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Ethanol Fuelled HCCI Engine: A Review

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***Abstract*—**The greenhouse effect and limitations on carbon dioxide emissions concern engine maker and the future of the internal combustion engines should go toward substantially and improved thermal efficiency engine. Homogeneous charge compression ignition (HCCI) is an alternative high-efficiency technology for combustion engines to reduce exhaust emissions and fuel consumption. However, there are still tough challenges in the successful operation of HCCI engines, such as controlling the combustion phasing, extending the operating range, and high unburned hydrocarbon and CO emissions. HCCI and the exploitation of ethanol as an alternative fuel is one way to explore new frontiers of internal combustion engines with an eye towards maintaining its sustainability. This study was done to extend database knowledge about HCCI with ethanol a fuel.

***Keywords*—**Ethanol combustion, Ethanol fuel, HCCI.

I. Introduction

GLOBALIZATION and the rise in mobility have resulted in the demand for sustainable fuel supply for engines and the reduction in the excess discharge of toxic concentrations of the exhaust gas constituents from the engines in used. To deal with these there are two major strategies now being adopted at the global stage i.e. i) the use of alternative and sustainable fuels and ii) the shift from traditional internal combustion engine technologies towards a better alternatives that enables to offer fuel economy and environmentally-friendly operation. For the latter, homogeneously-charge compression ignition (HCCI) engine concept is a promising idea that combines the best of the spark-ignition (SI) and compression ignition (CI) engine features towards reducing fuel consumption and emissions, providing superior performance [1].

The HCCI engine is a hybrid between two well-known SI and CI engine design which have the potential to combine the best characteristics between them. The HCCI engine is similar to SI counterpart for its mixture homogeneity and CI for high compression ignition feature. HCCI engines have higher thermal efficiency than SI and CI engines of similar displacement, while particulate matter (PM) and oxides of nitrogen (NO_x) emissions are extremely low in these types of engines [2].

Fuel autoignition takes place through the compression due to increased pressure and temperature history. 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 [3]. Diluted mixtures are needed in HCCI engine to keep the pressure rise rates at acceptable levels due to high combustion rate [4].

In general the merits of HCCI engine are:

- Using very lean mixture (high diluted) in HCCI engine makes it as low fuel consumption engine [5].
- Using the diluted mixture in HCCI engine makes it having low combustion chambers temperature and keep temperature combustion down which results in decreasing the amount of NO_x and PM during HCCI engine running [6].
- 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 [7].
- 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 [8].

On the other hand the demerits of HCCI combustion:

- 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 [9].
- 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 [10].
- HC and CO emissions are typically higher in HCCI than that of diesel engines due to low temperature combustion [11] but CO and HC emissions can be decreased by using an oxidation catalytic converter in HCCI engine.
- Cold start is the main problem for HCCI engine and this problem is recently weakened by using a dual mode SI-HCCI [12] or CI-HCCI [13] technique where the engine starts in the SI/CI mode for engine warm up.

Based on the findings made, HCCI is an engine that could be controlled kinetically by ignition and combustion of the air-fuel mixture. Temperature and pressure history of the mixture and chemical kinetic properties of the fuel play important roles for ignition of the air-fuel mixture. The

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following physical parameters will change the in-cylinder temperature and pressure which consequently affect ignition timing and combustion of the air-fuel mixture [2]:

- Initial intake temperature (T_{in})
- Air-fuel equivalence ratio (Φ)
- Exhaust gas recirculation (EGR) fraction
- Fuel octane number (ON)
- Initial intake pressure (P_{in})
- Compression ratio (CR)

HCCI combustion takes place by increasing the in-cylinder temperature, pressure or their combination during the compression stroke. Changing autoignition properties of the fuel and air-fuel ratio (AFR) can be the best way to control HCCI engine.

To control the HCCI engine, some investigations have been conducted by researchers that used variable valve timing (VVT) [14], [15], variable compression ratio (VCR) [16]-[18], variable exhaust gas recirculation (EGR) and variable octane number (dual fuel control) [19].

The main objective of this study is to obtain a literature review for ethanol fuelled HCCI engine. The outcome of this study can be used to understand ethanol fuelled HCCI combustion in greater detail.

II. USE OF ETHANOL IN ICEs

When the temperature of the air-fuel mixture in the combustion chamber reaches fuel ignition temperature, autoignition occurs in the cylinder and generates power. The fuel's autoignition reactivity is one of the most important parameter that affects HCCI combustion characteristics. The fuels with high octane number (high resistance to autoignition) need higher mixture temperatures during the compression stroke [20] while the fuels with low octane number (low resistance to autoignition) require lower mixture temperatures during the compression stroke to avoid engine knock in HCCI engine. All fuels have different ignition temperature and they can mix together to deal with changing ignition temperatures. In this study ethanol was chosen as reference fuel.

One of the most promising alternative fuels identified as a substitute in gasoline is ethanol. Ethanol or more precisely bioethanol is typically synthesized from biomass residue through fermentation techniques. Due to presence of oxygen, this fuel is able to mix and combust well with a high rate of combustion efficiency. As a result of this feature, it is also predicted to reduce exhaust pollutants, i.e. CO, NO_x and HCs, when used in conventional gasoline and diesel engines.

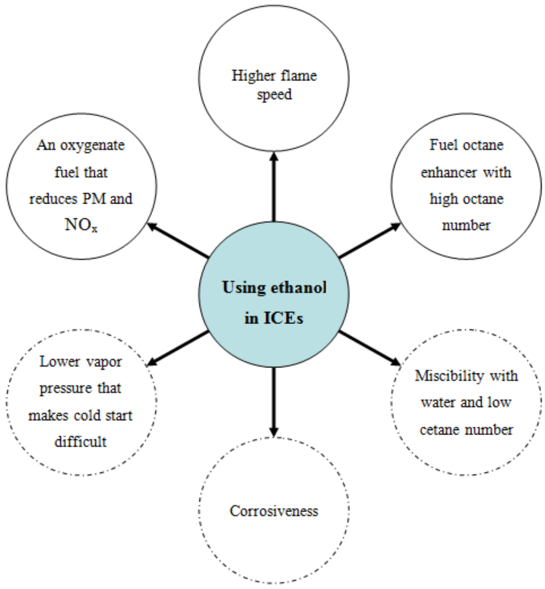

Fig. 1 Major benefits (solid circles) and disadvantages (dashed circles) pertinent to using ethanol in ICEs

Having a large palm oil yield makes Malaysia one of the most important countries for the production of ethanol fuel in the world. One of the planned shifts in Malaysia is bioethanol production from lingo cellulosic waste of palm oil. Lack of knowledge and insufficient researches are the biggest challenges that will prevent the country from moving forward in the technology in terms of development of automobile industry and HCCI engines [21].

Ethanol can be burned in ICEs as an alternative for gasoline which is produced from biomass. The similarity of ethanol to gasoline can be considered in many aspects in contrast to hydrogen and electric energy. There are many plans to use biomass-based fuels in combination with fossil fuels in automobiles using present technology with some modifications [22].

Fig. 1 shows the advantages and disadvantages of using ethanol in ICEs.

Ethanol is the most common alternative fuel for gasoline in ICEs. Original engine factories have developed the ability to run an engine with gasoline and ethanol blends as flexible fuel vehicles (FFV) and gasoline engines are capable of running on gasoline up to 100% ethanol with electronic control unit (ECU) calibration changes [23].

A. Literature of Ethanol Fuelled HCCI Engine

A HCCI engine fuelled with ethanol is a new and promising concept currently being explored by engine researchers as the next-generation of ICEs. Most researches conducted between 1997 and 2006 sought to improve ethanol fuel HCCI engines by employing supercharging technology, fuel reforming, residual gas trapping, valve timing and force induction.

Christensen et al. did the first study on ethanol fuelled HCCI engine and showed ethanol is a good alternative as a gasoline fuel replacement. In this study, HCCI engine was operated unthrottled with very lean mixture, generating no NO_x emission [24].

Christensen et al. used supercharger to boost pressure in HCCI engine. The results showed that achieving more IMEP for HCCI is noticeably related to application of a supercharger. Boosting pressure reduces HC emission while NO_x values drop. They showed that the main benefit of HCCI is the low level of exhaust NO_x emission [25].

Ng and Thomson investigated the effect of fuel reforming and EGR on HCCI operation by using a single zone reactor model and reaction mechanisms. They applied hydrogen and CO for reforming which widened the operating range of HCCI engine. Hydrogen can be used as additive due to its wide flammability limits. The results showed that EGR was more effective than reforming in widening the operating range. Moreover, reforming was practical in HCCI combustion to maintain complete combustion at lower intake temperature (T_{in}) [26].

Yap et al. studied internal residual gas trapping in a naturally aspirated HCCI engine. Residual gas trapping was used with internal trapping of exhaust gas to lower the thermal energy requirements for the autoignition of the air-fuel mixture. Moderate T_{in} extends the engine operation range of bioethanol fuelled HCCI engine. The NO_x emissions were reported as low due to the nature of homogeneous combustion.

They also reported that high pressure rise rates (at higher AFR) are the reason HCCI operations are limited. The application of intake air preheating with internal trapping of exhaust gas improves the liquid fuel evaporation [27].

Yap et al. extended their work using forced induction in conjunction with residual gas trapping and showed that the usable operation range of bioethanol fuelled HCCI could be increased effectively by using forced induction and trapping of residual gas. Combustion phasing could be controlled by boost. An increase in trapped residuals gas could lower the maximum possible load at given boost pressure. Using increased trapped residuals gas with higher boosting pressure make NO_x emission levels lower. However CO emissions increased due to increased pumping losses [28].

Zhang et al. used a SI Ricardo engine with valve timing approach. Varying the amount of trapped residuals was investigated at different AFRs, speeds and valve timings for HCCI engine fuelled with ethanol. They showed that valve timing and lambda had great effect on ignition timing and combustion duration. An ETAS linear oxygen sensor was used to determine lambda and in all the experiments the effect of valve timing was investigated in comparison with indicated mean effective pressure (IMEP), residual and speed. They showed that the operation range of HCCI engine fuelled with ethanol is limited to knock and misfire and that it could be expanded using the valve timing approach [29].

After the work done to improve HCCI operation, investigation has shifted toward adding fuel to ethanol and testing fuel flexibility of this fuel. Adding di-tertiary butyl peroxide to the net ethanol and diethyl ether (DEE) as combustion timing advancer was investigated by Mack et al. using engine experiments and numerical modeling. They found that adding DEE-in-ethanol mixture has a greater advance effect on combustion than pure ethanol [30].

Mack et al. also added diethyl ether (DEE) to pure ethanol (EtOH). They investigated whether pure ethanol is less reactive than diethyl ether in HCCI engines but adding DEE to ethanol had little effect due to elongation of heat release and considerable reduction in T_{in} [31].

Three high octane number fuels (ethanol, methanol and gasoline) were chosen to run the HCCI engine by Xie et al. The camshaft systems were modified with low valve lift to achieve enough temperature for intake mixture by residual gas trapping for stable HCCI engine operation. The results showed that HCCI could operate well with alcohol fuel and produce low NO_x emissions [32].

Gnanam et al. used one four-stroke, three cylinder diesel engine for conversion to a HCCI engine and selected two fuels (ethanol, iso-octane) for their experiment. They studied the effect of these fuels on HCCI combustion and operation. In this investigation they found that adding iso-octane to ethanol retards the on-set combustion and consequently IMEP and thermal efficiency decreased. They also showed that increasing the T_{in}, advanced the start of combustion [33].

Due to high peak pressure rise rate of HCCI engine at high load and higher boost pressures, several investigations were done to mitigate this problem by adding water to ethanol. Wet ethanol (ethanol-in-water) was used in HCCI engine by Flowers et al. and they examined the ethanol-water blend for HCCI. They showed that HCCI engine can operate on wet ethanol with mixture of 35% ethanol and 65% water (by volume) with high efficiency and low knock. Due to higher amounts of HC and CO, exhaust after-treatment is required such as oxidizing catalytic converter [34].

Megaritis et al. studied the effects of water blending as a combustion control method. They showed that water blending could reduce the rates of in-cylinder pressure rise during bioethanol fuelled HCCI combustion by trapping residual gas and forced induction. With lower concentrations of water in bioethanol, the effect of combustion becomes low but increasing water content up to 20% leads to a sharp decrease in the available HCCI operation range and lambda required for ignition of the air-fuel mixture [35].

Megaritiset et al. showed that with varying inlet valve events and blending of ethanol and water, the maximum rates of pressure rise could be reduced during HCCI combustion. They found that higher NO_x emission is generated in lower amounts of dilution (trapped gas) due to a considerably retarded or advanced inlet valve event for stable combustion. Lower water content in ethanol blend had a lower effect on ethanol combustion. But increasing the amount of water content up to 20% played an important role in reducing load range and in that case less lambda was required for combustion [36].

Several models for understanding ethanol fuel HCCI engine were developed from 2008 to 2009. Model-based control of six-cylinder HCCI engine by in-cylinder pressure feedback was developed by Blom et al. [10]. This HCCI model featured cylinder wall temperature dynamics compared with previous HCCI model [37]. They examined one simple physical model for the aim of thermodynamic description and chemical interactions of the HCCI engine.

Szybist (2008) studied the effect of EGR on HCCI combustion with negative valve overlap (NVO) approach numerically using CHEMKINPRO software. N-heptane, isooctane, ethanol, and toluene were chosen as fuel with well-established kinetic models. It was found that with increasing O_2 concentration in the air-fuel mixture (higher stoichiometric ratio); SOC advanced for n-heptane, iso-octane, and toluene but ethanol was not advanced. Using EGR which contains hot CO_2 and H_2O could advance SOC in HCCI combustion by suppressing the compression temperature [38].

An accurate multidimensional CFD model was developed by Viggiano et al. (2009) to simulate an ethanol HCCI engine. They used kinetic mechanism with 235 reactions and 43 chemical species. In this study the turbulent flow model coupled with a detailed kinetic mechanism. The effects of T_{in}, turbulent diffusivity and wall temperature were comparable with the in-cylinder pressure, heat release rate and engine efficiency. For both wall temperature and mixture initial temperature, similar effects were observed on the in-cylinder pressure and rate of heat release. The results showed that with increasing T_{in}, ignition timing could move toward TDC [39].

Combustion chamber geometry plays a critical role in HCCI combustion. Vressner and Johansson (2008) converted one single cylinder Scania D12 diesel engine to operate in HCCI with port fuel injected and ethanol as fuel. They examined the effect of combustion chamber geometry on HCCI performance. They found that HCCI combustion process was related to combustion chamber geometry. Diesel bowl combustion chamber performed well during operation of HCCI engine [40].

Joelsson et al. (2008) studied the effect of piston geometry on flow/turbulence in the cylinder. They used two engines with a quartz and metal piston with bowl type geometry. They showed geometry also affects temperature stratification which plays an important role in autoignition process. Piston in the metal engine has cooling effect more than quartz engine in the same ethanol AFR which results in lower temperature stratification in the metal engine [41].

Several studies were done to explore ethanol combustion characteristics. Mack et al. (2009) ran the HCCI engine on wet ethanol and showed that HCCI operation was more stable for ethanol blended with 40% water. Using higher water concentrations could extend HCCI operation range at higher T_{in}. The results showed that an increase in water concentration could reduce the maximum value of the heat release profiles and maximum in-cylinder pressures while HC and CO emissions had a tendency to increase [42].

Maurya and Agarwal (2009) studied effect of T_{in} and AFR on combustion parameters and emissions in HCCI engine. They found that the AFR and T_{in} had important effects on the maximum in-cylinder pressure, maximum pressure rise rate and the rate of heat release. The results also showed low level of NO_x emissions was generated in HCCI engine [43].

There was no low-temperature heat release (LTHR) in ethanol combustion in HCCI also no force is needed to adjust the T_{in} for changing the engine speed [20].

Sjoberg and Dec (2011) examined ethanol in HCCI engine with using EGR. They showed that ethanol molecule is stable that makes molecule break down prior to the start of combustion point. The autoignition timing of ethanol had lower sensitivity to addition of EGR [44].

Vigiano and Magi (2012) developed a multidimensional numerical model which could be coupled to a kinetic reaction mechanism for oxidation of ethanol and formation of NO_x. They verified this model against experimental data and studied ethanol HCCI combustion. They also analyzed swirl motion and ethanol thermo-physical properties on emissions and operation of the HCCI engine [45].

Saxena et al. (2012) used exhaust heat recovery (EER) in HCCI engine and studied the effect of wet ethanol on a wide range of HCCI stable operating conditions. They found that the best operating conditions for ethanol-water blend HCCI engine could be found with high P_{in} and high Φ [46].

Bahri et al. (2012) modified a single-cylinder, four-stroke, naturally-aspirated, air-cooled, direct injection diesel engine for HCCI operation using ethanol fuel [47]. An artificial misfire was generated for HCCI engine with port fuel injection system. Variations of Kurtosis and Skewness analysis of in-cylinder pressure and crankshaft rotational speed were compared to maximum heat release rate. The results indicate that in misfire cycles, some engine parameters such as IMEP and heat release decrease substantially. Kurtosis and Skewness of in-cylinder pressure is a reliable factor for misfire detection in an HCCI engine and they varied like IMEP during misfire cycles.

Bahri et al. (2013) extended their works and used experimental data from the HCCI engine and investigated the effect of misfire on the ethanol combustion characteristics and HCCI engine operation fuelled with ethanol [48].

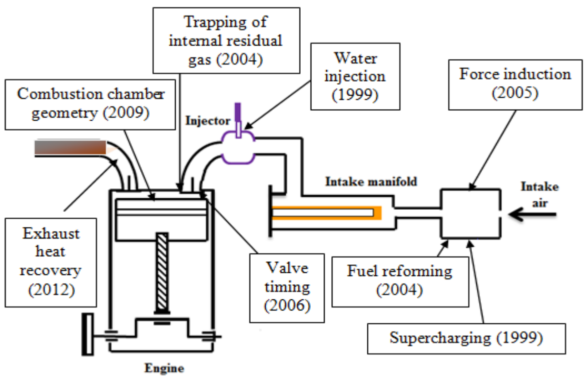

Fig. 2 Literature on HCCI engine fuelled with ethanol

TABLE I
SUMMARY OF IMPORTANT STUDIES ON ETHANOL

	Importance of the topic	**Reference**
1	Supercharging effect	Christensen *et al.* [24]
2	Effect of the fuel reforming	Ng and Thomson [26]
3	Trapping of internal residual gas	Yap *et al.* [27]
4	Forced induction (boosting)	Yap *et al.* [28]
5	Varying valve timing approach	Zhang *et al.* [29]
6	Ethanol fuel flexibility	Gnanam *et al.* [33], Xie *et al.* [32] and Mack *et al.* [30]
7	Ethanol-water blending (Wet ethanol)	Flowers *et al.* [34], Megaritiset *et al.* [35] and Mack *et al.* [42]
8	HCCI engine modeling	Blom *et al.* [10] and Szybist [38]
9	Combustion chamber geometry of HCCI engine	Vressner and Johansson [40] and Joelsson *et al.* [41]
10	Ethanol combustion characteristics	Maurya and Agarwal [43] and Sjoberg and Dec [20]
11	EGR effect on autoignition timing	Sjoberg and Dec [44]
12	Exhaust heat recovery	Saxena *et al.* [46]
13	Analyzing HCCI misfire and model based misfire detection	Bahri *et al.* [48]

They also designed one artificial neural network (ANN) model to detect misfire in the HCCI engine. Below is the list of major findings for the engine studied in that work:

1) Too much delay in CA_{50} leads the engine to operate in partial burn operation with many misfire cycles, resulting in a dramatic increase in exhaust HC and CO concentrations.
2) Ethanol HCCI combustion is very sensitive to the amount of Φ. Periodic variation in HCCI combustion metrics (SOC and CA_{50}) is observed as a result of a periodic fluctuation in the engine fueling.
3) Since MHRR is well correlated with IMEP and HCCI misfire, it offers a good potential to distinguish between misfire and normal cycles.
4) Cyclic SOC, CA_{50}, CA_{Pmax}, CA_{MHRR} and $CA_{maximum;dp/d\theta}$ are not strongly correlated with MHRR and they are not effective for HCCI misfire detection. But in-cylinder pressure at 5°, 10°, 15° and 20° CAD aTDC exhibit a strong correlation with MHRR and they can be potentially used to detect HCCI misfire.
5) The new ANN misfire detection (AMD) model was verified with experimental data including with a wide range of misfire and normal cyclic data. For the 7800 cyclic data tested, the AMD can detect misfire with an accuracy of 100%. The AMD can potentially be used to determine engine variables leading to misfire as the model could successfully detect the onset of misfire appearance when moving from a normal to a misfire HCCI region.

Table I shows a brief list of important literature for ethanol fuelled HCCI engine. It can be seen that several researchers have studied this engine.

As can be seen in Fig. 2 and Table I, the HCCI researches and investigations have shifted from intake and fuel preparing systems towards exhaust manifold and emission reduction.

III. CONCLUSIONS

A literature study and some background information were presented to highlight the advantages and drawbacks of using ethanol fuelled HCCI. Although many researchers proposed different HCCI testing methods with ethanol as reviewed in this article, there are still challenges remaining before utilization of ethanol HCCI engines can go into mass production. Ethanol fuelled HCCI engine is more difficult to control than other popular modern combustion engines. It is need to develop control methods for HCCI engines in order to overcome the challenge of maintaining proper ignition timing. This article attempts to find the research gap and to examine ways of answering research questions from previous activities about HCCI.

NOMENCLATURE

Φ	fuel-air equivalence ratio
AFR	air fuel ratio
AMD	ANN misfire detection
ANN	artificial neural network
CAD	crank angle degree
CFD	computational fluid dynamic
CI	compression ignition
CO	carbon monoxide
CR	compression ratio
DEE	diethyl ether
HC	Hydrocarbon
HCCI	homogeneous charge compression ignition
ECU	electronic control unit
EGR	exhaust gas recirculation
FFV	flexible fuel vehicle
ICE	internal combustion engine
IMEP	indicated mean effective pressure
NO_x	nitrogen oxides
NVO	negative valve overlap
ON	octane number
P_{in}	intake pressure
PM	particulate matter
SI	spark ignition
SOC	start of combustion
T_{in}	intake temperature
VCR	variable compression ratio
VVT	variable valve timing

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