REACTIVITY CONTROLLED COMPRESSION IGNITION COMBUSTION IN A LIGHT DUTY DIESEL ENGINE USING ALTERNATIVE FUELS

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ABSTRACT

Reactivity controlled compression ignition (RCCI) combustion has been introduced to implement controllable, clean, and high thermal efficiency without undermining the advantages of premixed combustion. However, simultaneous auto-ignition introduced by RCCI combustion affects the combustion under higher load operations. A series of experiments was conducted on a light duty diesel engine operated in the RCCI mode to study the effect of oxygenated fuel blends, fuel inhomogeneity, combustion timing, rate of heat release, exhaust gas recirculation and load extension. Gasoline, ethanol and methanol as port base fuels and diesel as base direct fuel were used for the experiments. The engine was tested at steady state conditions. A mixture of alcohol fuels and diethyl ether (DEE) as high reactive fuel presented inhomogeneity in an actual engine combustion and resulted in high temperature heat release (HTHR) at two different stages. The addition of diethyl ether in the ethanol blend resulted in dual phase heat release combustion and advanced ignition phasing of the prevailing heat release and suppressed the peak pressure rising rate and knocking tendency. It governed the end-gas heat release pattern and improved the indicated mean effective pressure (IMEP). Resultant dual phase heat release and dominant premixed combustion enhanced the fuel oxidation and reduction of soot precursors. Alternatively, diethyl ether addition increased the in-cylinder maximum pressure. With regard to the RCCI hypothesis, higher reactivity of DEE will enhance oxidation of hydrocarbons, thus resulted in lower HC emissions. Changing gasoline /diesel RCCI composition with gasoline /diesel-n-butanol has slight effects on engine IMEP reduction and combustion parameters. By raising the presence of n-butanol in the fuel mixture (in this case from 0% to 40%), the premixed ratio of optimum IMEP value decreased by as much as 15% (from rp=85% to rp=70%). It was found that high reactive fuel can be used as blending portion of port fuel to effectively control combustion timing and extend the high load region. In the present study, the three dimensional model with detailed chemical kinetics was also employed to investigate the second law analyses of reactivity controlled combustion with iso-octane / n-heptane.

ABSTRAK

Pembakaran nyalaan mampatan bertindak-balas terkawal RCCI telah diperkenalkan bagi mencapai keupayaan kawalan, bersih, dan kecekapan terma yang tinggi tanpa mengurangkan kelebihan pembakaran pra-campur. Walaubagaimanapun, auto-nyalaan serentak dari pembakaran RCCI memberi kesan pada pembakaran yang beroperasi pada beban tinggi. Satu siri ujikaji dijalankan pada enjin diesel kecil yang dikendalikan dalam mod RCCI bagi mengkaji kesan campuran bahan api beroksigen, ketidak homogenan bahan api, pemasaan pembakaran, kadar pelepasan haba, kitaran semula gas ekzos dan pengembangan beban. Petrol, etanol dan metanol sebagai bahan api pada liang masukan dan diesel sebagai bahan api langsung telah digunakan untuk kajian ini. Enjin tersebut telah diuji pada keadaan mantap. Campuran bahan api alkohol dan dietil eter (DEE) sebagai bahan api bertindak balas tinggi menyebabkan tidak homogen dalam pembakaran enjin sebenar dan menghasilkan pelepasan haba suhu tinggi (HTHR) pada dua tahap yang berlainan. Penambahan dietil eter dalam campuran etanol menyebabkan dua fasa pembakaran haba dan nyalaan lanjutan pada tahap pembebasan haba berlaku serta menghindarkan kadar kenaikan tekanan puncak serta kecenderungan ketukan. Ia mengawal corak pelepasan haba gas akhir dan meningkatkan tekanan efektif min tertunjuk (IMEP). Pelepasan haba dua fasa dan pembakaran premix terdahulu meningkatkan pengoksidaan bahan api dan mengurangkan pembentukan jelaga. Selain itu, tambahan dietil eter meningkatkan tekanan maksima dalam silinder. Berkenaan dengan hipotesis RCCI, kereaktifan DEE yang lebih tinggi akan meningkatkan pengoksidaan hidrokarbon, sehingga menghasilkan pelepasan HC yang lebih rendah. Penukaran komposisi RCCI petrol / diesel dengan petrol / diesel-n-butanol mempunyai sedikit kesan pada pengurangan IMEP dan parameter pembakaran IMEP. Dengan meningkatkan kehadiran n-butanol dalam campuran bahan bakar (dalam kes ini dari 0% hingga 40%), nisbah premix optimum nilai IMEP menurun sebanyak 15% (dari r_p = 85% hingga r_p = 70%). Didapati bahawa bahan api reaktif yang tinggi boleh digunakan sebagai campuran bahan api pada liang masukan untuk mengawal masa pembakaran secara berkesan dan memperluaskan kawasan beban tinggi. Dalam kajian ini, model tiga dimensi dengan kinetika kimia terperinci juga digunakan bagi mengkaji analisis hukum kedua pembakaran reaktif yang dikawal dengan iso-oktana / n-heptana.

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LIST OF ABBREVIATIONS

ABDC - After Bottom Dead Centre
AC - Alternating Current
AFR - Air-Fuel Ratio
AHRR - Apparent Heat Release Rate
ATDC - After Top Dead Centre
B - Butanol
BBDC - Before Bottom Dead Centre
BMEP - Brake Mean Effective Pressure
BTDC - Before Top Dead Centre
BTH - Brake Thermal Efficiency
CA - Crank Angle (deg)
CA10 - Crank Angle position where 10% of the heat is released
CA50 - Crank Angle position where 50% of the heat is released
CA90 - Crank Angle position where 90% of the heat is released
CD - Combustion Duration
CDC - Conventional Diesel Combustion
CFD - Computational Fluid Dynamics
CI - Conventional Compression Ignition
CLD - Chemiluminescence Detector
CNG - Compressed Natural Gas
CO - Carbon Monoxide
CO_2 - Carbon Dioxide
COV - Coefficient of Variation
CR - Compression Ratio
DAQ - Data Acquisition System
DEE - Diethyl Ether
DI - Direct Injection
DICI - Direct Injection Compression Ignition
DME - Dimethyl Ether
DOC - Diesel Oxidation Catalyst

DP - Dual Phase high temperature heat release
DPF - Diesel Particulate Filter
EGR - Exhaust Gas Recirculation
EVC - Exhaust Valve Closed
EVO - Exhaust Valve Opened
FCE - Fuel and Combustion and Emission Centre
FCM - Fuel Controller Module
GDI - Gasoline Direct Injector
GITE - Gross Indicated Thermal Efficiency
HC - Unburned Hydrocarbon
HCCI - Homogeneously Charged Compression Ignition
HD - Heavy Duty
HRR - Heat Release Rate(J/°)
HTC - High Temperature Combustion
HTHR - High Temperature Heat Release
I - Irreversibility (J/K)
IMEP - Indicated Mean Effective Pressure
IMEPg - Gross Indicated Mean Effective Pressure
ITE - Indicated Thermal Efficiency
IVC - Intake Valve Closed
IVO - Intake Valve Opened
K - Kelvin
LHS - Latin Hypercube Sampling
LHV - Lower Heating Value
LNT - Lean NOx-Trap
LPM - Liter Per Minutes
LTC - Low Temperature Combustion
LTHR - Low Temperature Heat Release
LTO - Low Temperature Oxidation
MCE - Multi Cylinder Engine
MPRR - Maximum Pressure Rise Rate
N_2 Nitrogen
NDIR - Non-Dispersive Infrared

NGF - Natural Gas Fraction
NOx - Nitrogen Oxides
NRHR - Net Rate of Heat Release
NTC - Negative Temperature Coefficient
PAH - Polycyclic Aromatic Hydrocarbons
PCCI - Partially Premixed Combustion
PEF - Port Energy Fraction
PFE - Premixed Fuel Energy Fraction
PFI - Port Fuel Injection
PID - Proportional Integral Derivative controller
PM - Particulate Matter
PN - Particle Number
PRF - Primary Reference Fuel
PRR - Pressure Rise Rate
RCCI - Reactivity Controlled Compression Ignition
RMS - Root Mean Square
R_p - Premixed Ratio
RPM - Revolutions Per Minute
SCE - Single Combustion Engine
SCR - Selective Catalytic Reduction
SDCI - Stoichiometric Dual-fuel Dieseline Compression Ignition
SI - Spark Ignition
SOI - Start Of Injection

LIST OF SYMBOLS

η_{th} - Indicated thermal efficiency
µk - Chemical potential of each species
µk,0 - Chemical potential of species at restricted dead state
µk0 - Chemical potential of species at true dead state
0 - Dead state; environment state
A - Total availability
a - Mass specific chemical exergy (J/kg)
Ach - Chemical availability
Atm - Thermal availability
Atot - Total availability
b - Number of hydrogen atoms
CH2O - Formaldehyde
CH4 - Methane
g - Mass specific Gibbs energy (j/kg)
h - Enthalpy (on a kilogram basis)
I - Irreversibility (J/K)
k - Number of species
N - Engine speed
p - Pressure
P0 - Mixture pressure at dead state
pa - Pascal
PG - Bio mass gas fuel
P_{intake} - Intake mixture pressure
P_{max} - Maximum in-cylinder pressure
Q - Heat loss (j)
r_p - Premixed Ratio
S - Entropy (J/K)
T - Temperature (K)
T0 - Mixture temperature at dead state
T_{intake} - Intake mixture temperature

tm - Thermomechanical exergy

V - Cylinder Volume

W - Work (J)

w - Work transfer

y - Mass fraction of a species; number of hydrogen atoms

z - Number of carbon atoms

δ - Minimal error

θ - Crank angle

γ - Specific heat ratio

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CHAPTER 1

INTRODUCTION

1.1 Overview

Modern life would not be possible without the use of combustion technology. In fact, combustion has been the primary means of heating, food preparation, and material processing for several thousand years. Combustion of liquid hydrocarbons is the primary energy conversion concept used in the transportation sector. The several researches in internal combustion engines are treated to resolve the emission pollution and fuel conversion efficiency. Diesel engines are well established power train for mass transports, marine prime mover, light-duty machinery and industrial equipment due to their enhanced thermal efficiency, higher torque capacity, improved durability and cost effectiveness compared to gasoline engine. However, conventional diesel engine is subjected to high rate of NOx and particulate matter (PM) discharges due to rich mixture, heterogeneous combustion and considerable diffusion combustion phase that are destructive to both human health and environment (Lee, 2017; Patil and Thipse, 2015; Tao, 2004).

Improvement in powertrain systems is prerequisite for low exhaust emission concentrations. At present, diesel particulate filter (DPF), selective catalytic reduction and lean NOx-trap (LNT) have been applied on many diesel vehicles to meet standard emission limits. However, these after-treatment systems have led to an increase in the production cost of the vehicles thus the selling price. As a result, clean combustion concept of low generating NOx and PM emissions (in addition to after- treatment systems) needs to be further refined (Eastwood, 2010).

Homogeneously charged compression ignition (HCCI) engines was introduced and recognized as the synergy between conventional compression ignition engines (CI) and spark ignition engines (SI). No throttling lost and homogeneous premixed charge will lead to gain enhanced thermal efficiencies, low NOx and low particulate matter (PM) emissions (Reyhanian and Hosseini, 2018). HCCI combustion is accomplished by controlled chemical kinetics and control of combustion phasing which lead to good transient response, cold start achievement. Hydrocarbons (HC) and carbon monoxide (CO) emissions are till the main challenges left of the HCCI combustion (Yao, 2009).

To implement controllable, clean and high thermal efficiency, the improvement of premixed combustion phase for CI engine is introduced. The hybrid combustion of premixed and mixing controlled phase govern the conventional diesel performance. The leading portion of NOx and PM emissions emerges from diffusion combustion stage. the heterogeneous combustion feature and longer duration of diffusion controlled combustion conduct to more heat transfer loss and hence, less work during the expansion stroke (Lee 2017).

The application of advanced diesel injection and achievement of a high rate exhaust gas recirculation (EGR) are two logical approaches for improving the premixed phase of combustion in diesel engines. limited operating range of LTC concepts challenges the evident emission reduction results as against conventional diesel combustion. Enhancement of engine speed and engine load restricts the premixing time of the diesel fuel and air. As a result, cylinder pressure rise rate (PRR) narrows the load range of partially premixed combustion (PCCI) concepts as diesel early injection theory (Noehre, 2006).

For this reason, reactivity controlled compression ignition (RCCI) combustion introduced as a representative dual-fuel combustion. RCCI combustion can be achieved by supplying low reactivity port fuel such as natural gas and gasoline as major portion of cylinder mixture with an advanced diesel injection strategy (Lim, 2014; Ryskamp, 2017), actually, the amount of high reactive fuel behaves as the ignition source. In this concept, major portion of the port fuel was premixed and the homogeneous condition of cylinder charge improved. RCCI combustion could be considered as hybrid of premixed HCCI engine and conventional diesel engine. Optimized combustion phasing, various gradient of reactivity and mixture concentration, stratifications of the temperature can be obtained by adjusting the injection timing, the quantities and reactivity of fuels and the exhaust gas recirculation (EGR). The heat release rate of combustion can be modulated by both reactivity stratification and concentration. the entire RCCI combustion structure was based on the premixed stage of combustion (Lee 2017).

1.2 Problem Statement

The stratification of fuel reactivity in RCCI strategy results in a broad combustion event and reduces pressure rise rates compared to other premixed combustion strategies. Indeed, in-cylinder fuel blending of two fuels with very different fuel reactivity (i.e., cetane number), allows the global octane number to be varied on a cycle-to-cycle basis. RCCI strategy results in low NOx and soot emissions, high gross indicated efficiency and low-pressure rise rates (i.e., ringing intensity) compared to those of HCCI combustion. The improved efficiency is found to be largely due to reduced heat transfer losses (Aroonsrisopon, 2002). The heat release rate of combustion can be modulated by both reactivity stratification and concentration.

RCCI combustion demonstrates acceptable control of combustion phasing without undermining the advantages of HCCI combustion but high power operation remains as an important hurdle to be overcome. Simultaneous auto-ignition introduced by RCCI combustion will enhance the maximum in-cylinder pressure rise rate and will limit the combustion under higher load operations (Wang, 2017). Furthermore, unstable combustion based on diesel injection strategy will confine combustion process which develops under low reactivity stratification condition (Wang, 2015).

Further investigation of fuel blend and heat release strategy is needed to fully realize the potential of high load dual-fuel RCCI operation. Of paramount interest is the feasibility of load extension, control of dual fuel RCCI operation focusing on oxygenated alternative fuels in high compression ratio engine.

1.3 Research Questions

In relation to the concerns that have been raised through the problem statement and objectives, this research attempts to answer the following questions:

1. Is it possible to achieve a wide load range optimized RCCI combustion in a light duty high compression ratio engine using fuel blending strategy?
2. How much is the effectiveness of fuel injection strategy on RCCI combustion phasing control?
3. What is the optimum combined fuel reactivity (octane number) for a wide range of RCCI combustion? i.e. is it possible to use the oxygenated fuel for injections to achieve reasonable RCCI combustion?
4. Although RCCI combustion has demonstrated better combustion phasing control than HCCI combustion without undermining the known benefits of HCCI combustion, can the applications of RCCI combustion be expanded beyond the medium load ranges in order to extend use of RCCI combustion by incorporating dual phase high temperature heat release?

1.4 Objective of the Research

This research is aimed at providing more insight into load range extension of RCCI strategy for light duty engines which realize high fuel conversion efficiency and low soot and NOx emissions. Furthermore, owing to the growing demand for alternatives to crude petroleum based fuels, low temperature RCCI combustion with alternative oxygenated fuels was studied. This was succeeded through in-cylinder numerical simulation and experiments of light duty single cylinder engine. In detail, the preliminary objectives of the study are as follows:

5. To introduce extra insightful information using exergy-based study of LTC strategies. To conduct the availability studies over a range of DI fuel increments and EGR rates of n-heptane/iso-octane RCCI combustion to

reveal the possible effects of the EGR and fuel reactivity as insightful sources that affect exergy destruction.

6. To explore the applicable operating range of RCCI combustion through adoption of different rate of oxygenated fuel. To characterize the combustion phasing control and ignition challenge of lower reactive oxygenated fuel by examining the PEF and EGR effect on the RCCI combustion modes through Gasoline/diesel-butanol dual-fuel RCCI combustion.

7. To describe the combustion characteristics of two-stage high temperature heat release in a supercharged RCCI engine with the purpose of improving high load condition while operating on a series of hybrid fuels consisting of oxygenated fuels and diesel.

8. To explore possible effects of fuel chemistry and reactivity (octane number) on RCCI combustion characteristics and engine behaviour by blending reformate synthetic fuels.

1.5 Scope of the Study

The base operating conditions studied in the present work come from the SCE (single cylinder engine) experiments that develops the underlying operating strategies for RCCI. At the core of the study, different dual fuel injection strategies demonstrated using different fuels focused on fuel reactivity. Single-cylinder engine experiments are able to provide a highly controlled research environment for combustion analysis. However, design variations to single-cylinder engine, such as compression ratio, are time consuming and are difficult to quantify a priori. The scopes of the study are presented into three major parts as follow:

1. To develop an experimental facility from a conventional diesel gen-set to a sophisticated RCCI engine:

- Design, modification and prototype of an adapted intake and exhaust manifold so as to meet the RCCI operation requirements.

- Realizing the hybrid drivers of port and direct fuel injection through an in-house ECU development.

- Customizing the new common rail injection system to supply adjustable fuel injection timing and rail pressure.

2. To perform the simulation work considering:

   - Closed cycle zero-dimensional computational tools combined with single-cylinder engine results to understand better the physical phenomena observed in the experiments. These tools used to improve engine conditions to have accurate and detailed simulation on the combustion process.

   - Multi-dimensional computational fluid dynamics (CFD) models provide valuable insight into the physical and chemical process taking place in-cylinder, such as liquid fuel injection, droplet evaporation, fuel/air mixing, ignition, combustion, and emissions formation. Therefore, multi-dimensional computational tools AVL FIRE (ESE) combined in this study with single-cylinder engine results to understand the physical phenomena observed in the experiments.

3. To accomplish experimental records: The methodology of research is to conduct experiments on the engine in order:

   - To validate models against experimental results.

   - To sweep a range of operating parameters to find optimum operating points under various RCCI strategies.

   - To understand the details of combustion and engine behaviour under various RCCI combustion strategies using different fuel blends.

   - To develop the combustion and engine behaviour under various RCCI combustion strategies using dual heat release concepts.

- To reveal the potential of alternative synthetic fuels under various RCCI combustion strategies focusing the load range operation and particle emissions.

- To compare and analyse the exhaust gas emissions (NOx, uHC and CO) characteristics of RCCI mode with regard to EGR and fuel octane number and oxygen content.

1.6 Contribution and Significance of Study

The effects of various port fuels and other additions to accelerate combustion process in RCCI modes and to regulate heat release process are even less well known. Therefore, additional experimental and numerical researches are required to investigate fuel blend, injection timing and intake parameters to predict the emission trends, efficiency and load extension in duel fuel RCCI combustions. the prominence of this study will be:

1. identify the operating regions in high compression ratio RCCI engine fuelled by various blended strategy.

2. treat the oxygenated structure and reactivity of fuels on RCCI performance and emission in a high-compression ratio RCCI engine.

3. incorporate dual phase heat release concept with sole purpose of improving the performance of RCCI operation at higher load condition.

4. prepare supporting data for tuning and validation of a chemical kinetics RCCI combustion model.

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