NUMERICAL AND EXPERIMENTAL INVESTIGATION OF SYNTHETIC BIOGAS PULSE COMBUSTION

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ABSTRACT

The pulse combustion propagation of a synthetic biogas mixture was numerically and experimentally studied. The gaseous fuel used in this study was a mixture of natural gas with 97% methane and CO_2. Three equivalence ratios; 0.75 (lean), 1 (stochiometric) and 1.2 (rich) were used in the experiments. An experimental setup that consists of a stainless steel pulse detonation tube with 100mm inner diameter and 1700mm length, ignition control system and filling station was installed to measure the characteristics of pulse combustion such as pressure and velocity. The effect of different equivalence ratio and different percentage of dilution on the performance of pulse combustion detonation was investigated by using Chapman-Jouguet theory. Two modes of pulse combustion propagation wave were observed: deflagration, detonation and in some cases deflagration to detonation transition (DDT). Results showed that the sensitivity of the mixture toward the detonation decreased with the increase of carbon dioxide dilution and increased with the increment of the equivalence ratio. In this study, for the mixture with 50% dilution, DDT and high speed deflagration with the velocity of around 700m/s were observed. The results were compared with calculated data using Chemical Equilibrium with Application (CEA) code and it was considered that CEA is useful software for calculating Chapman-Jougeut detonation parameters such as detonation velocity and pressure. From the analysis of detonation cell width in the soot foil technique, it was observed that the stochiometric mixture produces bigger cell width compared to rich mixture. So this indicates that the detonation wave of rich mixture can propagate through a smaller tube compared to lean and stochiometric mixtures.

ABSTRAK

perambatan pembakaran pulsa dari campuran Biogas sintetik berangka dan eksperimen dipelajari. bahan bakar gas yang digunakan dalam kajian ini adalah campuran dari gas alam dengan 97% methane dan CO_2. *tiga nisbah kesetaraan*; 0.75 (lean), 1 (stochiometric) and 1.2 (kaya) *digunakan dalam percubaan.* Sebuah setup eksperimental yang terdiri daripada sebuah letupan tabung pulsa baja stainless dengan diameter dalam 100mm dan panjang 1700mm, kawalan sistem pengapian dan pam petrol telah dipasang untuk mengukur ciri-ciri pembakaran pulsa seperti tekanan dan kelajuan. Pengaruh nisbah kesetaraan yang berbeza dan peratusan yang berbeza dari dilusi terhadap prestasi pembakaran letupan pulsa diselidiki dengan menggunakan Chapman- Jouguet teori. Dua mod pembakaran propagasi gelombang pulsa diamati: deflagration, letupan dan dalam beberapa kes letupan deflagration untuk peralihan (DDT). Keputusan kajian menunjukkan bahawa sensitivity campuran terhadap letupan menurum dengan peningkatan cecair karbon dioksida dan meningkat dengan kenaikan nisbah kesetaraan. Dalam kajian ini, untuk campuran dengan pengenceran 50%, DDT dan deflagration berkelajuan tinggi dengan kelajuan sekitar 700m/s diamati. Hasilnya dibandingkan dengan data dihitung dengan menggunakan Chemical Equilibrium dengan Aplikasi (CEA) kod dan dianggap bahawa CEA adalah perisian berguna untuk menghitung Chapman-Jougeut parameter letupan seperti kelajuan detonasi dan tekanan. Dari analisis sel lebar letupan di teknik foil jelaga, ia mengamati bahawa campuran stochiometric lebar menghasilkan sel lebih besar berbanding dengan campuran kaya. Jadi ini menunjukkan bahawa gelombang detonasi dari campuran kaya boleh tersebar melalui tabung kecil dibandingkan dengan ramping dan campuran stochiometric.

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LIST OF SYMBOLS

P - Pressure (bar)

u_u - Velocity of unburned gas (m/s)

u_b - Velocity of burned gas (m/s)

v_d - Detonation velocity (m/s)

P_u - Pressure of unburned gas (bar)

P_b - Pressure of burned gas (bar)

P_d - Detonation pressure (bar)

T_u - Temperature of unburned gas (K)

T_b - Temperature of burned gas (K)

T_d - Detonation temperature (K)

ρ_u - Density of unburned gas (kg/m^3)

ρ_b - Density of unburned gas (kg/m^3)

ρ_d - Detonation density (kg/m^3)

ρ - Density (kg/m^3)

T - Temperature (K)

v - Velocity (m/s)

h - Enthalpy (kJ/kg)

CJ - Chapman-Jougeut point

NG - Natural gas

c - Speed of sound (m/s)

q - Heat addition (kJ/kg)

C_p - Constant pressure specific heat (J/kmol)

C_v - Constant volume specific heat (J/kmol)

γ - Specific heat ratio (C_p / C_v)

ν - Specific volume (m^3/kg)

Ma - Mach number
R - Specific gas constant (J/kg.K)
v_D - Detonation velocity (m/s)
U_{CJ} - Detonation velocity (m/s)
x - Distance (m)
λ - Detonation cell width (mm)
d - Internal diameter (mm)
w - Width of duct (mm)
φ - Equivalence ratio
x_i - Species mole fraction
m - Mass (kg)
s - Entropy (J/kg.K)
CJ_U - Upper CJ point
CJ_L - Lower CJ point
CEA - Chemical Equilibrium with Application
FAME - Fatty Acid Methyl Ester
UFL - Upper Flammability Limit
CNG - Compressed Natural Gas
ETBE - Ethyl Tertiary-Butyl Ether
LFL - Lower Flammability Limit
PT - Pressure transducer
Phi - Equivalence ratio
DDT - Deflagration to Detonation Transition
LFG - Landfill gas

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CHAPTER I

1.1 INTRODUCTION

In general, a combustible mixture can support two modes of combustion: deflagration and detonation. In the deflagration regime, the combustion wave can propagate as a laminar flame at a typical velocity of the order of about 0.5 m/s, or it may accelerate to a turbulent flame where velocity can be orders of magnitude higher. The other extreme is the detonation mode, in which a detonation wave propagates at about 2000 *m/s* amplifying the pressure by a factor of 20 across the wave.

This thesis deals with the second mode, i.e. gaseous detonation waves. Detonation is defined as combustion supported shock wave with significant pressure and density rise across the wave. The main characteristic of detonation waves is the coupled motion of the shock front and the reaction zone behind it.

The earliest theory regarding detonation waves is the classical Chapman-Jouguet *(CJ)* theory [13]. This theory permits the calculation of the average static parameters of detonation (i.e. detonation velocity, pressure rise across the wave, etc.) which agree surprisingly well with experimental observations. The *CJ* theory is based on thermodynamic equilibrium and does not require knowledge of the chemical rate processes. Hence, it cannot predict the rate-dependent detonation parameters (i.e., initiation energy, critical tube diameter, etc.). The *CJ* theory states that the flow downstream of the wave is sonic relative to the shock (this is also called the *CJ* criterion).

Another important theory of detonations is the Zeldovich-von Neuman-Doring (ZND) theory. [7] This theory considers a one-dimensional steady structure for detonation waves, which consists of a normal shock wave followed by an induction zone and subsequently by a reaction zone.

Besides these classic theories, numerous theoretical, experimental, and computational researches have been performed in the past four decades on the different aspects of gaseous detonations. [20] Despite these efforts, there is no quantitative theory as yet capable of predicting the parameters of gaseous explosions from first principles based on the thermo-chemical properties of a mixture. For example, it is unclear what minimum energy is required for the initiation of detonation, or under which conditions a detonation wave may transit through a small opening into a big reservoir. Furthermore, whether it is possible or not to detonate a certain mixture cannot be determined a priori.

Knowledge of detonation characteristic in mixtures is important in assessing the probability of a detonation and its results. The knowledge and understanding of detonation characteristic can be useful for product or system design related to combustion fields. Applying this knowledge in industry can reduce the risk of critical accident. [50] Eventually if any accident occurs, this knowledge can be applied for trouble shooting and future prevention activities.

1.2 PROBLEM STATEMENT

Biogases are a wide range of fuels which have been used for decades in various industries such as gas-powered vehicles, power plant, cooking and lighting. An increasing trend is seen in the applications of biogas in these industries during last decades. Biogases consist of about two thirds methane and one third carbon dioxide. The most important feature of biogas is that they are renewable sources of energy, relatively cheap and more effective for reducing green house gases unlike other natural resources like coal, petroleum and even nuclear fuel.

As mentioned, biogas is a combustible gas and can be used as fuel for engine. In general, a combustible mixture can support two modes of combustion: deflagration and detonation. Detonation which is quite different from a deflagration is a shock wave sustained by the energy released by combustion. The detonation front propagates into unburned gas at a velocity higher than the speed of sound in front of the wave.

Knowledge of detonation characteristic in mixtures is important in assessing the probability of a detonation and its results. The understanding of detonation characteristic can be useful for product or system design related to combustion fields and could be useful for prevention of hazardous accidents of detonation in industrials such as petroleum pipeline, pulse detonation engines, etc. [50] Eventually if any accident occurs, this knowledge can be applied for trouble shooting and future prevention activities.

The Chapman-jouguet (CJ) theory is used to calculate the equilibrium detonation properties of an explosive. This theory is based on energetic considerations. It satisfies the conservation laws across a control volume separating two equilibrium states: the reactants and the detonation products. No knowledge of the detailed detonation structure is required.

In this thesis, it is focused on Chapman-Jouguet theory and investigating numerically on detonation of gaseous fuel especially synthetic biogases. This research has an experimental study aimed at understanding this fact.

Also the analysis of detonation wave is performed. The actual structure of a detonation wave is highly three-dimensional with convex segments and for simplification it is such as transverse wave structures. The cell width of detonation wave is useful data to predict the permitted space for detonation wave to propagate. [49]

1.3 OBJECTIVES

This project aims to investigate the detonation characteristic of gaseous fuels especially synthetic biogas and find thermodynamics properties such as pressure and CJ detonation velocity. Also the effect of diluents composition on the performance of the pulse combustion process of hydrocarbon-oxygen mixture is investigated.

The numerical calculation would be compared with experimental results done in the high speed reacting flow research laboratory (HIREF) at University Teknologi Malaysia (UTM).

1.4 SCOPES

This project has covered general scopes and is summarized as follows;

1. Literature review of the detonation and deflagration, CJ and ZND theory, CEA software and biofuels.

2. Numerically investigation on detonation of different gases especially biogases by using CEA software (Chemical Equilibrium with Applications) and find thermodynamics properties such as pressure and CJ detonation velocity.

3. Experimental investigation of the pulse combustion wave propagation in the pulse combustion tube without obstacles. Also analysis of detonation wave by using soot foil and the effect of different percentage of dilution on the detonation process are conducted.

4. Comparison the simulated results with experimental measured results for synthetic biogas (mixture of methane and carbon dioxide).

1.5 Thesis Outline

The chapter two presents literature review of the detonation and deflagration, CJ theory ZND theory, boifuels and CEA software and its governing equations. Then the chapter three discusses about the methodologies of model development and experimental setup respectively. The chapter four focuses on the results obtained of this study. Then the discussions of the results and comparison with experimental results are explained in this chapter. Finally conclusion and recommendation are presented in the chapter five. Also there are some samples of numerical calculation

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