Journal of Loss Prevention in the Process Industries 39 (2016) 141–151

Contents lists available at ScienceDirect

Journal of Loss Prevention in the Process Industries

journal homepage: www.elsevier.com/locate/jlp

Effect of pipe configurations on flame propagation of hydrocarbons–air and hydrogen–air mixtures in a constant volume

Sina Davazdah Emami [a, b], Siti Zubaidah Sulaiman [b], Rafiziana Md. Kasmani [b, **], Mahar Diana Hamid [a, *], Che Rosmani Che Hassan [a]

[a] Chemical Engineering Department, Faculty of Engineering, University of Malaya, 50603 UM Kuala Lumpur, Malaysia
[b] Energy Management Research, Department of Renewable Energy Engineering, Faculty of Petroleum and Renewable Energy Engineering, Universiti Teknologi Malaysia, 81310 Skudai, Johor, Malaysia

A R T I C L E I N F O

Article history:
Received 4 August 2015
Received in revised form
22 October 2015
Accepted 8 November 2015
Available online 30 November 2015

Keywords:
Bending
Tee junction
Flame propagation
Rate of pressure rise

A B S T R A C T

It is commonplace in industrial installations to have different piping arrangements for the efficient transport of substances/materials. However, the processing industry has raised some major concerns in terms of safety, due to the accidental gas explosions that have occurred frequently and caused serious damage. It is the aim of this study to comprehensively analyse the governing factors involved in flame propagation inside different pipe configurations. This research investigates confined pipe explosions using straight, 90-degree bending, and tee-junction pipes with different obstacle placements. Hydrogen-, ethylene-, propane- and natural gas–air mixtures, over a range of concentrations (equivalence ratio, $\Phi = 0.6–1.4$) have been used. The results show that, while there is no significant difference in the maximum pressure and rate of pressure rise in both tee-pipe arrangements investigated, the bending pipe consistently produces the worst set of results in terms of maximum pressure and flame speed in gas explosions, involving the most reactive mixtures. In addition, the detailed records of pressure traces and blast waves show that the duration of flame acceleration, the flame direction and the initial ignition point depend on the tee junction placement along the pipe length, resulting to different overall profile of the flame acceleration mechanism.

1. Introduction

Explosions in the chemical, gas and petroleum industries are still a significant problem, leading to injuries, death, the destruction of equipment, and downtime. In the chemical, hydrocarbon and plant process industries, we can find a large variety of scenarios in which internal gas explosions—confined or unconfined explosions—may occur. Such explosions can be caused by uncontrolled leaks, or simply by accidental purging with air or unpredictable failures (Grossel, 2010). For underground coal mine, coal dust explosion caused by gas explosion often cause secondary disaster and such an accident can bring more severe disasters than single-phase gas explosion. Moving at the speed of sound, pressure wave resulting from gas explosion lifts the deposited coal dust in the air, causing a dust explosion which is more severe than the first one (Beidaghy Dizaji et al., 2014; Bidabadi et al., 2015, 2014; Bidabadia et al., 2013; Soltaninejad et al., 2015). As a consequence, there is a need for pipeline protection against the propagation of unwanted combustion phenomena, such as deflagration to detonation transmission (DDT) (including decomposition flames), occurring in the process (Blanchard et al., 2010; Grossel, 2010).

In order to ensure that better precautions are taken in relation to pipeline gas carriers, it is essential to fully characterize and quantify their explosion mechanisms. In particular, knowledge is required about the maximum pressure, the maximum rate of pressure rise (i.e., deflagration index) and the flame speed, which are among the most important parameters for the risk assessment of process hazards and the safer design of process equipment (Hawkes and Chen, 2004; Salzano et al., 2012). Studies on flame propagation and explosion mechanisms in the pipes have been widely discussed (Blanchard et al., 2010; Chatrathi et al., 2001; Emami et al., 2013; Jianliang et al., 2005; Oh et al., 2001; H Phylaktou et al., 1993; Thomas et al., 2010), but most of these are focused on specific

* Corresponding author.
** Corresponding author.
E-mail addresses: rafiziana@petroleum.utm.my (R.Md. Kasmani), mahar.diana@um.edu.my (M.D. Hamid).

http://dx.doi.org/10.1016/j.jlp.2015.11.005
0950-4230/© 2015 Published by Elsevier Ltd.

experimental configuration and applications (i.e., using either bending or straight pipes/tubes). For this reason, holistic studies should be performed on flame propagation in different pipe configurations, considering the complicated problems involved in the interaction between fluid dynamics, heat transfer and turbulent combustion. For instance, Zhu et al. (2010) used a single-bend, U-shaped pipe and a Z-shaped pipe in their experimental setup, to investigate the effect of roadway turning on methane-air explosion propagation. The results showed that, by increasing the number of turnings, the explosion strength was significantly enhanced, while the flame speed and peak overpressure increased dramatically. In addition, the values of flame speed and maximum overpressure are enhanced by increasing the concentration of methane in the mixture in a horizontal pipe (Zhu et al., 2010). Another study on a straight pipe with a 60 L/D (length/diameter) showed that the pressure and velocity waves accelerate with the increasing reaction rate of methane-air (Zhao et al., 2015). Investigation on flame region distribution and hazard effects in a tube and a tunnel gas explosion also showed that the flame region is always longer than the original gas region in any cases, by only considering the initial concentration of mixture (Ma et al., 2015).

On the other hand, Razus et al. (2006) have studied the explosion pressures of hydrocarbon-air mixtures in closed vessels. They showed that the initial pressure, fuel concentration and heat losses have a significant effect on the maximum overpressure during flame propagation. Gu et al. (2000), and Liao et al. (2004), have investigated the flame instability and ratio of the laminar burning velocity of methane-air and natural gas–air mixtures at different equivalence ratios. Liu et al. (2015) have studied flame propagation and explosion development in propane-air mixtures, in a 1.16 m^3 vessel with central ignition, to evaluate the burning velocity of the fuel by considering the history of flame-front trajectory and pressure in the vessel. From their work, flame instability was observed at the equivalence ratio of 1.2 and above, suggesting that the flame instability is due to the effect of thermal-diffusion instability and hydrodynamic instability. Rich mixtures are known to be more susceptible to developing surface instabilities (flame cellularity), which can lead to higher burning rates and hence higher flame speed. This in turn could result in a more severe explosion than might otherwise be expected (on the basis of its laminar burning velocity alone).

On the determination of ethylene explosion severity, a number of experimental and numerical studies on flammable ethylene have been conducted (Kumar et al., 2007; Movileanu et al., 2011a, 2011b). In the oxidation of higher hydrocarbons, ethylene is among the key intermediates motivating researchers to apply the numerical methods for kinetic modelling, in order to find a suitable mechanism for ethylene oxidation at a wide range of temperatures, pressures, and equivalence ratios (Bergthorson and Dimotakis, 2007; Egolfopoulos et al., 1991; Jomaas et al., 2005). However, for the fuel transfer process, only a limited number of studies have been carried out. An investigation, conducted by Thomas et al. (2010), showed that the transition to detonation in pure ethylene can sustain a detonation by a decomposition reaction at pressures greater than atmospheric pressure. They also reported that the initial pressure does not play an important role in increasing the overall pressure; however, the initial pipe wall temperature, and (possibly) the mixture humidity, could affect the overall flame propagation mechanism, as similarly observed by Blanchard et al. (2011) and Ma et al. (2015). They showed that there is no possibility for this particular gas to promote shock waves since its over-driven detonations were not strong enough to enable confident measurement of its velocity. They concluded that, after DDT, flame speed decreases during the transition process in both straight and bent pipes with a 159 mm diameter. However, the maximum flame speed was observed at approximately 80% of the straight pipe length, and at approximately 70% if obstacles were present in these two configurations. This phenomenon gives a strong indication that the reflected pressure waves from the closed-end pipe do have a significant effect in slowing down the flame front during the flame propagation.

On the other hand, Xiao et al. (2011) have carried out an experimental study on half-open and closed horizontal ducts, and found that premixed hydrogen–air mixtures undergo different phases of flame shapes, indicating pronounced characteristics compared to other gaseous fuels. Research on the estimation of shock waves in hydrogen-oxygen mixtures in a 12-m diameter volume has also shown that wave intensification from a small [initial] amount of energy could create secondary combustion explosion centres, whose parameters exceed the values predicted by the Chapman-Jouguet condition (Petukhov et al., 2009). This contradicts the normal assumption that detonation is stimulated by a significant power effect. However, experimental researchers report a number of common findings, including the fact that when an explosion uses hydrogen fuels, DDT has the potential to be achieved at a magnitude of greater severity, compared to hydrocarbon fuels (Heidari and Wen, 2014; Thomas et al., 2010).

The numerical simulation and experimental study of flame propagation in a duct with a 90-degree curved section has also consistently reported a good agreement with the basic physical phenomena, such as the tulip flame, flame shedding, pressure evolution trends, flame propagation speed trends, and vortex development in the bend (Emami et al., 2013; Zhou et al., 2006). This previous work has discussed and illustrated the fact that the unburned mixture flow development in the bend was marked by an embedded transient secondary flow, in the form of two or more stream-wise vortices (Zhou et al., 2006). Hu et al. (2009) have also shown that, with the increase of the equivalence ratio, the laminar burning velocity increases for fuel-lean mixture combustion and decreases in the case of fuel-rich mixture combustion. The laminar burning velocity also intensifies the increases of initial temperature and pressure—an observation that similar investigations using different vessels have also consistently supported (Bauwens et al., 2012; Dahoe, 2005). However, what has been lacking is a comprehensive study of the governing parameters involved in flame propagation in different pipe configurations, by considering the physics and dynamics of the flame and pressure development of hydrocarbons–air and hydrogen–air explosions in a wide range of equivalence ratios. For this reason, the physics and dynamics of explosion development is investigated in different pipe configurations—i.e., closed-ended straight, 90-degree and tee pipelines—where the behaviour of the flame propagation and explosion characteristics of the fuel-air mixtures are observed in order to establish an appropriate vessel and piping design for safer application. An analytical analysis of the results obtained in this study is presented with respect to overpressure, rate of pressure rise, flame speed of premixed gas mixture explosions, and the effect of the ignition position.

2. Methodology

In this study, straight, 90-degree, and tee pipes with a constant volume (0.042 m^3) were used, with a 0.1 m initial diameter (refer to Fig. 1). Both pipe ends were closed. The pipes were made up of a number of segments, ranging from 0.5 to 1 m in length, bolted together with gasket seals between the connections and blind flanges at both ends. The flammable mixtures were ignited by an electrical spark, which gave 16 J of energy to the gas explosion tests. For this study, four pipe configurations were considered,