MODELING AND EXPERIMENTAL ANALYSIS OF EXHAUST GAS TEMPERATURE AND MISFIRE IN A CONVERTED-DIESEL HOMOGENEOUS CHARGE COMPRESSION IGNITION ENGINE FUELLED WITH ETHANOL

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A thesis submitted in fulfilment of the
requirements for the award of the degree of
Doctor of Philosophy (Mechanical Engineering)

Faculty of Mechanical Engineering
Universiti Teknologi Malaysia

SEPTEMBER 2013

To my lovely wife for her sincere help and accompany,
to my kind parents for their priceless support and motivation
and to all my teachers and lecturers who educated me during my studies.

ACKNOWLEDGEMENT

Firstly, I would like to express my appreciation to my supervisor Prof. Dr. Azhar Adbul Aziz for his valuable suggestions, guidance and continuous support throughout this research.

I would also like to thank my co-supervisors Dr. Shahbakhti, Dr. Mohd Farid Muhamad Said and other nice friends who helped me during my studies. I also would like to thank all staff of Automotive Development Centre (ADC) members for their valuable cooperation and interest. My thanks are also extended to senior technician Mr. Hishamudin for his valuable assistant.

Last but not least, I would like to thank my wife for her encouragement in which this thesis would not have existed without her patience, understanding and support.

ABSTRACT

Homogeneous charge compression ignition (HCCI) and the exploitation of ethanol as an alternative fuel is one way to explore new frontiers of internal combustion engines with an objective towards maintaining its sustainability. Here, a 0.3 liter single-cylinder direct-injection diesel engine was converted to operate on the alternative mode with the inclusion of ethanol fuelling and intake air preheating systems. The main HCCI engines parameters such as indicated mean effective pressure, maximum in-cylinder pressure, heat release, in-cylinder temperature and combustion parameters, start of combustion, 50% of mass fuel burnt (CA_{50}) and burn duration were acquired for 100 operating conditions. They were used to study the effect of varying input parameters such as equivalence ratio and intake air temperature on exhaust gas emission, temperature and ethanol combustion, experimentally and numerically. The study primarily focused on HCCI exhaust gas temperature and understanding and detecting misfire in an ethanol fuelled HCCI engine, thus highlighting the advantages and drawbacks of using ethanol fuelled HCCI. The analysis of experimental data was used to understand how misfire affects HCCI engine operation. A model-based misfire detection technique was developed for HCCI engines and the validity of the obtained model was then verified with experimental data for a wide range of misfire and normal operating conditions. The misfire detection is computationally efficient and it can be readily used to detect misfire in HCCI engine. The results of the misfire detection model are very promising from the viewpoints of further controlling and improving combustion in HCCI engines.

ABSTRAK

Nyalaan Mampatan Caj Homogen (HCCI) dan penggunaan etanol sebagai bahan api alternatif adalah salah satu kaedah untuk mempelbagaikan penggunaan enjin pembakaran dalam, dalam usaha melestarikan penggunaannya di masa hadapan. Dalam, kajian ini sebuah enjin diesel satu silinder jenis semburan terus dengan isipadu 0.3 liter, telah diubahsuai untuk beroperasi menggunakan bahan api etanol. Enjin telah melalui pengubahsuaian sistem bahan api dan pemasangan sistem prapemanasan udara masuk di samping pengubahsuaian kecil yang lain. Parameter utama seperti tekanan berkesan purata tertunjuk, haba keluaran, suhu kebuk pembakaran, tekanan pembakaran maksimum, permulaan pembakaran, 50% jisim bahan api yg terbakar (CA_{50}) dan masa pembakaran telah diperolehi bagi 100 keadaan operasi enjin. Parameter ini digunakan untuk mengkaji kesan perubahan parameter masukan seperti nisbah persamaan dan suhu masukan udara ke atas keluaran ekzos, suhu dan pembakaran secara ujikaji dan juga analisis berangka. Secara amnya, kajian tertumpu kepada ramalan suhu ekzos enjin serta pemahaman dan pengesanan fenomena salah-nyalaan apabila menggunakan bahan api etanol. Usaha ini memperlihatkan beberapa kebaikan serta kekurangan penggunaan etanol dalam enjin HCCI. Analisis data yang diperolehi telah membantu penyelidik memahami bagaimana salah-nyalaan mempengaruhi operasi enjin HCCI. Satu teknik berunsurkan model simulasi untuk mengesan salah-nyalaan telah dibangunkan dan telah terbukti keberkesanannya setelah dibuat pelbagai perbandingan dengan hasil ujian yang dilaksanakan di makmal. Teknik ini telah terbukti efisien dalam meramalkan salah-nyalaan di dalam enjin HCCI ini. Keputusan yang dihasilkan oleh model ini amat berpotensi untuk membantu mengawal dan meningkat kecekapan pembakaran di dalam enjin HCCI.

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LIST OF SYMBOLS

a - Crank ratio

a_i - Output of a neuron

a_j - Input function of a neuron

A_o - Orifice area

B - Bore of cylinder

C_D - Orifice discharge coefficient

C_v - Specific heat at constant volume

C_p - Specific heat at constant pressure

d_o - Orifice plate diameter (airbox)

dU - Change of internal energy of the mass in the system

dQ - Heat release rate from combustion;

dW - work performed on piston;

$dQht$ - Heat transfer to the cylinder walls

$dQcr$ - Energy loss and leakage due to mass flow crevice in the regions between the piston and the cylinder wall

e - Error

g - Acceleration due to gravity

h - Height

L - Stroke length

l - Connecting rod length

m - Charge mass in cylinder

$\dot{m}_a$ - Air mass flow rate

$\dot{m}_f$ - Fuel mass flow rate

n - Total number of repeated measurements made

n_1 - Polytropic index

N - Engine speed

o_{ip} - The desired output vectors

P - In-cylinder pressure

P_f - Pressure at EOC

P_{IVC} - Pressure at IVC

P_{man} - Density of manometer

P_k - Pressure at k crank angle degree

P_s - Pressure at SOC

R - Universal gas constant

s - Distance between the crank shaft axis and the piston pin axis

S - Stroke

S_1 - Mean error

S_m - Standard error of the mean

t_{ip} - The network output (target),

T - Temperature

T_{IVC} - Temperature at IVC

V - Cylinder volume

V_c - Clearance volume or compression volume

V_d - Engine displacement volume

V_{IVC} - Volume at IVC

ΔV_k - Difference engine volume at k crank angle degree

V_f - Volume at EOC

V_s - Volume at SOC

X_{mean} Mean value

U - Internal energy per mass unit

θ - Crank angle

θ_{pmax} - Crank angle of maximum in-cylinder pressure

Φ - Equivalence ratio

γ - Specific heat ratio, (C_p/C_v)

ΔP - Pressure drop across the orifice plate

ρ - Density

Δt - Time change

LIST OF ABBREVIATIONS

aBDC	-	After Bottom Dead Center
aTDC	-	After Top Dead Center
AC	-	Actual
AFR	-	Air Fuel Ratio
AI	-	Artificial Intelligence
AMD	-	Ann Misfire Detection
ANN	-	Artificial Neural Network
ATAC	-	Active Thermo-Atmosphere Combustion
BD	-	Burn Duration
BP	-	Back Propagation
bTDC	-	Before Top Dead Center.
CAD	-	Crank Angle Degree
CA_x	-	Crank Angle For x% of Mass Fraction Burnt Fuel
$CA_{max,dp/dh}$	-	Crank Angle at Maximum Pressure Rise Rate (dp/dh)
CA_{MHRR}	-	Crank Angle at MHRR
CA_{Pmax}	-	Crank Angle at P_{max}
CFD	-	Computational Fluid Dynamics
CI	-	Compression Ignition.
CIHC	-	Compression-Ignited Homogeneous Charge
CR	-	Compression Ratio
CPS	-	Combustion Pressure Sensor
CVF	-	Crankshaft Velocity Fluctuation
CO	-	Carbon Monoxide
CO_2	-	Carbon Dioxide
DAQ	-	Data Acquisition System

DEE	-	Diethyl Ether
E85	-	85% Ethanol and 15% Water
ECU	-	Electronic Control Unit
EER	-	Exhaust Energy Recovery
EGR	-	Exhaust Gas Recirculation.
EOC	-	End of Combustion.
EtOH	-	Ethanol
EVC	-	Exhaust Valve Closing
EVO	-	Exhaust Valve Opening
FFV	-	Flexible Fuel Vehicle
HC	-	Hydrocarbons
HCCI	-	Homogeneous Charge Compression Ignition
HRR	-	Heat Release Rate
ICE	-	Internal Combustion Engine
IMEP	-	Indicated Mean Effective Pressure.
IVC	-	Intake Valve Closing
IVO	-	Intake Valve Opening
LED	-	Light Emitting Diode
LTHR	-	Low Temperature Heat Release
MFB	-	Mass Fraction Burned
MHRR	-	Maximum Heat Release Rate
MPRR	-	Maximum Pressure Rise Rate
NO_x	-	Oxides of Nitrogen
NVO	-	Negative Valve Overlap
O_2	-	Oxygen
OBD	-	On-board Diagnostic
ON	-	Octane Number
P_{in}	-	Intake Pressure
P_{max}	-	Maximum In-cylinder Pressure
P_{TDC}	-	In-cylinder pressure at top dead center
P_x	-	In-cylinder pressure at x crank angle degree
PCCI	-	Premixed Charge Compression Ignition
PFI	-	Port Fuel Injection

PM - Particulate Matter
PPM - Parts Per Million
PRR - Pressure Rise Rate
RMS - Root Mean Square
RPM - Revolution Per Minute
SI - Spark Ignition
SOC - Start of Combustion.
ST - Stoichiometric
STD - Standard Deviation.
T_{ad} - Adiabatic Flame Temperature
T_{in} - Intake Temperature
T_{exh} - Exhaust Gas Temperature
TDC - Top Dead Center
TS - Toyota-Soken
VVA - Variable Valve Actuation
VCR - Variable Compression Ratio
VVT - Variable Valve Timing

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CHAPTER 1

INTRODUCTION

1.1 Background

Internal combustion engines (ICEs) are devices in which the combustion of fuel, specifically fossil fuel, with an oxidizer (air) takes place inside the engine‘s combustion chamber. The result of detonation of the mixture, heat energy will be created which the detonation force will be applied onto the piston surface areas resulting in the production of mechanical energy.

There are three types of reciprocating ICEs i.e: i) spark ignition (SI), ii) compression ignition (CI) and iii) homogeneous charge compression ignition (HCCI) engines respectively. The differences are based on several factors but namely on fuel preparation and ignition. However the principle of operating is the same (Basshuysen and Schäfer, 2004). Figure 1.1 shows the four-stroke cycle SI engine where the piston and valve movements during the intake, compression, expansion, and exhaust strokes are shown.

The first engine operating process is the intake stroke as the piston is pulled downward towards its lower position, the bottom dead center (BDC). At this lower position, air and fuel will be induced into the combustion chamber through intake manifold and opened intake valve.

The second process is the compression stroke in which both intake and exhaust valves are closed and as piston is pushed towards its upper position, top dead center (TDC), the volume is reduced, thus the air-fuel mixture is compressed. Highly depends on engine type, the charge is ignited near to TDC.

The third process is the power stroke which takes place after compression stroke and continues sometime into the expansion stroke and followed by a rapid combustion. During combustion the fuel releases heat in a totally enclosed (nearly constant volume) vessel which produces burned or unburned exhaust gases in combustion chamber and work is generated.

The last process is the exhaust stroke in which the engine’s exhaust valve will be activated by the cam pushing on the rocker arm and the exhaust and the burned are pushed by the piston to goes out and exit from the cylinder through the opened exhaust valve. These four strokes are repeated continuously to make engine running.

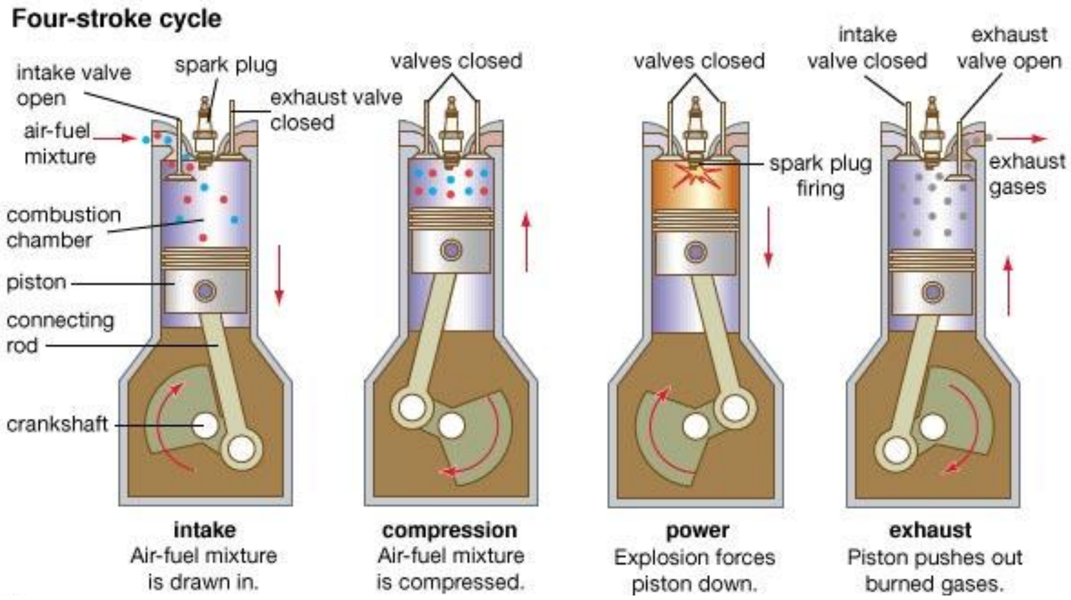

Figure 1.1 SI engine fundamental (James, 2013).

1.1.1 Spark ignition engine

In a spark ignition (SI) engine premixed air-fuel mixture is induced into the cylinder from intake manifold. In port fuel injected (PFI) system, fuel is atomized and vaporized by using injector and mixed with the air behind the intake valve. Before arriving piston to the TDC, charge is ignited with using spark plug (Figure 1.1), thus a turbulent flame is produced through the combustion chamber. The important characteristics of a SI engine are listed as follows (Stone, 1992):

- SI engine operates close to stoichiometric air-fuel ratio (AFR).
- In SI engine flow rate of air is controlled by throttling.
- Fuel consumption is influenced by efficiency directly, which results in higher carbon dioxide (CO_2) emissions.
- With using 3-way catalysts in SI engine, carbon monoxide (CO), nitrogen oxides (NO_x) and unburned hydrocarbons (uHC) emissions decrease.

1.1.2 Compression ignition engine

In a compression ignition (CI) engine or better known as diesel engine, fuel is directly injected during intake stroke where air is induced into the cylinder (Figure 1.2). During the compression stroke due to the high compression ratio, the air temperature will become high and near to TDC, fuel is atomized and injected to the hot air and creates combustion with a diffusive flame. The important characteristics of a CI engine are listed as follows (Vressner, 2007):

- High compression ratio and low fuel consumption.
- CI engines operate unthrottled which results in less pumping losses.
- The load is controlled by the amount of injected fuel.

- NO_x emissions and particulate matter is highly generated due to diffusive combustion. New after-treatment systems are designed to reduce NO_x.
- Increasingly popular for using in passenger car due to lower fuel consumption and higher power output.

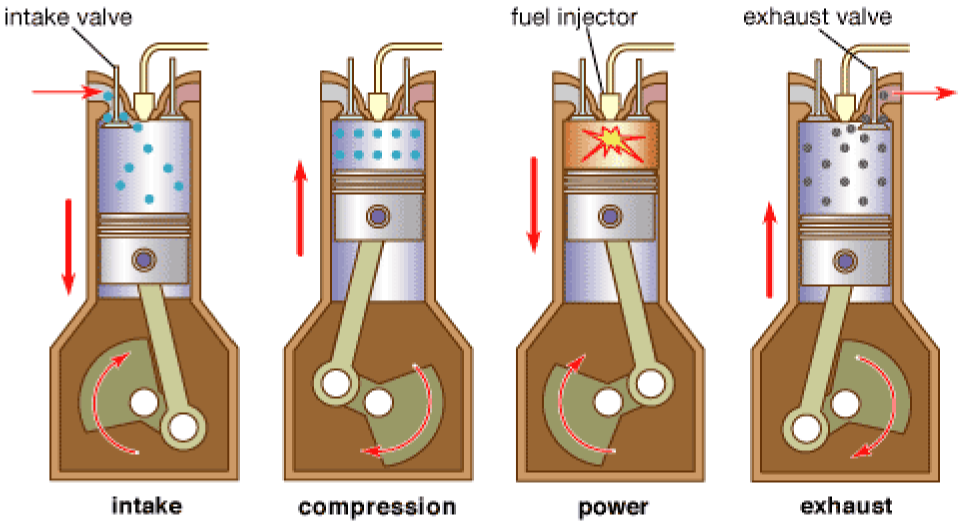

Figure 1.2 CI engine (James, 2013).

1.1.3 Homogeneous charge compression ignition engine

The homogeneous charge compression ignition (HCCI) engine is relatively a new concept recently being developed by researchers as the ‘next-generation’ of ICEs. It synergizes the best features of diesel and gasoline engines. It is stated to be compatible with wide variety of bio-fuels. HCCI engines are said to be of higher thermal efficiency than diesel and gasoline engines of similar displacement, with promising low ultra NO_x and PM (Particulate matter) emission indexes. Fuel autoignition take places through the compression due to increased pressure and temperature history. Diluted mixtures are needed in HCCI engine to keep the pressure rise rates at acceptable levels due to high combustion rate (Zhao, 2007).

HCCI characterized by the merging of the best elements of diesel and gasoline behaviors respectively. The characteristic of HCCI engine is similar to CI for high compression ignition feature and SI counterpart for its mixture homogeneity. As shown in Figure 1.3, autoignition takes places simultaneously at several locations in combustion chamber with no external ignition source (spark in SI and fuel injection in CI engines). The HCCI engine runs unthrottled similar to the CI engine and with comparing to the SI engine, the pumping losses are reduced. HCCI engine like CI have high compression ratio (CR) to create fast combustion near TDC to improve efficiency. If above take into account, these limitations make HCCI to be a combustion concept instead of an engine type (Stanglmaier and Roberts, 1999).

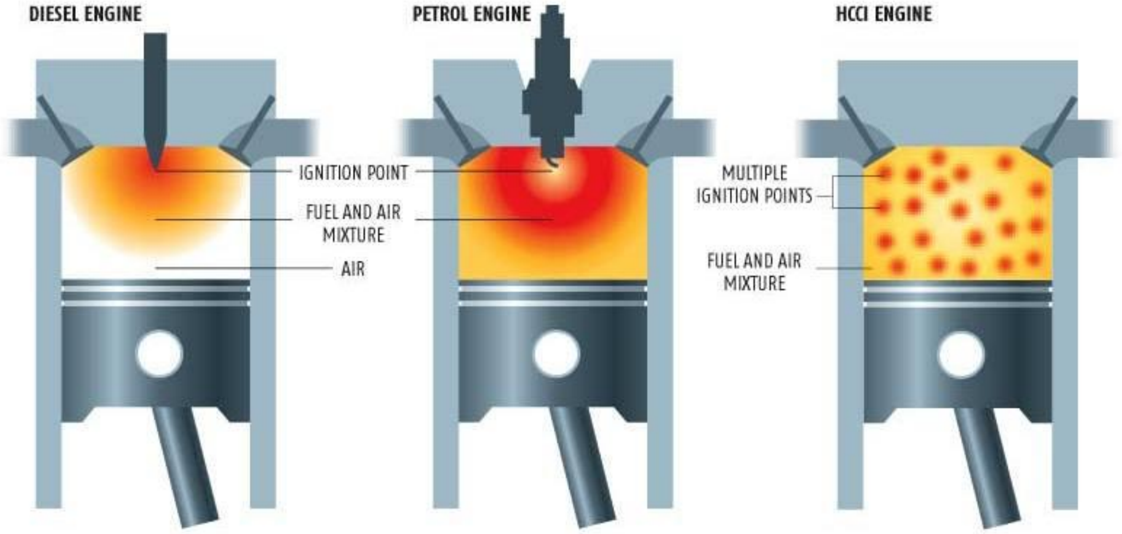

Figure 1.3 HCCI combustion versus tradition CI and SI combustion (Marshall, 2006).

In general the merits of HCCI engine are:

1. Using very lean mixture (high diluted) in HCCI engine makes it as low fuel consumption engine (Sankaran *et al.*, 2007).
2. Using the diluted mixture in HCCI engine makes it having low combustion chamber’s temperature and keep temperature combustion down which results in decreasing the amount of NO_x and PM during HCCI engine running (Aceves *et al.*, 2001).

3. Higher thermal efficiency and as most of the combustion energy is released during the combustion and expansion stroke, HCCI has less waste exhaust energy compared to SI and typical CI engines (Shahbakhti *et al.,* 2010)
4. The results from other research showed that HCCI engines can be capable to operate with several fuels such as gasoline, diesel fuel and most alternative and renewable fuels (Epping *et al.,* 2008).

On the other hand the demerits of HCCI combustion:

1. Achieving high load for this kind of engine is difficult due to an increase in pressure. Using this engine should be common with a CI or SI switching to HCCI (Santoso *et al.*, 2005).
2. Controlling ignition timing (start of combustion (SOC)) is a major problem because it governed by the temperature, pressure history and needs a new electronic control unit (Blom *et al.*, 2008).
3. HC and CO emissions are typically higher in HCCI than that of diesel engines due to low temperature combustion (Aceves et al., 2004) but CO and HC emissions can be decreased by using an oxidation catalytic converter in HCCI engine.
4. Cold start is the main problem for HCCI engine and this problem is recently weakened by using a dual mode SI-HCCI (Santoso *et al.,* 2005, Koopmans *et al.*, 2003) or CI-HCCI (Canova *et al.*, 2007) technique where the engine starts in the SI/CI mode for engine warm up.

1.2 Problem Statement

Globalization and the rise in mobility, price variation of the fuels based on crude oil, more stringent environmental regulations for engine makers and the exhaust emission problem have urged and have motivated internal combustion engine (ICEs) designers to overcome these challenges. This is merely to confirm that future ICEs will be more sustainable and adaptable for economical and robust operations.

Some of the ways of overcoming these are through the adoption of new engine. HCCI engine is a new technology that is adaptable for use with wide range of fuels. The other factor that is suitable for air pollution is using of ethanol as an alternative fuel.

Despite lower NO_x and PM, the level of HC and CO emissions are high due to lean burn and low temperature combustion (Shudo *et al.,* 2007). Exhaust after-treatment system is needed to help an HCCI engine to mitigate high amount of HC and CO. Taking the catalyst converter to the light off temperature (250-300 °C) (Jean *et al.,* 2007) plays an important role for realizing HCCI engines as a practical solution. As the catalyst temperature drops below the light-off, the converter becomes ineffective in reducing exhaust emissions (Tanikawa *et al.,* 2008). Therefore, it is essential to understand and analyzing exhaust temperature (T_{exh}) for an ethanol fuelled HCCI engines.

Also, delayed combustion phasing and unstable combustion can cause HCCI misfire resulting in high HC and CO emissions (Ghazimirsaied and Koch, 2012). The unburned fuel from engine misfire will enter into the catalytic converter, and this can have a cooling effect on the catalyst (Baghi Abadi *et al.,* 2011). Misfire can be generated in several ways in HCCI engines, which makes analyzing of misfire essential for engine developers.

Thus, it is necessary to investigate the effect of input variable such as intake temperature and air-fuel ratio, on the T_{exh} and understanding and detecting misfire in an ethanol fuelled HCCI due to lack of accurate study on misfire in HCCI engine.

1.3 Objectives of Research

This research focuses on the effect of operating parameters on HCCI engine exhaust gas temperature and the effect of misfire on HCCI engine operation. Hence, three main objectives of this investigation are as follows:

- To convert a CI engine to operate on HCCI mode.

- To study the effect of varying operating parameters on HCCI engine performance, T_{exh} and emissions and also the ethanol combustion characteristic.

- Understanding and analyzing misfire in an ethanol fuelled HCCI engine and to develop a model for fast detection of misfiring in HCCI engine.

1.4 Scope of Research

The scope of this research comprises of the following aspects:

a) To convert a single-cylinder diesel engine to operate in HCCI mode and to undertake modifications such as:

  - To develop new intake manifold for HCCI engine for containing preheating and fuelling system.

- To develop heating system.
- To develop new fuel system for ethanol port fuel injection.
- To develop electrical circuit for controlling fuelling and fuel injection system.

b) To perform numerical analysis for defining heat release, ethanol combustion characteristics and find combustion timing characteristic such as start of combustion (SOC), 50% of mass fraction burnt (CA_{50}) and burn duration (BD).

c) Experimental investigation on the HCCI engine fuelled ethanol operation such as:

- Effect of input parameters on HCCI performance, operation and engine out emissions.
- Study on T_{exh} of HCCI engine.
- Develop model for fast prediction T_{exh} in HCCI engine.

d) Experimental investigation on the effect of misfire on HCCI engine, such as:

- Investigate into the engine characteristics for misfire detection.
- Statistical analysis for misfire detection in HCCI engine.
- Develop model for fast detection of misfire in HCCI engine.

1.5 Research Methodology

The flowchart presented in Figure 1.4 describes the research methodology considered in this thesis. First, an introduction as well as a literature study is presented. Then, an attempt to prepare laboratory setup and the engine modifications such as electrical circuit for fuel injecting, intake manifold for containing heater, fuel system for ethanol injection as port fuel injector and chassis for joining engine and encoder. Next, do the experimental work and get desire data. A comparative study among the proposed scheme should be carried out to highlight the effect of initial condition on HCCI performance, exhaust gas temperature and emission. Develop model for determining ethanol combustion characteristics and ignition timing. Study on the effect of misfire in HCCI engine operation and develop model to present an appropriate computational for fast detecting misfire in HCCI engine.

1.6 Significance of Research

Low exhaust temperature in HCCI significantly limits efficiency of an exhaust after-treatment system to mitigate high HC and CO emissions in HCCI engines. Thus, an efficient investigation should be done for T_{exh} of HCCI to develop method to improve exhaust after-treatment systems. Also, delayed combustion phasing leads to autoignition which occurred with the downward movement of the piston and makes HCCI engine operates near misfire region which result in producing partial-burn and misfire cycles with too much CO and HC emission. Furthermore, understanding the HCCI operation change during misfire is very essential. However, new methods to detect HCCI misfire help researcher and factories to overcome this problem. Consequently, a specific attention for designing effective misfire detection systems is required. To the best of the authors' knowledge, this study is the first study undertaken to develop a misfire detection technique for HCCI engines.

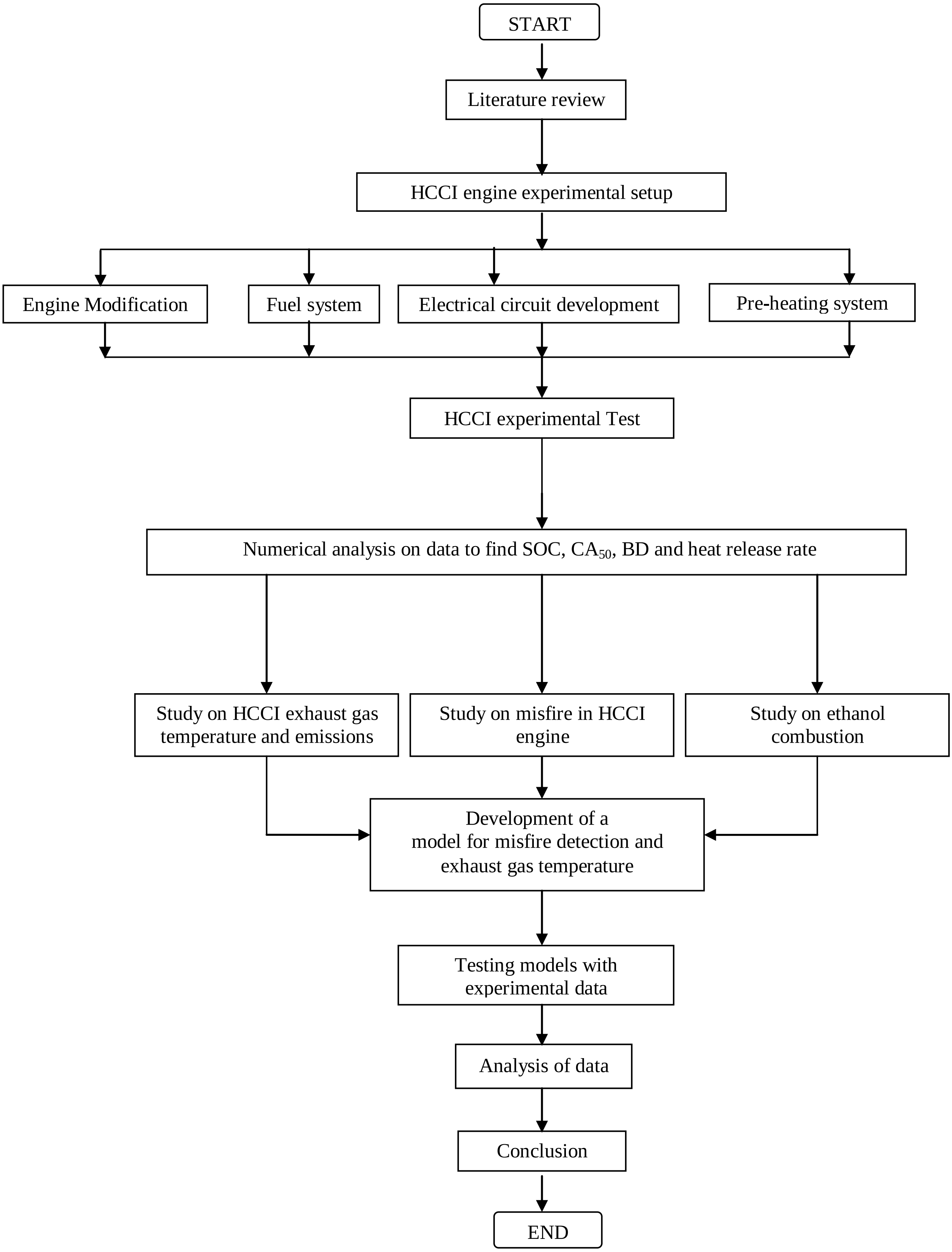

Figure 1.4 Research procedure flowchart.

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