PREMIXED FLAME ACCELERATION IN STRAIGHT AND BEND CLOSED PIPE

MISS HASIMAWATY BINTI MAT KIAH

A thesis submitted in fulfilment of the
requirements for the award of the degree of
Master of Engineering (Gas)

Faculty of Petroleum and Renewable Energy Engineering
Universiti Teknologi Malaysia

SEPTEMBER 2013

ABSTRACT

There were many studies on premixed flame propagation in tubes, including open tubes and enclosures. Yet, no sufficient data obtained for explosion properties in medium scale piping system to assist engineers or practitioners in determining the potential hazard posed due to explosion. In this work, an experimental study had been carried out to investigate the explosion properties in a pipeline using two pipe configurations, i.e. straight and 90 degree bend. A horizontal steel pipe, with 2 m long (L) and 0.1 m diameter (D), giving L/D ratio of 20 was used in the range of equivalence ratios (Φ) from 0.5 to 1.8. The 90 degree bend pipe had a bend radius of 0.1 m with added a further 1 m to the length of the pipe (based on the centerline length of the segment). Natural gas/pure oxygen mixture was prepared using partial pressure method and a homogeneous composition was achieved by circulating the mixture using a solid ball which was placed in the mixing cell. It was shown that stoichiometric mixtures gave the highest flame speed measurement, both on straight and bend pipes. Stoichiometric concentration (Φ = 1.0) gave significant maximum overpressure of 5.5 bars for bend pipe, compared to 2.0 bars on straight pipe explosion test; approximately 3 times higher. This was due to bending part that acted like obstacles. This mechanism could induce and created more turbulence, initiated the combustion of unburned pocket at the corner region, causing high mass burning rate and hence, increased the flame speed. It was also shown that the flame speed was enhanced by factor of 3 for explosion in bend pipe compared to straight pipe. It can be concluded that the bend can create greater turbulence effect compared to straight pipe configuration and applying appropriate safety devices before the area of the bends is recommended as one of the effective methods to prevent the explosion from happen.

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LIST OF SYMBOLS

AFR	-	Air fuel ratio
ATEX	-	Atmospheres Explosives
C	-	Speed of sound, m s^{-1}
CJ	-	Chapman Jouguet
CP	-	Hose
C_i	-	Gas proportion in fuel mixture without air
CH_4	-	Methane
CTA	-	Constant Temperature Anemometry
DDT	-	Deflagration to detonation
D	-	Diameter, m; Detonation velocity, m s^{-1}
dP/dt	-	Rate of pressure rise, bar s^{-1}
$(dP/dt)_{max}$	-	Maximum rate of pressure rise, bar s^{-1}
E	-	Expansion ratio
FLACS	-	Flame Acceleration Simulator
K	-	Pressure loss coefficient = 1 (for 90 degree bend)
K_G	-	Severity factor or deflagration index
L	-	Length, m; Volume, L
LEL, LFL	-	Lower explosive or flammability limit
LFL_{Mix}	-	Flammability limit (Le Chatelier's law)
m_{fuel}	-	Mass of fuel, kg
m_{ox}	-	Mass of oxygen, kg
NG	-	Natural gas
N_b	-	Number of mole for product

N_u	-	Number of mole for reactant
N_2	-	Nitrogen
n_{fuel}	-	Mole of fuel
n_{ox}	-	Mole of oxygen
O_2	-	Oxygen
P	-	Pressure, bar
PPE	-	Personal protective equipments
P_{exp}	-	Explosion pressure, bar
P_{max}	-	Maximum explosion pressure, bar
P_{loss}	-	Head of pressure loss
R	-	Gas constant
R_e	-	Reynold number
r	-	Radius, m
S, S_f	-	Flame speed, m s^{-1}
S/P	-	Special procedure
S_L	-	Laminar flame or burning velocity, m s^{-1}
S_o	-	Mixing parameter
S_t	-	Turbulent flame speed or burning velocity, m s^{-1}
sin α	-	Angle of slope
T_f, T_i	-	Temperature, ^oC
t, t_f, t_i	-	Time, s
U, S_u, V_u	-	Burning velocity, m s^{-1}
UEL, UFL	-	Upper explosive or flammability limit
u, S_g	-	Unburnt gas velocity, m s^{-1}
V, V_o	-	Volume, m^3; Valve number
VOCs	-	Volatile organic solvents
v	-	Kinematic viscosity
X_f, X_i, x	-	Distance of sensors (thermocouple or pressure transducer), m
Z	-	Compressibility factor
ρ	-	Density
Φ	-	Equivalent Ratio

ΔP	-	Overpressure, bar
θ_{exp}	-	Time interval between ignition and the moment when explosion pressure is attained, s
β	-	Turbulent factor
π	-	Pi = 3.142

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CHAPTER 1

INTRODUCTION

1.1 Motivation / Introduction

In process industries, explosion is still a major problem that causes accidents, losses and properties damages. To prevent this explosion in many process and operation system like chemical processes plant, process equipment, piping and vent manifold system, protection against undesired phenomena such as deflagration to detonation transition (DDT) is highly required and this mechanism need to be controlled properly [1]. There is sharply increase in the number of piping system, explosive mixtures handling and collective system, closures and transport due to the strict rules raised by the environmental and safety personnel in handling the volatile organic solvents (VOCs). It is compulsory for operators to control over these mixtures to make sure the flammable gases can be discharged safely [2]. Due to the risk and consequence from the above situation, protection systems such as venting and correct placement of flame arresters are considered necessary to reduce the overpressure generated during the unexpected explosion cases. To apply this safety devices effectively require lots of knowledge and fully understanding regarding the explosion behavior and parameters and well researched in this area is required.

Venting in tubes and pipes has been studied intensively [3-4], however there is uncertainty on the determination of ignition position in advance, leading a major difficulty of venting an explosion in large L/D configuration. For encountering many situations and conditions of explosion, specified flame arresters must to be installed at correct places in order to follow and comply with ATEX (Atmospheres Explosives), a standard by European Union describing what equipment and work environment is allowed in an environment with an explosive atmosphere. For the flame arrester, questions on the best location of these devices and concerns have been raised with safety standard for flame arresters in regards to the lack of knowledge of where deflagration to detonation will/can occur in a pipe and the contributing factors on this phenomenon [5]. Understanding the mode of flame acceleration and combustion behavior along the pipe is essential in order to install/apply appropriate protective systems either passive or active. Until today, the continuous concerns about to position the flame arrester correctly as highlighted by the safety concept bring to the main cause for prediction of the burning mode at various points in a pipe by the researchers.

Furthermore, obstacles such as presence of baffle and bends in pipe are rampant in many processes and applications. The knowledge of effects on explosion properties and phenomena including overpressure, burning rate, flame acceleration and deflagration to detonation transition (DDT) is vital for the proper installation of explosion safety devices such as venting and flame arrester into the operating system. In industrial processes, the full-bore obstacles such as tube bends have extensively applied. Over past years, explosions in pipes and ducts, flame acceleration and DDT were well researched subject [6], however there were concentrated on the effects of baffle type obstacles or items in the path of the flow [7-8]. To the author's knowledge, there is sparse study on the explosions through pipe bends used extensively in industrial applications, and the effects on flame acceleration, overpressure enhancement and the contribution on DDT severity.

1.2 Problem Statement

The aim of the research is to provide detailed physical and dynamic flame propagation mechanism for gas explosion in a medium size (industrial scale) of closed pipe and determine the effect of pipe configuration on the flame acceleration and explosion pressure. Data obtained from the experimental work will be compared with the previous published experimental data and also can be a reference to future researcher in order to validate the predictive protection system that would be applied to the similar pipe configuration. Turbulent enhancement factor also can be determined according to the collected results for both pipe configurations in order to compare the explosion behaviors and profile or mechanism.

Work by Phylaktou et al [9], using a 3 m long and 162 mm diameter tube (L/D ratio of 18.5) with closed at both ends, showed that the flame speed and overpressure for methane-air explosions with 90 degree bend pipe have increased compared to the explosions conducted in straight pipe. The flame speeds was enhanced in a factor of 5 and this condition is similar to the effect using baffle of 20% blockage ratio at the same position. Limited studies were done on medium scale. That is why this study was conducted as to complete the circle of small, medium and large scale in piping system. In present work, the effect of L/D on explosion properties for L/D ratio of 20 (straight pipe) and L/D ratio of 38 (90 degree bend pipe) has been investigated.

Chatrathi [10] found that for propane-air mixtures in 152.4 mm diameter pipe with the open end and rear ignition, the development of flame speed increased about 24% after a 90 degree bend placed half-way down a tube. Zhou et al [11], observed that the flame front experienced a ‘flame shedding’ inside the bend when travelling through a rectangular 90 degree bend. This observation has a good agreement with 3D particle modeling of the surge inside of the bend. It is found that large vortexes (turbulent) were produced just downstream of the inside wall of the bend while flow followed a more streamlines pattern (laminar) around the outside of the bend.

Other study was done in different methods using constant temperature anemometry (CTA) to observe the explosion in 90 degree bend [12]. From the work, it demonstrated that an obstacle such as bend encouraged the enhancement of turbulence effect over the first 30% of the inner diameter of the pipe rapidly inside the bending part. Ignition position also affects the explosion properties especially the shape of flame. Sato et al [13] investigated the effects of ignition position for methane-air explosions using an open ended small square channel with 90 degree bend and found out that it can influence the shape of the flame front and its speed. However, with restricted amount of explosions have been conducted, there is quite sparse comparison with work done in straight pipe or obstacles.

Present work aims to provide additional information and knowledge related to the explosion parameters (flame speed, overpressure and rate of pressure rise) for natural gas-oxygen mixtures and to understand its behavior when involving straight and 90 degree bend pipe. The results collected will be compared with the previous published experimental results in order to predict the flame pattern and worst explosion pressure for various pipe configurations. Passive and active safety devices like flame arrester and venting respectively will be proposed to be installed at certain location along the pipe as the one of important effective technique to prevent the explosion from happened.

1.3 Objectives of Research

This research study embarks on the following objectives:

a) To determine/measure the data of explosion properties in closed pipe with and without 90 degree bends such as flame speeds, rate of pressure rise, overpressures and unburnt gas velocity at different concentrations of natural gas/oxygen mixture.

b) To investigate the effects of pipe configuration (straight and 90 degree bends) can have on flame acceleration, overpressure enhancement and compare the data obtained with the previous published experimental data.

1.4 Scope of Research

Study on the effect of pipe configuration, i.e. straight and bend. Only straight and 90 degree were used and investigated. The fuel used is natural gas/oxygen with equivalent ratio, $\Phi = 0.5$ to 1.8. Parameters to be studied are flame speed, overpressure and rate of pressure rise. These parameters are very important in basically determining the explosion severity and hazard posed during explosion. Determination of critical points and parts for the high pressure was accessed in order to install passive or active safety device as one of the protection measured technique. This study investigates the explosion properties in a pipe of L/D equal to 20 which can be simulated as an industrial scale pipeline.

CHAPTER 2

LITERATURE REVIEW

2.1 Research Background

With increasing number of pipelines explosions every year, research on improving the safety design of process equipment has become a major concern among researchers. In the pipeline system, the ignited air-fuel mixtures can lead to the critical growth of the explosion properties such as uncontrolled and harmful of overpressures. The fast development of overpressure is influenced by the natural confined behavior of the pipe and its long length which is jointed and installed separately in many applications of the process industries. It is well known that turbulence flow in the pipe will increase the diffusion of heat and mass due to the wrinkling of the flame front and thereby cause higher burning rate [14]. The ongoing reaction of gas mixtures will induce the transformation of flame propagation from deflagration to detonation type. Consequently, increasing burning rate causes the rate of pressure rise in confined space increases and leads to destructive explosion. As these parameters largely contribute to the explosion behavior, further studies need to be carried out on these parameters to quantify the effect they can have on the explosion severity and to avoid such condition to occur.

2.2 Gas Explosion

Explosion is a process where combustion of a premixed gas cloud (fuel-air mixture) that causes rapid increase of pressure, volume and followed by the excessive release of energy or heat. The critical boost of this pressure and its development can be influenced and caused by a few factors such as run-away reactions, nuclear reactions, leaking or storage failure of high pressure vessels, high explosives metal, vapor explosions and burned of mist or dust in existence of air or other oxidizers. One classic example of the most serious accidents in the history of chemical industry was happened on 1 June 1974 at Flixborough (Nypro plant). A report explained that the plant was entirely busted. The incident killed 28 people and total of 89 people were critically injured and suffered. Almost two thousands of residences and more than hundred shops destroyed. The estimated losses were more than 100 million dollars.

In an accidental explosion, the expansion can be mechanical (via the sudden rupture of a pressure vessel) or it can be the result of a rapid chemical reaction. Explosion basically can be categorized as confined and unconfined explosion. Confined explosion are explosion within tanks, process equipment, closed closures/rooms (confined space) and in underground installations. Meanwhile, unconfined gas explosions occur in an open area such as process plants. The development of pressure during the explosion in a confined vessel is not much affected by a high flame velocity and therefore even a slow combustion process will generate and increase the pressure

[15]. Basically, reasons such as fuel and oxidizer type used, location or position of igniter applied in the test system and etc can manipulate the explosion mechanism in many ways of reaction. The difference between these two type explosions is that the value for overpressure for confined explosion is higher than the unconfined ones. In a confined place, the speed of flame increases and its acceleration may be more than a few hundred meters per second. When the gas is burning, the temperature increases as well as burning rate will increase, therefore causing the development of pressure. Without proper application of safety equipments to relief the explosion pressure, this would lead to rapid increase in pressure.

When the fuel-air mixture is ignited, the flame will propagate in two modes; deflagration and detonation. Figure 2.1 shows mechanism for an explosion to happen from ignition to detonation. Bjerketvedt et al [15] stated that the ordinary mode of flame propagation during the gas explosion is deflagration, as expected to be similar to the present work. Deflagration is defined as a combustion wave propagating at subsonic velocity where the burning velocity, U is smaller than the speed of sound, C in the unburned gas ahead of the flame. The typical flame speeds for deflagration are normally the highest about a thousand meter per second (1 to 1000 m/s) with the maximum explosion pressures can reach up to a few bars. The main mechanism of propagation of combustion is a flame front moving through a gas mixture in technical terms the reaction zone (combustion chemistry) takes place through the medium of heat and mass diffusion process for laminar flame. It propagates with a velocity 3-4 m/s. In the most benign form, the deflagration may only flash flame [15].

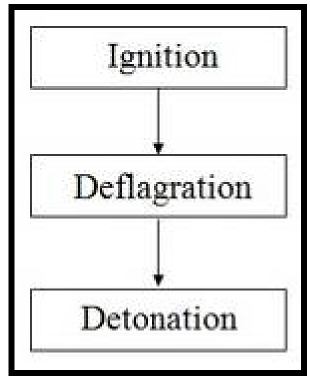

Figure 2.1 Steps for explosion mechanism [15]

The definition of detonation is a combustion wave propagating at supersonic velocity relative to the unburnt gas immediately ahead of the flame. Deflagration is different from detonation which is a supersonic exothermic front accelerating through a medium that finally drives a shock front propagating directly in front of it. The detonation velocity, D, is larger than the speed of sound, C, in the unburnt gas. At supersonic velocity, combustion wave propagation occurred relative to the unburnt gas immediately ahead of the flame [15] which the propagation mechanism can change to supersonic explosion. This phenomenon of ignitable mixtures of combustible gas and air (or oxygen) occurs when a sudden transition deflagration to detonation (DDT) of explosive combustion. Detonation is defined as explosive compound decomposed by releasing a shockwave rather than the heat generated by deflagration [16]. The detonation velocity can reach the maximum value up to 2000 m/s and the maximum pressures generated are close to 20 bars.

2.3 Explosion Properties

Gas explosion is one of the worst accidents in the world because it can cause huge damage and fatalities. The present work is conducted to measure and determine the explosion properties such as flame speed, burning velocity, unburned gas velocity, explosion pressure, rate of pressure rise, laminar flame speed, turbulent flame speed, burning velocity, etc. Explosion behavior such as flame propagation, flame acceleration and transition to detonation was comprehensively reviewed recently by Ciccarelli and Dorofeev [6].

2.3.1 Flame Speed, Burning Velocity and Unburned Gas Velocity

The measured rate of the growth or expansion of the flame front in a combustion reaction represents the value of flame speed. Bjerketvedt et al [15] defined the flame speed, S or S_f as the velocity of the flame relative to the ground or another fixed frame. Whereas flame speed is generally used for a fuel, a related term is explosive velocity, which is the same relationship measured for an explosive. The burning velocity, U or S_u, is the velocity of the flame front with respect to the unburnt gas immediately ahead of the flame. Equation 2.1 shows the relation between flame speed, S, burning velocity, U and unburned gas velocity ahead of flame, u or S_g.

$$\boxed{S = U + u} \tag{2.1}$$

Figure 2.2 shows the transmission of flame in cylindrical vessel. During the explosion, flame front will expand due to increase of flame temperature. The flame will propagate through the length of pipe with the unburned gas mixtures in front of the flame and the burned gas mixtures behind the flame. The density different of both gases mixtures affected its transmission process. The density of unburned gas is lower than burned gas. The burning rate will increase and hence lead to the increase of flame speed, S_f and pressure development.

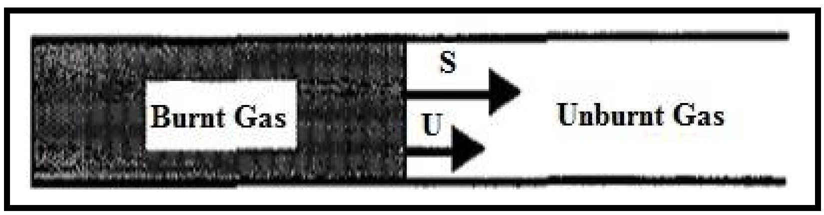

Figure 2.2 Transmission of flame in cylindrical vessel [15]

Factors such as expansion of combustion product, unsteadiness and turbulent deformation of the flame can cause the flame speed to be higher than burning velocity. Normal flame speeds observed for hydrocarbon-air mixtures in a range of 10-100 m/s and the speeds can possibly increase up to 1000 m/s under certain conditions. The unburned gases in front of the flame can induce turbulence effect in that reaction area which produces small and large eddies as it flows through objects or orifices medium. The effect of this turbulence can cause a rapid increase in flame speed and develop the acceleration of the flame. According to Dahoe et al [14], flame acceleration are divided to three phases which is flame stretching and folding, flame front wrinkling (caused by turbulent eddies and fluid dynamic instabilities) and flame surface (creation by shock of flame interactions). The flame will accelerate more rapidly at higher level of flame surface wrinkling but the final choking velocity is similar for all geometric configurations and governed only by properties of the gas mixture.