THERMAL AND GEOMETRICAL FEATURES OF JET FIRES

Adriana Palacios, Mercedes Gómez-Mares and Joaquim Casal

Centre for Studies on Technological Risk (CERTEC).
Department of Chemical Engineering. Universitat Politècnica de Catalunya.
Diagonal 647. 08028-Barcelona, Spain.

Abstract: In many severe accidents involving explosions or large fires, jet fires have been the first step of a domino effect sequence: a recent historical analysis has shown that among the accidents registered in the data bases, in approximately 50% of the cases in which it was a jet fire it caused another event with severe effects. However, the knowledge of jet fires essential features –behaviour, effects– is still rather poor. In this communication, the results obtained with relatively large jet fires (with flame length up to 10 m) are discussed. The fuel was propane, and both sonic and subsonic jet exit velocities were obtained from different outlet diameters. The distribution of the temperatures of the flame main axis was measured with a set of thermocouples. The jet fires were filmed with a videocamera registering visible light (VHS) and a thermographic camera (IR). The main flame geometrical features were analyzed as a function of the jet main variables, as well as the thermal effects (thermal radiation intensity as a function of distance).

Keywords: jet fire; flame length; major accidents; accident modelling; risk analysis.

1. INTRODUCTION

Among the diverse major accidents which occur in industrial plants or in the transportation of hazardous materials, fires are the most frequent ones: 59 % of these events are fires, followed by 35 % for explosions and 6 % for gas clouds (Gómez-Mares et al., 2008). Often, fire accidents have a shorter damage radius than those corresponding to other major accidents (explosions, toxic clouds), their dangerous effects being restricted to a relatively small area. Nevertheless, these areas typically contain other equipment (pipes, tanks, etc.) that can be damaged and, thus, incorporated into the accident via the domino effect. This is especially important in plants with a compact layout such as offshore oil platforms and some processing and storage plants.

Jet fire direct effects are the least severe among the different fire accidents, due to their relatively reduced size as compared to a pool or a flash fire. However, jet fires can affect equipment and, as they can be locally very intense – especially if there is flame impingement– the equipment may subsequently fail and ultimately amplify the scale of the accident. In fact, jet fires have been in many cases the first step of severe accidents which have involved –due to the domino effect– explosions or large fires: a recent historical analysis (Gómez-Mares et al., 2008) has shown that among the accidents registered in the data bases, in approximately 50 % of the cases in which there was a jet fire it caused another event with severe effects.

However, the current knowledge on the main features and behaviour of jet fires is still rather poor. Several authors have published experimental data, although many of them were obtained from small scale jet fires or from flares, and most of them at subsonic jet exit velocity, i.e. at conditions quite different from those found in a real accidental jet fire. Other authors have published mathematical models to estimate the shape and size of the flames. However, most of these models assume shapes (for example, a frustum of a cone) that do not correspond to those found in accidental jet fires but to other phenomena such as, for example, flares. Finally, rather scarce information has been published on the thermal features of jet fires: flame temperature distribution, emissivity and emissive power of the flames, which are especially interesting to estimate the heat flux reaching a given target.

An experimental study has been developed analyzing the main features of relatively large jet fires (flames length up to 10 m). The fuel was propane, and both sonic and subsonic jet exit velocities were obtained with several outlet diameters. The distribution of temperatures on the flame main axis was measured with a set of thermocouples. The jet fires were filmed with a video-camera registering visible light (VHS) and a thermographic camera (IR). The main geometrical features of the flames were analyzed as a function of the fuel mass flow rate and the jet outlet diameter: lift-off, flame shape, flame size length.

2. EXPERIMENTAL SET-UP

The experimental facility (described in detail in Palacios et al., 2009) consisted of a set of pipes which allowed the obtention of vertical jet fires. The gas pipe exit had an interchangeable cap to select different exit diameters (ranging between 10 mm and 43.1 mm). In addition, pressure measurements were taken at the gas outlet in order to calculate the mass flow rate. The fuel (commercial propane) was contained in a tank located on an upper site.

Jet flame geometric parameters were studied analyzing the images filmed by two video cameras located orthogonally to the flame. An AGEMA 570 Infrared Thermographic Camera (IR), located next to one of the previously mentioned video cameras, was used to know the temperature and radiation distribution of the jet flame, and also to compare the geometric parameters obtained by the video cameras. The IR camera vision field was 24º x 18º, the spectral range 7.5 to 13 micrometers Type B (Pt 30% Rh / Pt 6% Rh) and S (Pt 13% Rh / Pt) thermocouples were used to measure the flame axial temperature distribution; they were arranged in a mast. A meteorological station was used to measure the ambient temperature, the relative humidity and the wind direction and velocity.

A Field Point module was employed as a collection data system. It is formed by a communication module FP-1001(RS-485,115kbps), three connection terminals FP-TB-1 and three input/output (I/O) modules. The diverse measurement devices (thermocouples, pressure gage, etc.) were connected to this system. Two laptops were used to collect the data from the different sensors. They controlled the measurement devices operation. The IR camera, the meteorological station and the Field Point were connected to them. Furthermore, the two laptops were connected through a network in order to synchronize the data acquisition.

3. FLAME SIZE

Diverse authors have proposed the following expression to predict the flame length as a function of Froude number and orifice diameter over the buoyancy-dominated flow regime:

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

According to them, when applied to higher jet velocities, i. e. over the momentum-dominated regime, *n* would become 0 and *L* would be independent from *Fr*. As for the present results, the subsonic propane data obtained when plotting *L/d* versus *Fr* (Figure 1) were also correlated according to the same expression. In the buoyancy dominated regime the experimental data *L/d* can be correlated with (Palacios et al, 2009):

$$\frac{L}{d} = 53 \cdot Fr^{0.12} \tag{2}$$

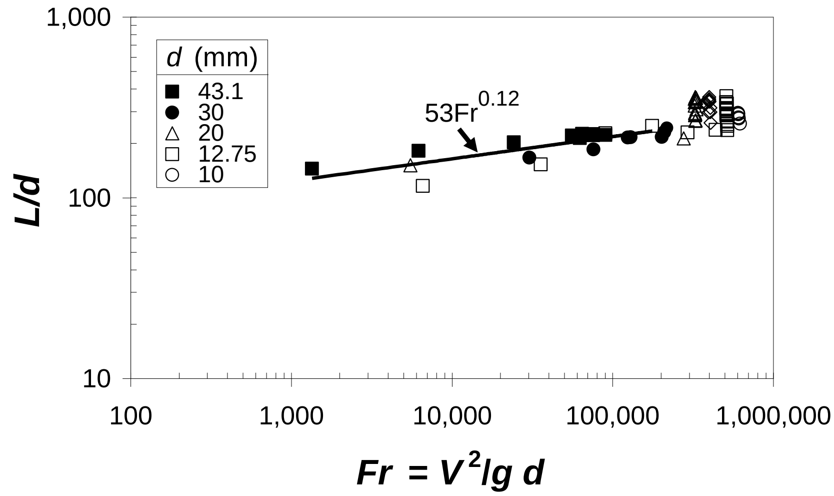

Fig. 1. Variation of normalized flame length as a function of Froude number: experimental results (subsonic and sonic velocity) and Eq. (2) (subsonic data).

Taking into account the agreement with the present experimental data, this expression would thus be suitable for predicting the length of flames for Froude number values up to approximately 1.75 x 10^5 (Figure 1). However, in this work, the results for propane flames were extended to the regime where the sonic exit velocity is reached. And it should be noted that for a given value of *Fr* (i.e. for a constant sonic velocity of the gas at the orifice) and an orifice outlet diameter, larger flame lengths can still be obtained (Figure 1). This is due to the fact that for a given outlet diameter, flame height increases with mass flow, as a result of the increment in the gas density inside the pipeline. Again, additional research would be required in the sonic flow regime.

4. FLAME TEMPERATURE

The temperature of the flame is important because it is directly associated to the radiative characteristics of the fire. The thermal radiation emitted from the fire is usually estimated from the emissive power, which is a function of the flame temperature and emissivity. In large accidental fires, the temperature is not uniform over the flame due to the turbulence and to the existence of fluctuating luminous, less-luminous and non-luminous parts. This is especially significant in pool fires, in which the combustion is rather poor.

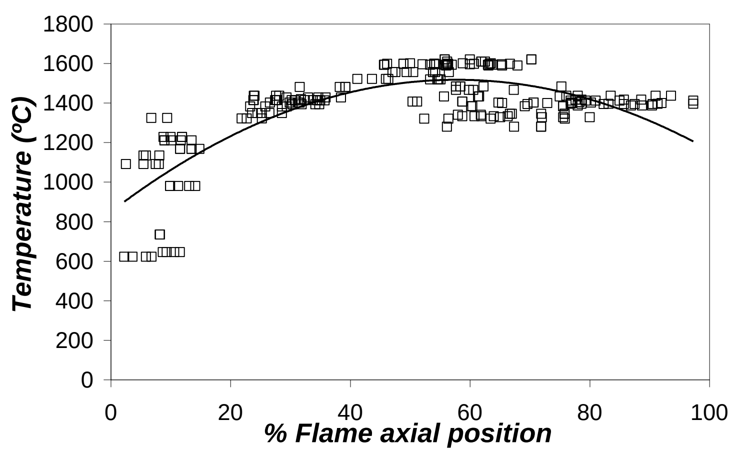

Fig. 2. Flame temperature variation as a function of jet fire axial position.

In accidental jet fires, due to the turbulence of the phenomenon and the important entrainment of air by the jet –and to the fact that the fuel is often a gas– the combustion is much more efficient and thus the variation of the temperature is not as significant as in a pool fire.

To measure the variation of the temperature in the jet fires, a set of four thermocouples were located along the jet axis. The measurement was especially difficult due to the turbulence and fluctuation of the jet fire, and consequently the experimental data showed always a certain scattering. Figure 2 shows a typical temperature distribution as a function of the jet fire axial position. It can be observed that the temperature in the jet axis increases with height, reaching a maximum at an intermediate height (at approximately 60% of the visible flame length) and then decreasing again; the temperatures over the top zone of the flame are significantly higher than at its bottom.

5. CONCLUSIONS

The results obtained with relatively large vertical jet fires (flame length up to 10 m) have shown that they can be considered to have a spindle/cylinder shape, subjected however to certain turbulences and intermittences.

As for the flame length, the data obtained at subsonic conditions could be correlated –at the buoyancy-dominated regime– as a function of Froude number (Eq. (2)). This expression should not be applied to sonic flow. The results obtained show clearly that the length of the jet fire continues increasing at sonic flow, when the mass flow rate is increased (i.e. when more fuel is feeded to the fire). This indicates again that more research effort is required in the sonic jet fire field.

Finally, the values obtained when measuring the axial flame temperature distribution clearly show that the flame temperature of a jet fire can not be assumed to be uniform: it increases from the bottom of the flame, reaching a maximum and then decreasing again. The distribution can be represented by a polynomial equation, which reaches its maximum temperature at the middle of the jet flame. The maximum temperatures reached were about 1600 ºC. This variation of temperature can be important when estimating the emissive power of the jet.

NOTATION

A	constant in Eq. (1) (-)
d	orifice or outlet diameter (m or mm)
Fr	Froude number ($V^2 g^{-1} d^{-1}$) (-)
g	acceleration of gravity (m s^{-2})
L	length of the flame (m)
n	constant in Eq. (1)
V	velocity in the jet at the gas outlet (m s^{-1})

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