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COMBUSTION PROCESS OF HOMOGENEOUS CHARGE COMPRESSION IGNITION ENGINE USING NUMERICAL MODELING

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By

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Thesis submitted to the School of Graduate Studies, Universiti Putra Malaysia, in fulfillment of the requirements for the Degree of Master of Science

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Abstract of thesis is presented to the Senate of Universiti Putra Malaysia in
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March 2014

Chairman : Nuraini Abdul Aziz, PhD
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A zero dimensional thermodynamic numerical model is developed to simulate the combustion characteristics and performance of a four stroke gasoline engine using homogeneous compression combustion ignition (HCCI) method. This model which applies the first law of thermodynamics for a closed system is inclusive of empirical model for predicting the important parameters for engine cycles: the combustion timing and mass burnt fraction during the combustion process. The hypothesis is the increasing intake temperature can reduce the combustion duration and the fuel consumption at wide range of equivalence ratio, resulting in decreasing peak pressure and friction losses, and hence, increasing the engine efficiency. The intake temperature were increased from 373-433 K with increment of 20 K. The engine was operated over a range of equivalence ratios of 0.2 to 0.5 at constant engine speed of 1200 rpm and intake pressure of 89,950 K Pa. Simulations were performed using Simulink® under different engine operating conditions. The model was successfully developed to predict the combustion characteristics and performance. Validations show good agreements between the experimental data and simulation results. Increasing intake temperature allows reducing the combustion duration by 0.99 °CA and 0.26 °CA at equivalence ratios of 0.2 and 0.5, respectively, followed by decreasing the heat released to the wall about 22.79%. The brake power reduces up to 3.56% at any equivalence ratios. However, the brake specific fuel consumption decreases about 6.09%-5.76% at 0.2-0.5 of equivalence ratios, respectively. Increasing intake temperature does not increase the power output. However, it is able to improve the efficiency at richer mixture as the fuel consumption and brake specific fuel consumption also can be decreased.

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

PROSES PEMBAKARAN BAGI ENJIN PENCUCUHAN MAMPAT BERCAJ SERAGAM MENGGUNAKAN PERMODELAN BERANGKA

Oleh

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Pengerusi : **Nuraini Abdul Aziz, PhD**
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Satu permodelan berangka dengan dimensi termodinamik sifar telah dibangunkan untuk mendapatkan simulasi ciri-ciri dan prestasi enjin petrol berlejang empat menggunakan kaedah pencucuhan mampat bercaj seragam. Model yang mengaplikasi hukum pertama termodinamik bagi system tertutup ini merangkumi model empirik untuk meramal parameter penting bagi kitaran enjin: pemasaan pembakaran dan pecahan jisim yang terbakar semasa proses pembakaran. Hipotesis adalah peningkatan suhu masukan boleh mengurangkan tempoh pembakaran dan penggunaan bahan api pada nisbah setara dalam julat yang besar, menghasilkan pengurangan tekanan puncak dan tenaga geseran, dan oleh yang demikian, mengingkatkan kecekapan enjin. Suhu masukan telah ditingkatkan daripada 373 K kepada 433 K dengan kenaikan sebanyak 20 K. Enjin telah dijalankan di bawah nisbah kesetaraan daripada 0.2 kepada 0.5 pada kelajuan enjin tetap sebanyak 1200 rpm dan tekanan masukan sebanyak 89,950 KPa. Simulasi dijalankan menggunakan perisian Simulink® dalam pelbagai keadaan operasi enjin. Model telah dibangunkan dengan jayanya untuk meramal ciri-ciri pembakaran dan prestasi, yang mana persamaan yang hampir bagi keputusan eksperimen dan simulasi. Peningkatan suhu masukan membolehkan pengurangan tempoh pembakaran sebanyak 0.99 °CA dan 0.26 °CA masing-masing pada 0.2 dan 0.5 nisbah kesetaraan, diikuti oleh pengurangan pelepasan haba kepada dinding sebanyak 22.79%. Kuasa brek berkurangan sehingga 3.56% pada mana-mana nisbah kesetaraan. Walaubagaimanapun, penggunaan bahan api tentu brek berkurangan kira-kira 6.09%-5.76% masing-masing pada 0.2-0.5 nisbah kesetaraan. Peningkatan suhu masukan tidak meningkatkan pengeluaran kuasa. Namun, ia mampu meningkatkan kecekapan pada campuran yang lebih pekat dan mengurangkan penggunaan bahan api dan penggunaan bahan api tentu brek.

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Najihah, March 2014

This thesis was submitted to the Senate of 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:

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LIST OF ABBREVIATIONS

ATDC	After top dead center
AFR	Air-to-fuel ratio
BTDC	Before top dead center
CAD	Crank angle degree
EGR	Exhaust gas recirculation
HV	heating value
IVO	Intake valve open
IVC	Intake valve close
LHV	Low heating value
MFB	Mass fraction burning
RES	residual gas
SOC	Start of ignition
fmep	frictional loss mean effective pressure
imep	Indicated mean effective pressure
bmep	Brake mean effective pressure
bsfc	Brake specific fuel consumption
sfc	Specific fuel consumption
ifce	Indicated fuel conversion efficiency
bfce	Brake fuel conversion efficiency
iP	Indicated power
bP	Brake power

Latin character

A	Area	(m^2)
a	Crank radius	(m)

B	Cylinder bore	(m)
c	Mass heat capacity	(J/kg.K)
c_m	Piston mean speed	(m/s)
C	Constant value/factor/coefficient	
D	Diameter	(m)
E_c	Activation energy	(J kg)
h	Enthalpy	(J/kg)
h_t	Heat transfer coefficient	(W/m^2K)
k	Constant	
l	Length	(m)
L_v	Axial valve lift	(m)
m	Mass	(kg)
M	Molecular weight	(kg/kmole)
n_R	Number of cylinder	
N	Engine speed	(rpm)
P	Power	(J/s)
p	Pressure	(Pa)
Q	Heat	(J)
R_u	Universal gas constant (8314.34)	(J/kgK)
r	Radius	(m)
s	Piston stroke	(m)
t	Time	(s)
T	Temperature	(K)
u	Internal energy	(J/kg)
v	Specific volume	(m^3/kg)
V	Volume	(m^3)
W	Work done	(J)

CHAPTER 1

INTRODUCTION

1.1 Background

Decreasing primary fuel resources and stringent emission legislations have been motivating many researchers from automotive field to develop and study on engines that are capable of reducing the amount of hazardous emissions and the fuel consumption while maintaining the engine high thermal efficiency. The two conventional engines of spark ignition (SI) and compress ignition (CI) have been utilized over the years and studied to have critical exhaust products problems. The problems have been solved using the after-treatment methods which have added more cost on installation and maintenance. Yet, hazardous emissions are still relatively higher than the emission legislation requirement.

In order to cope with future emission legislation requirements and reduce fuel consumption while maintaining high engine efficiency, one of the most important advancements is to implement Homogeneous Charge Compression Ignition (HCCI) combustion in engine. HCCI is a high efficiency technology to be utilized in any sizes and classes of transportation as well as in stationary applications such as in electric generators (Shahbakti, 2009).

In comparison to SI and CI engines, HCCI engine has higher part load efficiency due to no throttling losses which then contribute to no pumping losses, no particular matters production and very low NO_x emissions (Heywood, 1988). It is difficult to reduce smoke and NO_x simultaneously through combustion improvement only. Emission control has become one of interest among automotive researchers because current methods like the Three Way Catalyst (TWC) used in SI and non-thermal plasma used in CI are expensive and consume extra 2-4% of overall fuel consumption (Taylor, 2008; Bauer and Bosch, 2011). However, in HCCI engine, the fuel and air should be mixed homogeneously in the combustion chamber before the combustion starts and the mixture would be ignited spontaneously due to temperature increasing at the end of the compression stroke (Maurya and Agarwal, 2009).

The HCCI engine has the advantage of high compression ratio similar to the CI engine; no throttling losses and lean mixture. The auto-ignition temperature, which is equal to the temperature after compression stroke, requires range of 1400K-1500K for completing Carbon Monoxide (CO) and Hydrocarbon (HC) components oxidization and can be below 1800K to prevent NO_x formation, due to high dilution of charge by low equivalence ratio of below 0.3 as in Figure 2

(Johansson B. , 2007; Kitamura, et.al, 2003). Thus, the NO_x formation and soot formation can be reduced simultaneously.

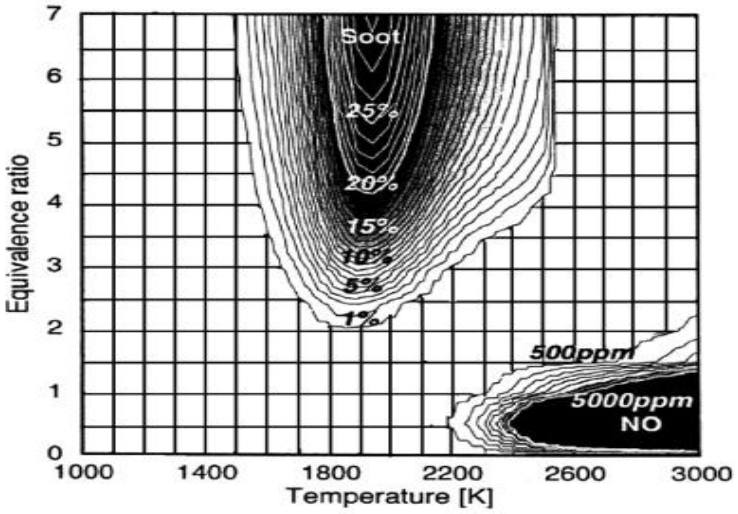

Figure 1.1. Equivalence Ratio versus Temperature Map (Johansson B. , 2007)

However, there are several downsides of HCCI combustion. Firstly, there is no direct combustion trigger, like in SI (triggered by spark) and CI (triggered by fuel injection) engines. This auto-ignition behavior makes the combustion being very sensitive to its initial conditions like inlet pressure, temperature, fuel composition and homogeneity of the mixture (Marriott and Reitz, 2002; Li, Zhao, Brouzos and Ma, 2006; Zhao, 2007; Yao, Zheng and Liu, 2009). These initial conditions need to be controlled to obtain the correct combustion phasing.

Secondly, HCCI combustion process is unstable especially at lower and higher engine loads. It has been proven to work well on medium load where on low load, as it tends to misfire and on high load, it tends to damage the engine (Maurya and Agarwal, 2011). Thirdly, HCCI has smaller operating region than that of the two conventional engines. At high loads, early combustion can produce unacceptable peak cylinder pressure causing excessive noise, potentially damaging the engine and increasing Nitrogen Oxides (NOx) production, while the late combustion leads to incomplete combustion and increasing Carbon Monoxide (CO) and Unburned Hydrocarbons (UHC) (Olsson J. O., et al., 2002).

The combustion timing can be controlled indirectly through adjustments of parameters involved in the cylinder charge preparation. One of the possible ways is controlling the mixture reactivity which can be actuated by the equivalence ratio. Equivalence ratio control is done by the fuelling system of the engine. The control of injected air-fuel can be done by adjusting the throttle opening size. However, this size will not only affect the in cylinder mixing, but also the residual gas fraction in a manner that it is not possible to change only this parameter to control of series of engine runs. In this study, the effects of equivalence ratio and intake temperature on the combustion phasing and engine efficiency are predicted by numerical simulation of thermodynamic equations of homogeneous charge compression ignition combustion system so that a leaner mixture of AFR can be utilized accordingly to an appropriate intake temperature to improve the engine efficiency.

1.2 Problem Statement

Different combinations of equivalence ratio and intake temperature have different effects on the combustion timings and the performance of a four-stroke HCCI engine. At increasing engine speeds, combustion timing holds significant role to ensure completeness of combustion process and avoid undesirable pressure rise rate in the cylinder which would cause high fuel consumption and engine damage (Olsson J. O., et al., 2002; Bogemann, 2009). Combustion timing is essential in order to control the load to obtain low fuel consumptions, low emissions and high engine efficiency. It is dependable of chemical reactions inside the cylinder which is influenced by factors such as equivalence ratio and intake temperature. High equivalence ratio increases the overall in cylinder activities and speeds up the combustion process. It will result in combustion timing to decrease and allow undesirable pressure rise rate. This phenomenon may contribute to piston engine damage. However, at low equivalence ratio, compression ratio and intake air temperature must be set properly to ensure auto-ignition. Otherwise, misfiring will occurred and result in very low combustion efficiency. Increasing intake air temperature is able to improve combustion process at low equivalence ratio and decreasing intake air temperature is able to reduce the pressure rise rate and heat release rate at high equivalence ratio. Therefore, both are the best candidates to enhance the combustion characteristics of an HCCI engine. The numerical model is able to simulate the effect of both parameters to the combustion characteristics. Although the computational model is unable to obtain the exact characteristics because there are many complex phenomena taking place in the engine hardly being modeled through numerical method, it is capable to estimate the trend of engine characteristics and allows engine designer to change and test many different parameters without building up the real engines. Therefore, this study is focusing on the simulation.

1.3 Hypothesis

At constant speed, as the equivalence ratio is decreased, the intake temperature must be increased to have higher engine efficiency and advance the start of combustion. Increasing intake temperature can produce higher combustion efficiency and lower fuel consumption at any low equivalence ratios. At constant temperature, the equivalence ratio plays important parameter to boost the power produced and increase the combustion efficiency.

1.4 Objectives of Research Work

The main objective of this research is to study the effects of equivalence ratio and intake temperature values on the four-stroke, gasoline fueled HCCI engine performance and combustion phasing using computer simulation. Thus, specific objectives to achieve main objective are:

1. To develop a physical based four-stroke gasoline fueled HCCI engine model based on thermodynamic equations of HCCI engine using Simulink® software for predicting power characteristics in order to study the effects of some parameters on the engine performances.
2. To predict burn duration of different combinations of equivalence ratios and intake temperature which is needed to study the combustion timing.
3. To evaluate the combustion characteristic and engine performance of the HCCI engine with varying equivalence ratio and intake temperature under constant speed.

1.5 Scope of Research Work

The scope of work covers the evaluation of HCCI engine performance on several combinations of equivalence ratios and intake temperature. In this study, the engine performance and combustion characteristics are based on the numerical analysis and then validated with the experimental data from literatures. The fuel chosen for this study is gasoline because it is easily evaporated and homogeneously mixed with air. For this fuel, the engine operating condition is varied from 0.2 to 0.5 of the fuel-air equivalence ratios. For each equivalence ratio, the intake air temperature is varied from 373 K to 433 K. Combustion characteristics are evaluated from burn duration of fuel based on the different combinations of equivalence ratios and intake temperatures.

The four-stroke engine model is developed under Matlab/Simulink® for numerical simulation. The parameters, engine geometries and valve timing layout are adopted from existing spark ignition engines. Modification is made on the ignition method to suit the combustion behavior of an HCCI engine. This study focuses on the developing HCCI engine model based on the thermodynamic equations of an engine with some assumptions made on the changing characteristics of fuel-air mixture inside the combustion chamber and no throttle body effect during wide open throttle condition. The simulation results are validated with the experimental data from the literature.

1.6 Thesis Organization

The details of this thesis are structured in six chapters. Chapter 1 is the Introduction. This chapter explains problem statement, objectives and scope of this study. Chapter 2 is the Literature Review. It gives fundamental of HCCI engine processes, theory of HCCI engine modeling and reviews of previous researches related to this study. Chapter 3 is the Research Methodology. This chapter describes the method used to develop the numerical HCCI engine model and to simulate the model for performance prediction. Chapter 4 is the Numerical Engine Development. It describes the model development including theory of each component in details, procedure for data validation and procedure of the simulation program. Chapter 5 is the Results and Discussions. In this chapter, model validation is done by comparing the simulated data and the experimental data. The combustion characteristics and engine performance are discussed. The last chapter, Chapter 6, is the Conclusion and Recommendation where this research work is concluded and suggestions for future research are included.

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