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EFFECTS OF PISTON CROWN PROFILES ON PERFORMANCE OF A GASOLINE HOMOGENEOUS CHARGE COMPRESSION IGNITION ENGINE USING COMPUTATIONAL FLUID DYNAMICS

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By

HASSAN ABDULHADI JASIM

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

October 2016

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Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirements for the Degree of Master of Science

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October 2016

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Homogeneous charge compression ignition (HCCI) combustion incorporates the advantages of both spark-ignition (SI) engines and compression ignition (CI) engines. The homogeneous mixture is inducted into the cylinder without throttling losses and compressed until the mixture reaches the auto-ignition point, and combustion then occurs spontaneously without discernible flame propagation. This feature helps to reduce emission levels while producing a relatively high thermal efficiency.

In the present study, the first objective is to analyse the performance of HCCI engine with different piston crown profiles using computational fluid dynamic (CFD) method, where the software is commercially known as ANSYS FLUENT. The second objective is to evaluate the most suitable piston crown profile to be used in the gasoline-fuelled HCCI engine. Using ANSYS software to create a three-dimensional CFD, the mesh creation and specific zone names with dissimilar topologies of each zone were meshed separately. FLUENT was used to model complex combustion phenomena in an HCCI engine. The validation and simulation were conducted based on an HCCI single-cylinder, four-stroke engine fuelled with gasoline at an engine speed of 1500 rpm and with a compression ratio of 11.7:1, it was then evaluated using three split injections. Combustion parameters such as cylinder pressure, temperature and heat release rate were obtained from the validation work. The CFD model yielded good results for experimental and CFD simulation.

This study focuses on how different piston crown designs affect the performance of HCCI engines. Six different designs were created and evaluated through CFD analysis, where all other engine operating parameters were the same as in the experimental work. For simplicity, the pistons were named A, B, C, D, E and F. The study analyses the in-cylinder pressure, in-cylinder temperature, heat release rate, turbulent kinetic energy, turbulent dissipation rate, NO_X formation, indicated mean effective pressure (IMEP) and power output of different piston designs, and it evaluates the most suitable piston to be used in HCCI engines to improve engine performance.

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The results demonstrate that improved piston crown design in HCCI engines can improve engine performance. All pistons in the investigation reached a peak pressure and temperature above the experiment. In piston A there is an increase of 9.6% in indicated mean effective pressure (IMEP) and 9.76% in power output compared with the experimental results, followed by pistons B, C, D, E and F, in order from highest to lowest, which was caused by higher peak pressure towards the end of combustion, leading to diffusion combustion. Piston A's design could be used in an HCCI engine configuration to improve engine performance.

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

KESAN PROFIL PUNCAK OMBOH PADA PRESTASI ENJIN PENCUCUHAN MAMPATAN CAJ HOMOGEN GASOLIN MENGGUNAKAN PERKOMPUTERAN DINAMIK BENDALIR

Oleh

HASSAN ABDULHADI JASIM

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Pembakaran homogen caj pencucuhan mampatan (HCCI) menggabungkan kelebihan kedua-dua enjin percikan pencucuhan (SI) dan enjin pencucuhan mampatan (CI). Campuran yang seragam dimasukkan ke dalam silinder tanpa kehilangan pendikitan dan dimampatkan sehingga campuran mencapai titik auto-nyalaan, dan pembakaran berlaku secara spontan tanpa boleh beza perambatan api. Ciri ini membantu untuk mengurangkan tahap pelepasan manakala menghasilkan kecekapan haba yang agak tinggi.

Dalam kajian ini, objektif pertama adalah untuk menganalisis tekanan dalam silinder yang mempunyai profil puncak omboh berbeza, dengan menggunakan kaedah perkomputeran dinamik bendalir (CFD), di mana perisian tersebut dikenali secara komersial sebagai ANSYS FLUENT. Objektif kedua adalah untuk menilai profil puncak omboh yang paling sesuai yang akan digunakan dalam enjin HCCI berbahan bakar gasolin. Perisian ANSYS digunakan untuk mewujudkan CFD tiga dimensi, penciptaan jaringan dan nama zon tertentu dengan topologi berbeza dimana setiap zon dijejaringkan secara berasingan. FLUENT digunakan untuk memodelkan fenomena pembakaran kompleks dalam enjin HCCI. Pengesahan dan simulasi telah dijalankan berdasarkan enjin HCCI satu silinder, empat lejang dengan petrol pada kelajuan enjin 1500 rpm dan dengan nisbah mampatan 11.7:1, ia telah dinilai dengan menggunakan tiga suntikan terpisah. Parameter pembakaran seperti tekanan silinder, suhu dan kadar pembebasan haba diperolehi daripada kerja-kerja pengesahan. Model CFD menghasilkan hasil yang baik untuk eksperimen dan simulasi CFD.

Kajian ini memberi tumpuan kepada bagaimana profil puncak omboh berbeza memberi kesan kepada prestasi enjin HCCI. Enam profil yang berbeza diwujudkan dan dinilai melalui analisis CFD, di mana semua parameter operasi enjin lain adalah sama seperti dalam eksperimen. Untuk keringkasan, piston dinamakan A, B, C, D, E dan F. Kajian ini menganalisis tekanan di dalam silinder, suhu dalam silinder, kadar pembebasan haba, tenaga kinetik bergelora, kadar pelesapan bergelora, pembentukan NO_X, tekanan berkesan min tertunjuk (IMEP) dan output kuasa profil omboh yang berbeza dan ia menilai omboh yang paling sesuai untuk digunakan dalam enjin HCCI untuk meningkatkan prestasi enjin.

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Keputusan menunjukkan bahawa profil puncak omboh diperbaiki dalam enjin HCCI boleh mengurangkan paras pelepasan gas. Semua omboh dalam kajian mencapai tekanan dan suhu puncak melebihi eksperimen. Dalam omboh A terdapat peningkatan sebanyak 9.6% dalam tekanan min berkesan tertunjuk (IMEP) dan 9.76% dalam pengeluaran kuasa berbanding dengan keputusan eksperimen, diikuti oleh omboh B, C, D, E dan F, untuk nilai dari tertinggi ke terendah, yang disebabkan oleh tekanan puncak yang lebih tinggi pada akhir pembakaran, yang membawa kepada pembakaran resapan . Profil omboh A boleh digunakan dalam konfigurasi enjin HCCI untuk meningkatkan prestasi enjin.

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I certify that a Thesis Examination Committee has met on 6 October 2016 to conduct the final examination of Hassan Abdulhadi Jasim on his thesis entitled "Effects of Piston Crown Profiles on Performance of a Gasoline Homogeneous Charge Compression Ignition Engine using Computational Fluid Dynamics" 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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TABLE OF CONTENTS

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LIST OF TABLES

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LIST OF FIGURES

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LIST OF ABBREVIATIONS

3D	3 – Dimensional
A/F	Air Fuel Ratio
BDC	Bottom Dead Center
CAD	Crank Angle Degree
CFD	Computational Fluid Dynamic
CI	Compression Ignition
CO	Carbon Monoxide
CO_2	Carbon Dioxide
DPM	Discrete Phase Model
EGR	Exhaust Gas Recirculation
EVC	Exhaust Valve Close
EVO	Exhaust Valve Open
HRR	Heat Release Rate
IC	Internal Combustion
IVC	Intake Valve Close
IVO	Intake Valve Open
IMEP	Indicated Mean Effective Pressure
NO	Nitric Oxide
NO_2	Nitrogen Dioxide
NO_X	Nitrogen Oxides
PISO	Pressure – Implicit with Splitting of Operators
PM	Particulate Matter
RNG	Re – Normalized Consumption
SOC	Start of Combustion
SOI	Start of Injection
TAB	Taylor Analogy Breakup
TDC	Top Dead Center
TKE	Turbulent Kinetic Energy

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CHAPTER 1

INTRODUCTION

1.1 Background

The recent years have seen the world more concerned about climate change, health impacts of emissions and resource scarcity have made emissions and consumption of fuels as critical concerns that require consideration. Although engines have wide applications, the major sources of environmental pollution in the current times are the emissions from transportation vehicles (Yasar et al., 2013). This follows their increase all over the globe as developing countries continue to develop and persons that were initially poor rising to the middle-class level. Moreover, coupled with the association of vehicle ownership with a high class, middle-class populations continue to desire and to seek ways of owning cars (Kachuri et al., 2016). This has resulted in increased number of vehicles as well as increased traffic jams and especially in cities. Additionally, the number of cars around the globe is expected to triple by 2050 because of the increased development of the developing countries (Campen et al., 2014; Kachuri et al., 2016). These have become areas of increased emissions from diesel engines and increased fuel consumption for spark ignition engines.

Therefore, the situation, poses a double impact: negative health impacts and environmental pollution. Persons that especially affected by the health risks are drivers while environmental pollution poses a threat to global warming (Gong et al., 2014). Emissions realized from the transportation vehicles are the major sources of environmental pollutions and particularly the emission of particulate matter (PM).

Particulate matter, being among the common air pollutions, is a mixture of liquid droplets and small particles. The articles pose a threat to human health to a certain degree. For instance, the particles with a diameter of fewer than 10 micrometers and which pass through the nose and throat and enter the lungs have greater harm in comparison with larger particles (Engerer & Kunert, 2015). The exhaust emissions from motor vehicles are ubiquitous with the exposure taking place using outdoor and indoor air and in numerous occupational environments. Most of the people that are exposed to the emissions are operators of heavy equipment and drivers (McDonald et al., 2007; Yasar et al., 2013).

Gasoline and diesel are the most common fuel in combustion engines and comprise a complex combination of chemicals, for instance, organic compounds that are volatile, nitroarenes, polycyclic aromatic hydrocarbons (PAH) and carbon monoxide. Although the same particles are emitted from engines powered by diesel or gasoline the surface properties and the distribution of the particles are different suggesting the variations in the health impacts linked to such exposures. This has led to research on the various ways through which these emissions can be reduced as part of compliance with regulations, especially in developed countries. The transition in engine technology can be realized as more research studies are being conducted as well as the continued commercialization of technologies for hydrogen engines, electric vehicles, cell engines and hybrid vehicles.

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1.2 Introduction

A homogeneous charge compression ignition (HCCI) engine is a relatively new mode of the combustion process, which has in the recent times generated great interest to be used in a vehicle and the generation of stationary power (Khaliq et al., 2012). HCCI engine is the auto-ignition process by which the combustion occurs instantaneously when the fuel-air mixture has enough chemical activation energy at the end of compression stroke. Thus, both high efficiency and low emissions can be obtained (Najafabadi et al., 2013). The engine is further defined by Ghafouri et al. (2014) as the combination between the compression ignition (CI) and spark ignition (SI) engine. Figure 1.1 shows the comparison between CI, SI and HCCI engines.

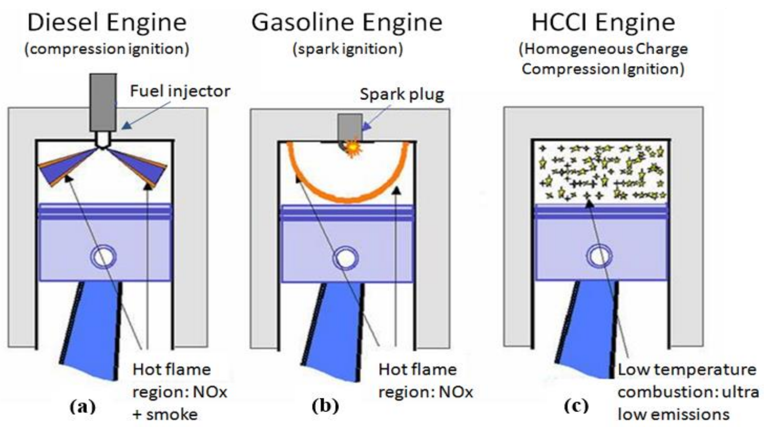

Figure 1.1: Comparison between (a) diesel, (b) gasoline and (c) HCCI engines (Ghafouri et al., 2014).

CI engines are used to describe the combustion which occurs in diesel engines. The CI engines are mainly used in some passenger cars, larger trains and trucks and high power generation and marine applications. In the conventional diesel engine, air enters the cylinder during the intake stroke. In the compression stroke, the air is compressed by the piston. The fuel is sprayed by an injector into the cylinder as the compression nears its end and the fuel is burnt as it is diffused into the cylinder.

The process of combustion takes place in three phases. The first involves the emission of the atomized oil droplets from the nozzle of the fuel valve into the space for combustion at the commencement of the ignition, its evaporation and mixing with hot air which is compressed. This leads to some chemical changes in the fuel. The mixture reaches an ignitable condition leading to the commencement of spontaneous combustion. In the second phase, the ignition and the beginning of the combustion lead to the setting up of a flame which accelerates through the chamber surrounding and burning other droplets and leading a fast heat generation with increased temperature and pressure. In the third phase, the hot and turbulent conditions in the combustion chamber ignite and burn the remaining fuel charge as it is injected.

The CI engines do not experience pumping losses and as such have increased part load efficiency. The control of loads is accomplished through the change in the level of fuel.

The diesel engines have problems with the emission of NO_X and smoke. Given that the fuel and the air are not mixed well, the resulting combustion leads to the production of particulate matter.

In the conventional SI engine, fuel and air enter the cylinder and then mix in the intake stroke. In the process of the compression stroke, the mixture is compressed by the piston and is prepared for combustion. Towards the end of this stroke, the mixture is ignited by a spark plug leading to the initiation of a flame which passes through the charge and as such burning the reactants. The disadvantage of the flame is that it leads to the introduction of high local temperatures and as such leading to the production of NO_X (Kannan et al., 2015). Spark ignition engines which are fitted with three-way catalysts can be taken as very clean, but they have problems during their part load conditions (Kamaruddin et al., 2012).

In the HCCI engine, the engine has the capability of running very lean mixture with an equivalence ratio of about 0.2 or even lower given that there is no need for the propagation of the flame as multiple sites for ignition are developed as a result of compression. The capability of the HCCI to operate at very lean mixture and pre-mixed conditions provide the potential for its efficient functioning with low NO_X and particulate emissions. This is because as opposed to the other engines, the air-fuel mixture is able to attain homogeneity to a certain degree. Significant attention has been accorded to the analysis of HCCI engines in the recent years. The analyses have been conducted on the assumption that the combustion of HCCI is controlled by the local rates of reaction that are chemical-kinetic in nature and having no propagation of flames. The idea has received support from spectroscopic data which indicate that the radical formation order in HCCI combustion is correspondent to self-ignition as opposed to propagation (Nemati et al., 2011).

1.2.1 Advantages and Disadvantages of HCCI Engines

When compared with the CI and the SI engines, the HCCI engines have relatively high part load efficiency, very low levels of NO_X emissions (Bedoya et al., 2012). This comes through the dilute mixture of fuel and air. HCCI engines do not have problems with the formation of soot because of the employment of the homogenous charge (Barari et al., 2016). The HCCI engines also have the capability to operate on numerous types of fuel including diesel, biodiesels and gasoline. Moreover, it has the capability to combine the low level of fuel consumption as is the case of the diesel engines with the low exhaust emissions characterized by the SI engines having three-way catalysts.

A side from their potential for being less expensive because of the way in which they are constructed, they do not need (a) sophisticated inlet duct shapes for the generation of the particular turbulence within the combustion chamber; (b) a high-pressure system for injection; and (c) after treatment systems for the exhaust gas. The ignition in the HCCI engines is determined by the chemical-kinetic rates of reaction of the air/fuel mixture whose control comes from temperature, time and the composition of the mixture.

It appears that the diesel engines may not achieve the emission levels of particulate matter and NO_X through future legislation. In the same way, the SI engines do not have the capability of reaching higher rates of efficiency during part loads because of the way

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they are constructed and their working principles. The HCCI engine can, therefore, be taken as a combination of the CI and the SI and as such connects their attractive properties and has the potential of emerging as the driving propulsion of vehicles. The reasons that underlie these advantages include increased specific heat ratio of a very lean mixture; increased cycle efficiency that comes from the use of a higher compression ratio; faster combustion. Because of these, the HCCI has gained a strong interest globally (Yao et al., 2009). The advantages that make the HCCI be regarded as a combination are indicated in Table 1.1.

Table 1.1: The advantages of HCCI engine (Barari et al., 2016).

SI engine	**CI engine**	**HCCI engine**
Low efficiency at part loads	High efficiency during all load conditions	Relatively high efficiency at low load conditions
Low emission of particulate matter	High emission of particulate matter	Low emissions of particulate matter
		Ability to use any fuels
		Less maintenance, no spark plug

Despite their advantages of relatively high efficiency and reduced emissions, the HCCI engines have their challenges. In the HCCI engine, the combustion occurs when the mixture auto-ignites instantaneously at any location. The implication is that the start of combustion is not well defined, like having a spark plug in SI engines. The ignition occurs in such a way that it is in numerous points which enables the mixture to burn in a simultaneous manner. The lack of a direct initiation of combustion leads to difficulty in controlling the auto-ignition process.

To achieve the dynamic operation of the HCCI engine, the conditions that induce combustion much be changed. This means that the engine must control the compression ratio, gas pressure and temperature, ratio of fuel and air in the mixture and quantity of exhaust recirculation. Although this has been achieved, the difficulty lies in ignition at higher loads. At increased loads, the rate at which pressure rises can increase instantly, increasing engine noise and leading to knocking.

Moreover, the control of combustion duration is also a challenge. In the exhaust gas recirculation (EGR) process, some of the exhaust gases are channeled back to the combustion chamber for the promotion of auto ignition. Having sustained levels of exhaust gases in each of the engine cycles result in cycle-to-cycle coupling given that a large proportion of the cylinder charge is retained in the cylinder in the next cycle (Kamaruddin et al., 2012). The disadvantages of HCCI engines are summarized in Table 1.2.

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Table 1.2: The disadvantages of HCCI engine (Barari et al., 2016).

Attribute	Explanation
Combustion	Lack of a direct initiator of combustion
Ignition	Challenge in start of ignition
High load conditions	Instantaneous pressure rises, leading to knocking and may cause engine damage
Timing	Challenge in controlling the ignition timing

1.3 Research Focus

Only a few studies have considered the impact of piston shapes on the performance of engines. Conducted a study which reveals that the geometry of pistons bowls impacts greatly on combustion at conditions of low load and especially in the case that multiple strategies of injection are employed (Gugulothu & Reddy, 2015). They concluded that the geometries have an impact on engine performance.

Conducted a study of the impact of the different shapes of pistons on the performance of gasoline direct injection engines (Zheng et al., 2015a). Findings indicated that flat top pistons are of benefit in the maintenance of turbulence intensity within the cylinder for high-pressure injectors with multi-holes. The explanation to this is that the structure enables the combustible mixture to form around the spark plug during ignition. Pistons having smoother surfaces enable the strengthening of kinetic energy at the ignition time and as such accelerate combustion and increase the temperature and pressure within the cylinder. Increased temperature and pressure within the cylinder enhance emission and the decrease in the emission of soot comes from subsequent oxidation.

Although the studies reveal that there is the impact of the piston types or shapes on the performance of SI engines, no study has examined the same with HCCI engines. The current research focuses on studying the functioning of the HCCI engines with different piston crown designs to establish the most optimal design. Moreover, factors examined in defining this optimality include operating loads, and emissions. This comes from the notion that the piston crowns designs affect the performance of the engines at particular loads, and that there are designs that lead to increasing performance engine.

1.4 Hypothesis

The flat piston is common in internal combustion engine, where it does not improve the mixing process (Zheng et al., 2015a). However, in CI engines, they have different piston crown designs, and so to some of the SI engines (Zheng et al., 2015a), to improve the mixing, as well as the performance of the engine. It is hypothesized from the study that, the performance of HCCI engine will be improved with the piston which can create a better homogenous mixture and high turbulent level. Therefore, this study, contributes significantly to the performance of HCCI engines with different piston crown designs.

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1.5 Objectives

The objectives of the study are to:

1. analyse the performance of HCCI engine with different piston crown profiles.
2. evaluate the most suitable piston crown profile to be utilized in the gasoline-fuelled HCCI engine.

1.6 Scope of Study

The current study involves the design of the piston crown in a manner that enhances the combustion process. The design will be done through the use of ANSYS software and as such, the simulation software will facilitate both design and testing. The study will analyze the performance of different piston crown designs through the collection of data from the simulation software. The engine is a single cylinder, where the simulation starts from 0 – 720 crank angle degree (CAD). The engine speed is 1500 rpm, based on Hunicz et al. (2015). The simulation is based on a gasoline fuelled HCCI engine. However, the study uses single-reaction n-octane as a surrogate fuel (Cai & Pitsch, 2015), which is available from ANSYS software.

1.7 Thesis Outline

The thesis has five chapters. The second chapter is that of the literature review. In this chapter, explains the HCCI engines and their operation more closely, drawing comparisons with the diesel and the spark ignition engines. Moreover, the role of piston crowns in the modeling of the HCCI engine is discussed, together with the possibility of having variations of engine performance through the use of varied piston crowns. The literature reviewed provides the foundation for methodology and compare findings with those of other researchers where applicable.

Chapter three is methodology or simulation methods. Given that the research is solely based on simulation of the piston crown designs and establishing their performance, the chapter majorly involves model preparation and a description of the grid generation of HCCI engine that created the needed mesh by moving the dynamic mesh model. Moreover, the chapter includes the definition of the variables to be measured and the actual simulation. This enables the collection of data and their subsequent analyses to provide the results required for discussion.

Chapter four entails the presentation and the discussion of the findings. This involves the reporting of the stages of modeling together with the measures obtained from the various variables. Moreover, explains these results by comparing them with the findings of past studies and explaining any phenomenon established through the use of available literature. This enables the validation of the results.

Chapter five which is the last is the conclusions and recommendations. It comprises the restatement of the aim and the objectives of the current study, the methods used and the summary of the results. Further, the challenges experienced in the course of modeling that can affect the validity and the reliability of the findings are also discussed. This leads to the statement of the recommendations for future research. The study ends with the conclusions chapter.

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