward flames are the worst case condition for fire safety because buoyancy contributes, in this orientation, to longer flames. Therefore, a set of expressions allowing the calculation of flame length and lift-off distance would be of great interest.

This study provides an assessment of relatively large vertical propane jet fires issued from a straight tube into quiescent air at atmospheric pressure and temperature (experimental turbulent diffusion flames of up to 10 m in length). The main geometrical features of the flames (expressed in terms of flame length and lift-off distance) are analyzed for sonic and subsonic exit velocities, which were obtained with different outlet diameters. A dimensional analysis was also carried out to be able to correlate these experimental results with the dimensionless numbers obtained. Furthermore, mathematical expressions to estimate jet fire length are proposed.

Literature Survey

Various guidelines for predicting the length of vertical jet fires in quiescent air, through the study of how jet fire length varies with certain variables (orifice diameter, jet velocity, etc.), have been recommended.[1,5–16] However, according to our findings, most of this research has been focused on either subsonic flames or small-scale jet fires, with flame lengths of up to 2.5 m.

Several authors have correlated flame length with the Froude number (Fr) in the buoyancy-dominated jet regime. The flame lengths become dimensionless when they are divided by the orifice diameter (d) of the release point; this dimensionless ratio is then plotted against the Froude number.[1,7–13] In the majority of these studies, the same expression to predict flame length as a function of Fr and d over the buoyancy-dominated flow regime is proposed (Eq. 1).[7–10,13] Table 1 summarizes the information about the type of fuel and the Froude number's range of applicability.

$$\frac{L}{d} = A \cdot Fr^{n} \tag{1}$$

Table 1. Values of A, n, and Fr Ranges of Applicability (Eq. 1) Based on Experimental Data

Author	Fuel	Fr Range	A	n
Kiran and Mishra[7]	LPG	Up to 4.5×10^4	30	0.2
Suris et al.[8]*	Hydrogen	Up to 3×10^4	14 or 16	0.2
	Methane		27 or 29	
	Propane		40	
Sonju and Hustad[9]*	Methane	Up to 1×10^5	21	0.2
	Propane		27	
McCaffrey[10]*	Methane	Up to 3×10^4	28	0.2
Santos and Costa[11]	Ethylene	Up to 2×10^4	24	0.2
	Propane		36	
Bagster and Schubach[13]*	Methane	Up to 1×10^5	23	0.2

*These authors define L as the distance from the gas release point to the tip of the visible flame.

Most of these studies conclude that buoyancy is the dominating mechanism for hydrocarbon jet flames when Fr is less than or equal to a given value. Beyond this Froude number range, momentum essentially becomes the dominant mechanism, making the normalized flame length reach a constant value and making it independent of Fr.[1,7–11] This kind of correlation is useful and suitable only for subsonic jet exit velocities.

Becker and Liang[14] suggested that flame length be correlated with the Richardson ratio, which determines the transition between forced and natural convection. However, this equation is the result of a study based on laboratory sized flames with orifice diameters ranging between 0.69 and 4.57 mm. This flame length correlation was expanded on by Kalghatgi[15] to include both regimes (forced and natural convection), using small-scale experiments. Although this author used four different gases (ethylene, hydrogen, methane, and propane), most of the experimental data were limited to subsonic flow, only hydrogen flames of up to 2 m were obtained at sonic conditions. Besides, these proposed correlations require a vast number of calculations to obtain the parameters involved in the iterative equations.

Another study developed by McCaffrey and Evans[16] analyzes very large methane jet flames, which were obtained with orifice diameters ranging between 38 and 102 mm. They suggest a general expression which assumes that sonic flame length is 200 times the value of the fictitious exit diameter resulting after the supersonic expansion. Nevertheless, this expression is based on the behavior of the data obtained for subsonic jets.

Concerning the shape of jet fires, some authors have assumed it to be cylindrical, correlating both the length and diameter of subsonic jet flames with Fr.[9,12,13] Other authors have assumed the shape to be the frustum of a cone,[17,18] which can represent a flare under the influence of wind fairly accurately but does not correspond to the shape of a real jet fire.

Flares, which are widely used in processing plants to safely dispose of flammable gases, have also been studied.[18–20] Some of these studies analyze data on large flame lengths[20]; these data are indeed suitable for flares but the diameters used are out with the values generally considered in risk analysis.[13]

Another variable that influences the distance covered by a jet fire is the lift-off distance (i.e., the centerline distance from the gas release point to the start of the detached and

Table 2. Values for *c* (Eq. 2) Based on Experimental Data

Author	Fuel	Orifice Diameter Range (mm)	*c* (s)
Kiran and Mishra[7]	LPG	2.2	1.8×10^{-3}
Santos and Costa[11]	Ethylene	5–8	0.8×10^{-3}
	Propane		2.6×10^{-3}
Peter and Williams[21]	Methane	4–12	3.6×10^{-3}

stabilized flame). Lift-off is a function of diverse variables (i.e., jet exit velocity, outlet diameter, Froude number, etc.) and various authors have tried to establish a relationship using these variables.[6,7,9–12,15,16,21–24]

For subsonic conditions, some authors have proposed a correlation for the normalized flame lift-off distance (S/d) as a function of the ratio between the jet exit velocity (V) and outlet diameter (Eq. 2)[7,11,21]:

$$\frac{S}{d} = c \cdot \frac{V}{d} \tag{2}$$

where the constant (c) has the dimension of time. Different values have been proposed in Table 2. In it the authors used outlet orifice diameters of up to 12 mm. Sonju and Hustad[9] experimented with propane and methane jet flames using orifice diameters ranging between 2.3 and 80 mm. Their lift-off distances agree fairly well with Eq. 2 when c is equal to 3.6×10^{-3} s (the value proposed by Peters and Williams[21]), thus indicating that the lift-off distance does not depend on the orifice diameter.[7,9,11,21] However, Rokke et al.[6] and Schuller et al.[12] experimented with diameters ranging between 3.2 and 29.5 mm and 10 and 80 mm, respectively. They concluded that the lift-off distance depends on the outlet orifice diameter. This was also reported by Broadwell et al.[22] and Lee et al.[24]

Concerning subsonic and sonic conditions, McCaffrey and Evans[16] reported on subsonic and sonic lift-off distances (lift-off distances of up to 4 m) for large methane jet flames. Their study proposed the use of two correlations, which assume that S is independent of the orifice diameter, to estimate the lift-off distance in the two regimes (sonic and subsonic velocities). However, it also concluded that the large scatter in their data in the sonic regime was not a characteristic of these kinds of flames, based on other flames produced at the laboratory scale. As a result, they suggested that far more systematic research on this phenomenon at sonic conditions should be carried out.

It can be seen that whether the lift-off distance, in either sonic or subsonic regimes, is dependent on or independent of the orifice diameter is still uncertain. Besides, the majority of the studies have been focused on the lift-off distance, but only at subsonic exit velocities.[6,7,9–12,21,23,24] Thus, an equation to calculate lift-off distance in sonic conditions, which is the most common situation in accidental gas releases, would be of utmost interest, because of the lack of research on this phenomenon.

Experimental Set-Up and Procedures

Open field experiments were performed with relatively large propane jet fires in still air. The experimental set-up was built in the Can Padró Safety Training Center, near Barcelona. A schematic of the experimental set-up is shown in Figure 1. It comprised a pipe with which vertical jet fires at sonic and subsonic exit velocities could be obtained (Figure 2). The influence of the release source size was studied by using interchangeable nozzles, which allowed different circular orifice outlet diameters (d) ranging from 10 to 43.1 mm to be selected. Six orifice exit diameters of 10, 12.75, 15, 20, 30, and 43.1 mm were used (the last orifice diameter represented a full rupture of the pipeline).

The fuel used was propane (with a composition of 97% propane, 1.5% butane, and 1.5% other gases such as hydrogen, methane, and nitrogen) stored in a 4 m^3 pressurized vessel. The fuel flowed through ~50 m of pipe (with an inner diameter of 43.1 mm and no thermal isolation). The pressure at 0.05 m before the release point (P_{in}) was measured using an electronic pressure transmitter (Barksdale, electronic pressure transmitter type UPA5). This was taken as the upstream stagnation pressure of the flow. The temperature at the exit orifice diameter (T_{or}) was obtained using an uncoated K-type thermocouple (nickel-chromium/nickel-aluminum). By apply-

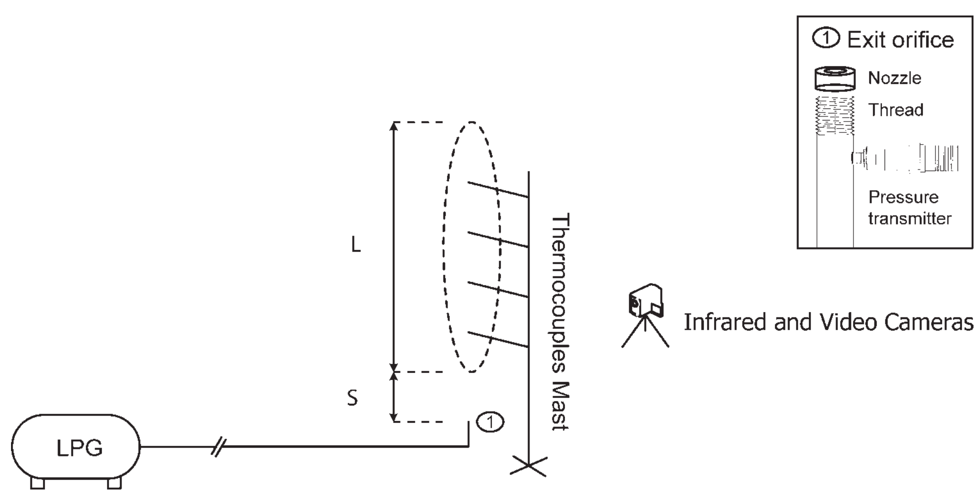

Figure 1. Schematic of the experimental set-up.

ing the appropriate thermodynamic relations, it was possible to calculate the static pressure at the outlet orifice (P_{or}), the temperature inside the pipeline (T_{in}), the jet velocity at the outlet orifice (V), and the mass flow rate (m) for both sonic and subsonic regimes.

The main geometrical features of the flame (i.e., lift-off distance and flame length) were determined by analyzing visible and infrared images once the stationary state was reached (the transient state lasted approximately 0.8–1.5 s). These were obtained from two VHS cameras that registered visible light and an infrared thermographic camera (Flir Systems, AGEMA 570). The thermographic camera had a field of view of 24° horizontal and 18° vertical, and its spectral range was between 7.5 and 13 μm. The visible cameras were positioned orthogonally to the flame, one of which was positioned next to the thermographic camera during the experiments. Furthermore, a meteorological weather station (Davis Instruments, GroWeather) continuously recorded the following meteorological conditions: wind direction, wind speed, ambient temperature, relative humidity, and solar radiation. The uncertainty due to the experimental setup was estimated to be ±11%.

The experimental data were registered in real time by using a FieldPoint device hardware (a complete description of this system can be found in Muñoz[25]).

Figure 2. A vertical jet fire.

[Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

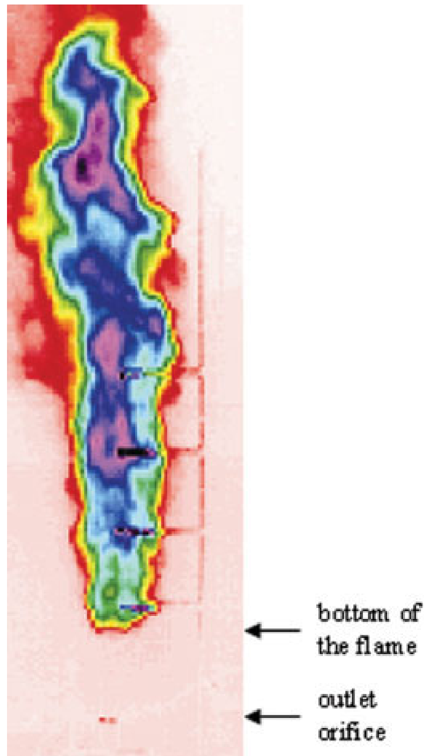

Figure 3. An infrared image of a vertical jet fire.

[Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

Results and Discussion

From the analysis of both the visible and infrared images, it can be seen that the shape of a vertical jet fire in still air could be approximated to a cylinder, as has already been noted by other authors.[9,12,13]

Total flame length

Visible light and infrared thermographic video recordings were used to determine the total flame length: visible flame length (L) plus lift-off distance (S).

The study was centered essentially on lift-off distance and visible flame length rather than on total flame length. The reason is that total flame length can be easily obtained by adding visible flame length and lift-off distance. Furthermore, to calculate the radiation from a jet fire on a given target, it is the visible flame shape and size that is required.

In each test, a segment of infrared thermographic recordings corresponding to the stationary state was selected, digitalized, and divided into a sequence of digital images at four frames per second. In the majority of the tests, the same procedure was followed using a series of 25 digital images per second, which were obtained from the VHS films. The two features (L and S, respectively) were obtained from the analysis of each image using two different software programs that allow image processing. The lift-off distance was measured from the outlet orifice to the zone at which the stabilized flame started; it was clearly shown by the infrared thermographic images (Figure 3).

The flame length was defined as the distance from the base of the lifted flame to the flame tip.

In some studies, the reported experimental total flame lengths, visible flame lengths, and lift-off distances correspond to time-averaged values.[7,9,11] In the present study, the reported average values for flame length and lift-off distance were obtained in accordance with the intermittency criterion developed by Zukoski et al.[26] The intermittency (I) is defined as the fraction of time during which at least part of the flame lies above a horizontal plane located at elevation Z above the burner.[27] In this article, I is defined as the fraction of time during which flame length and lift-off distance are at least higher than L and S, respectively. Therefore, the average flame length and lift-off distance values are defined as the length and distance at which I reaches a value of 0.5.

As a later stage, a dimensional analysis was carried out to correlate the experimental results. Five dimensionless groups were thus obtained. Four of these five groups included the Froude number (Fr) and the Reynolds number (Re), as well as the expressions of flame length (L) and lift-off distance (S), both normalized by the orifice diameter (d). Finally, by using these groups, a set of mathematical expressions to estimate jet fire length are suggested.

Visible flame length

A common trend was observed for the subsonic flow range when normalized flame lengths (L/d) were plotted as a function of Fr (Figure 4). As explained later on in this article, the data corresponding to sonic flow are not significant in such a plot.

The variation in flame length as a function of several variables, such as outlet diameter, mass flow rate, and the Froude number and Reynolds number, was analyzed. The mass flow rate ranged between 0.006 and 0.54 kg/s.

With regard to the present results, the subsonic data obtained when L/d is plotted against Fr (Figure 4) were also correlated according to Eq. 1. The subsonic data for L/d were correlated with:

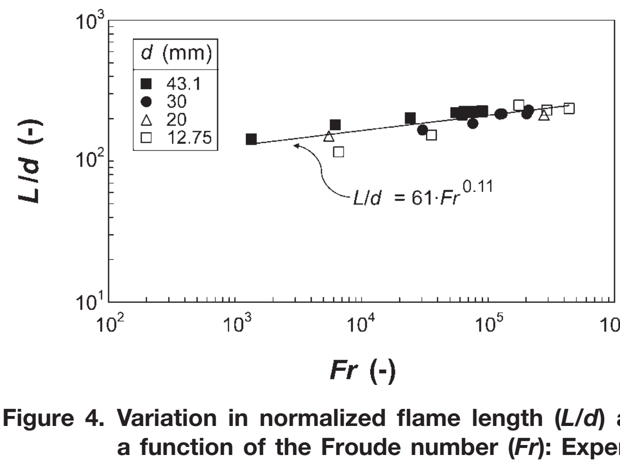

Figure 4. Variation in normalized flame length (*L/d*) as a function of the Froude number (*Fr*): Experimental results for subsonic velocity, for various orifice outlet diameters (*d*).

Equation 3 is also shown.

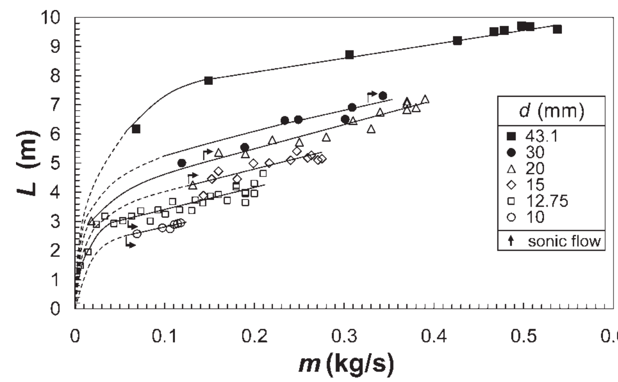

Figure 5. Variation in the sonic and subsonic flame lengths (*L*) with fuel mass flow rate (*m*), for various orifice outlet diameters (*d*).

$$\frac{L}{d} = 61 \cdot Fr^{0.11} \qquad (3)$$

However, in the present study, the results for flames were extended to the regime in which the sonic exit velocity was reached. It should be mentioned that for a given value of Fr in the sonic flow range (i.e., for a constant sonic velocity of the gas at the orifice) and an orifice outlet diameter, larger flame lengths are still possible if the gas pressure inside the pipeline (P_{in}) continues to increase. This is because the gas density inside the pipeline (ρ_{in}) increases with P_{in}. Since the mass flow rate (m) is a function of density, for a given outlet diameter, m increases with an increase in ρ_{in} and P_{in}. This variation in flame length could not be predicted any further using an expression such as Eqs. 1 or 3. Thus, additional research was required in the sonic flow regime.

In Figure 5, L was plotted against the mass flow rate (m) for subsonic and sonic data. The transition to sonic flow is marked for each outlet diameter. The solid lines represent experimental data. The dashed lines correspond to an extrapolation of the experimental data, which is based on the behavior of the experimental data obtained with the lowest mass flow rate values combined with the fact that they should meet the origin of coordinates. It is important to highlight that with an orifice diameter of 10 mm the flame had to be maintained with a permanent ignition source (i.e., a torch); otherwise, blow-out (self-extinction of the jet fire immediately after ignition) occurred. Figure 5 shows that for a given outlet diameter (d), flame length increases with m, and for a given mass flow rate, L increases with d. Similar results were obtained by Kalghatgi.[15]

In an attempt to achieve a single expression suitable for predicting L in the two regimes (subsonic and sonic flows), the L/d ratio was plotted as a function of the orifice's Reynolds number (Re) in a log–log plot that included all the experimental data from the different orifice diameters (Figure 6). In this way all data follow the same trend and the relationship between the two dimensionless groups can be expressed fairly accurately by the following expression:

$$\frac{L}{d} = 5.8 \cdot Re^{0.27} \qquad (4)$$

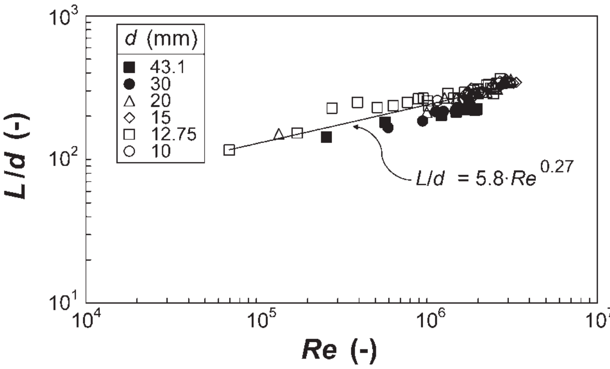

Figure 6. Variation in the sonic and subsonic normalized flame lengths (*L*/*d*) as a function of the orifice's Reynolds number (*Re*), for different orifice outlet diameters (*d*).

Equation 4 is also shown.

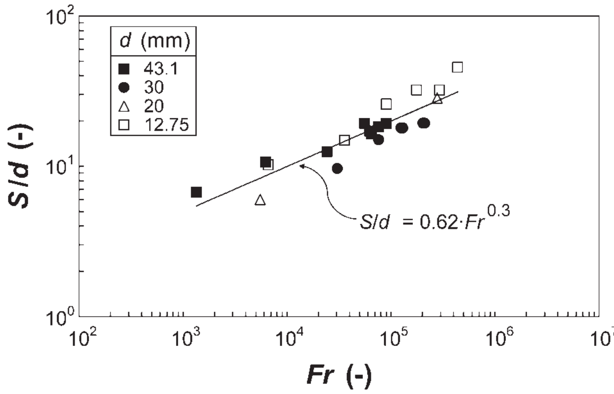

Figure 8. Variation in the normalized lift-off distance (*S*/*d*) as a function of the Froude number (*Fr*): Experimental subsonic results for various orifice outlet diameters (*d*).

Equation 5 is also shown.

Thus, Eq. 4 can be used to estimate the flame length as a function of *Re* for sonic and subsonic regimes. Figure 6 shows that in the two regimes (under sonic and subsonic conditions) *L* is again a function of the mass flow rate (*m*) and the orifice diameter (*d*), as *Re* is a function of the two variables, *m* and *d*.

Lift-off distance

The lift-off distance can be defined as the centerline distance from the gas release point to the start of the detached and stabilized flame. The prediction of lift-off distance is relevant because, together with flame length, it determines the position of the flame and the distance over which there can be flame impingement on nearby equipment. The lift-off distance is attributed to the fact that, in this zone, the flow velocity exceeds the turbulent burning velocity[20]; however, these two velocities become equal at a downstream position (i.e., beyond the lift-off distance).[21]

The present subsonic data show that lift-off distance increases with jet exit velocity. Figure 7 shows how *S* varies as a function of *V*. Other than very low values for *V* the lines in the figure are essentially straight. At low values of *V* the lines (dashed lines) should meet the origin of coordinates. The largest orifice diameter (43.1 mm) gave significantly higher values for *S* than the smaller orifice diameters (from 12.75 to 30 mm); values for the latter follow a common trend. Thus, it can be said that lift-off distance at subsonic conditions is a function of two variables: orifice diameter (*d*) and jet exit velocity (*V*). It should be noted that the data for *d* at 10 mm have been excluded. This is because these data were obtained by applying a constant ignition source, which prevented blow-out from occurring. As a result, the end of the lift-off distance corresponds to the height at which this torch was located.

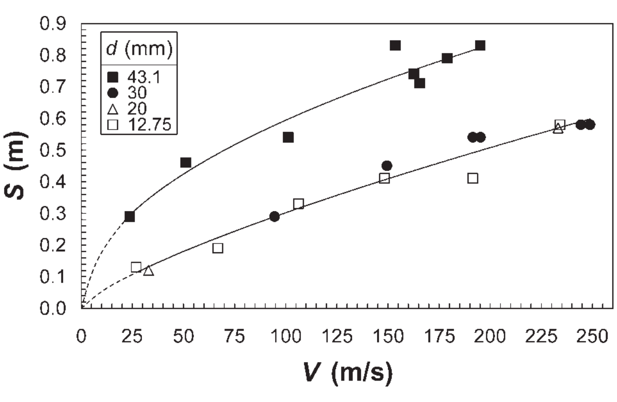

Figure 7. Variation in the lift-off distance (*S*) with subsonic jet exit velocity (*V*), for various orifice outlet diameters (*d*).

As for the subsonic data discussed herein, *S*/*d* values were plotted as a function of *Fr* (Figure 8). Subsonic experimental data could be correlated fairly accurately using a single expression (Eq. 5), which again shows the dependence of lift-off distance on orifice diameter (*d*) and jet exit velocity (*V*) in subsonic conditions.

$$\frac{S}{d} = 0.62 \cdot Fr^{0.3} \tag{5}$$

This expression is relatively similar to that obtained by Schuller et al.[12] for orifice diameters ranging between 10 and 80 mm.

Once the sonic condition has been achieved, the fluid velocity cannot be further increased and remains constant at the speed of sound in that gas. Nevertheless, as occurs with flame length, larger lift-off distances can still be obtained (using a specific outlet orifice diameter) if the gas pressure inside the pipeline continues to be increased. Thus, Eqs. 2 and 5 are restricted to subsonic flow conditions and cannot be applied to sonic flow.

Experimental subsonic and sonic normalized lift-off distances (*S*/*d*) are plotted against the fuel mass flow rate (*m*) in Figure 9. The change from subsonic to sonic flow is marked for each outlet diameter (*d*). The solid lines represent data from the present study, while the dashed lines are an extrapolation following the trend of the data obtained with the lowest m values combined with the fact that they should meet the origin of coordinates. In this figure it is clear that for a specified d, S/d increases with mass flow rate; furthermore, the trend of the results remains unaltered when the flow changes from subsonic to sonic. Thus, the dependence of lift-off distance upon the mass flow rate and orifice diameter for the two regimes can also be established.

In an attempt to find a valid expression for the subsonic and the sonic flows, the lift-off was plotted against the orifice's Reynolds number (which varied between 7×10^4 and 4×10^6) for all data (Figure 10), revealing the same trend for all data. The relationship between S and Re is expressed in the following equation:

$$S = 6 \times 10^{-4} \cdot Re^{0.5} \tag{6}$$

This expression can be used to estimate the lift-off distance as a function of the Reynolds number, for sonic and subsonic regimes, and propane as a fuel.

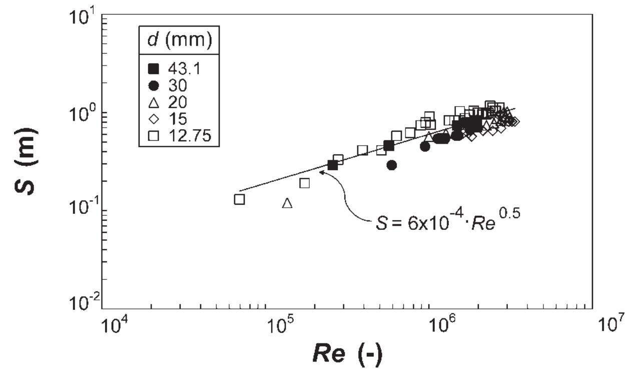

Figure 10. Variation in sonic and subsonic lift-off distances (*S*) when plotted against the orifice's Reynolds number (*Re*), for various orifice outlet diameters (*d*).

Equation 6 is also shown.

Conclusions

The literature survey revealed a significant lack of research in this area. For example, although jet fires have been studied most of the research has focused on either small-scale flames or subsonic jets. Furthermore, although there have been studies with flares, the orifice diameters used were not the values generally considered in risk analysis. Finally, very often accidental jet fires occur with gas being released at such a pressure that sonic flow at the outlet is achieved. Thus, there was a lack of information on sonic jet fires.

Experimental data on propane jet fires were obtained for subsonic and sonic regimes, with orifice diameters ranging between 10 and 43.1 mm. At 10 mm, blow-out occurred and measuring flame lift-off was impossible; the end of the lift-off corresponded to the distance at which the ignition source was located, and not to the real point at which the flame would have started if blow-out had not occurred. However, measuring flame length was made possible by maintaining the ignition source.

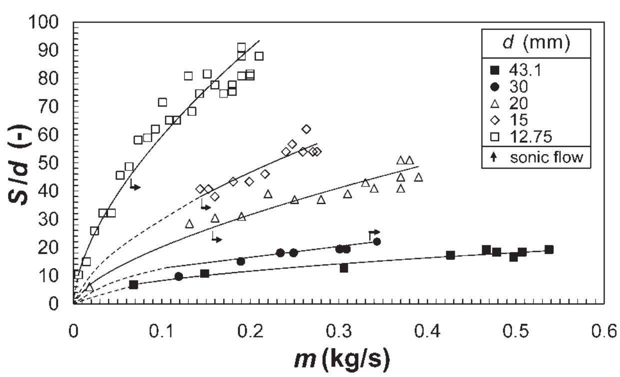

Figure 9. Variation in the sonic and subsonic normalized lift-off distances (*S/d*) with fuel mass flow rate (*m*), for various orifice outlet diameters (*d*).

Sonic and subsonic data were correlated to four of the five dimensionless groups obtained by dimensional analysis.

The results obtained show that flame length increases with the orifice diameter and the fuel mass flow rate. For subsonic flow, the length of flame can be predicted relatively accurately as a function of the Froude number (Eq. 3). This expression reiterates the dependence of flame length on orifice diameter and exit velocity at subsonic conditions. Nevertheless, this expression cannot be applied to sonic flow jet fires because in this regime the outlet gas velocity and therefore Fr are constant even if both the fuel mass flow rate and the flame length increase (as a result of the gas pressure inside the pipe or container increasing, the gas density also increases). Thus, an expression that allows flame length in the sonic flow range to be estimated is of utmost interest. For both sonic and subsonic flows, flame length can be predicted with a simple expression (Eq. 4) which correlates the normalized flame length with the orifice's Reynolds number.

Two expressions, Eqs. 3 and 4, have been suggested for predicting L at subsonic conditions, as a function of Fr and Re, respectively.

Together with flame length, the lift-off distance defines the position of the flame and the distance over which flame impingement can occur on other equipment. The dependence of lift-off on d in both the sonic and subsonic regimes is shown in this study. For subsonic flow, S can be estimated as a function of d and Fr (Eq. 5). A new correlation is proposed (Eq. 6) to estimate S as a function of the orifice's Reynolds number, for sonic and subsonic regimes, and using propane as a fuel.

The results and the expressions obtained in this study contribute to a better understanding of jet fires, allowing a better prediction of flame length. However, it cannot be stated up to what size of flames these experiments can be applied. More data, especially from large-scale field tests, are needed to extend the flame length and lift-off correlations for the two regimes discussed in this article (sonic and subsonic flows). Therefore, it would be useful to expand upon these correlations to include larger orifice diameters and other fuels.

Acknowledgments

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Notation

A = constant in Eq. 1
c = constant in Eq. 2 (s)
d = orifice or outlet diameter (m) [mm]
Fr = Froude number ($V^2/g{\cdot}d$)
g = acceleration of gravity (m/s^2)
I = intermittency
L = length of the visible flame, from the base of the lifted flame to the flame tip (m)
m = fuel mass flow rate (kg/s)
n = constant in Eq. 1
P = pressure (Pa) [bar (gauge), bar (absolute)]
Re = Reynolds number ($d{\cdot}V{\cdot}\rho/\mu$)
S = lift-off distance (m)
T = temperature (K) [°C]
V = velocity in the jet at the gas outlet (m/s)

Greek letters

μ = dynamic viscosity at the outlet orifice (kg/m·s)
ρ = density at the outlet orifice (kg/m^3)

Subscripts

in = inside the pipeline or the tank
or = at the outlet orifice

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