# GAS EXPLOSION CHARACTERISTICS IN CONFINED STRAIGHT AND 90 DEGREE BEND PIPES

SITI ZUBAIDAH BINTI SULAIMAN

UNIVERSITI TEKNOLOGI MALAYSIA

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SITI ZUBAIDAH BINTI SULAIMAN

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I dedicate this thesis to my lovely husband, son, parents, parent's in-law and friends. I couldn't have done this without you. Thank you for all your support and help during my PhD journey.

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# ABSTRACT

Gas explosion inside a pipe is a complex phenomenon. Extensive studies have been carried out to investigate factors governing to the explosion development i.e. the flame speed and the maximum pressure. However, most of the works are limited to open straight pipes. Worst, the effect of the obstructions on the explosion severity is still unclear. Most of the gases used in the industrial piping are highly combustible and has a potential to initiate detonation hazard. In this work, gas explosions inside closed pipes are considered. Experimental and Computational Fluid Dynamic (CFD) analyses using FLACs are adopted to investigate the physical and dynamic behaviour on gas explosion development in pipes. Hydrogen, acetylene, ethylene, propane and methane were used as fuels. The effect of pipe configuration (straight and 90 bend pipe) with different length to diameter ratio (L/D) was investigated. From the results, it was observed that the presence of 90 degree bend enhances the explosion severity by a factor of 1.03-3.58 as compared to that of the straight pipe. Based on the simulation analysis, the compression effect at the bending region and at the end of the pipe plays an important role to attenuate the burning rate, which resulting to a higher flame speeds and hence, increases the overpressure. Interestingly, a maximum overpressure of 14 barg with flame speed of 700 m/s was observed in the smaller pipe of L/D=40 with acetylene fuel which indicated that the detonation-like event take place. The ability of the flame to quench becomes insignificant in a smaller pipe, promoting a strong interaction of the fast flame and turbulence, particularly at the bending. This phenomenon amplifies the mass burning rate, increases the flame speeds and leading to a higher pressure rise. From the results, it shows that fuel reactivity and pipe size and configuration gives a significant effect to the overall overpressure and flame acceleration development which can lead to a catastrophic explosion.

# ABSTRAK

Letupan gas di dalam paip adalah satu fenomena yang kompleks. Kajian menyeluruh telah dijalankan bagi mengkaji faktor-faktor yang mengawal kejadian letupan seperti kelajuan api dan tekanan maksimum. Walau bagaimanapun, sebahagian besar daripada kajian-kajian yang telah dijalankan terhad kepada paip lurus terbuka. Malangnya, kesan halangan terhadap tahap letupan masih tidak jelas. Kebanyakan gas yang digunakan di dalam paip perindustrian adalah sangat mudah terbakar dan berpotensi untuk mengundang bahaya letupan. Dalam kajian ini, letupan gas di dalam paip tertutup dipertimbangkan. Ujikaji dan Pengkomputeran Dinamik Bendalir (CFD) digunakan untuk mengkaji tingkah laku fizikal dan dinamik kepada kejadian letupan gas di dalam paip. Hidrogen, asetilena, etilena, propana dan metana telah digunakan sebagai bahan api. Kesan konfigurasi paip (lurus dan 90 darjah lentur) serta perbezaan nisbah panjang kepada diameter (L/D) telah dijalankan. Hasil daripada keputusan, didapati bahawa kehadiran 90 darjah lentur meningkatkan tahap letupan dengan faktor 1.03-3.58 berbanding dengan paip lurus. Berdasarkan analisa simulasi, kesan mampatan di rantau lenturan dan dihujung paip memainkan peranan penting bagi meningkatkan kadar pembakaran, yang membawa kepada perambatan kelajuan api yang lebih tinggi serta meningkatkan tekanan lampau. Menariknya, tekanan lampau maksimum 14 barg dengan kelajuan api 700 m/s diperhatikan dalam paip yang lebih kecil daripada L/D=40 pada bahan api asetilena dan ini menunjukkan bahawa fenomena letupan telah berlaku. Keupayaan untuk pemadaman api menjadi tidak penting di dalam paip yang lebih kecil dan ia menggalakkan interaksi yang kuat di antara api dengan pergolakan terutama di bahagian lentur. Fenomena ini menguatkan lagi kadar pembakaran, meningkatkan kelajuan api dan kenaikan tekanan yang lebih tinggi. Daripada keputusan, ia menunjukkan bahawa kereaktifan bahan api serta saiz paip dan konfigurasi memberikan kesan yang besar kepada pembangunan tekanan lampau dan kelajuan api yang boleh membawa kepada bencana letupan.

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| | | |
|---|---|---|
| ADC | - | Analogue/digital conversion |
| $a$ | - | Constant |
| BR | - | Blockage ratio |
| CFD | - | Computational Fluid Dynamics |
| CO | - | Carbon monoxide |
| $CO_2$ | - | Carbon dioxide |
| $C_2H_2$ | - | Acetylene |
| $C_2H_4$ | - | Ethylene |
| $C_3H_8$ | - | Propane |
| $CH_4$ | - | Methane |
| $CH_2O$ | - | Formaldehyde |
| $CH_2CO$ | - | Ketene |
| CO | - | Carbon monoxide |
| $c_p$ | - | Specific heat |
| $c_\mu$ | - | constant in k-ε equation ($c_\mu$=0.09) |
| $\mu_{eff}$ | - | effective viscosity |
| DNS | - | Direct numerical simulation |
| $Da$ | - | Damköhler number |
| dP/dt | - | Rate of pressure rise |
| dt | - | time step |
| E | - | Expansion ratio |
| Ea | - | Activation energy |
| FS | - | Full scale |
| FLACs | - | Flame Acceleration Computational simulator |
| G | - | Generation rate of turbulence |
| H | - | Hydrogen |
| $H_2O$ | - | Water |
| K | - | Thermal conductivity |

| | | |
|---|---|---|
| K | - | kinetic energy of turbulence |
| K-H | - | Kelvin – Helmholtz |
| $Ka$ | - | Karlovitz number |
| L | - | Lenght |
| Le | - | Lewis number (dimensionless) |
| L-D | - | Landau – Darrieus |
| LPG | - | Liquefied petroleum gas |
| LFL | - | Lower flammability limit |
| L/D | - | Ratio of pipe length to diameter of pipe |
| LES | - | Large eddy simulation |
| $l_T$ | - | Turbulent length scale |
| MISC | - | Malaysian International Shipping Company |
| Mach | - | Object speed divided by speed of sound, (dimensionless) |
| Ma | - | Markstein length |
| NG | - | Natural gas |
| O | - | Oxygen |
| OH | - | Hydroxide |
| P | - | Pressure |
| $P_{max}$ | - | Maximum pressure |
| PG: | - | Pressure gauge |
| $P_1$-$P_6$ | - | Pressure transducer at position 1-6 |
| R | - | Gas constant |
| $R$ | - | Flame radius |
| R-T | - | Rayleigh –Taylor |
| R-M | - | Richtmyer –Meshkov |
| $Re_T$ | - | Turbulent Reynolds number |
| SGS | - | Sub grid-scale |
| $S_f$ | - | Flame speed |
| $S_g$ | - | Unburned gas velocity |
| $S_L$ | - | Laminar flame |
| $S_T$ | - | Turbulent flame |
| $T_b$ | - | Maximum flame temperature |
| $T_u$ | - | Unburned gas temperature |
| $T_1$-$T_7$ | - | Thermocouple at position 1-7 |
| $t_f$ | - | The time after the distinct change of output signal |

| | | |
|---|---|---|
| $t_i$ | - | The time before the distinct change of output (flame arrival time) |
| UFL | - | Upper flammability limit |
| V1 & V2 | - | Valve 1 and valve 2 |
| V | - | Voltage |
| W | - | Width |
| WHRU | - | Waste heat recovery |
| $X_f$ | - | Distance of the next thermocouple from the ignition point |
| $X_i$ | - | Distance of the previous thermocouple from the ignition point |
| Y | - | Reactant concentration |
| $\rho u$ | - | Density of unburned gas |
| $\rho b$ | - | Density of burned gas |
| $\tau_r$ | - | Reaction time, |
| $\beta$ | - | Zeldovich number (dimensionless) |
| $\gamma P$ | - | Fuel dependent parameter |
| $\varepsilon$ | - | rate of dissipation |
| 1D | - | 1 diameter |
| 2D | - | 2 dimension |
| $\Phi$, ER | - | Equivalence ratio, |
| $\delta$ | - | laminar flame thickness |

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# CHAPTER 1

# INTRODUCTION

## 1.1 Background

The potential for the gas explosion hazard in the process industry or the oil and gas sector is a reality which safety design must recognize and consider in a processing plant. If the potential hazards are not properly addressed, the result will be catastrophic. The result of the explosion blast can damage the structures, loss of properties as well as fatality or injury to personnel. In order to aid a European directive on equipment and protective system compliance also known as ATmosphères Explosives *(*ATEX) guideline, a safety device needs to be correctly placed in order to minimize the explosion severity (Oakley and Thomas, 2004). However, there are still some uncertainties to identify the potential location of the safety devices due to the lack of knowledge of where the deflagration or deflagration to denotation (DDT) will occur and the factors contributing to these effects. Thus, it is important to predict the mode of flame propagation and combustion behavior in order to install appropriate protective systems.

In a processing plant, transmission and distribution line, an offshore sector and mining industry, the explosion incident often takes place in a confined area within the vessel, pipes, channels or tunnels. Mostly, the vessel, pipe, channel or tunnel carries a reactive or combustible material in order to transport from one section to another and some, for storage purposes. If leaks are found in pipes or vessels, even though a very tiny pin hole leak, this constitutes a very significant safety hazard and possibly leads to the development of explosion. Garrison (1988) reported that the pipe explosion occurred in chemical or petrochemical plant, or gas pipeline is related to the stress cracking due to piping vibration problem. Such failure causes a series of explosions, and fires occurred as at the Ethylene Plant in Texas in June 1997 (Thomas *et al.*, 2010).

Worst, one case of the gas explosion incidents on average could happen in each industrialized country every day (Bjerketvedt *et al.*, 1997). One of the most classic and destructive accidents in the chemical industry had happened in June 1974, in the Nypro plant at Flixborough. The worst industrial disaster that involved detonation gas or vapor totally destroyed the plant; 28 people killed and 36 others injured. The incident happened due to 50 tons cyclohexane in form of a vapor cloud released from the ruptured pipe. This cloud was ignited after 1 minute of its release before the disaster happened (Thomas *et al.*, 2010).

In Malaysia, fire and gas explosion accidents are not rare. In 2003, a major fire occurred in the exhaust system of the propane compressor gas turbine at the MLNG Tiga Plant in Bintulu, Sarawak leading to a temporary shutdown. The incident occurred due to the natural gas seeping from the ruptured pipe and mixing with the air inside the waste heat recovery unit (WHRU) at a very high temperature of 570 °C. Methane only requires a 4% volume in air to reach its lower flammability limit and the auto-ignition temperature of 537 °C (Ismail, 2005). Thus, the auto ignited methane gas leakage led to the explosion inside the WHRU. Another incident involved the gas explosion occurred in a chemical tanker, Bunga Alpinia owned by the Malaysian International Shipping Company (MISC), on 26$^{th}$ July 2012. The incident killed one crewman while four men were missing. The explosion started during the methanol loading from the tanker to the terminal through the pipeline. It is believed that due to pipe leakage and bad weather (with lightning) caused the

incident (Goh, 2012, Ahmad, 2012). The most recent gas explosion incident involved a Petronas transmission gas pipeline at northern district of Sarawak (interstate between Lawas town and Long Sukang) (Then, 2014). However, no fatality was reported but some houses and vehicles were damaged. Lacking of proper safety management system in a gas pipeline would lead to a catastrophic disaster as mentioned in the incidents above. Hence, the fundamental explosive parameters on gas explosion as well as the physical and dynamic mechanism during explosion development are vital to be understood in order to minimize the potential for explosion severity.

## 1.2 Problem Statement

Deflagration, a subsonic process of explosion wave propagation can occur as initial and transition stage in the explosion development. Although this is a deflagration phenomenon, the results are applicable to quite a number of subjects. Many pipe configurations in processing industry, gas pipeline or mining industry incorporate with tees, elbows and valves. So, if the fuel or flammable material inside the pipe at right concentrations and appropriate ignition conditions are presented, it is possible that initially a slow flame front propagation may cause the detonation. Detailed research on flame propagation and combustion behaviour along the pipe/channel/tube/duct is essential in order to identify the worst-case explosion impact and to install an appropriate protective system in place.

Extensive and comprehensive studies on understanding the dynamic flame propagation have been carried out by the researchers, (Blanchard *et al.*, 2011, Zhu *et al.*, 2012, Zipf Jr *et al.*, 2014). However, most of the studies focused on the flame propagation in obstructed pipes/tubes by using plates and orifices with the open end pipe. The presence of an obstacle in a pipe is favorable to randomize the flow and

increase the flame speed and overpressure up to 5 times higher as compared to that of the straight pipe/tube (Phylaktou *et al.*, 1993). However, Blanchard *et al.*, (2010) in their work depicted that the presence of 90 degree bend in closed pipe/tube could cause the pressure to decrease due to the weaker flame-reflective wave interaction after bending than that of the bending region. In a closed pipe/tube, the end wall is acted as an obstacle and has a tendency to initiate the flame perturbation and subsequently, affect the explosion parameter.

Flame front and reflective wave interaction are a common phenomenon in a closed pipe. The interaction between flame and acoustic/shock wave reflected from the end tube may affect the flame evolution (Liberman *et al.,*2010). Zhu *et al*., (2012) observed that the effect of reflective acoustic wave could enhance the pressure evolution by a factor of 1.5 as compared to the open end pipe. The findings contradicted with the study done by Thomas *et al*., (2010). They depicted that the interaction between flame and reflective acoustic wave gave adverse effect towards the flame propagation and pressure development. (Blanchard *et al.*, 2010). Different findings have been reported by Wang *et al*., (2012). They observed that the flame-reflective wave interaction was stronger at the bending region. The non-agreeable findings could be due to the experimental method, fuel reactivity and the intensity of the fuel concentration.

In spite of extensive research on flame propagation being done on straight and bending pipes, yet there are still many baffling problems particularly of the turbulent hot flame interaction and pressure wave (acoustic wave) effects at the end wall pipe. This phenomenon is not well explored, and the understanding of this phenomenon should be examined thoroughly, as it has been recognized as one of the factors contributing to the onset of detonation (Li *et al.*, 2005). Thus, it is crucial to understand the mechanism causing the flame propagation and leading to detonations hazard in such that the effective corrective action can be inherently safer. Therefore, this research aims to provide an additional knowledge related to the gas explosion in closed straight and bend pipe; in terms of physical and dynamic mechanisms, kinetic mechanism as well as contributing effects on explosion development.

## 1.3 Objectives

The objectives of this research are:-

i. to evaluate the explosion parameters such as maximum pressure, $P_{max}$, flame speed, $S_f$, rate of pressure rise, dP/dt and unburned gas velocities, $S_g$ in both straight and 90 degree bend pipes with the influence of fuel reactivity and fuel concentration.

ii. to quantify the effect of length and pipe diameter to physical and dynamic explosion mechanism in pipes.

iii. to validate the experimental results with numerical analysis using a commercial software, Flame Acceleration Simulator, FLACs version 10.1 developed by Gexcon AS.

## 1.4 Scopes of Research

Studies on gas explosion in closed pipe showed that the evolution of explosion depends on the nature of initial explosive mixtures and the geometrical characteristics. The initial explosive material consists of mixture composition, fuel reactivity, an initial temperature and pressure whereas the geometrical characteristics describe the dimension and shape of the pipe as well as the presence of the obstacles. With some limitations, the scopes of work were emphasized to assess the effects of pipe configuration, pipe size and fuel reactivity on the explosion severity. The scopes of work considered in the study are as follow:-

i. The explosion test was performed in a closed pipe at the ambient condition. The ignition source was placed at the centre of one of the blind flanges.

ii. The experimental work involved in different configurations i.e. straight pipe and straight pipe with 90 degree bends with a radius of 0.1 m. The bend position was fixed at 3.0 m from the ignition point.

iii. Two different diameter and length pipes were adopted in this work giving length-to-diameter ratio (L/D) of 40 and 51 to observe the explosion development on the effect of pipe diameter and length.

iv. The two pipe size of 0.10 m and 0.05 m Schedule 40 were chosen to replicate the gas reticulation and commercial pipelines in the processing plant.

v. Premixed hydrogen, acetylene, ethylene, propane and methane–air with different concentrations or equivalence ratios, Φ (lean, stoichiometric, rich) were used to compare the explosion characteristics.

vi. CFD code FLACs was used to simulate the dynamics of flame propagation at stoichiometric concentration for each fuel.

## 1.5 Limitations of the study

The main limitations are as follows:

i. Lack of facility for the vapor removal causes the water vapor not to be completely removed from the pipe wall. This condition can lead to the moisture problem inside the pipe wall.

ii. In FLACs software, the geometry domain was constructed based on a circular, square or rectangular object. Due to the limitation, 90 degree sharp bends were constructed (instead of curved bend) to replicate the actual pipe configurations.

## 1.6 Significance of the study

The study focused on quantifying the gas explosion mechanism in a closed pipe on different configurations and L/Ds. The influent factors governing the explosion development were highlighted. Moreover, the results of the study will be beneficial to the following:

i. This research explores the complex mechanism on the flame propagation, particularly on the interaction of the fast flame and reflective wave, which is considered as one of the contributing factors to the catastrophic explosion.

ii. This research will give additional fundamental data on gas explosion mechanism in a closed pipe for different sizes and configurations as well as fuel reactivity.

iii. This research will provide additional information towards application on severity of the gas explosion where the protection system can be applied correctly.

iv. Minimize the fire explosion in a pipe system

## 1.7 Thesis Outline

The thesis consists of six chapters. Chapter 1 includes the introduction, statement of the problem, objectives, significance of the study as well as the scope and limitation. Chapter 2 covers related literature based on the extensive reviews and analysis reported by various authors. The topic covers the general overview on gas explosion, gas explosion parameters, laminar flame, turbulent flame and flame instabilities, and factor influencing the flame propagation in a closed pipe. Chapter 3 presents the research methodologies used in the study. The schematic diagram of the experimental rig consisting of all equipment is discussed in this chapter. The study procedure highlighted includes the equipment used, data acquisition system, and data analysis. In Chapter 4, analysis is done on the gathered data from the experimental work which includes flame speeds, pressure time histories, and the rate of pressure rise. The data are organized in a sequential order i.e. straight to bending pipe explosion in order for readers to understand the physical and dynamic explosion mechanism and the effect of bending to the overall explosion development. The results discussed include the effect of fuel reactivity and concentrations to explosion parameters and numerical analysis on the flame structures and flame evolution. The influence of L/D is covered in Chapter 5 with the discussion on the quantification of detonation alike on the effect of pipe diameter and length. Chapter 6 offers the summary of findings, the conclusion, and recommendations in accordance with the findings for the future works.

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