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Experimental study on propane jet fire hazards: Comparison of main geometrical features with empirical models

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ABSTRACT

An experimental study of jet fires is performed to understand the flame geometry of jet fires. Horizontal jet fire experiments are performed by varying the mass flow rate of fuel through a 19 mm nozzle. The exit velocities varied from 25 to 210 m/s, flame lengths from 1 to 6 m and Froude Numbers from 2×10^3 to 2×10^5. The experimental measurement includes the flame detection using standard CCD camera to capture the details of flame morphology. The frames obtained from CCD camera are reconstructed using image visualization technique to obtain the flame morphology like flame length and lift-off length. The modeling includes comparison of experimentally determined jet flames with empirical correlations. The flame length is well validated with three empirical correlations. The lift-off length is found to be under-predicted by all the models. With extended analysis on image processing, it is observed that lift-off length is sensitive to the threshold intensity value chosen for image processing, whereas, flame length parameter is independent of the threshold intensity value. The deviation between experimental and predicted values is also attributed to soot formation which affects the lift-off lengths and the heat radiated by jet fires. The flame area obtained from image visualization methods are compared to flame area obtained from empirical models. The effect of air entrainment is also studied on flame geometry. It is observed that the horizontal extent of visible flame length is affected by the wind flowing in the downwind direction of jet fire. The vertical extent of the jet fires is found to reduce with wind flowing in the crosswind direction.

1. Introduction

Loss of hydrocarbon containment can lead to different types of leaks. Jet fires, which are usually caused due to high pressure gas leaks, have the tendency to reach full intensity instantaneously and similarly be shut down very quickly. The intensity is heavily dependent on the flow rate which influences the fire size, its geometry and the radiation intensity. This unique feature of jet fires has far reaching consequences for controlling, isolating and developing mitigation strategies for jet fires. Due to same reason, jet fires pose significant hazards to onshore and offshore oil and gas industries which handle high pressure flammables in large quantities. The jet fire may result in weakening or melting of surrounding equipment or a mechanical failure due to a high thermal radiation. It may also warm up the fluid inside the equipment if a pipeline or a storage vessel is exposure to a jet fire, which might result in an unexpected increase of pressure and possibly an additional accident. This is possibly due to domino effect. A study on several accident databases has revealed that 50% of the accidents involving jet fires often lead to an additional event with severe consequences (Gómez-Mares et al., 2008). A study in jet fires is thus required to design possible mitigation measures that will reduce exposure of process equipment to jet fires.

Following the offshore piper alpha incident which involved a major fire accident, fires are a major cause of concern in both the onshore and offshore oil and gas industry. Public domain information concerning different kinds of fires had to be identified and quantified (Cowley and Johnson, 1992). Many initiatives have also been taken to understand the nature of jet fires for realistic hazard assessment. Several experiments of horizontal and vertical jet fires ranging from small to large sizes and mathematical correlations have been developed by various industrial groups and academia and are summarized by Lowesmith et al. (2007). These are discussed in

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Nomenclature

c	effect of wind momentum flux (N)
D	Effective source diameter (m)
d	Nozzle diameter (m)
Fr	Froude Number
G	Initial jet momentum flux (N)
h	Lift-off length (m)
L	Flame length (m)
M	Molecular weight of the fuel (kg/kmol)
M	Mass flow rate (kg/s)
U	Exit velocity (m/s)
W	Mass fraction (-)
X	Horizontal excursion of the flame (m)
Z	Vertical excursion of the flame (m)
Ξ	Richardson Number
ρ|	Density (kg/m3)
Ω	Balance between jet momentum and wind momentum in release direction (N)
Ψ	Parameter

Subscripts

B_0	Characteristic length in still air
a	Air
j	Expanded jet
x	Release direction of the flame
z	Perpendicular direction to flame

detail in the subsequent sections of the paper. Currently, there is dearth in experimental data for large scale propane jet fires. Additionally, the prediction correlations for flame morphology were determined empirically based on experiments and it varies based on the method used to determine the flame morphology. The models are strongly dependent on experimental data and are limited to experimentally investigated configurations. Various methods like visual observation (Becker et al., 1981), photographic images from normal camera (Kalghatgi, 1983), high speed camera (Deimling et al., 2011), IR camera have been used in the past (Palacios et al., 2009). In these studies, the number of images and time duration taken for analysis vary significantly. The results are also bound to vary with the type of camera and the number of images considered for the analysis. To address these discrepancies, an attempt is made to compare the jet fire flame morphology obtained from visualization techniques with the prediction correlations. The proposed study focusses on the horizontal jet fire experiments performed in Brayton Fire Training Field in College Station, Texas. The study provides a review of the hydrocarbon jet fires from the literature. The experimental measurement includes flame detection using standard CCD camera to capture the details of flame morphology. The frames obtained from CCD camera are reconstructed using image visualization method to obtain the flame morphology like flame length and lift-off length. The flame morphology obtained from the experiment is then compared with empirical models.

2. Background

Jet fires are non-premixed flames where fuel comes from a source like a jet and is mixed with air supported from outside. Flame geometry like flame length and lift-off length is required for developing rational designs for burners and flares in the petroleum industry (Rokke et al., 1994). Knowledge on flame geometrical properties also helps in developing fire protection methods for offshore platforms and rigs.

The flame length is defined as the distance of the furthest flame edge from the fuel source (usually the nozzle outlet) and is controlled by the mixing process of fuel and air. The flame can exist in laminar or turbulent regime. In laminar regime, the flame length of jet fire is usually directly proportional to the jet velocity (Kiran and Mishra, 2007). Above a threshold velocity, the turbulence initiates above the flame and extends towards the nozzle with increase of velocity (Kiran and Mishra, 2007). When the flame is fully turbulent, the flame length will reach a constant value (Kiran and Mishra, 2007). The turbulence is often influenced by air entrainment.

Several correlations for lift-off distance were also developed by many researchers and it is defined as the distance at which the flame gets separated from fuel source (Kalghatgi, 1984). The lift-off length is influenced by air entrainment after the flame achieves a stable length. After a stable limit is reached, it becomes increasingly sensitive to the air entrainment (Kalghatgi, 1984). The correlations discussed here focus on the experimental parameters like flow rate of the vapor rather than chemical properties like heat of combustion. The correlations pertinent to the present investigation are briefly described here and later a comparison is made based on the experiments performed.

A number of jet fire experiments have been conducted in the past using hydrocarbons. One of the early experimental works on gaseous propane jet fires was conducted by SINTEF NBL in Norway with a flow rate of 0.3 kg/s (Wighus and Drangsholt, 1993). Their results concluded that key parameters of jet fires namely heat flux and velocity could be reproduced well in small scale jet fires tests. Their study on jet fires focused on thermal radiation and heat flux, but was limited to small scale tests.

A common approach to relate flame length to Froude number based on the jet inlet conditions was initiated by Suris et al. (Suris et al., 1978) by performing experiments using small scale vertical methane and propane flames.

$$\frac{L}{d} = A(Fr)^{0.2} \tag{1}$$

where

$$Fr = \frac{u^2}{gd} \tag{2}$$

where H-flame length in m, d-nozzle diameter in m, g-acceleration due to gravity in m/s^2 and u- exit velocity in m/s. Their study was comprehensive but played a minor role as the experiments were not validated for horizontal jet fires.

Similar theoretical analysis focused on lift-off characteristics was performed byPeters and Williams (1983). In their study, the flame was considered as an ensemble of laminar diffusion flamelets. The flame length and lift-off length were described using flamelets. However, there were many uncertainties in the calculations due to kinetic data that was required to perform the analysis. Based on their work, Sonju and Hustad performed jet fire experiments using methane and propane (Sonju and Hustad, 1985). The nozzle sizes ranged between 2 and 80 mm. They obtained jet flames up to 8 m in their tests. The resulting Froude number varied