PULSE COMBUSTION STUDIES OF PROPANE AND NATURAL GAS MIXTURES

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requirements for the award of the degree of
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Librarian
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Sir,

CLASSIFICATION OF THESIS AS RESTRICTED
- PULSE COMBUSTION STUDIES OF PROPANE AND NATURAL GAS MIXTURES
MOHD HAFFIS BIN UJIR

Please be informed that the above mentioned thesis entitled " Pulse Combustion Studies of Propane and Natural Gas Mixtures" be classified as RESTRICTED for a period of three (3) years from the date of this letter. The reasons for this classification are

(i) Main research of the project is still in progress

(ii) There are elements of commercialization that cannot be exposed to public at this moment

Thank you.

Sincerely yours,

Dr Mazlan Abdul Wahid
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07-5534565

Note: This letter should be written by the supervisor, addressed to PSZ and a copy attached to the thesis.

To mak, abah, my siblings,
my nephews and niece, pikah, yaya, ami
Thanks for your support

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Alhamdulillah, thank to Allah S.W.T and our prophet Muhammad S.A.W.

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ABSTRACT

The phenomenon of pulse combustion of hydrocarbon-oxygen mixtures was investigated experimentally. An experimental rig that consists of a stainless steel tube with inner diameter of 100mm and length of 1700mm, data acquisition system, ignition control unit and filling system was built in order to measure the characteristics of pulse combustion such as, pressure, velocity and impulse. Three equivalence ratios of fuel-oxidizer; 0.75, 1 and 1.25 were chosen to investigate the effect of fuel concentration on the pulse combustion wave propagation. It was found that combustion of high fuel concentration mixture propagates as a detonation wave while for low fuel concentration mixture; the combustion wave propagates as deflagration wave. Two types of hydrocarbon fuels were used, i.e, propane and natural gas with 92.7% methane. Results showed that natural gas is not sensitive to detonation propagation compared to propane. It was found that in smooth inner wall tube, combustion wave propagates as a detonation wave if the percent of dilution gas is not more than 35% and it is a function of the equivalence ratio. In order to accelerate the combustion wave into detonation wave within 0.5m of the tube, array of obstacles with identical blockage ratio was placed inside the tube, near to the ignition source. It was observed that the obstacle enhances the transition process within the given length. The ignition source was set at three energy levels, i.e., 25mJ, 5J and 100J. The chosen level of ignition energy did not affect the combustion wave propagation in a smooth inner wall tube but in a rough inner wall tube, it improved the generated impulse force. Impulse measurement using an accelerometer was made to measure the impulse produced by the combustion wave. Generally, the detonation wave produces larger impulse force as compared to deflagration wave.

ABSTRAK

Fenomena pembakaran denyut telah diselidik secara ujikaji. Rig ujikaji yang terdiri daripada tiub besi tahan karat dengan garis pusat dalam 100mm dan 1700mm panjang, sistem pengumpulan data, unit kawalan nyalaan dan sistem pengisian telah dibina untuk tujuan mengukur ciri pembakaran denyut seperti tekanan, halaju rambatan dan denyut dorongan. Tiga nisbah campuran bahan api-pengoksida, 075, 1 dan 1,25, telah dipilih untuk menkaji kesan kepekatan bahan api terhadap rambatan gelombang pembakaran denyut. Didapati bahawa pembakaran bagi campuran bahan api berkepekatan tinggi merambat secara detonasi manakala campuran bahan api berkepekatan rendah merambat secara deflagrasi. Dua jenis bahan api fosil telah digunakan iaitu propana dan gas asli yang mengandungi 92.7% metana. Keputusan menunjukkan bahawa gas asli tidak sensitif terhadap rambatan detonasi berbanding propana. Didapati, di dalam tiub tanpa halangan, gelombang pembakaran terambat secara detonasi jika peratusan gas pencair tidak melebihi 35% dan bergantung kepada nisbah campuran bahan api. Untuk memecutkan gelombang pembakaran dalam jarak 0.5 m tiub tersebut, susunan halangan dengan nisbah halangan yang sama telah ditempatkan di dalamnya berhampiran dengan sumber nyalaan. Ia telah diperhatikan bahawa halangan tersebut membantu proses pertukaran dalam jarak yang diberikan. Sumber nyalaan telah ditetapkan pada tiga peringkat tenaga iaitu 25mJ, 5J dan 100J. Nyalaan dengan tahap yang telah dipilih tidak memberi kesan yang nyata terhadap gelombang pembakaran di dalam tiub tanpa halangan tetapi membantu dalam tiub berhalangan dengan menambahbaik denyut dorongan yang terjana. Pengukuran denyut dorongan menggunakan pengukur pecutan telah dilakukan untuk mengukur denyut dorongan yang dihasilkan oleh gelombang pembakaran. Secara amnya, gelombang detonasi menghasilkan denyut dorongan yang besar berbanding gelombang deflagrasi.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS

$\O$	-	Equivalence ratio
D	-	Tube's internal diameter (m)
d	-	blocakge passable diameter (m)
$\nu_{x,i}$	-	Velocity (m/s)
X_i	-	Species' mole fraction
Y_i	-	Species' mass fraction
P	-	Pressure (Pa)
ρ	-	Density (kg/m^3)
MW	-	Molecular weight (kg/kmol)
$\dot{m}$	-	Mass flow rate (kg/s)
$\dot{m}''$	-	Mass flux (kg/s-m^2)
Ma	-	Mach number
M_{CJ}	-	Chapman-Jouguet Mach number
c	-	speed of sound (m/s)
q	-	Heat addition (J/kg)
R	-	Specific gas constant (J/kg-K)
R_u	-	Universal gas constant (J/kmol-K)
ref	-	Reference state
ν_D	-	Detonation velocity (m/s)
CJ	-	Chapman-Jouguet point
C_v	-	Constant-volume specific heat (J/kmol)
C_p	-	Constant-pressure specific heat (J/kmol)
γ	-	Specific heat ratio (C_p / C_v)
υ	-	Specific volume (m^3/kg)
atm	-	Atmospheric pressure

h	-	enthalpy (J/kg)
λ	-	Detonation cell width (mm)
Ec	-	Direct ignition energy (J)
S	-	Obstacle spacing (m)
I	-	Impulse (Ns)
I_{sp}	-	Specific impulse (s)
m	-	tube weight
S_{cw}	-	Closed wall area
A	-	Tube cross section area ($m^{2)}$
g	-	Gravititional acceleration (m/s^2)
Δx	-	Horizontal deflection
V	-	Tube volume (m^3)
CNG	-	Compressed natural gas
AC	-	Alternating current
DC	-	Direct current
MS/s	-	Megasample per second

LIST OF APPENDIXES

CHAPTER 1

INTRODUCTION

1.1 Introduction

Combustion is a process where fuel and oxidizer will chemically react upon the presence of ignition to produce heat and sometimes light that is useful for mankind. The use of combustion in heat generation process started since the first time man discovered fire. From a simple wood stove to a complex turbine engine, men have discovered a wide range of combustion application but where fuel and oxidizer are always required. Between the two, the amount of fuel available is finite and its supply is decreasing by time. As shown in Figure 1.1, British Petroleum predicted based on their survey that the fossil fuel reserve to production ratio for the world is less than 100 years where 41.6 years for oil, 60.3 years for natural gas and 133 years for coal [1]. In the survey, Malaysia energy production in 2007 was 60.2 billion of cubic meters of natural gas and 33.8 million tones of oil [1]. The survey also shows that hydrocarbon reserved in Malaysia at the end of 2007 was 0.7 billion tonnes of oil and 2.48 trillion cubic meters of natural gas. By keeping this trend, the source of hydrocarbon in Malaysia will exhaust in 19.4 years for oil and 40.9 years for natural gas. Therefore concerted efforts are very much required not only to search for alternative energy but also to find method that able to combust and convert these fuels efficiently and effectively.

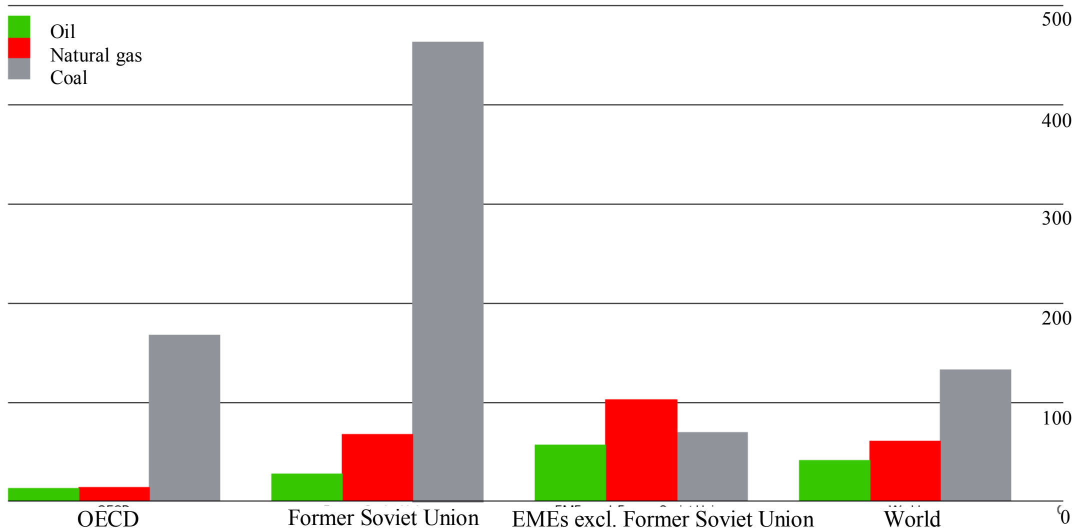
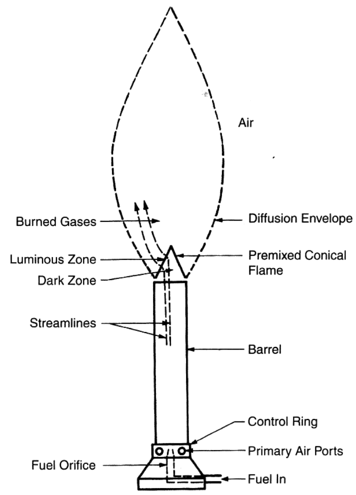
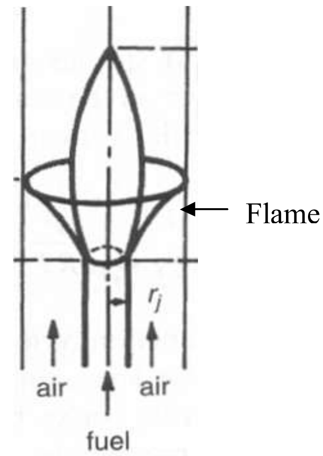


Figure 1.1: Fossil fuel reserves-to-production (R/P) ratios at end of 2007 [1]

1.2 Combustion

Combustion process can occur either in steady or unsteady (pulsating) manner. In steady state combustion, combustion zone or called flame is stationary and fuel-oxidizer is flowing toward the reaction zone either premixed or nonpremixed (diffusion) such as shown in Figure 1.2. In steady state mode, the combustion process is controlled by the flowrate of fuel and air (oxidizer). In pulsating combustion, reaction process occurs at an interval of time either the fuel-oxidizer is flowing toward the flame or stationary just before the reaction take place. In most of pulse combustion device, fuel is premixed with oxidizer.





a) Premixed flame b) Diffusion flame

Figure 1.2: Steady state combustion [2]

Combustion wave propagate either at low speed (deflagration) or high speed (detonation) propagation velocity. The general property that differentiates between deflagration and detonation is its propagation velocity. In deflagration mode of propagation, the combustion wave propagates at subsonic speed whereas in detonation mode of propagation, the combustion wave propagates at supersonic speed. Figure 1.3 shows the region of deflagration and detonation in Rankine-Hugoniot curve.

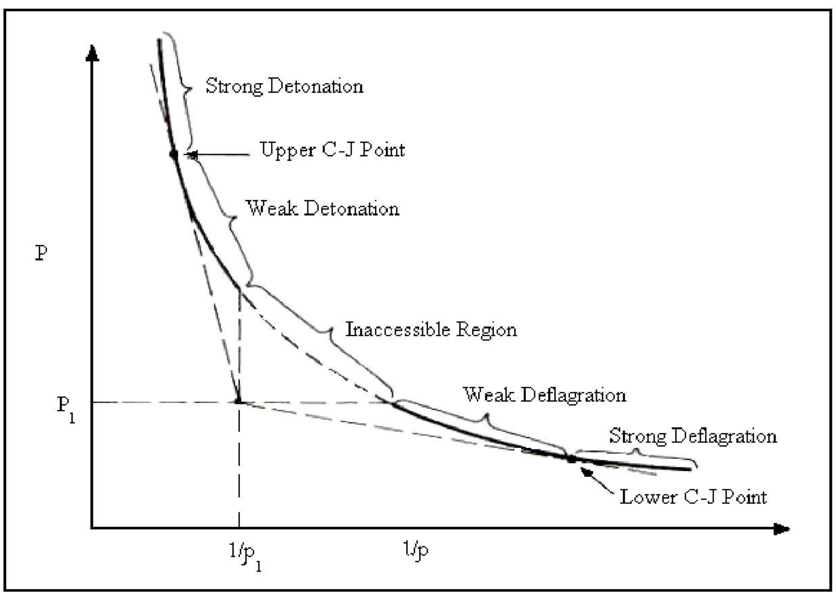


Figure 1.3: Rankine-Hugoniot curve with limiting Rayleigh lines. [5]

Deflagration mode of pulsating combustion occurs in pulse combustor. Figure 1.4 shows the example of pulse combustor. The nature of this device is depending on its geometry. The important aspect that needs to be considered in developing a pulse combustor is to identify its proper geometry so it can be self-sustained. A pulse combustor operates based on one of the three principles; 1) Schmidt tube, 2) Helmholtz resonator and 3) Rijke tube. Most of the pulse combustors today were designed based on the principle of Helmholtz resonator [6]. The pulse combustor can be divided into 2 categories; valved and valveless. The valved pulse combustor is easy to design but it cannot be operated continuously over a long period of time due to fatigue failure of the valve cause by ram pressure. On the other hand, valveless pulse combustor can be operated over a long period of time since it does not depend on the movement of the valve but it is difficult to be designed since one need to understand the pulsating flow of gas. The interest of pulse combustor (deflagration) as a propulsion system declined in late 50's due to the emergence of gas turbine engines. Nowadays, the interest of pulse combustor is more for on-land applications such as boiler, dryer and heat generator [7].

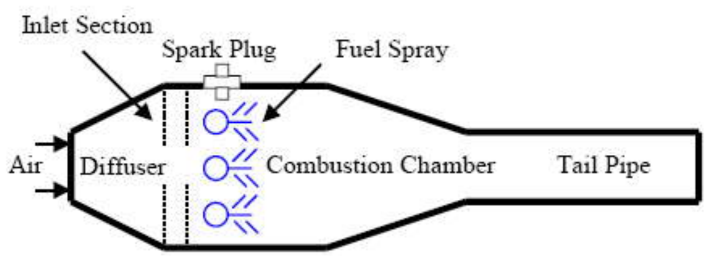


Figure 1.4: Pulse combustor [6]

The advantage of pulsating combustion is that the reaction occurs either self-sustaining or controlled and consumes just enough amount of fuel to react and pulsate. A study on pulse combustion by Mazlan et. al [3] shows that in an operating helmholtz pulse combustor with operating frequency equal to 125Hz, the air-fuel equivalence ratio was below 1. Therefore, in pulsating combustion, there is less or no excess fuel. Since the resident time of each cycle of the pulse combustion is short, NOx production during the combustion process is low. It was reported by Sonodyne Inc. [4] that a pulse combustor produce only 20-70mg/m^3 nitrogen concentration compared to a steady state burner that produce 100-7000 mg/m^3 nitrogen concentration with the same amount of fuel consumption. Furthermore, the burning efficiency of their combustor was about 90-99% while for the steady state was about 80-86%.

Device that applies detonation combustion process is still being investigated and most of the researches are aiming for a detonation-based propulsion system [5,8,9,11-14,33,42-44]. Detonation process offer several advantages for a propulsion system such as more compact system and highly efficient combustion process due to rapid energy conversion [8]. Although the studies on detonation phenomenon started earlier than that of gas turbine, the interest of applying detonation in propulsion system was started only in the early 90's [9]. Before this, the studies on detonation were performed mainly on the hazardous prevention purpose. Due to its high energy conversion process, detonation has been recently considered for propulsion. In fact, according to Wildon et. al.[10], 20 m^2 square detonation may produce power that equal to the power the earth receives from the sun [10]. Compared to a conventional propulsion system that applies constant pressure combustion process (Brayton cycle), detonation process is closer to constant-volume process (Humprey cycle) which offer more efficient energy conversion process [11]. Figure 1.5 shows the comparison among Brayton, Humprey and detonation cycle.

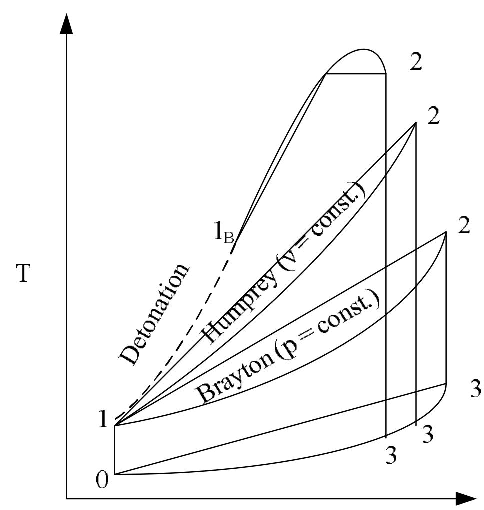


Figure 1.5: Temperature versus entropy for brayton, humprey and detonation cycle [11]

By applying constant-volume process, a propulsion system could save up to 7% of fuel consumption compared to conventional gas turbine [12]. In addition, since compression of air is not required, pulse detonation engine has fewer components thus allows it to produce higher specific impulse at all Mach number compare to other propulsion engines [13]. The comparison of pulse detonation engine to other types of propulsion system is shown in Figure 1.6.

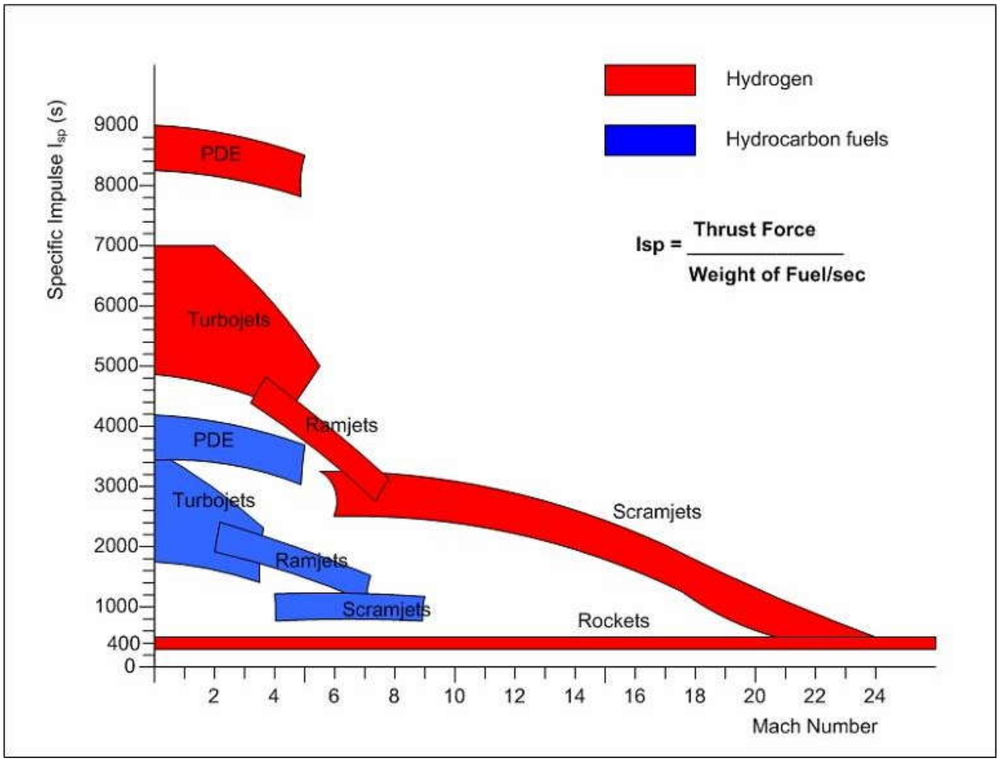


Figure 1.6: Specific Impulse versus Mach number for propulsion engines [13]

1.3 Problem Statement

In combustion process where hydrocarbon fuel reacts with air as the oxidizer, the flame may propagate at a few meters per second depending on the type of fuel. Air is known as the common oxidizer in combustion process. In the combustion process, air is known to comprise of 21% oxygen and 79% nitrogen. Even though the nitrogen may react with the oxygen during the combustion process and produce NOx, it is considered as diluent species in the process. By decreasing the amount of nitrogen, the combustion rate can be increased due to shorter route of combustion process thus increasing the released energy. At some point where the percent of oxygen is high enough and the characteristics of geometry meet the required specification, detonation mode of combustion wave propagation can be produced.

In a fuel-oxidizer mixture where the oxidizer contains 100% oxygen, detonation propagation can be initiated with a small amount of ignition energy. Increasing diluent gas such as nitrogen in the mixture will decrease the possibility of detonation to be initiated. In a fuel-air mixture, the method of direct ignition energy that is required to initiate detonation is more than 1kJ which is not practical to be used in a transportation system [14]. Multiple point spark ignition had been proven to assist combustion wave to propagate as detonation wave [29-31]. The detail study on the effect of variable single point spark ignition energy on pulse combustion is still lacking. Not only via high ignition energy, detonation propagation also can be generated using a deflagration to detonation transition technique. This technique requires some set up of internal configuration within the flame propagation channel. Different types of fuel require different type of configuration. Some fuel requires a few meters of obstacle set up to create DDT. To apply this kind of pulse combustion in a propulsion system, the length of DDT should be shortened. This research is focused on the possibility of shortening the length of DDT in pulse combustion process of hydrocarbon fuel in low amount of oxygen addition via combination of configuration of obstacle assisted by high ignition energy (below critical detonation ignition energy).

This work is an experimental study aimed at understanding the single pulse combustion phenomenon especially the case for detonation propagation of combustion wave. The experiments are conducted using detonation tube that is closed at one end, open at the other and are filled with reactive mixture that is combusted by means of spark generated by a system with variable ignition energy. Since a pulse detonation engine applies intermittent combustion process, impulse generation from single pulse detonation tube is an important aspect to determine the efficiency of the PDE. The conventional method to measure the impulse is to use pendulum arrangement of pulse detonation experimental rig. Using this method, one requires a larger space of experimental area to allow the tube to swing due to the generated detonation wave. Even though the pendulum arrangement is the cheapest method to measure the impulse, it only measure the maximum impulse force based on the maximum deflection of the tube. The use of accelerometer to determine the impulse generated from the combustor is an interesting method to be explored. There has been no existing study in the literature that applies accelerometer to measure impulse. By using an accelerometer, analysis on impulse generated by pulse detonation wave can be done in detail. Since the propagation of detonation wave produces several reflected wave (wave that travel back to the thrust wall) that is the source of impulse force, the use of accelerometer allow researchers to differentiate the impulse force generated by the reflected wave due to transmitted detonation wave into atmosphere with the generated impulse force cause by the other reflected wave.

Along with the aim to study the potential of applying detonation in a propulsion system, the result from this research also can be used to prevent hazardous accident from occurring. As the use of gas-type fuel in transportation is increasing, study on combustion propagation of gas fuel is required. One of the hydrocarbon fuel used in this research is natural gas which is being used a gas fuel in transportation ad power generation. Since the natural gas is delivered through a link of pipeline, accidentally combusted natural gas may propagate along the pipeline. The combustion wave of natural gas may transit to detonation due to the presence of valve gate that act as obstacle. Since detonation wave propagate at supersonic speed and produce high propagation pressure, the accident could cause damage in several places that are connected with the link of pipeline. Even though there was no specific incident reported in Malaysia, accidents that occur in other countries should be a lesson to prevent hazardous accident. For example, Ukraine gas pipe line that transporting Russian gas to Europe had hit by a explosion in May 2007 [58]. The blast damaged 30m of pipe line. Even though the explosion did not cause any casualties, it cause uneasy situation between Ukraine and Russia. Another example of explosion of fuel pipe line was in Nigeria [59]. The accident that occurred in May 2006 cause casualties between 150 and 200 people. Thus, investigation on how the combustion wave of natural gas can be transited to detonation is required so that prevention of the transition can be done.

1.4 Research Objectives

This study is about propagation of single pulse combustion wave in an obstructed channel. The objective of this study is mainly:

1) To investigate the effect of diluent composition and elevated ignition energy on the pulse combustion process of hydrocarbon-oxygen mixture toward detonation propagation.
2) To measure the generated impulse using an accelerometer.

1.5 Research Scope

This work involves primarily experiments on single pulse detonation combustion and will concentrate only on gaseous hydrocarbon fuel which is propane and natural gas of 97.2% methane. The reactive mixtures of hydrocarbon-oxygen will be diluted with nitrogen gas at various proportions. In order to conduct series of experiments, a complete experimental rig will be constructed. The study comprise of the development of single pulse detonation experimental rig which comprise of:

a. Combustor section with various types of obstacles
b. Partial pressure filling system
c. Ignition system with variable ignition energy