Chapter 2

Literature Review

2.1 Introduction

This section summarizes relevant researches have done on diesel engine with an overview of the characteristics of alternative fuels used diesel engine. The combustion, performance and emissions behaviour of different fuels fuelled conventional diesel engine are also included in this chapter. In addition, the reason for high NOx and smoke emissions from the conventional diesel engine are also explained. The second portion of the literature review involves an overview of HCCI mode engine. It includes advantages and challenges of the HCCI mode engine and reviews the methods, which are used for preparing the homogeneous charge and control the combustion process. The information observed from the many literatures, which is used to understand the concept of HCCI mode engine.

2.2. Compression Ignition Engine

2.2.1 Biodiesel fuelled

2.2.1.1 Non-edible Biodiesel

Murugan et al. (2013) investigated the performance and emission characteristics of tyre pyrolysis oil and it was blended with Jatropha Methyl Ester (JME) with five different blends by varying TPO, from 10% to 50% at steps of 10% on a volume basis. From the results, it is found that the CO, HC and smoke emissions were lower by about 9.09%, 8.6% and 26% respectively for JMETPO20, compared to
diesel at full load. Nitric oxide emission was higher by about 24% for JMETPO20, compared with diesel at full load.

Mohamed Shehata (2013) studied performance, combustion and emission characteristics of cottonseed oil, palm oil and flax oil fuelled diesel engine. The test were carried out for investigating the effect of biodiesel fuels on diesel engine. The results have shown that the biodiesel-fuelled engine has lower brake thermal efficiency and higher BSFC due to lower calorific value and high mass of fuel burning per cycle. The biodiesel fuel decreased CO emissions due to high O₂ concentration in fuel molecule. The NOx emissions from biodiesel-fuelled engine have increased due to high cetane number.

The Effect of Karanja biodiesel and its blends on a direct injection compression ignition (DICI) engine was analysed by Avinash Kumar Agarwal et al. (2013) with varying the engine speed and load. The results indicated that maximum torque attained by 10% and 20% KOME blends were higher than the mineral diesel, while higher biodiesel blends produced slightly lower torque. The BSFC for lower KOME blends were lower comparable to mineral diesel. However, BSFC increased for higher biodiesel blends. BSCO, BSHC and smoke emission of Karanja biodiesel blends were lower than mineral diesel, but BSNOx emissions were slightly higher.

Subramanian et al. (2014) studied the effect of different biodiesel–diesel blends (B5, B10, B15, B20, B25, B50 and B100) on combustion, performance and emissions characteristics of a diesel engine. The authors concluded that the ignition delay period was decreased with all biodiesel blends due to higher cetane number. Carbon monoxide (CO), hydrocarbon (HC) and smoke emissions were decreased with all biodiesel–diesel blends. However, oxides of nitrogen (NOx) emission increased in
the range of 1.4–22.8% with all biodiesel–diesel blends at rated load due to oxygenated fuel, automatic advance in dynamic injection timing (DIT), higher penetration and higher in-cylinder temperature.

Srithar et al. (2014) conducted a research on compression ignition engine, where the engine operated using pongamia pinnata oil, mustard oil and they were blended with diesel at various mixing ratios. The effect of dual biodiesel on engine performance and exhaust emissions were examined in a single cylinder, direct injection, air-cooled and high-speed diesel engine at various engine loads with constant engine speed of 3000 rpm. From the results, it was observed that the brake thermal efficiency was found to be higher than the diesel. The emissions of smoke, HC and NOx were higher than that of diesel fuelled compression ignition engine.

Agarwal et al. (2015) investigated the effect of fuel injection pressure and injection timing on combustion and emission characteristics of karanja biodiesel fuelled compression ignition engine. The tests were evaluated at different injection pressures such as 300, 500, 750 and 1000 bar at different start of injection timings and constant engine speed of 1500 rpm. The duration of fuel injection was slightly decreased with increasing blend ratio of biodiesel (Karanja Oil Methyl Ester: KOME) and significantly decreased with increasing fuel injection pressure. Increasing fuel injection pressure has improved the thermal efficiency of the tested fuels. Lower Karanja biodiesel blends (up to 20%) showed lower BSHC and BSCO emissions in comparison to mineral diesel.
2.2.2.2 Waste Cooking Oil (WCO)

Yang et al. (2013) experimentally evaluated the performance, combustion and emission characteristics of pure biodiesel (waste cooking oil) and its blended fuels fuelled conventional mode diesel engine (CI). The results showed that the biodiesel/blended fuels operated engine has resulted higher brake specific fuel consumption, especially at low engine speed and partial load conditions. The brake thermal efficiency of biodiesel was found to be slightly higher compared to diesel at 50% and 100% load and the opposite trend was observed at 25% load. With respect to emissions, a slight reduction in the major emissions such as HC and NOx were observed with the use of biodiesel.

Jinlin Xue et al. (2013) produced biodiesel from waste edible oils (WEO), such as waste cooking oils and frying oils respectively, and studied their effects on engine performances and emissions characteristics. The use of WEO biodiesel, led to slight difference in combustion characteristics such as ignition delay, rate of pressure rise, peak pressure and heat release rate. The substantial reduction in PM, HC and CO emissions accompanying with the imperceptible power loss, the increased in fuel consumption and NOx emission on conventional diesel engines with nor fewer modification, compared to diesel fuelled compression ignition engine.

H. Sanli et al. (2015) produced biodiesel from waste frying oil and used as a fuel in a direct injection (DI) diesel engine with neat and 20% (v/v) blend with petroleum-based diesel fuel (PBDF). The tests were performed at constant load of 600 Nm and three different engine speeds (1100, 1400 and 1700 rpm). The results showed that the brake specific fuel consumption of ester fuels were higher than the diesel. The BSFC of ethyl ester biodiesel was slightly lower as compared with methyl
ester biodiesel. *The thermal efficiencies of the ester fuels were higher than those of PBDF.* Ethyl ester biodiesel had slightly better thermal efficiency than methyl ester biodiesel. In comparison to PBDF, ester fuels have emitted less CO and THC emissions, but they caused to produce more NOx, CO₂ emissions.

### 2.2.1.3 Animal Fat oil (AFO)

*Carmen C. Barrios et al.* (2013) evaluated the influence of animal fat based biodiesel and diesel blends on conventional diesel engine and compared with pure diesel and soybean biodiesel blends fuelled diesel engine. The tests were conducted using 6 animals fat based blends of animal fat based biodiesel/diesel and soybean biodiesel/diesel in different proportions B10 (10% biodiesel and 90% pure diesel fuel), B20, B25, B30, B40, B50 and D100 (pure diesel). Experimental results shown that the nitrogen oxides emission was increased compared to pure diesel fuelled engine.

*Rasim et al.* (2014) used FOME (Fish Oil Methyl Ester) and COME (Cooking Oil Methyl Ester) in a diesel test engine. According to the test results, it was observed that the fish oil based fuel has better performance and exhaust emission parameters than those of cooking oil. The *brake specific fuel consumption of methyl ester fuels have increased* up to 5.69% compared to diesel fuel. However, *HC and CO emissions were reduced compared to the diesel fuel was found to be around 16.24% and 19.81%, respectively. However, the level of NOx emissions was increased.*

*Rasim Behcent et al.* (2014) compared the exhaust emissions from two different biodiesel such as fish and chicken waste oil and their blends. The each methyl esters were blended with the commercial diesel fuel with a ratio of 20% on volume basis. According to the test results, it was observed that the *brake power,
torque values, carbon monoxide (CO), un-burnt hydrocarbon (UHC) and carbon dioxide (CO₂) concentrations of blended fuels were decreased. The NOx concentration and brake specific fuel consumption (BSFC) values were increased compared to diesel fuel.

Mustafa et al. (2015) used animal fat based biodiesels were blended with certain amounts of diesel fuel and bio ethanol. The neat biodiesels, diesel fuel and the blends were tested in a direct injection diesel engine and the engine performance, combustion and emission characteristics were investigated. The engine tests showed that the brake specific fuel consumption of biodiesels were about 16% higher while those of the blends containing 20% bio ethanol were about 15.7% higher than those of diesel fuel on average. According to brake specific emission results, biodiesel emitted lower CO emissions but they emitted higher carbon dioxide (CO₂) and NOx emissions as compared to diesel fuel.

2.3. HCCI Mode Engine

2.3.1 Methods of Homogeneous Charge Preparation

Cinar et al. (2010) analysed the effects of premixed ratio of diethyl ether (DEE) on the combustion and exhaust emissions of a single-cylinder, HCCI-DI engine. The DEE injection was conducted into the intake air charge using low-pressure injector. The premixed fuel ratio (PFR) of DEE was changed from 0% to 40% and results were compared to neat diesel operation. The test result shown that the NOx and soot Emissions were decreased up to 19.4% and 76.1%, respectively, while exhaust gas temperature decreased by 23.8%. On the other hand, CO and HC emissions were increased.
Sudheesh et al. (2010) investigated performance and emission characteristics of homogeneous charge compression ignition (HCCI) engine using biogas as a primary fuel and diethyl ether (DEE) as an ignition improver. The biogas was inducted and DEE was injected on single-cylinder engine. From the results, it was found that the biogas-DEE-HCCI mode showed wider operating load range and higher brake thermal efficiency (BTE) at all loads as compared to those of biogas-diesel dual-fuel and biogas SI modes. The nitric oxide (NO) and smoke emissions were extremely low, and carbon monoxide (CO) emission was below 0.4% by volume at best brake thermal efficiency points.

Dong et al. (2011) studied the fuel stratification for extending the high load limits of homogeneous charge compression ignition (HCCI) combustion. The tests were carried out with a dual-fuel-injection system, a port injector for preparing a homogeneous charge and a direct in-cylinder injector for creating the desired fuel stratification. The result showed that the weak gasoline stratification leaded to an advanced combustion phase and increased in NOx emission.

Qiang et al. (2012) investigated an influence of pilot injection quantity and EGR rates on HCCI-DI engine. The results showed that the NOx emission decreased as the pilot injection quantity increased. However, smoke emission has slightly increased with the rise of pilot quantity, but it was always in a low level. The HCCI-DI combustion with low level of EGR was an effective method for reducing in NOx emission, and smoke emission was increased as increasing the EGR rate.

Jang et al. (2013) analysed operating range of DME fuelled HCCI engine, with different direct injection timing and exhaust gas re-circulation rates. The author has conducted a research on single cylinder engine with using both port fuel injector
and direct injector. The result has shown that, indicated mean effective pressure for direct injection was higher than port injector engine due to late combustion. The exhaust emissions of CO and HC were decreased due to lack of mixing time.

Turkcan et al. (2014) conducted the experimental analysis on the effects of a two-stage direct injection strategy on the HCCI engine fuelled with alcohol–gasoline blends (gasoline, E10, E20, M10 and M20). The results showed that the maximum pressure rise rate (MPRR) increased as an earlier start of the first injection (SOI1) timing by using alcohol–gasoline blends. It was found that the start of second injection (SOI2) timing has strong effects on the HCCI combustion and performance parameters as compared to the SOI1 timing although injection ratio (IR) was changed.

Rakesh Kumar Maurya et al. (2014) experimentally investigated the performance, combustion and emission characteristics of HCCI engine fuelled with ethanol and methanol fuels, and compared it with baseline gasoline fuel. The experiments were conducted on a modified four-cylinder four-stroke engine at different engine speeds using port fuel injection technique for preparing homogeneous charge. The results showed that the methanol and ethanol are good replacements to gasoline fuel in HCCI combustion mode.

Das et al. (2015) investigated the effect of main injection timing on homogeneous charge compression ignition engine. The tests were carried out in a range from 26 to 8 crank angle degrees before top dead centre with an interval of 3deg. From the result, it was observed that the start of combustion depended on fuel air equivalence ratio than main injection timing. From the results, it was observed
that there was an improvement in performance and emissions with marginal loss in thermal efficiency, when the main injection timing was 20° before top dead centre.

2.3.2. Methods of HCCI Combustion Control

Swami et al. (2010) controlled the HCCI-combustion by the intake air temperature, where the inlet air was heated to different temperatures in order to determine the optimum level at every output. Subsequently, exhaust gas recirculation (EGR) was done at the identified charge temperature and brake thermal efficiency was found to improve. Nitric oxide and smoke levels were very low. However, HC levels were high at about 1700–2700 ppm. Brake thermal efficiencies were comparable to or even better than the compression ignition mode of operation.

Fathi et al. (2011) analysed the influence of Exhaust Gas Recirculation (EGR) on combustion and emissions of n-heptane/natural gas fuelled Homogeneous Charge Compression Ignition (HCCI). The results indicated that the applying EGR reduced the mean charge temperature, leading to a retarded Start of Combustion (SOC) and prolonged burn duration. The heat transfer rate was decreased with increasing the EGR additions, under examined condition EGR addition improved fuel economy, reduced NOx emissions and increased HC and CO emissions.

Zhang et al. (2011) analysed the effect of inlet air temperature and excessive air co-efficient on homogeneous charge compression ignition engine (HCCI) fuelled with ethanol, methanol, and gasoline. The results were indicated that the increasing intake temperature significantly increased the in-cylinder peak pressure. The emissions of HC and CO both were decreased and NOx emission for gasoline was slightly increased with the increased of intake temperature.
Qiang Fang et al. (2012) studied the influences of pilot injection and exhaust gas recirculation (EGR) on combustion and emissions in a HCCI-DI combustion engine. The effects of pilot injection quantity and EGR rate on HCCI-DI were investigated. The NOx emission has a dramatically decreased as the pilot injection quantity increased, but it is still in a high level that needs to be reduced. The smoke emission has a slight increased with the rise of pilot quantity, but it is always in a low level. The HCCI-DI combustion with low level of EGR is an effective method to reduce NOx emission further, and smoke emission increases as EGR rate increases. There were optimal EGR rates and pilot quantities to achieve low NOx and low smoke emissions.

Lei et al. (2013) described knocking combustion of diesel fuelled homogeneous charge compression ignition (HCCI) engine. The effects of engine load, speed and internal/external exhaust gas re-circulation (EGR) on the knocking combustion of HCCI engine were experimentally studied. The author resulted that the knocking intensity was increased with increasing the load, speed and internal EGR. However, the external EGR has reduced the knocking density.

Mohamed et al. (2013) investigated the effect of EGR on hydrogen/diesel fuelled HCCI engine. Hydrogen was inducted alone with air by the port fuel injector and diesel was injected into the cylinder using a high-pressure common rail system. The tests were carried out with constant inlet air temperature of 30°C, and varying the diesel fuel injection pressure (3bar, 4bar) and different EGR percentages (0%, 40% and 51%). Finally, author concluded that the exhaust emission of NOx level was decreased for all operating conditions. The level of HC and CO emissions were not significant influenced by the addition of hydrogen.
Agarwal et al. (2013) experimentally investigated the cyclic variation in the HCCI combustion engine operating at different intake air temperatures (120°C to 170°C) and fuel injection quantity at different engine speeds using gasoline like fuels. From the result, observed that the combustion stability improved on increasing intake air temperatures. It was also found that the faster HCCI combustion tended to have smaller cyclic variations in combustion duration. A large deviation from the normal distribution was observed in combustion duration distribution for the knocking and misfire operating conditions.

Saxena et al. (2014) studied the phenomena, which was affecting the combustion of the homogeneous charge compression ignition (HCCI) engine, used a well-mixed fuel/air charge like spark-ignited engines and relied on compression ignition like diesel engine. Similar to diesel engine, the use of high compression ratios and removal of the throttling valve in HCCI allowed for high efficiency operation, thereby allowing lower CO₂ emissions per unit of work delivered by the engine. The use of a highly diluted well-mixed fuel air charge allowed for low emissions of nitrogen oxides, soot and particulate matters.

Ming et al. (2015) investigated the performance and emissions characteristics of n-butanol fuelled HCCI combustion with high compression ratio. The results were indicated that n-butanol fuelled HCCI combustion had ultra-low NOx and smoke emissions with minimal requirement for intake dilution through exhaust gas recirculation. At higher engine loads, both boost and EGR were required to limit the high pressure rise rates and to modulate the combustion phasing for high thermal efficiency.
Ahmet Uyumaz. (2015) determined the effects of pure n-heptane, the blends of n-heptane and n-butanol fuels B20, B30, B40 and the blends of n-heptane and isopropanol fuels P20, P30, P40 on HCCI combustion. The inlet air temperature was used to control HCCI combustion and the effect of air temperature was also examined. Test results showed that the HCCI combustion was advanced with the increase of inlet air temperature. However, NO emissions were only measured as 1 and 2 ppm with B20 and n-heptane at high inlet air temperatures due to knocking. In addition, higher HC emissions were obtained especially at lower inlet air temperature.

Can et al. (2015) analysed the effect of intake air temperature on a HCCI-gasoline engine fuelled with the blends of 20% n-heptane and 80% iso-octane fuels. The experimental investigations were carried out with various air temperature varied from 40°C to 120°C. The results showed that in-cylinder pressure and heat release rate were increased with the increase of intake air temperature. Increased intake air temperature caused combustion too advanced and decreased the combustion duration. It was also found that CO and HC emissions firstly increased and then started to decrease after the 90°C intake air temperature.

Mao-Bin et al. (2015) analysed the effect of air dilution and compression ratio on the homogeneous charge compression ignition (HCCI) engine fuelled with n-butanol. The results showed that air dilution and decreased in ECR could retard the auto-ignition timing and effectively decreased the MPRR (maximum pressure rise rate) of the HCCI engine.
2.4. Fuels Used in HCCI Engine

Ganesh et al. (2010) studied the performance and emissions behaviour of Homogeneous charge compression ignition (HCCI) engine fuelled by diesel fuel with external mixture formation. A fuel vaporiser was used to achieve excellent HCCI combustion in a single cylinder air-cooled direct injection diesel engine. In this study, a vaporized diesel fuel was mixed with air, forms a homogeneous mixture and inducted into the cylinder during the intake stroke. Experiments were conducted with diesel vapour induction without EGR and diesel vapour induction with 10%, 20% and 30% EGR, and the results were compared with those of conventional diesel fuel operation (DI at 23° BTDC and 200 bar injection pressure).

Horng et al. (2011) investigated the combustion and emissions characteristics of partial homogeneous charge compression ignition (HCCI) engine by injecting gasoline and ethanol into the intake port and diesel fuel injected at in-cylinder. From the results, it was observed that the addition of auxiliary fuels into the intake port of a diesel engine has decreased exhaust emissions; in particular, smoke and nitrogen oxides under various engine speeds and loads. The decreased in exhaust emissions were more pronounced for premixed ethanol than for premixed gasoline.

Bang et al. (2013) conducted the experimental investigation on a single cylinder port fuel injection four-stroke HCCI-CAI engine fuelled with gasoline, n-butanol, and their blends of 30% n-butanol and 70% gasoline by volume. The tests were carried out at different inlet-exhaust cam lift and different exhaust valve closing time at two-engine load. From this research, author concluded that the auto ignition timing was advanced with the addition of n-butanol due to high cetane number. From
the result, observed that the exhaust emissions were decreased, if increasing the rate of mixture dilution.

Teoh et al. (2014) used kerosene and analysed the impact of premixed kerosene on performance, emission and combustion characteristics of partial homogeneous charge compression ignition engine (HCCI). In this study, partial HCCI engine was achieved by injecting kerosene fuel into the intake port and small amount of diesel was used to start the combustion process. From the heat release rate profile, it was observed that, two-stage and three-stage ignition occurred in some of the cases. In addition, the increase of premixed ratio to some extent significantly reduced nitric oxide (NO) emissions.

Maurya et al. (2014) experimentally investigated the performance, combustion and emissions characteristics of HCCI engine fuelled with ethanol and methanol fuels. The experiments were conducted on a modified four-cylinder, four-stroke engine at different engine speeds using port fuel injection technique for preparing homogeneous charge. To achieve auto-ignition of air–fuel mixture in the combustion chamber, intake air pre-heater was used. Results showed that methanol and ethanol are good replacements to gasoline in HCCI combustion mode.