UNIVERSITI PUTRA MALAYSIA

NUMERICAL SIMULATION OF THE EFFECT OF CH4, H2 AND DIESEL FUEL MIXTURE ON FOUR STROKE ENGINE

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By

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November 2015

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Gaseous fuels have been investigated to be a helpful substitute in compression-ignition engine by researchers. There was extension in the ignition delay of diesel-CH_4 dual-fuel mode as compared with usual diesel fuel mode. Methane has a low flame propagation speed as well as slight flammability whereas hydrogen has the extreme opposite characteristics. As such adding hydrogen can enhance methane's combustion process making it extra convenient in diesel engine application. H_2-Diesel produced many of the unwanted effects such as rapid burning rate and increased diffusivity and reduced ignition energy of hydrogen that may lead to knocking, an impact that is harmful to engine's mechanical durability as well as safety. Methane addition has the ability to make hydrogen combustion stable and smoother which can prevent imperfect combustion. Methane can also lower the combustion temperature of hydrogen so as to repress NO_x emission. In the present study, the author proposes that by adding hydrogen into methane and diesel, it can improve the combustion process. The usage of GAMBIT software was chosen to create the entire computational domain of the engine and for Computational Fluid Dynamics (CFD) the FLUENT code was used. The engine was operated under dual-fuel and tri-fuel modes with different values of excess air (λ) including 1.2, 1.4, 1.6, 1.8, 2, 2.2 and 2.4. Moreover, torque (20.18 N.M), intake temperature (330 K), and engine speed (2000 rpm) were taken constantly at an atmospheric pressure. Diesel-CH_4, diesel-H_2 dual-fuel operation, and diesel-CH_4-H_2 tri-fuel operation were employed in this work. H30-M70, H50-M50 and H70-M30 were designed for the mixtures percent of hydrogen to methane which are 30:70, 50:50 and 70:30 %, respectively, and then used them in the simulations. Due to knocking, the maximum quantity of substitution by hydrogen was limited to 50%. Therefore, the quantity of diesel was employed 50 percent by mass from the total fuel at diesel mode and the other 50 percent was substituted by the methane and hydrogen as mentioned above.

The addition of gaseous fuels increases the peak in-cylinder pressure and peak temperature at both the low and medium values of the exceed air. Meanwhile, at high value of exceeds air, no effects on the peak temperature were noted between Diesel-H70-M30 for tri mode and Diesel-H_2 for dual mode. Compared with CH_4-Diesel at 2.4 exceed air, the peak pressure increases by 28.57% and 33.414% by way of adding the limit value of hydrogen to methane, such as H30-M70 and H50-M50, respectively. Compared with H50-M50, it begins to decrease by 0.726% and 3.81% with H70-M30 and H_2-Diesel operations, respectively, that may be because of the low value of fuels in air compared with other cases. The addition of methane in hydrogen produces a smoother combustion of hydrogen and ascertains that the engine is safe and it has mechanical durability.

Tri-fuel and dual-fuel modes have a similar suppression effect on CO_2 emission but with hydrogen there is more reduction in CO_2 emission compared with methane. However, Diesel-H_2-CH_4 operations decrease the CO emission compared with the Diesel-CH_4 operation and decrease the NO emission compared with the Diesel-H_2 operation at every exceed air. High hydrogen fraction in methane (H70-M30) is suggested at all exceeds air in order to reduce CO/CO_2 emissions, whereas low hydrogen fraction in methane (H30-M70) can suppress the uncontrolled hydrogen combustion and limit the increment of the NO emission.

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

SIMULASI BERANGKA DARIPADA CH_4, H_2 DAN DIESEL TERHADAP PENGGUNAAN ENJIN 4 STROK

Oleh

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Bahan api gas telah ditemui sebagai pengganti berguna dalam enjin mampatan penyalaan oleh penyelidik. Terdapat lanjutan dalam tempoh lengah operasi dwi-bahan api diesel-CH_4 berbanding dengan operasi bahan api diesel biasa. Metana mempunyai kelajuan perambatan api yang rendah serta kemudahbakaran sedikit manakala hidrogen mempunyai ciri-ciri yang bertentangan. Penambahan hidrogen, boleh meningkatkan proses pembakaran metana dan menjadikannya lebih mudah dalam aplikasi enjin diesel. H_2-Diesel menghasilkan pelbagai kesan yang tidak diingini seperti kadar pembakaran yang cepat, peningkatan keterasapan dan pengurangan tenaga pencucuhan hidrogen yang boleh membawa kepada ketukan enjin, kesan yang memudaratkan ketahanan mekanikal enjin dan juga keselamatan. Penambahan metana mempunyai keupayaan untuk menghasilkan pembakaran hidrogen yang stabil dan lancar yang boleh mengelakkan pembakaran tidak normal. Metana juga boleh menurunkan suhu pembakaran hidrogen untuk menindas pelepasan NO_x. Dalam kajian ini, Gambit digunakan untuk mencipta domain pengkomputeran keseluruhan enjin dan komersial Pengkomputeran Dinamik Bendalir (CFD) kod FLUENT digunakan. Enjin ini telah dikendalikan di bawah dwi-bahan api dan mod tri-bahan api dengan perberbezaan nilai lebihan udara (λ) termasuk 1.2, 1.4, 1.6, 1.8, 2, 2.2 dan 2.4. Selain itu, daya kilas (20.18 NM), suhu pengambilan (330 K), dan kelajuan enjin (2000) telah ditetapkan pada tekanan atmosfera. Diesel-CH_4, operasi dwi-bahan api diesel-H_2, dan operasi tri-bahan api diesel-CH_4-H_2 telah digunakan dalam penyelidikan ini. Tiga campuran hidrogen-metana daripada 30:70, 50:50 dan 70:30 % hidrogen kepada metana, ditetapkan sebagai H30-M70, M50-H50 dan H70-M30, masing-masing, telah dibeli dan digunakan dalam simulasi ini. Oleh disebabkan pengetukan, jumlah maksima penggantian hidrogen adalah terhad kepada 50%. Oleh itu, kuantiti diesel telah bekerja 50 peratus dengan kadar aliran jisim daripada jumlah bahan api pada mod diesel dan 50 peratus lagi telah dibahagikan terhadap metana dan hidrogen seperti yang dinyatakan di atas.

Kajian mendapati bahawa nilai tekanan puncak dan suhu puncak di dalam silinder telah meningkat dengan penambahan bahan api gas pada nilai exceeds air yang rendah dan sederhana. Perbandingan diantara menggunakan Diesel-H70-M30 untuk mod tri dan Diesel-H_2 untuk mod dual menunjukkan tiada kesan kepada nilai suhu puncak pada nilai exceed air yang tinggi. Semasa exceeds air bernilai 2.4, tekanan puncak meningkat dengan penambahan had hydrogen kepada metana, seperti H30-M70 dan M50-H50 dan mula berkurangan dengan H70-M30 dan operasi H_2-Diesel. Operasi Diesel-H_2-CH_4 mengurangkan pelepasan CO/CO_2 berbanding dengan operasi Diesel-CH_4. Operasi Diesel-

H_2-CH_4 juga mengurangkan pelepasan NO berbanding dengan operasi Diesel-H_2 pada setiap exceeds air. Kajian telah mencadangkan bahawa pengurangan pelepasan CO/CO_2 berlaku apabila kandungan bahagian hydrogen di dalam metana adalah tinggi (H70-M30) pada semua keadaan exceeds air. Kandungan bahagian hidrogen yang rendah di dalam metana (H30-M70) boleh menyekat pembakaran hidrogen yang tidak terkawal dan mengehadkan kenaikan pelepasan NO.

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I certify that a Thesis Examination Committee has met on 19 November 2015 to conduct the final examination of Hayder Abdullah Luaibi Alrazen on his thesis entitled "Numerical Simulation of the Effect of CH_4, H_2 and Diesel Fuel Mixture on Four Stroke Engine" 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.

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LIST OF ABBREVIATIONS

t — t F

8

6

6

λ Exceed Air (1/φ air-fuel ratio)

Mass Flow Rate

CHAPTER 1

INTRODUCTION

1.1 Background

Diesel engines, , are commonly used both on and off roads due to their low Hydro Carbon (HC), high thermal efficiency and Carbon Monoxide (CO) emissions. On the other hand, they are a major contributor in terms of Nitric Oxides (NO_x) emissions as well as in terms of their Particulate Matter (PM). There have been many methods applied to reduce emissions. Diesel Particulate Filter (DPF) and Selective Catalytic Reduction (SCR) were used to reduce PM and NO_x emissions, respectively. As devices and catalysts are tough in retrofitting the engines of vehicles, these methods are based on the use of precious and expensive metals. As such, many compromising methods were put forward which also include the Dual-Fuel-Combustion (Sahoo et al., 2009).

Spark-ignition engines use mostly natural gas (NG). In diesel engines, the NG is applied under dieseling dual-fuel operation (Korakianitis et al., 2011; Papagiannakis & Hountalas, 2004). Papagiannakis et al. (Papagiannakis & Hountalas, 2004; Papagiannakis, Rakopoulos et al., 2010) worked on a diesel-NG dual-fuel single-cylinder diesel engine. The study outcome showed that there was an extension in the ignition delay of diesel-NG dual-fuel operation as compared with the usual diesel fuel operation. The highest rate of heat release and in-cylinder pressure was lowered as the NG addition was increased at low to middle loads, but it was raised at high load because of the enhanced rate of burning of the diesel-NG cooperated combustion. The CO/HC rapid increase and reduction of particulate paved way for the trade-off impact for the diesel-NG dual-fuel engine. CO emission control could be fulfilled via the intake air pre-heating and increasing the amount of the pilot diesel (Papagiannakis, Kotsiopoulos et al., 2010). NO emission's slight reduction was also seen. Poompipatpong and Cheenkachorn (Poompipatpong & Cheenkachorn, 2011) emphasized on the impact on the emissions of a 4-cylinder diesel-CNG dual-fuel engine by the compression ratio and with the engine speed. It was found in their experiment that the increased compression ratio and increased engine speed could attain the increased thermal efficiency and reduced emission of CO. Inferior thermal efficiency was seen when the engine load was low. In diesel fuel and natural gas together with the fuelled diesel engines, the major limitations are Undesirable thermal efficiency and much higher CO/HC emissions at low to middle loads (Korakianitis et al., 2011).

For the internal combustion engines, another best alternative fuel is hydrogen. This is due to its ability to enhance the engine efficiency as well as the emission reduction. Diesel-H_2 dual-fuel engine has gained considerable momentum in recent years (Bose & Banerjee, 2012; Liew et al., 2010). The process of diesel-H_2 dual-fuel combustion in one heavy-duty diesel engine was studied by Liew et al. (Liew et al., 2010). It was shown that the peak in cylinder pressure drastically increased at 70 percent of full engine load and this influence was to be under control for the purpose of safety as well as for the engine's mechanical durability. It was observed that hydrogen's combustion efficiency was considerably less when a small quantity of hydrogen was added. Gatts et al. (Gatts et al., 2010) also explored on the combustion efficiency of hydrogen through the measurement of unburned hydrogen in the exhaust gas. It was shown by these studies that the engine load was dependent on the hydrogen combustion efficiency and the hydrogen must be added at high load for attaining high energy conversion efficiency for the hydrogen fuel as well as for the diesel fuel. Results of Liew et al. and Lilik et al. (Liew et al., 2012; Lilik et al., 2010) indicated that HC/CO/CO_2/PM emissions reduced almost linearly when the hydrogen addition was increased, which indicates that the reductions in carbon-based gaseous as well as particle emissions are associated with hydrogen quantity being added. NO_x emission on the other hand, decreased at low to middle loads, whereas it increased at high load because of the rapid burning rate of hydrogen which resulted in high combustion temperature as well as improved the formation of NO_x. The thermal efficiency is based on the load and speed of engine, as well as on hydrogen quantity being added which was shown in the study conducted by Miyamoto et al. (Miyamoto et al., 2011). Kumar Bose and Banerjee (Bose & Banerjee, 2012) explored the hydrogen addition's impact on emission reduction as well as performance trade-off with hot and cooled EGRs. They showed that 10 percent and 20 percent of EGR indicated a powerful potential in the reduction of NO_x as well as smoke emissions. This also maintained a simultaneous reduction on HC/CO/CO_2/BSFC together with the gain of sustainability on the Brake Thermal Efficiency (BTE).

In the case of conventional gas-diesel dual-fuel engines, there is an engine efficiency sacrifice and higher level of some of the emissions such as that of HC/CO which cannot be solved without using the after-treatment equipment. Some new methods have to be developed. Hydrogen enrichment has the ability to enhance the process of combustion of some gases fuels including LPG and NG, so as to enhance the total gases fuels energy usage efficiency. Prior times, using the mixture of CNG- Hydrogen for spark-ignition fuel engine has been explored much in studies (Acikgoz & Celik, 2012; Mariani et al., 2013) and is shown to be good for the elimination of some negative aspects of NG spark-ignition engines (Korakianitis et al., 2011). The enhancement is related with the unique characteristics of hydrogen, including its broad flammability, rapid burning velocity, less ignition energy and its carbon-free nature. In the recent times, for increasing the performance of conventional gas-diesel dual-fuel engines, studies started focusing on tri-fuel engines. Lata et al. (Lata & Misra, 2011; Lata et al., 2012) did a series of in-depth experimental and theoretical studies on diesel engines which use hydrogen-LPG mixture as the gaseous fuel, along with the diesel fuel. The main results of these studies showed that low efficiency at low load for LPG-diesel dual-fuel mode was enhanced with the hydrogen enrichment while the engine was functioning at above 10 percent of the full load. Similar to this, methane has a low flame propagation speed as well as slight flammability whereas hydrogen has the extreme opposite characteristics. As such, adding hydrogen can enhance methane's combustion process making it extra convenient in diesel engine applications. For hydrogen-diesel dual-fuel mode, the rapid burning rate, increased diffusivity and reduced hydrogen ignition energy enable the combustion to become unstable, particularly at increased engine loads that might result in knocking. The knocking is harmful to engine's mechanical durability as well as safety, as discussed earlier. Methane enrichment has the ability to make the combustion of hydrogen stable and smoother which can prevent imperfect combustion. Methane can also lower the combustion temperature of hydrogen so as to repress NO_x emission. This study focuses on comparing the combustion characteristics as well as emission features of a diesel engine under diesel-CH_4 and diesel-H_2 dual-fuel operations, as well as under diesel-CH_4-H_2 tri-fuel operations, where the gaseous fuels substitute up to 50 percent of the overall fuel. Under the tri-fuel operation, hydrogen and methane are blended with different percent fractions and then the 2 gaseous fuels are combusted together with the diesel fuel.

1.2 Problem Statement

For conventional gas-diesel dual-fuel engines, there is an engine efficiency sacrifice and higher level of some of the emissions such as that of HC/CO which cannot be solved without using the after-treatment equipment. This equipment however is expensive. Therefore, novel method has to be developed. Adding hydrogen can enhance the process of combustion of some gaseous fuels including LPG and NG, so as to enhance the total gases fuels energy usage efficiency. Flame propagation speed of methane is low and also it has narrow flammability. Meanwhile, the hydrogen has contrary traits; therefore hydrogen enrichment can enhance the process of methane combustion and make its convenient for application of diesel engine. For hydrogen-diesel dual-fuel mode, rapid burning rate, increased diffusivity as well as low ignition energy hydrogen increased the combustion abnormal characteristics such as knocking. The knocking is harmful to the mechanical durability as well as safety of engine. On the other hand, a hydrogen affects emissions by reducing the hydrocarbon (HC), CO, CO_2, PM, and smoke. The effective method to solve these problems is to blend H_2, CH_4, and diesel to meet the characteristics required by the engine. Methane addition makes hydrogen combustion smoother as well as much more stable and blocks abnormal combustion. Methane can also lower the combustion temperature of hydrogen so as to repress NO_x emission.

1.3 Hypothesis

The current study proposes that by adding hydrogen into CH_4 fuel and diesel it can improve velocity of combustion and therefore enhancing the combustion characteristics. Mix of natural gas with hydrogen is required to increase the lean-burn attributes as well as minimize the actual engines emissions (mainly CO_2, HC as well as CO), but the possibility involving greater NO_x emissions will be involving concern. This helps combustion behaviour of action with the possibility to formulate engines with increased performance and lower environmentally friendly impact. Hydrogen itself provides the possible to be an alternate to be able to regular fuel, since it is absolutely carbon-free along with not too difficult to make but high pricey. The employment of NG/hydrogen mixtures comprising H_2 gives good possibility to offer the rewards associated with the particular hydrogen without having large modification involving currently existing CNG engine.

1.4 Research Objectives

The aim of the current study is to simulate dual and tri fuel diesel engines consist of methane, hydrogen, and diesel. The current study also observes the impact of mixing ratios with variation of exceed air. The specific objectives are as follow:

1. To perform CFD simulation on CH_4-diesel and H_2-diesel for dual-fuel mode and on CH_4-H_2-diesel for tri-fuel modes.
2. To determine amount of gaseous addition for best condition.
3. To evaluate the combustion characteristics and emissions of a compression ignition engine with varying engine operations under different ratios of exceed air (λ).

1.5 Scope of Research

This study concentrates on the impact of combining tri fuels namely methane, hydrogen and diesel on combustion characteristic. Furthermore the effect of λ (exceed air) was looked into at each of the engine operations both dual and tri-modes. This study has the scope to deliver combustion characteristics and emissions. There has also been an attempt to illustrate the engine's combustion chamber using 2 dimensional analyses, hence enabling better comprehension of the behaviour of combustion chamber.

1.6 Thesis Layout

This thesis has been divided orderly into five chapters, the thesis starts with introduction in Chapter 1 which includes a background of dual and tri-fuel diesel engine.

Chapter 2 explains benefits for using alternative fuels of diesel engines and explains the effect of hydrogen addition on performance and combustion as well as emissions in direct diesel engines.

Chapter 3 elaborates on the methodology used that includes a description of the grid generation of diesel engine using the Gambit software that created the needed mesh by moving the dynamic mesh or MDM model and also defines the conditions of the boundary and sets the solver variables in the Fluent software.

Chapter 4 illuminates the results which were accomplished from CFD simulation as well as the corresponding discussions.

Chapter 5 displays the recommendation for future studies and final conclusion of this project.

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