UNIVERSITI PUTRA MALAYSIA

NUMERICAL STUDY OF COMBUSTION CHARACTERISTICS AND EMISSION IN DIESEL ENGINE USING LPG-HYDROGEN-DIESEL FUEL MIXTURE

RADHWAN ALI ABD AL-REDA

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By

RADHWAN ALI ABD AL-REDA

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia,
in Fulfillment of the Requirements for the Degree of Master of Science

April 2017

DEDICATION

To my parents whose support and understanding helped to make this possible

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfillment of the requirement for the Degree of Master of Science

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Chairman : Associate Professor Nuraini Abdul Aziz, PhD
Faculty : Engineering

Towards the effort of reducing pollutant emissions, especially nitrogen oxides, and smoke, from diesel engine direct injection (DI), engineers have proposed various solutions; one of these solutions is the use of alternative gaseous fuel. Using alternative gasses fuels like liquefied petroleum gas (LPG), hydrogen (H_2), etc., for the modified diesel engine are receiving more interest from many scientists due to many reasons including the national concerns of the liquid fuels limited resources, the environment advantage and the needs to use a reliable, durable, and efficient engine. However, diesel-H_2 and diesel-LPG dual fuel engine produced many of the unwanted effects such as rapid burning rate, increase diffusivity, and high emission levels. Therefore, researchers started focusing on tri-fuel engines. Hence, LPG addition to the diesel-H_2 operation has the ability to make hydrogen combustion smoother and stable which can prevent imperfect combustion, such as the sharp increase of peak in-cylinder pressure and temperature also lowers the combustion temperature of hydrogen in order to repress Nitrogen Oxides (NO_x) emission. As a result, better performance engine can be obtained when H_2 is added with LPG to make a secondary fuel for diesel dual fuel engine.

In the present study, the usage of ANSYS design modular was chosen to create the entire computational domain of the engine and for Computational Fluid Dynamic (CFD) the FLUENT approach was used for Ricardo Hydra diesel engine, a single cylinder engine that operates using the direct injection method. A two-dimensional CFD code was used in the study in order to examine the emissions and combustion characteristics of a diesel engine, diesel-LPG, diesel-H_2 under dual-fuel, and diesel-LPG-H_2 under tri-fuel operations, with different air-fuel ratios (λ) such as 1.2, 1.6, 2, and 2.4. In addition, in order to choose the best reduction towards the emission, evaluate the best manner of fuel gasses under dual and tri-fuel conditions was conducted. Moreover, torque (20.18 Nm), intake temperature (298 K), and engine speed (2000 rpm) were taken constantly to an atmospheric condition. The effects of a number of the cells on the expected result were utilized in order to analyze the most accurate one. The simulation data of in-cylinder pressure and verification of Nitrogen Oxides (NO_x) emission appears to achieve a good agreement with data from previous work. The results obvious the successfully established a CFD simulation was obtained for predicting the emissions and combustion characteristics on the diesel, dual, and tri-fuel engine operations. Knowledge of utilizing the dual and tri-fuel in modify diesel engine and understanding the acceptable values of the mixture to give the best results. The addition of gasses fuels increases the peak temperature under all values of excess air. However, the addition of gaseous fuel only increased the in-cylinder pressure for excess air values of 1.2, 1.6, and 2. On the other hand, at 2.4 excess air, the peak pressure increased through the increase of the limit value of H_2, such as 60L-40H and 50L-50H, when added to LPG. A decrease is then observed with diesel-H_2 modes. This might be a result of the low amount of fuels in the air when compared to other similar cases and lean burn operation engine. At dual fuel operations, adding H_2 decreases CO and CO_2 emissions when compared with the emission from LPG. Conversely, diesel-LPG-H_2 tri-fuel operations lowered the CO emission when compared to diesel-LPG. It also lowered Nitrogen Oxides (NO_x) emission when compared to the diesel-H_2 operation for all excess air. In order to lower CO/CO_2 emissions, high H_2 fraction is proposed in LPG (50L-50H). On the other hand, lower H_2 fraction in LPG (90L-10H) can lower the uncontrolled combustion of hydrogen combustion and restrict the increase of Nitrogen Oxides (NO_x) emission.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk Ijazah Master Sains

KAJIAN BERANGKA CIRI-CIRI PEMBAKARAN DAN PELEPASAN DI DALAM ENJIN DIESEL MENGGUNAKAN CAMPURAN BAHAN API LPG-HIDROGEN-DIESEL

Oleh

RADHWAN ALI ABD AL-REDA

April 2017

Pengerusi : Profesor Madya Nuraini Abdul Aziz, PhD
Fakulti : Kejuruteraan

Ke arah usaha mengurangkan pelepasan bahan pencemar, terutamanya nitrogen oksida dan asap daripada enjin diesel pencucuhan terus, para jurutera telah menyarankan pelbagai penyelesaian; salah satunya adalah penggunaan bahan api alternatif. Penggunaan bahan api alternatif seperti gas petroleum cair (LPG), hidrogen (H_2) dan lain-lain, untuk enjin diesel terubahsuai telah menarik perhatian para saintis kerana beberapa faktor termasuk kebimbangan terhadap sumber bahan api cecair yang terhad, membawa kebaikan kepada alam sekitar dan keperluan untuk menghasilkan enjin yang lebih dipercayai, tahan lama dan efisien. Walau bagaimanapun, enjin bahan api duaan diesel-H_2 dan diesel-LPG memberikan banyak kesan yang tidak diingini seperti kadar pembakaran yang cepat, peningkatan daya keresapan dan paras pelepasan yang tinggi. Oleh itu, para penyelidik mula memberi tumpuan kepada enjin tiga bahan api. Justeru, penambahan LPG ke dalam operasi diesel-H_2 berupaya membakar hidrogen dengan lebih lancar dan stabil di mana ia boleh menghalang pembakaran tidak sempurna, seperti peningkatan tekanan dan suhu yang mendadak di dalam silinder dan juga menurunkan suhu pembakaran hidrogen bagi mengekang pelepasan NO_x. Disebabkan itu, enjin akan memberikan prestasi yang lebih baik apabila H_2 ditambah pada LPG, setelah menjadi bahan api sekunder bagi enjin diesel bahan api duaan.

Dalam kajian ini, penggunaan perisian reka bentuk modular ANSYS telah dipilih untuk menghasilkan keseluruhan domain pengiraan bagi enjin manakala bagi Pengiraan Dinamik Bendalir, kod FLUENT telah digunakan pada enjin diesel Ricardo Hydra, enjin satu silinder tunggal yang beroperasi menggunakan kaedah pencucuhan terus. Kod Pengiraan Dinamik Bendalir dua dimensi telah digunakan di dalam kajian ini untuk menilai pelepasan dan ciri-ciri pembakaran daripada operasi enjin diesel, diesel-LPG, diesel-H_2 di bawah bahan api duaan, dan diesel-LPG-H_2 di bawah operasi tiga bahan api, dengan nisbah udara-bahan api (λ) yang berbeza iaitu 1.2, 1.6, 2, dan 2.4. Tambahan pula, untuk memilih pelepasan dengan pengurangan terendah, penilaian terhadap dua bahan api dan tiga bahan api dengan keputusan terbaik telah dijalankan. Selain itu, daya kilas (20.18 Nm), suhu pengambilan (298 K), dan kelajuan enjin (2000 rpm) sentiasa ditetapkan pada keadaan atmosfera. Kesan jumlah sel terhadap keputusan jangkaan telah digunakan bagi menganalisis keputusan yang paling tepat. Data simulasi bagi tekanan dalam silinder dan pengesahan pelepasan NO_x menunjukkan persetujuan dengan data daripada kerja terdahulu. Keputusan juga menunjukkan simulasi CFD bagi meramal pelepasan dan ciri-ciri pembakaran oleh operasi enjin diesel, dua bahan api dan tiga bahan api telah berjaya dihasilkan. Pengetahuan berkenaan pengunaan dua dan tiga bahan api di dalam enjin diesel terubahsuai dan pemahaman terhadap nilai campuran yang boleh diterima untuk memberikan keputusan terbaik turut telah dicapai. Penambahan bahan api gas telah meningkatkan puncak suhu bagi semua nilai dengan udara lebihan. Walau bagaimanapun, penambahan bahan api gas hanya meningkatkan puncak suhu dalam silinder pada paras udara lebihan 1.2, 1.6, dan 2. Sementara itu, bagi udara lebihan pada nilai 2.4, terdapat peningkatan pada tekanan puncak melalui penambahan nilai had H_2, seperti 60L-40H dan 50L-50H, apabila ditambah pada LPG. Penurunan dapat dilihat pada diesel-H_2 mod. Ini berkemungkinan disebabkan oleh jumlah bahan api yang rendah di dalam udara berbanding kes-kes yang serupa dan operasi enjin yang melalui pembakaran bahan api dengan udara lebihan. Bagi operasi dengan dua bahan api, penambahan H_2 mengurangkan pelepasan CO dan CO_2 berbanding dengan pelepasan dari LPG. Sebaliknya, operasi dengan tiga bahan api (diesel-LPG-H_2) mengurangkan pelepasan CO berbanding diesel-LPG. Ia juga mengurangkan pelepasan NO berbanding operasi dengan diesel-H_2 bagi seluruh nilai udara lebihan. Bagi mengurangkan pelepasan CO/CO_2, pecahan dengan jumlah H_2 yang tinggi telah diperkenalkan ke dalam LPG (50L-50H). Selain itu, pecahan dengan jumlah H_2 yang rendah di dalam LPG (90L-10H) didapati boleh mengurangkan pembakaran hidrogen yang tidak terkawal dan mengehadkan peningkatan pelepasan NO.

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I certify that a Thesis Examination Committee has met on 13 April 2017 to conduct the final examination of Radhwan Ali Abd Al-Reda on his thesis entitled "Numerical Study of Combustion Characteristics and Emission in Diesel Engine using LPG-Hydrogen-Diesel Fuel Mixture" in accordance with the Universities and University Colleges Act 1971 and the Constitution of the Universiti Putra Malaysia [P.U.(A) 106] 15 March 1998. The Committee recommends that the student be awarded the Master of Science.

Members of the Thesis Examination Committee were as follows:

Mohd Idris Shah bin Ismail, PhD
Senior Lecturer
Faculty of Engineering
Universiti Putra Malaysia
(Chairman)

Abd. Rahim bin Abu Talib, PhD
Associate Professor
Faculty of Engineering
Universiti Putra Malaysia
(Internal Examiner)

Md. Abul Kalam, PhD
Associate Professor
University of Malaya
Malaysia
(External Examiner)

NOR AINI AB. SHUKOR, PhD
Professor and Deputy Dean
School of Graduate Studies
Universiti Putra Malaysia

Date: 2 June 2017

This thesis submitted to the Senate of the Universiti Putra Malaysia and has been accepted as fulfillment of the requirement for the degree of Master of Science. The members of the Supervisory Committee were as follows:

Nuraini Abdul Aziz, PhD
Associate Professor
Faculty of Engineering
Universiti Putra Malaysia
(Chairman)

Abdul Aziz Bin Hairuddin, PhD
Senior Lecturer
Faculty of Engineering
Universiti Putra Malaysia
(Member)

ROBIAH BINTI YUNUS, PhD
Professor and Dean
School of Graduate Studies
Universiti Putra Malaysia

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This is to confirm that:

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Signature:
Name of Chairman of Supervisory Committee: Associate Professor Dr. Nuraini Abdul Aziz

Signature:
Name of Member of Supervisory Committee: Dr. Abdul Aziz Bin Hairuddin

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LIST OF ABBREVIATIONS

BTE	Brake Thermal Efficiency
AFR_{st}	Stoichiometric Air to Fuel Ratio
A/F	Air Fuel Ratio
BDC	Bottom Dead Center
2D	2-Dimensional
BSEC	Brake Specific Energy Consumption
EGR	Exhaust Gas Recirculation
CFD	Computational Fluid Dynamics
CAD	Crank Angle Degree
CI	Compression Ignition
SI	Spark Ignition
LPG	Liquefied Petroleum Gas
CO_2	Carbon Dioxide
CNG	Compressed Natural Gas
CO	Carbon Monoxide
PM	Particulate Matter
C_3H_8	Propane
H_2	Hydrogen
EVC	Exhaust Valve Close
EVO	Exhaust Valve Open
IC	Internal Combustion
HC	Hydrocarbons
MDM	Moving Dynamic Mesh

IVC	Intake Valve Close
IVO	Intake Valve Open
TAB	Taylor Analogy Breakup
DPM	Discrete Phase Model
DI	Direct Injection
NO_x	Nitrogen Oxides
NO	Nitric Oxide
N_2O	Nitrous Oxide
NO_2	Nitrogen Dioxide
TDC	Top Dead Center
NG	Natural Gas
PISO	Pressure-Implicit with Splitting of Operators
RNG	Re-Normalized Group
λ	Excess Air ($1/\varphi$ air-fuel ratio)
$\dot{m}$	Mass Flow Rate (kg/hr)
X	Mass Fraction of Fuels

CHAPTER 1

INTRODUCTION

1.1 Background

The use of gaseous fuels for internal combustion engines have long been suggested as a potential way to maintain engine efficiency and performance while reducing emissions (Xu et al., 2010). These days, studies on various alternative fuels for diesel engines have been conducted with the goal of reducing diesel fuel consumption as well as particulate and nitrogen oxide (NO_x) emissions. Therefore, Liquefied petroleum gas (LPG) has been suggested as one of the most suited alternative fuels that work not only as a petroleum fuel replacement but also as an alternative that is able to lower smoke, NO_x and particulate matter emissions (Jothi et al., 2007). Therefore, development of LPG vehicles is being undertaken in order to come up with a vehicle that is economical and results in lower pollution levels. This interest has led several researchers works on the utilization of LPG mixtures with a number of new fuels in diesel engines. Vijayabalan and Nagarajan, (2009) modified a vertical, single cylinder air-cooled diesel engine so that it can take LPG in dual fuel mode. They then studied the engine's emission, performance, and combustion characteristics. LPG was prepared to combine with air before being compressed and ignited using a minimal pilot spray of diesel. The resulting of dual fuel engine exhibited reduced amounts of oxides of nitrogen and smoke given at the whole load condition range. However, because of poor ignition, it showed higher carbon monoxide and hydrocarbon emissions with poor brake thermal efficiency under lower load conditions. To improve the lower load performances, a glow plug was introduced inside the combustion chamber. There was a 3% improvement in the brake thermal efficiency and carbon monoxide, hydrocarbon, and smoke emissions were reduced by 50%, 69%, and 9%, respectively, under lower load condition. However, the NO_x emission was unaffected by the glow plug's presence. Ganesan (2002) modified a normal diesel engine in order for it to operate in dual fuel mode using diesel as a pilot fuel and LPG as the primary fuel. The experiments were conducted to observe the engine's combustion parameters, brake thermal efficiency, and emission for various diesel substitutions. The higher combustion level resulted in an increase in brake thermal efficiency from 35% for the diesel mode to up to 37% in dual fuel mode under a full load state. It was also observed that in the dual fuel mode, the NO_x ranks decrease was up to 60% under a full load state. The ignition delay period increase by two degrees of crank angle while there was a decrease in the peak pressure under light diesel and high load substitutions conditions.

Additionally, due to its availability and emission considerations, hydrogen has been suggested as another good alternative fuel for internal combustion engines. Hence, hydrogen has the capacity to improve engine efficiency while reducing emissions (Saravanan et al., 2008). Hydrogen's combustion characteristics differ from hydrocarbon fuels since it has a wider flammability range, rapid combustion, and higher adiabatic flame temperature. Hydrogen is considered a clean fuel since it does not produce dangerous exhaust gasses like unburned hydrocarbon, particulate matter, and carbon monoxide (CO) and it does not release greenhouse gasses such as carbon dioxide (CO_2) (Mansour et al., 2001). Thus, the interest for diesel-H_2 dual-fuel engines has considerably increased in recent years (Bose and Banerjee, 2012). Gatts et al., (2010) studied the combustion efficiency of hydrogen by examining the amount of unburned hydrogen that was observable through the exhaust gas. These studies revealed that hydrogen combustion efficiency depended on the engine load. When operating under high load states, hydrogen has to be added in order to achieve high efficiencies for both hydrogen and diesel fuels. Liew et al., (2012); Lilik et al., (2010) demonstrated that HC/CO/CO_2/PM emissions were decreased in an almost linear pattern when hydrogen addition was increased. This also indicated that decreases in particle and carbon-based gaseous emissions were affected by the amount of hydrogen being added. Under low to middle load states, there was a decrease in NO_x emission. However, at high load state, NO_x emission increased because of hydrogen's fast burning level that resulted in higher combustion temperatures and enhanced NO_x formation (Ghazal, 2013b). Miyamoto et al., (2011) suggested that thermal efficiency was affected by factors such as engine load, speed, and the amount of hydrogen that was added.

However, the works mentioned above only conducted studies on the use of either LPG or H_2 as a secondary fuel, researchers started focusing on tri-fuel engines. Recently, Lata and Misra, (2011); Lata et al., (2012) conducted some experimental and theoretical investigations to evaluate the performance of a dual fuel engine that used a mixture of LPG-H_2 as the main fuel and the diesel fuel as a pilot fuel. As a result, these studies revealed that efficiency could be improved at low load condition states in a dual fuel operation as well as the emissions improved when hydrogen and LPG are mixed to serve as the secondary fuel. On the other hand, the mixture of LPG and H_2 may be a potential solution for higher energy and lower emission level.

This study will compare the emissions features and combustion characteristics. As well as, different fuel configuration in diesel engines using normal diesel fuel, diesel-LPG, diesel-H_2 dual fuel, and diesel-LPG-H_2 tri-fuel under different gasses substations and different excess of air.

1.2 Problem Statement

Diesel engines are the most popular engines as it has high energy power, durability, and low CO emission (Stavinoha et al., 2000). However, the main problem with most of the vehicles nowadays is the emission of Nitrogen Oxides (NO_x) which can be controlled by different methods such as exhaust gas recirculation and use of alternative gasses fuels (Renald and Somasundaram, 2012). Therefore, using alternative gasses fuels for the modified diesel engine are receiving more interest from many scientists due to many reasons including the national concerns of the liquid fuels limited resources, the environment advantage and the needs to use a reliable, durable, and efficient engine (Elnajjar et al., 2011). However, diesel-H_2 and diesel-LPG dual fuel engine produced many unwanted effects such as rapid burning rate, increased diffusivity, and high emission levels (Lata et al., 2012; Miao et al., 2014). Therefore, researchers started focusing on tri-fuel engines. Thus, the mixture of LPG and H_2 may be a potential solution for high energy and low emission level (Aravind et al., 2015; Miao et al., 2014). Since hydrogen has wide flammability limits while the LPG has low flame propagation speed and narrow flammability limits (Lata et al., 2011). As a result, hydrogen enrichment enhances the process of LPG combustion such as enhance the efficiency and reduced the emissions. As well as, the advantage with LPG presence is to improve hydrogen combustion by avoiding uncontrolled combustion, such as the sharp increase of peak in-cylinder pressure and temperature. It seems that LPG and H_2 are complementary with each other on reducing CO_2/CO emissions and enhanced the engine efficiency (Miao et al., 2014). Consequently, better performance engine could be obtained when H_2 is added with LPG to make a secondary fuel for diesel dual fuel engine (Lata et al., 2012).

1.3 Research Questions

1. What are the effect of mixing the gasses fuel LPG, H2, and diesel fuel on the combustion characteristics and emissions of a diesel dual fuel engine?
2. What are the important concepts for modeling the mesh in a diesel engine in CFD?
3. How accurate is the computational fluid dynamic CFD approach simulation?

1.4 Research Objectives

The aim of the current study is to simulate diesel, dual and tri-fuel diesel engine consists of LPG, hydrogen, and diesel. Consequently, the specific objectives are as follow:

1- To examine the combustion characteristics and emissions of a diesel direct injection single cylinder engine under different gasses fuel substations and different excess air.
2- To evaluate the effect of gasses fuel fraction under dual and tri-fuel conditions, for better reduction towards the emissions.

1.5 Hypothesis

- The commercial CFD code can predict accurate results to simulate the phenomena inside a dual fuel engine in comparison with published experimental data (Wannatong et al., 2007).
- RNG k-ε turbulence model can give more accurate results than Standard k-ε turbulence model.
- The mixture of LPG with hydrogen is expected to enhance the lean-burn characteristics in addition to decreasing the real engine's emission (CO and CO_2), but the probability including higher NO_x emission will be involving concern.

1.6 Scope of Study

The focus of the present study was on the effect of the different value of excess air (λ) and the different mixing ratio of gaseous fuel substitutions namely LPG, hydrogen with normal diesel fuel on combustion characteristics and emissions in the dual and tri-fuel engine. These two parameters are considered for overcoming the high emission levels from a diesel engine by mixing this gaseous fuel in a diesel engine. The scope of this study is to examine the engine characteristics (in-cylinder pressure and temperature) as well as the emissions (NO_x, CO, and CO_2) under diesel, dual and tri-fuel engine. Also, an effort has been done to illustrate the distribution and formation region for in-cylinder temperature and emissions at various crank angle degree in the combustion chamber of the engine with two-dimensional analysis for better understanding the behavior of gaseous distribution in the combustion chamber. This study is limited to the numerical analysis of normal diesel, dual (diesel-LPG, and diesel-H_2) and tri-fuel engine (diesel-LPG-H_2) under different gasses fuel substitutions and a different value of excess air (1.2, 1.6, 2, and 2.4) in a constant engine speed, pressure, and temperature to examine the engine characteristics (in-cylinder pressure and temperature) and emissions (NO_x, CO, and CO_2).

1.7 Thesis Layout

This thesis has been systematized into five chapters; the thesis begins with the introduction in

Chapter 1 which includes a background of dual fuel engine. Then, it is followed by the problem statement. After that, the objective and scope of the study are presented.

Chapter 2 explains benefits for using alternative fuels as well as explains the combustion process of dual fuel engine and the effect of addition LPG and hydrogen on performance, combustion, and emission. Then, the previous numerical simulation studies and their results have been considered.

Chapter 3 illuminates the methodology that utilized includes an explanation of the grid generation for the diesel engine by using the ANSYS design modular that generated the needed mesh from moving dynamic mesh model (MDM), defines the boundary condition, and sets the solver variables in the software fluent.

Chapter 4 illustrates the results, which has attained from CFD simulation and the corresponding discussions.

Chapter 5 presents the conclusion of this research and the recommendation for future studies.

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