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AN EXPERIMENTAL STUDY OF THE PERFORMANCE OF A HOMOGENEOUS CHARGE COMPRESSION IGNITION (HCCI) ENGINE FUELED WITH PALM OIL BASED BIODIESEL

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The study of palm oil-based biodiesel, which is widely available in tropical climate countries, in HCCI engines are being focuses. A single cylinder diesel engine with a port fuel injector and heated intake air were used to operate the HCCI engine at 2700 rpm using palm oil-based biodiesel. The fuels used in this study are diesel and palm oil-based biodiesel with four different blends of 5%, 10%, 15%, and 20% (POB5, POB10, POB15, and POB20, respectively). The parameters varied for the study were different lambdas, λ of 3.1, 2.9, 2.6, 2.4 and intake air temperature of 70, 80, and 90°C. When using diesel fuel on HCCI mode, it is found that the engine power, torque, and BTE are lower and fuel consumption is higher compared to conventional Compression Ignition Direct Injection (CIDI) mode. The in-cylinder pressure pattern for HCCI mode shows that the combustion is advanced, and the in-cylinder pressure peak is higher at rich mixture compared to CIDI mode. The in-cylinder pressure decreases in the case of higher amount of biodiesel. Combustion intensity for biodiesel fuel is lower, which affects the heat release rate, whereas a high intake temperature triggers the combustion easily, enhances the fuel mixture auto-ignition proses. Increasing the amount of biodiesel will increase the NOx emissions insignificantly, however it is still lower than that of CIDI. This is due to the fact that there are more oxygen contents in biodiesel. The emissions of HC and CO were reportedly higher in many literatures when the engine operates in HCCI mode. The same pattern occurred in this study, where the emissions of HC and CO were higher than that of CIDI mode. However, it was found that, the HC and CO were improved (decreased) in HCCI mode when increasing the POB content, and so with the CO2. This means that POB based biodiesel improved the emissions of HCCI engines. Therefore, it can be concluded that palm oil biodiesel is the future potential to be used as a replacement to the conventional diesel in HCCI engine, as it provides an alternative way to reduce the dependency on fossil fuel, thus decreasing the percentage of emission levels.

1. Introduction

The major contributor in worldwide oil consumptions is the transportation sector. The oil reserves depleted at an alarming rate, while the consumption shows a high growth rate. If oil discovery and consumption are at the current trends, the world oil resource will be used up by

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2038 [1]. The concerns on energy efficiency and toxic emissions such as NOx and PM lead to a worldwide study in improving the internal combustion engines that are able to achieve a higher energy efficiency and lower emissions levels. HCCI is a hybrid technology of compression ignition (CI) and sparks ignition (SI) operations. HCCI engine operation is able to maintain fuel efficiency relatively the same as compared to that of compression ignition direct injection (CIDI) engine, but the NOx and PM emissions are reduced [2], [3]. HCCI engines are part of the low-temperature combustion (LTC) technologies that are widely investigated worldwide. Low emission engines with relatively higher combustion efficiency are achieved when the engine is operated in the region of low equivalence ratio. Therefore, lean combustion engines have low heat release temperature, hence becoming the main factor in reducing the emission levels [4]. The homogeneous mixture can reduce the formation of particulates because of the low existence of rich mixture regions, whereas compressing the mixture until ignition reduces the rise in-cylinder temperature, and hence reduces the NOx formation [5]. Furthermore, HCCI engines are known to be operated with different types of fuels. Biodiesel is considered as an environmentally friendly and sustainable alternative to fossil fuels and can be operated in HCCI mode. The following are the characteristic of HCCI combustion [6]–[8].

- Ignition occurs simultaneously at numerous locations within the combustion chambers.
- The ignition can occur with using external event such as with the aid of PFI, EGR etc.
- Fuel can be used either lean or rich.
- Mixture is lean most of the time
- More than one of the fuels can be used.
- High compression ratio (CR) can be used.

HCCI combustion can be achieved with various methods such as exhaust gas recirculation (EGR), port fuel injector (PFI), variable valve timing (VVT), variable compression ratio (VCR), late and early direct injection. In this study we used PFI. Peng, Zhao and Ladommatos [9], conducted an experiment on HCCI engine using premixed n-heptane/air/EGR mixture by a PFI. It was reported that SOC is retarded with increase in EGR rate. However, Kim and Lee [10] used cooled EGR on HCCI engine, in which the premixed fuel is supplied via a port fuel injection system located in the intake port of DI diesel engine. The application of cooled EGR can suppress the advanced and sharp combustion at high inlet temperatures. Despite the reduction of NOx, there are some concerns limiting the amount of EGR rate because high soot concentration may be deposited on the cylinder wall and this will lead to inefficient combustion. The major benefits of late direct fuel injection technique is that mixture combustion is controlled by the injection timing, which is unlike the PFI and the early direct injection techniques. Electronic port fuel injector also was used to achieve HCCI mode. The use of the PFI is good for fuel vaporization when entering the combustion chamber [15]. Wu et al. [16] used the earliest premixed/direct injected system for HCCI operation. In this system, most of the fuel was injected into the intake manifold to form a homogeneous charge and premixed charge was injected with a small amount of fuel directly injected into the cylinder. This system can reduce both NOx and smoke emissions better than a conventional diesel engine. Also, Pedrozo and Zhao [17] used dual fuel system, where diesel acts as the main injector and ethanol fuelled supplied through PFI, which form premixed fuel showed better trade-off combustion and improved NOx emission.

Biodiesel can be considered as feasible alternative substitution fuel for diesel engine with little or without any modification up to 20% biodiesel blend [18]. HCCI engine creates a homogeneous mixture during the suction of air into the chamber and takes complete combustion with the benefit of oxygen content inside the biodiesel fuel [19]. Although the properties of each biodiesel come from different sources, so that the manifold injection system need to gives enough mixing time for biodiesel fuel and air to forms a homogeneous mixture [20]. In the meantime, the study on HCCI engine using vegetable oil has also been used such as pine oil [21], hone oil methyl ester [22], and rapeseed methyl ester [23], Jatropha oil is one of the edible oils and successfully operated on HCCI engine as reported by Ganesh, Nagarajan and Ganesan [24]. Jeon and Park [25] investigated the effects of soybean biodiesel on an AVL 5402 single-cylinder research engine equipped with a common rail injection system was used with various pilot injection timing and quantity. At a high combustion temperature, it was found that biodiesel combustion generated low concentrations of soot compared to neat diesel. Also, a study by How et al. [26] using three types of different injection; single, double, and triple injection fuelled with B20 and B50 coconut-based biodiesel reported that the SOI timing is affected with reduced emission level of NOx to below 100 ppm. Gajendra, Akhilendra, and Avinash [27] used a modified two-cylinder engine, in which, one cylinder was operated in HCCI mode while the other was operated in conventional CI mode. They used PFI to achieve HCCI combustion and fuelled with biodiesel (B20 and B40). The results indicated a stable combustion but reduced power output for HCCI in biodiesel compared to diesel, due to low peak heat release rate for biodiesel. The emission of NOx showed a significant reduction although CO, HC and smoke were increased when more biodiesel was added. Maurya and Agarwal [28] investigated biodiesel-fuelled HCCI combustion using port fuel injector incorporated fuelled with ethanol. The study was carried out on a modified two-cylinder, four-stroke engine. The inlet temperature was varied with different λ (mixture formation). Combustion results were more stable for biodiesel HCCI than the diesel HCCI due to a lower rate of heat release for biodiesel. Milovanovic et al. [11] studied a single-zone combustion model with convective heat transfer loss used to simulate the HCCI engine using n-heptane, dimethyl ether and biodiesel (methyl-butanoate and methyl-formate) fuels. The results showed that biodiesels are in better control of the combustion process when compared with that of the n-heptane and dimethyl ether. Because HCCI engines are fully controlled by chemical kinetics, it is important to study the fuel's properties. Different fuels will have different properties such as cetane number, autoignition temperature etc. The experiment by Huang et al. [21] on pine oil at different blends and compared to diesel fuel found that the biodiesel fuels have lower BSFC compared to diesel fuel. As the load increased, BSFC reduced and at a certain load. Meanwhile, when canola methyl ester biodiesel used as a fuel in HCCI mode engine, it consuming the minimum amount of fuel and produces the same energy as biodiesel fuelled DI diesel engine. HCCI engine creates a homogeneous mixture during the suction of air into the chamber and takes complete combustion with the benefit of oxygen content inside the biodiesel fuel [19].

The main objective of this study is to experimentally investigate the performance and emissions levels of an HCCI engine fuelled with palm oil-based biodiesel. The specific objectives are to: 1) analyse the performance (brake power, torque, BMEP, BSFC and BTE) of an HCCI engine using palm oil-based biodiesel, 2) investigate the combustion behaviour (in-cylinder pressure, heat release rate) of HCCI engine fuelled with palm oil-based biodiesel, 3) evaluate the emissions levels (CO, CO2, NOx, UHC) of palm oil-based biodiesel in HCCI engine. The first section of the paper mostly explains on the research gap of the study. The problem statement, previous study and objective of the study also include in this section. The second section explain the method used during the experiment. Lastly, the third section, elaborates and discusses the result from the experiment.

2. Method of experiment

2.1 Apparatus of experiment

The modification of the existing engine to operate in HCCI mode requires major changes in the air intake system. The easiest option to convert CI engine to HCCI mode is by using the air intake heater port and installation of a port fuel injector (PFI). The modified air intake system requires electric heater installed. Preheating system is one of the control techniques to control the combustion in HCCI mode engine. The installation of the electric heater is to preheat the intake air temperature to switch to HCCI mode. The intake manifold was modified to accommodate the heater pipe. The heater operation ranges from 250°C to 650°C with input power of 2000 W. In order to achieve mist fuel spraying pattern, a high pressure 200 bar injector was used as PFI. A metal block was fabricated to hold the injector at the intake section of the engine. The PFI injector was connected on the same fuel pipeline of DI. This enables the PFI injector mechanism to work simultaneously with DI injector (HCCI-DI). The engine able to operate in either DI and PFI systems (HCCI). That is what necessitates the use of a combination of engine and electronic computer unit (ECU). The wiring attached on the PFI connected directly with the ECU to control fuel injection. The PFI injector mechanism can give an opening signal of fuel quantity (pulse width) up to 6.0 ms. The use of an ECU is to control the fuel injection rate for precise fuel-air mixing. The ECU used in the study was a commercial type for motorbikes or any small size engines and can be re-programmed to suit the specific engine. The ECU has been pre-programmed according to the engine specification. The ECU system uses these conditions to calculate timed outputs for engine's injections and ignition timings. Injection timing (EOI) is determined via a look-up table based on the engine speed (RPM). Ignition timing (IGN) is

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determined via a look-up table based on engine speed and throttle position. The main function of the ECU program was to control time and give signal of when to inject the fuel. Injector opening time is the Pulse width (PW) signal and will determine how much fuel is injected. Tmchi RVV rv2.2 is a software to configure the HC V5A ECU. It runs under the Windows OS and communicates with the ECU via a USB cable and *comm* adaptor board. The data which can be displayed include the engine speed (RPM), manifold absolute pressure (MAP), a throttle position sensor (TPS), engine temperature (ET) and fuel pulse width of the injector (PW).

The lambda (λ) sensor comes with a digital display, which uses an MTX-L digital air-fuel ratio gauge and a Bosch heated wideband oxygen sensor. The lambda sensor is capable of self-calibrating. The oxygen sensor is located inside the exhaust gas pipe. The data of the air/fuel ratio is continuously obtained by the sensor at different engine loads during the engine operation. An eddy current dynamometer from Tops Landtop was used in the study. The dynamometer model is GFA174A-5 with a mechanical power of 5 kW and a maximum voltage of 230V. The dynamometer is connected to its own data logger and software, which can be used to measure engine power and torque. An exhaust gas analyzer (model EMS 5002) is a stand-alone device used to measure the emissions of O_2 (0-25%), CO (0-10%), CO_2 (0-20%), HC (0-2000 ppm) and NO_x (0-5000 ppm). Lambda value can also be measured by the gas analyzer. The exhaust gas analyzer has an accuracy of 1% with fast response time and is connected via a 12V DC connection. The error tolerance as shown on Table 1. The fuels used in this study are diesel and palm oil-based biodiesel with four different blends of 5%, 10%, 15%, and 20% (POB5, POB10, POB15, and POB20, respectively). Table 2 shows the properties of the blended biodiesel used in this study, which was measure using standards ASTM method.

Table 1 The accuracy of experimental equipment with the rate of uncertainties of each parameter

Item	Measuring Instrument	Accuracy / Sensitivity
In-cylinder Pressure	Optrand model D52294-R41	0.84 mV/psi at 200°C
Fuel Flow Meter	50 ml burette	±0.1 ml
Power	Dynamometer GFA174A-5	120 VAC ±10% or 220 ±10%
Lambda (λ)	MTX-L digital air-fuel ratio gauge Bosch heated wideband oxygen sensor	
Air intake temperature	Air heater with heater controller 988A-20CC-CCRR	±0.1%
NO_x	EMS 5002 gas analyzer	±25 ppm
HC	EMS 5002 gas analyzer	±4 ppm
CO_2	EMS 5002 gas analyzer	±0.3%
CO	EMS 5002 gas analyzer	±0.02%

Table 2 Measured properties of diesel and palm oil based-biodisel.

Properties	Unit	Test Method	Diesel	B5	B10	B15	B20
Density at 15°C	kg/L	ASTM D 4052-11	0.8409	0.8437	0.8449	0.8470	0.8484
Kinematic viscosity 40°C	mm^2/s	ASTM D 445-14	3.650	3.644	3.843	3.875	3.944
Calorific value	MJ/kg	ASTM D 240-14	44.022	43.616	42.229	41.817	41.578

Cetane number	-	ASTM D 4737-10	55	52	50	48	46

2.2 Technique of experiment

The HCCI engine mode requires a PFI to allow the fuel and air homogenize before entering the combustion chamber. Meanwhile, electrical heater to increase chemical activation energy of the engine. The experiment start with slowly increased the engine speed but must limit below 3000 rpm with increasing some load up to 30% of the CIDI engine’s load. Once the engine speed was stable, the heater was then turned on. The intake air temperature was set at 70°C. The engine was run for about five more minutes before the intake air temperature gave a stable reading (no fluctuation). The transition point could be observed when there was a light ringing sound (or knocking) produced by the engine. The load was slowly decreasing up to 0-5 % and immediately closed the CIDI valve. The transition from CIDI to HCCI mode was then achieved.

The load was set to 0% and tested for different λ condition start from the highest to lowest (low to rich mixture). By reducing the engine speed, the engine was in an unstable condition meanwhile, increasing the engine speed will stop the engine. In addition, the idle speed of the engine in HCCI mode in current study is between 2600-2800 rpm. Thus, the engine speed was selected at 2700 rpm. The decided air intake temperature in this experiment is 70°C, 80°C and 90°C. The stable λ for all blends are 3.1, 2.9, 2.6, and 2.4. It was found for mixtures leaner than this, combustion was not seen. Hence λ = 3.1 was selected as the lean limit for the experiments. On the richer side, combustion was smooth until λ = 2.4. For mixtures richer than λ = 2.4, the combustion was erratic and noisy due to knocking. Hence λ = 2.4 was chosen as the rich limit (knocking limit) for this experiment. The experiment was carried out from the lowest air intake temperature of 70°C to the highest of 90°C. The temperature was selected in this range because of the same experiment condition (temperature) from the previous studies [9], [10], [12], [30], [31], which show stable HCCI combustion. The baseline data of the CIDI engine was created in order to compare the engine performance between CIDI and HCCI at the same operating condition. The comparison will be discussed in the next chapter. Figure 1 show the schematic diagram of the whole setup of the engine testbed. Table 3 shows the engine specifications. Each of the experiment was repeated thrice and the data was summed up to the average.

Table 3 Engine specification

Model	Yanmar, L48N6
Number of cylinder	One-cylinder, four-stroke
Bore x Stroke	70mm x 50mm
Maximum speed	3600rpm
Power output	3.5 kW [4.7 hp]
Engine starting system	Electrical starter
Injection system	DI and PFI
Cooling system	Air-cooler
Fuel	Diesel

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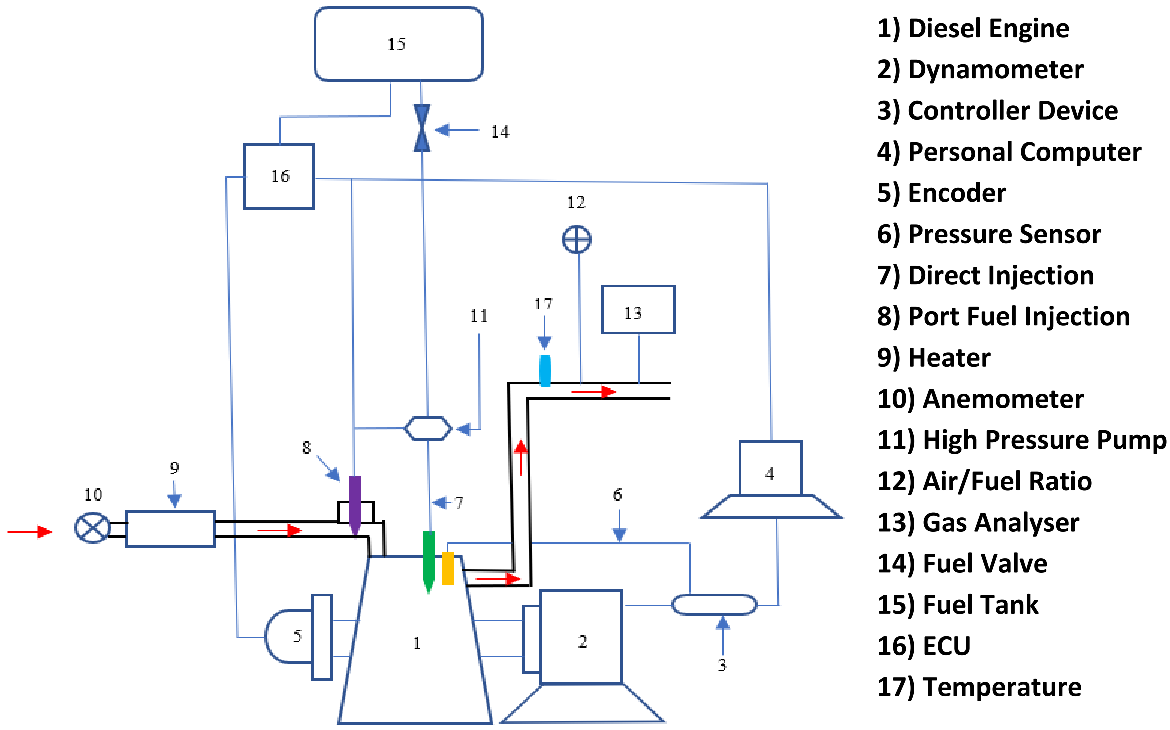

Figure 1 Schematic diagram of engine test bed

3 Results and Discussions

3.1 HCCI Engine Performance

The HCCI engine was operated at 2700 rpm at CIDI and HCCI mode of combustion. As stated before, at this engine speed, the engine has the most stable power and fuel consumption rate. The engine speed was set constant so that a direct comparison can be made between the two modes of combustion.

3.1.1 Power

Figure 3 shows the comparison of power between CIDI and HCCI at 70°C, 80°C, and 90°C against different types of fuels. Each figure has a different value of λ; a) λ=3.1 b) λ=2.9 c) λ=2.6 d) λ=2.4 (Figure 3). The engine power of the HCCI engine decreases over the CIDI mode of combustion. This may be due to the loss of thermal energy during the combustion process and thus, reduces the power output. Moreover, HCCI combustion occurred spontaneously in the combustion chamber where the autoignition is controlled by the mixture composition and its time-temperature history [32]. Diesel fuel shows the highest power output compared to palm oil biodiesel. It was observed that the increase in palm oil-blend content reduces engine power. POB5 shows the highest power output compared the other blends at all λ conditions. The increased percentage of blends lead to the lower engine power due to decreased calorific value, as shown in Table 2. The HCCI combustion was also observed as the λ decreases the output power increased in both CIDI and HCCI. The trends of HCCI power at different intake temperature varies when changing the λ. As the λ decreases, the engine power increases significantly for all tested fuel. It can be said that engine power improved using higher intake temperature at lower λ value. The power increases at lower λ due to the richer mixture conversion from the chemical energy to mechanical energy. This is because the spontaneous conversion of chemical reaction toward the high temperature region inside the combustion chamber in the high load operation. However, HCCI has limitation at the high load operation, where the engine is unstable and produces noise when the λ near the stochiometric. It made the HCCI engine unable to operate at a higher load and only suitable to operate in low load conditions [33].

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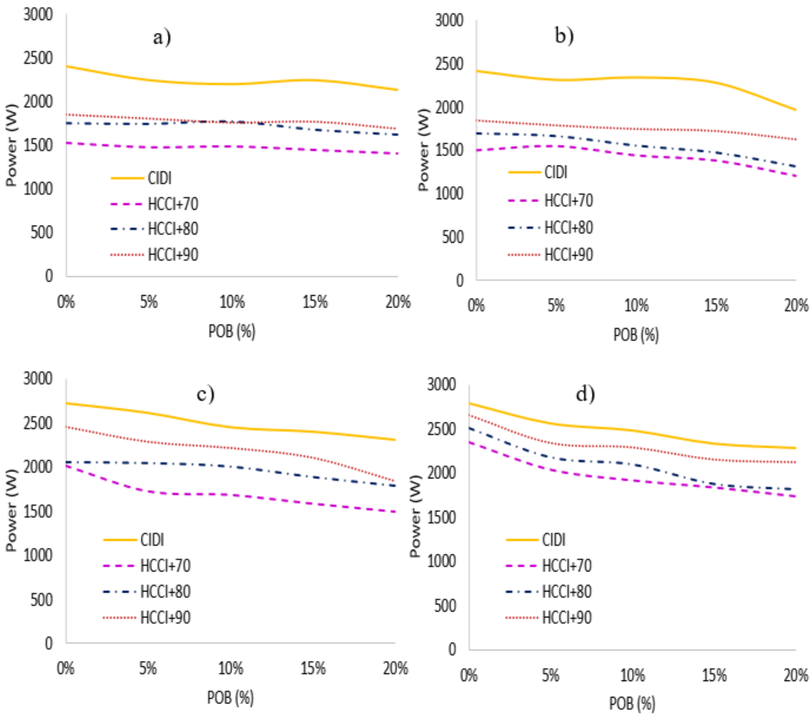

Figure 3 The comparison of power between CIDI and HCCI mode of combustion a) λ=3.1 b) λ=2.9 c) λ=2.6 d) λ=2.4

3.1.2 Brake Specific Fuel Consumption

Lower BSFC is a good indicator because it not only shows economical fuel consumption, but it affects the emission levels as well [34]–[36]. Figure 4 shows the BSFC comparison between all CIDI and HCCI modes at different λ condition. It was observed that the, CIDI mode has a lower BSFC compared to HCCI mode at all λ condition. The difference in BSFC for different engine modes (CIDI and HCCI) was due to the result of engine power is reported in Figure 4.4. HCCI produce less engine power due to reduced air intake density during the combustion. Also, the increase of BSFC when run in HCCI mode is because HCCI engine produces less engine power as it runs with a lean fuel-air mixture with reduced air density. In addition, the decrease in BSFC can be seen when the number of biodiesel blends are added. Since then, POB20 has lower BSFC among the others at all λ. This was due to the higher viscosity and lower calorific value of POB20 as compared to other blends. The result shown here is in agreement with most of the previous study [18], [37]–[40]. It was observed the BSFC increased when the λ was increased. Figure 4.4 a) at λ 3.1 has the highest BSFC. This can be contributed to the lower output of engine power during the leaner mixture of engine operation. Thus, the rate of decrease in BSFC is high at lower λ than compared to high λ. It is very related to the engine power which produces more output with more fuel. It also shows that BSFC reduces when the intake air temperature is increased. The reason for limited intake temperature is because the power generated during the HCCI mode is lower due to the unstable operation. If the HCCI engine can achieve a compatible intake air temperature, a lower BSFC than the CIDI engine would be possible in the near future. Therefore, as stated by Hasan et al. [41] the BSFC for the HCCI engine can be improved further by using other parameters to control the combustion such as high compression ratio, leaner mixture and exhaust gas recirculation.

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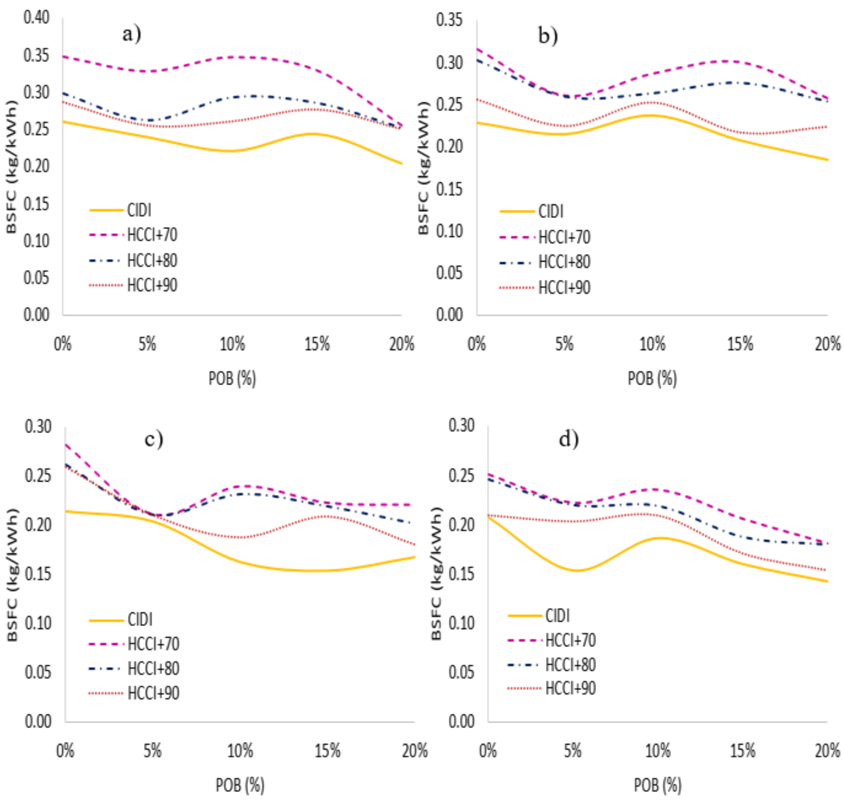

Figure 4 The comparison of BSFC between CIDI and HCCI mode of combustion a) λ=3.1 b) λ=2.9 c) λ=2.6 d) λ=2.4

3.1.3 Brake Thermal Efficiency

A typical engine efficiency for a diesel engine is about 30% given a high compression ratio [42]. Higher engine efficiency is good because the engine uses less fuel and produces more power. When the efficiency between the two modes of combustion is compared, the HCCI engine yields a lower efficiency than the CIDI engine. Figure 4.5 shows the difference of BTE for different intake air temperatures 70°C, 80°C, and 90°C compared with CIDI. A higher BTE was obtained in DI mode than that of the HCCI mode engine. This is because the HCCI engine was run at low load compared to the DI mode where the rise in intake temperature led to increased movement of air molecules that easily came in contact with fuel. Low BTE for HCCI engine is also agreed by Khandal, Banapurmath and Gaitonde [43]. When temperature was raised to 90˚C, the BTE was also increased. Gowthaman and Sathiyagnam [44] reported that, a higher intake air may be the possible reason for a higher performance. Thus, by changing the intake temperature of the HCCI engine the possibility of controlling the HCCI combustion [45]. High BTE was observed at 90°C at all λ. A high intake temperature in the HCCI engine mode improved the combustion of the engine, as it increased the movement of air and vaporization of the fuel to produce a more homogenous mixture. This led to better combustion and a high BTE. The different blend ratios of biodiesel affected the BTE. It was observed that the BTE decreases with increased biodiesel ratios. This is due to higher kinematic viscosity and lower cetane number as the blend ratio increased, which causes low vaporization of fuel and leads to incomplete combustion. The BTE of POB5 is close to that of diesel fuel. The lesser biodiesel blend is comparable to diesel fuel at all engine loads [46]–[49]. This was due to the characteristics of palm oil biodiesel, which are almost similar to that of diesel fuel in term of density and viscosity of the fuels.

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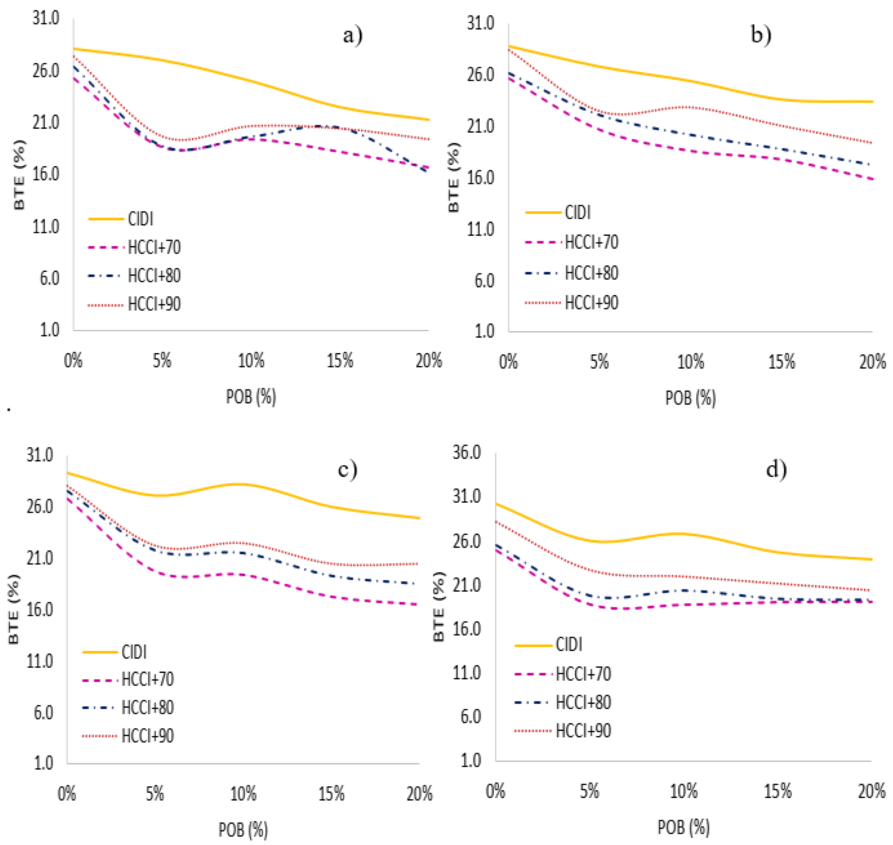

Figure 5 The comparison of BTE between CIDI and HCCI mode of combustion a) λ=3.1 b) λ=2.9 c) λ=2.6 d) λ=2.4

3.1.4 Brake Mean Effective Pressure

BMEP of a diesel engine is directly related to the brake power. Figure 6 shows the variation of BMEP between CIDI and HCCI mode of combustion at different λ value, a) λ=3.1 b) λ=2.9 c) λ=2.6 d) λ=2.4. The variations of BMEP for the CIDI engine is higher than the HCCI engine. Diesel fuel has a maximum BMEP compared to other fuels. The result also shows that the BMEP decreased when running the engine on biodiesel, where low BMEP was obtained with B20 biodiesel. Most of the authors reported that, lower heating values of biofuels and their blends are responsible for this phenomenon [29], [50]–[53]. In all operations, BMEP was always the highest when the engine was operated in CIDI mode. This shows that the HCCI engine is able to work in low load conditions. It was also observed that, high intake temperature results in a higher BMEP. BMEP is increased with increasing the inlet air temperature [22], [44]. BMEP is created with a higher combustion temperature due to more energy in the fuel-air mixture. The HCCI engine highly depends on the intake temperature to determine its operating range. The operating range is limited between misfiring and knocking in the HCCI engine [54].

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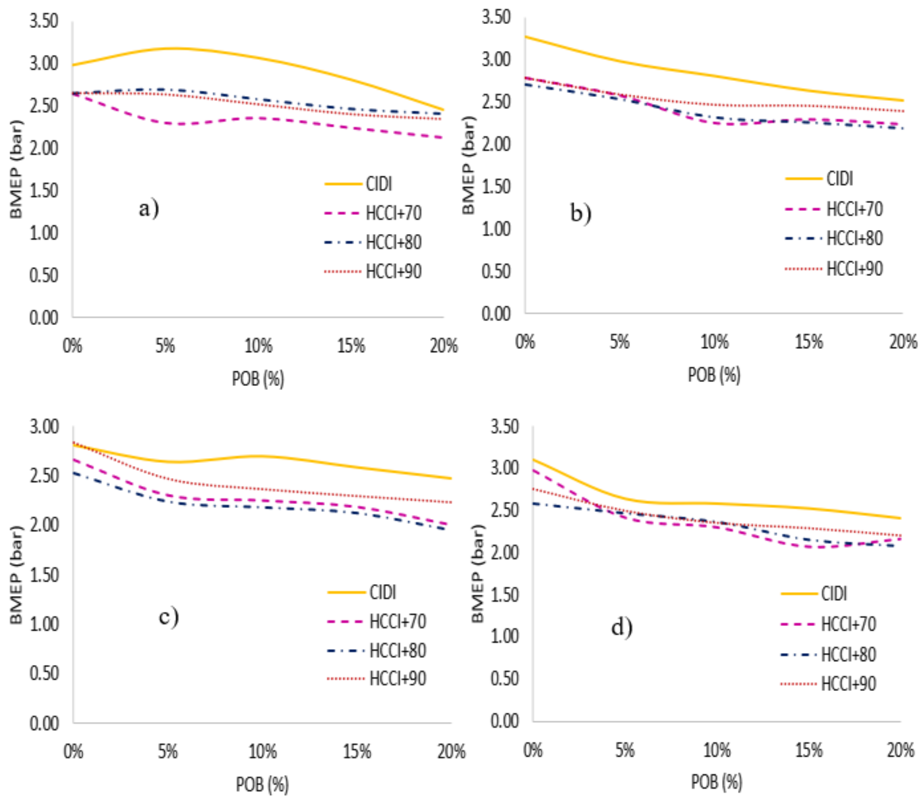

Figure 6 The comparison of BMEP between CIDI and HCCI mode of combustion a) λ=3.1 b) λ=2.9 c) λ=2.6 d) λ=2.

3.2 Combustion Behaviour

In-cylinder pressure, heat release rate and temperature are dependent on the engine speed, equivalence ratio, engine load, intake pressure, temperature, and energy content of the fuel configurations. On the other hand, by using the different types of fuel, these can control the peak pressure of in-cylinder pressure. The difference in chemical properties contained inside the fuel trigger the variation of engine combustion. Singh, Singh, and Agarwal [27] proved from their experiment which showed that the chemical kinetics of diesel HCCI were found to be faster compared to biodiesel HCCI. Further explanation is in the following sub-topic.

3.2.1 In-cylinder pressure and heat release rate

Diesel fuel has higher peak of in-cylinder pressure and heat release rate (HRR). Figure 7 shows that the in-cylinder pressure increased with increasing intake air temperature for diesel fuel. High intake air temperature advances the start of combustion and reduces the volumetric efficiency of the engine. Advance combustion also affects the NO_x and UHC emissions [55]. The HCCI mode at 90°C shows a higher peak in-cylinder pressure compared to CIDI. Same with HRR at intake air temperature 90°C triggers a rapid increase. In HCCI mode, when the intake temperature was increased, the in-cylinder pressure and HRR increased. HRR follow the pattern of in-cylinder pressure. However, the power output for HCCI still lower than CIDI. Somehow, the power output for HCCI still lower than CIDI because the advanced combustion and high rise rate of in-cylinder pressure may be the reason for poor combustion. Another reason is HCCI engine operates with a lean air-fuel charge for all λ conditions and causes the engine to operate at low load condition compared to the CIDI engine. Therefore, it shows different value of maximum in-cylinder pressure of each diesel and biodiesel fuel. The biodiesel reported slightly higher viscosity compared to the diesel [56] , causes higher specific fuel consumption than the conventional engine [57]. Figure 7 fuelled with diesel have higher HRR than Figure 8 fuelled with biodiesel fuel. Singh, Singh, and Agarwal [27] proved from their experiment which showed that the chemical kinetics of diesel HCCI were found to be faster

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compared to biodiesel HCCI. Diesel fuel in HCCI mode increases the peak temperature because the high calorific value and heating value [58], thus, increasing the HRR [38]. Furthermore, the in-cylinder pressure decreases in HCCI mode because the dilution of the fuel mixture had led to lower in-cylinder pressure. Meanwhile, in CIDI mode, the availability of a higher premixed charge to start the combustion had led to higher pressure. The HCCI engine has low load and hence lesser pressure than the CI mode, whereas increasing the intake temperature will lead to improved mixing of fuel and air. CIDI mode has the ability to operate at high load, which is opposite to that of HCCI engine. The high load limit of the HCCI region was bounded by the knocking combustion or the rapid heat release rate at richer mixture [9]. Kim and Lee [10] also proved the same finding on the effects of inlet temperature on combustion. Heating the inlet charge over 100 °C at a premixed ratio of 0.5 in diesel premixing causes severe knocking and therefore charge heating is limited up to 90°C in this condition. So, in order to control the combustion phasing, the parameter condition such as intake temperature and mixture formation must be changed.

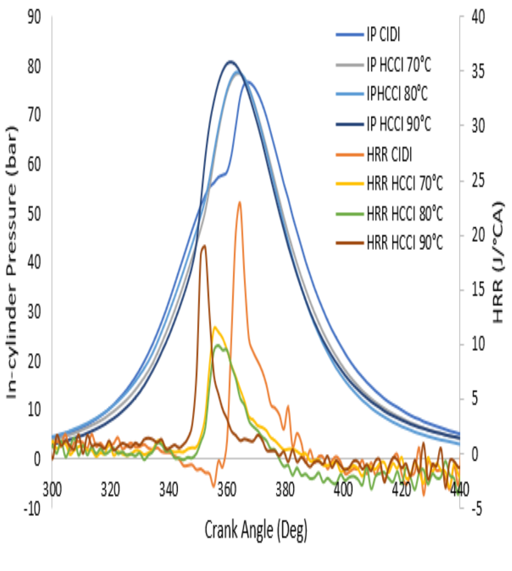

Figure 7 The comparison of in-cylinder pressure between CIDI and HCCI mode of combustion at λ=2.4 of diesel fuel

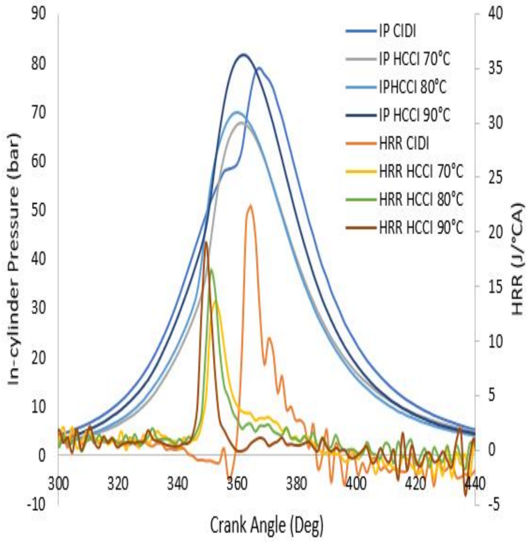

Figure 8 The comparison of in-cylinder pressure between CIDI and HCCI mode of combustion at λ=2.4 POB20

Also, Figure 20 shows peak in-cylinder pressure and HRR reduces when decrease λ (rich mixture). A rich mixture causes HCCI engine to consume more fuel. Richer mixture at a high intake air temperature causes advanced start of combustion. However, this parameter condition causes uncontrolled combustion phenomenon. Due to that reason, the intake air temperature had to be limited [12]. Another reason behind this is, more fuel introduced leads to an increase in peak in-cylinder and HRR [31]. Similarly, high λ (lean mixture) gives a slower rate of combustion due to delayed combustion phenomenon, which shifts the heat release curve towards ATDC side. Too lean mixture may produce misfire and the too rich mixture may produce knocking to the engine. Therefore, HCCI can only be operated at low to medium load condition [8], [21]. Another possibility to control the peak of HRR is to use the EGR. It can be assumed that an inert gas absorbs the heat during the combustion, thus reducing the combustion rate which can avoid the engine noise [59].

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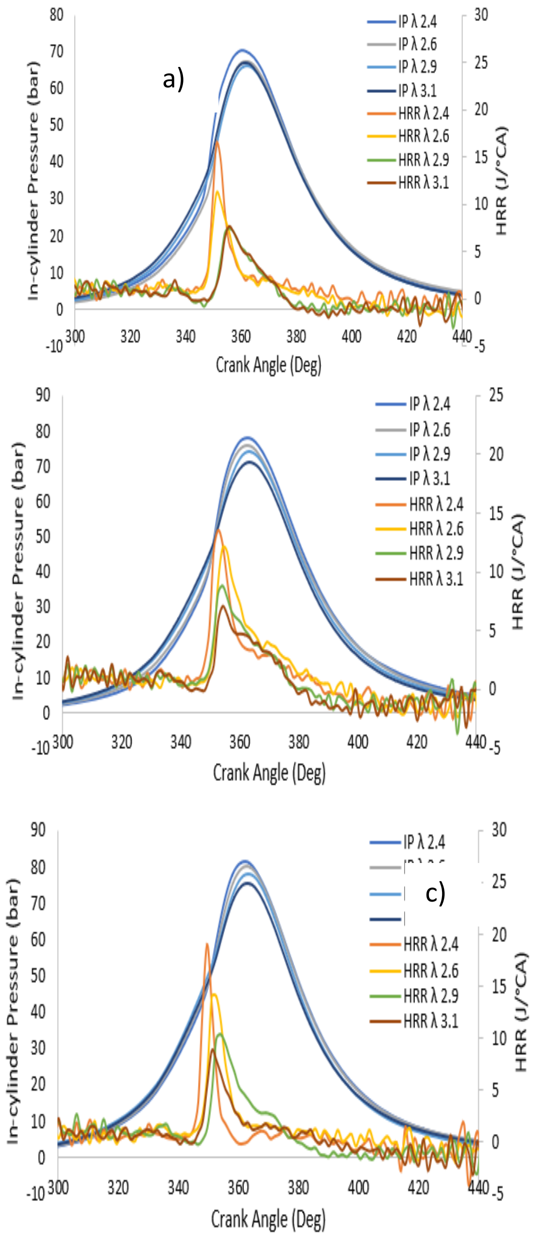

Figure 9 The effects of varying intake temperatures, lambda, and biodiesel blend ratios on the in-cylinder pressure for HCCI mode at an engine speed of 2700 rpm (a) HCCI 70̊ C POB20 (b) HCCI 80˚C POB20 (c) HCCI 90˚C POB20.

Figure 10 and Figure 11 summarize the result of maximum peak pressure and start of combustion (SOC) of the HCCI engine and the effects of using different biodiesel blend rates (DI, POB5, POB10, POB15 and POB20) with different intake temperatures. Figure 10, shows the peak in-cylinder pressure of diesel fuel is 82 bar at an inlet temperature of 90˚C, which then decreased to 79 bar at 70̊C. The peak pressure for all fuels was then decreased with decreased intake temperature and increased palm oil-based biodiesel blend ratio. This is because the viscosity and density of biodiesel ir :s with increased blend ratio of the b :l, which leads to increased viscosity and density of the fuel, causing difficulty in producing a good mixture and better combustion. Figure 11 shows the effects of intake temperature on SOC in HCCI engine using diesel and biodiesel fuel. The SOC is advanced with increasing intake temperature. Increasing intake temperature causes increased in-cylinder temperature at the end of the compression stroke, which leads to auto-ignition occurring earlier. The SOC is retarded when the amount of biodiesel increased. The use of biodiesel in HCCI mode, which has a higher viscosity and density, leads to ineffective mixing between fuel and air. Besides that, intake temperature is an important factor to improve the in-cylinder pressure inside the combustion chamber, as discussed by Gowthaman and Sathiyagnanam [44] who varied air temperature to control the HCCI engine.

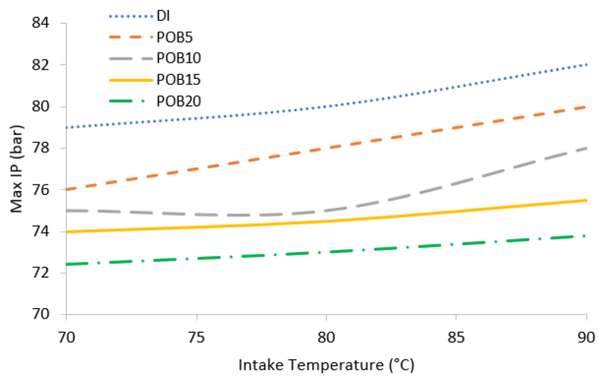

Figure 10 The effects of intake temperature on peak in-cylinder pressure in HCCI engine for diesel and biodiesel fuel.

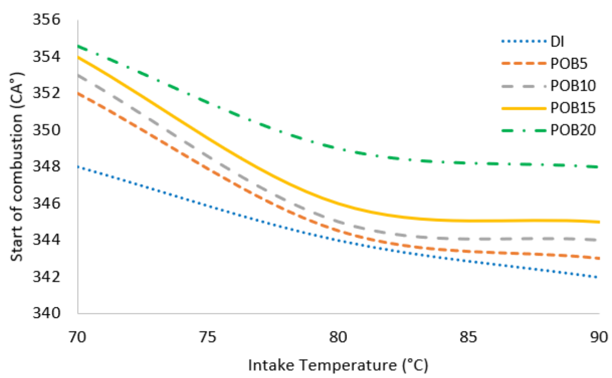

Figure 11 The effects of intake temperature on start of combustion in HCCI engine for diesel and biodiesel fuel.

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3.3 Emission Levels

As noted, fuel properties of biodiesel had affected the emission levels as well as the performance of the engine. Biodiesel has a special characteristic in lowering the emission level as it is a non-toxic and bio-degradable [60]. The emission levels were observed at the same parameter as performance was. A little increase for NO_x when compared to diesel fuel [34], [36], [61], [62] will further be discussed in the following.

3.3.1 Nitrogen Oxide

HCCI is considered one of the latest low combustion technologies that can minimize the formation of NO_x and PM while sustaining the benefits such as an efficiency close to CI engine [54], [63]. CIDI mode using diesel fuel generally has higher NO_x emission compared to HCCI, as shown in Figure 12. NO_x emissions are high with an increase of percentage blend of the biodiesel [61]. It was observed that the NO_x emission increased from the lowest to highest blending ratio of POB5, POB10, POB15, and POB20. The light increase of NO_x when increasing the palm oil biodiesel content due to the excess oxygen that supplied with the fuel-borne oxygen in the fuel [64]. The increasing amount of palm oil blend lowers the heat release rate and in turn reduces the peak combustion temperature inside the engine cylinder. It was observed, there is a big gap of reduction of NO_x emission on HCCI compared to CIDI mode of combustion as illustrated. The graph shows two axes; axis on the left and the right which indicate the NO_x emission for CIDI and HCCI mode, respectively. The left axis indicates the value of NO_x emission almost negligible for HCCI. The reason is mainly due to the low temperature combustion [65]. Furthermore, The NO_x emission with respect to λ showed increasing trends with the increasing of palm oil- blend. Jiang-ru and Jing [66] reported that NO_x almost negligible when λ is equal to or larger than 2.5. Besides, the figure shows NO_x increases with increasing the intake temperature. The temperature is responsible for producing NO_x. According to Nathan, Mallikarjuna, and Ramesh [14], [67], with the increase of intake air temperature, the mixture burned with a higher temperature, the quenching effect weakened for the higher temperature, which increases the NO_x formation rate. Also, another study showed that the NO_x emission is reported to increase with biodiesel [68], [69]. Therefore, the formation of NO_x emission, is due to the reaction between nitrogen and oxygen molecule at higher combustion chamber temperature. Pan et al. [13] stated that by increasing the intake air temperature, the mass of intake air was decreased, which increased the equivalence ratio closer to stoichiometric. Thus, the low λ (richer mixture) contributed to the rise of NO_x emission.

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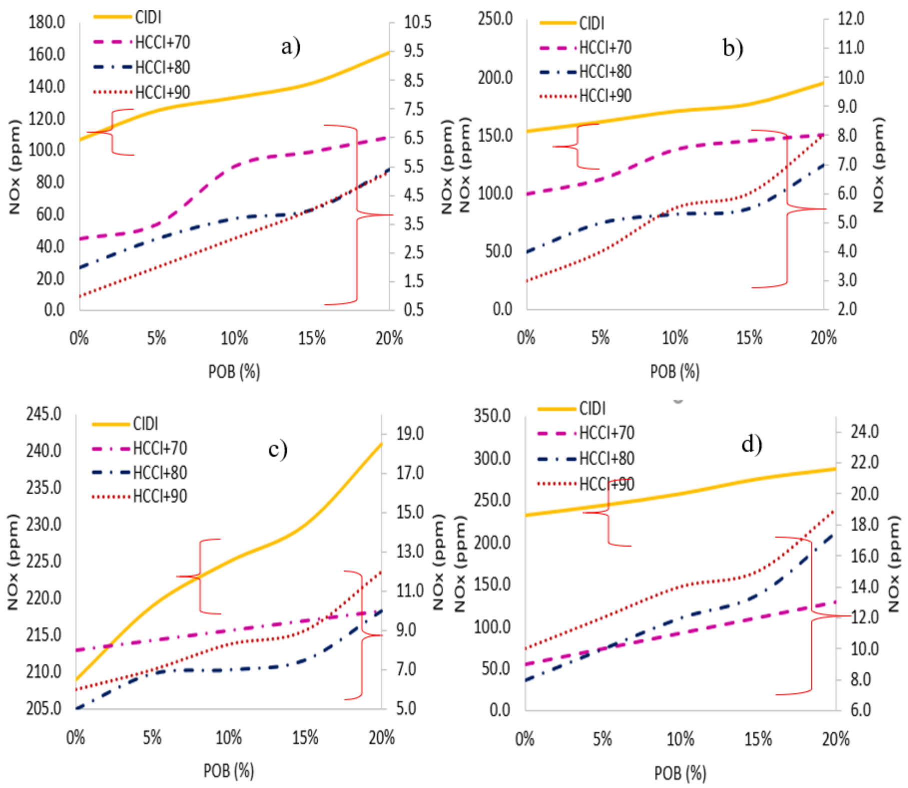

Figure 12 The comparison of NO_x between CIDI and HCCI mode of combustion a) λ=3.1 b) λ=2.9 c) λ=2.6 d) λ=2.4

3.3.2 Hydrocarbon

For HCCI combustion, there are four types of HC formation mechanisms: quenching effects at the chamber wall; slit effects; adsorption effects of cylinder lubricant oil film; partial burning and misfire [32], [70], [71]. The emissions of unburned HC are the result of incomplete combustion of the hydrocarbon fuel in the engine. Also, the amount of HC emission produced depends on a number of factors such as biodiesel type, engine type and test procedure used [72]. From the result, the HCCI mode engine has higher HC emission compared to CIDI mode as shown in Figure 13. CIDI mode has lower HC emission compared to HCCI mode. HC emission is well known as one of the major problems in the HCCI engine [32], [73]–[75]. The high amount of HC emission generated at lower combustion temperature. In addition, Singh and Agarwal [76], [77] stated that the cause of increasing HC emissions are due to lower bulk cylinder temperature and trapping of the homogeneous air-fuel mixture in crevice volumes and dead volumes in the combustion chamber. It is also observed that there is a trend of HC increasing when the intake air temperature is increased. As a result of increasing intake temperature, the rise of HC emissions obviously can be seen for all fuels. The mixture does not combust completely and results in higher HC emissions due to incomplete combustion around the piston ring crevices. The graph shows the trends of HC emission HCCI at intake air temperature 90°C is the highest followed by 80°C and 70°C, respectively. The study conducted by Pan et al. [13] has a similar result. They reported that a lower level of cylinder gas temperature increased the mass of incomplete combustion fuel. Highest HC emissions were measured at lower λ. Figure 13 shows an increasing HC emission come from richer charge mixture. As the increase of λ, the mixture becomes lean, peak temperature in cylinder decreases, incomplete combustion is easier to occur, thus the unburned hydrocarbons increase. Therefore, increases in λ cause a reduction to such NOx, which in turn increases the emission of HC. In order to have complete combustion in HCCI mode, the test engine needs more air thus, the HC emission can be minimized. Therefore, the amounts of HC emissions from the HCCI engine can be controlled by improving the mixture strength or increase the

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combustion temperature by using exhaust gas recirculation [78]. However, by using biodiesel shows low HC emission compared to diesel fuel. It also was observed the trend of HC decrease as the content of palm oil biodiesel increased. Furthermore, it was also found that the HC emission of POB20 is minimum compared to other fuels. The higher the biodiesel percentage in biodiesel-diesel blends, the lower the HC emissions [79]. This is due to the fact that the palm oil-blends has higher viscosity, which can help enhance oxidation of unburned hydrocarbons. Adding biodiesel to diesel fuel increases the oxygen content resulting in better combustion, and this results in lower HC emissions [46], [80], [81]. When the biodiesel is used with a high intake air temperature, there is a high tendency of biodiesel to oxidize with air [82]. It also shows the HC emission increases because increased air intake temperature is generally produced due to the poor oxidation process. This leads to unburned HC emission in-cylinder temperature boundary layer and piston ring gap increases [83]. Thus, the reason behind this phenomenon is because of low volumetric efficiency owing to lower air flow to the engine at a higher air intake temperature.

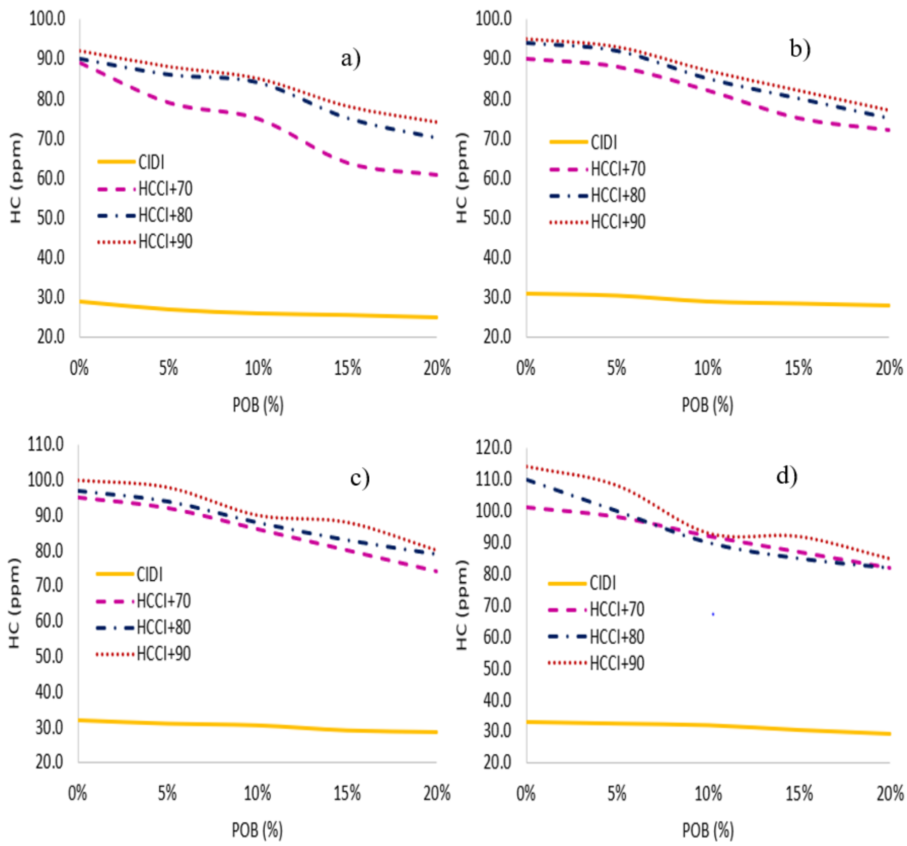

Figure 13 The comparison of HC between CIDI and HCCI mode of combustion a) λ=3.1 b) λ=2.9 c) λ=2.6 d) λ=2.4

3.3.3 Carbon Monoxide

CO is produced during the combustion process by depending on the combustion temperature and mixture homogeneity. HCCI mode has a relatively leaner mixture due to a low in-cylinder temperature combustion. The homogeneous air-fuel mixture was created before the start of the combustion process in the HCCI engine [42]. Meanwhile, for CIDI combustion, CO emission is controlled primarily by the fuel-air ratio. Under fuel-rich conditions, CO production is the result of incomplete combustion. CO can also be produced by dissociation when the mixture of CIDI combustion chamber is fuel-lean. In general, CIDI combustion has very low CO emission because they always operate under fuel-lean conditions [60]. Therefore, Figure 14, shows that the CO emission is less for CIDI mode compared to that of HCCI mode at all λ. The larger amount of the unburnt fuel remains unburnt during expansion

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stroke because of low exhaust gas temperature of HCCI engine. These results lead to a rapid rise in HC and CO emission levels. Also, the temperature is not high enough to continue the oxidization process of CO into CO_2 when the engine operated at partial loads, and hence decreasing in combustion efficiency of HCCI over DI engine combustion. How et al. [84] stated that the reason for the formation CO in the HCCI engine is due to low combustion region such as boundary layer near the cylinder wall. The heat was not enough to burn the CO reaction. High CO related to high HC becomes a major problem in HCCI combustion. In the meantime, as λ increases the emission of CO increase as well. For richer mixtures, CO concentration decrease, for high λ which is learner mixture, the CO emissions increases. The richer mixture means the load is being applied and cause the combustion temperature to increase [44]. The creation and oxidation of CO emission for HCCI engines are mainly controlled by chemical reaction which requires hydrogen atom to react with oxygen, that is $H+O_2=OH+O$, then the created OH and O will be oxidized. The CO increases because of the lean mixture which is not good for the oxidation of CO [66]. It was observed that palm oil biodiesel fuel has low CO emission compared to diesel fuel. This reduction could be attributed to the biodiesels having higher oxygen content than diesel which can result in more complete combustion, leading to less CO in the exhaust stream. The increase in palm oil biodiesel content causes a reduction of CO emission. POB20 emits minimum CO emission level compared to other fuel. Kumar and Raj [55] reported that the presence of oxygen in biodiesel promotes earlier start of combustion and controllable intake air temperature leads to higher combustion temperature and more time for oxidation of CO and soot particles at expansion stroke. Also, it can be seen that palm oil biodiesel is making the oxygen content crucial for the oxidation of CO. The result is in agreement with Huang et al.[21], which studied the low-temperature combustion at various load by using pine oil biodiesel. The CO emission of pine oil is high compared to diesel fuel under high load condition. The CO tends to decrease with increasing intake air temperature for all tested fuel. Intake air temperature affected the formation of CO emission as leads to higher combustion temperature and more time for oxidation of CO at expansion stroke as in agreement with the claimed earlier made by Kumar and Raj [55]. Intake air temperature at 90°C with increasing content palm oil biodiesel operated in HCCI mode has low CO emissions compared to other intake air temperature. Intake air temperature significantly affected on CO emission level as well the biodiesel fuel. As reported by Pan et al.[13], by increasing the intake air temperature leads to a higher level of cylinder gas temperature which accelerated the oxidation of CO significantly. The other cause stated by Pan et al. [13] is due to the increase of air-fuel flame quenching and air mixture trapped in crevices and quench layer also caused the increase of CO emission in HCCI engine. Also, Olsson et al. [54] added that in order to keep CO emissions minimum, heating of inlet air is needed in the HCCI engine.

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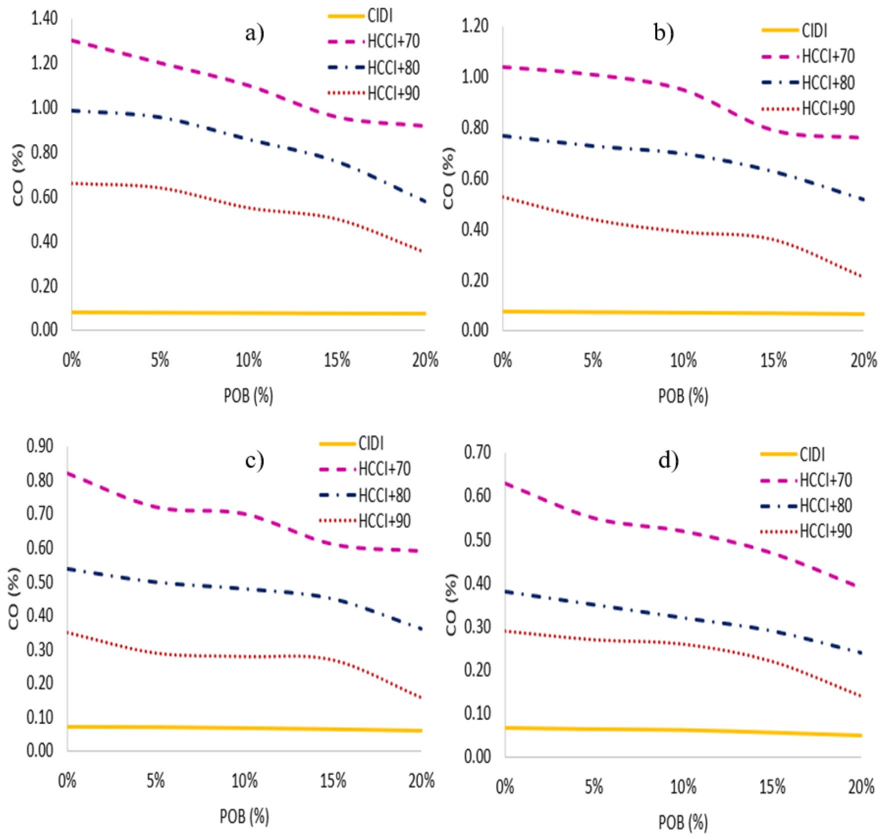

Figure 14 The comparison of CO between CIDI and HCCI mode of combustion a) λ=3.1 b) λ=2.9 c) λ=2.6 d) λ=2.4

3.3.4 Carbon Dioxide

With regards to CO_2 emissions, the opposite trends are encountered with respect to CO emissions. From Figure 15, CIDI mode was found to have maximum CO_2 emission compared to HCCI mode. CO_2 forms mainly due to the successful conversion of CO [42]. During the engine combustion, incomplete oxidation of CO into CO_2 was contributed by low in-cylinder temperature and lack of oxygen in the reaction zone. Combustion of homogeneous fuel and air mixture in HCCI mode resulted in lower in-cylinder temperatures, which prevented oxidation of CO to CO_2. This is the reason for high CO and low CO_2 emission in the HCCI engine [85]. One of the most significant reasons for the increase of CO_2 emissions was richer charge mixture. CO_2 emission tends to decrease when the mixture becomes leaner. It was observed an increase in lambda causes a reduction of the emissions of CO_2 for all test fuels. As the engine operates with the leaner mixture the whole fuel able to be oxidized [28]. It can be said that rich mixture leads to more CO_2 is generated thus, incomplete combustion occurs. It was also observed that the increase of palm oil biodiesel leads to a decrease in CO_2 emission level. Meanwhile, replacing diesel fuel with biodiesel is one of the significant methods to minimize CO_2 emission [86]. It also shows a low concentration of CO_2 when palm oil biodiesel was added. This is because palm oil biodiesel has more oxygen content, complete mixing of the air and fuel makes fuel find enough oxygen to react with. Thus, CO_2 emission is reduced. Diesel fuel has high CO_2 emission compared to biodiesel fuel. High CO_2 emission of an engine is the indication of better combustion of fuel. The fuel contains a fixed amount of carbon, this carbon gets converted into CO, HC and CO_2 depending upon completion of combustion inside the cylinder. Meanwhile, inlet temperature has a very strong effect which generates higher combustion temperature [54]. CO_2 emissions from the HCCI engine increase by increasing intake air temperature. The graph in Figure 15 exhibits CO_2 emissions increased with the increase in intake temperature. As stated earlier, CO emissions decrease with the increase of inlet air temperature, because CO could be

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oxidized due to higher inlet temperatures. Thus, CO–CO_2 reaction is related to the combustion temperature [13].

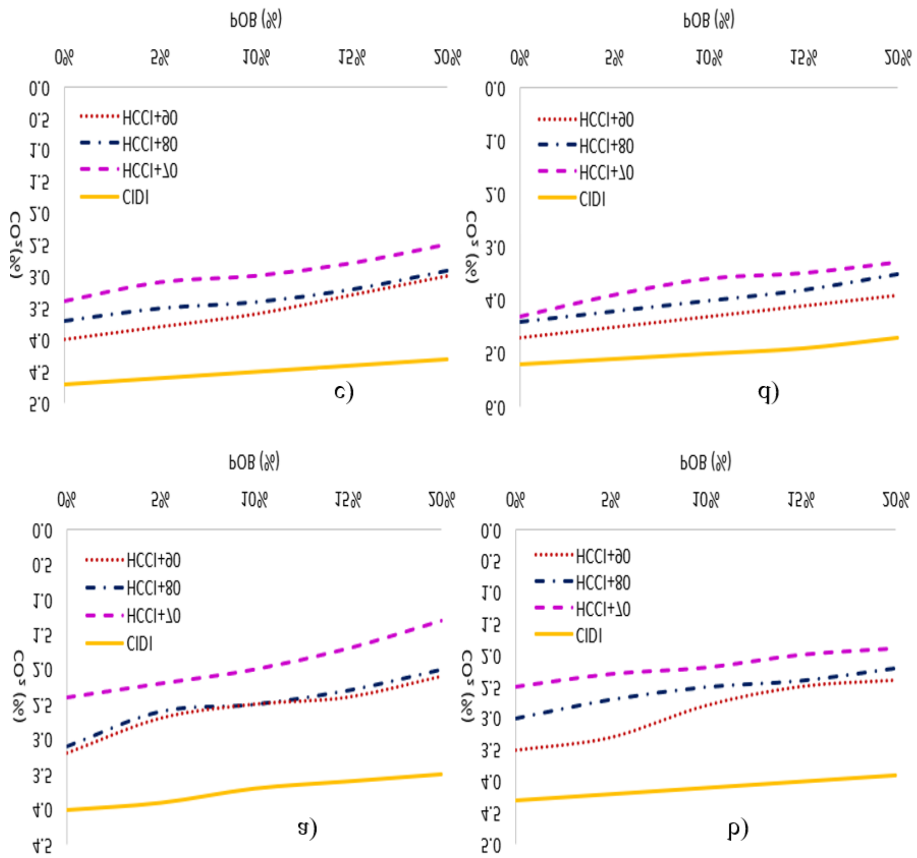

Figure 15 The comparison of CO_2 between CIDI and HCCI mode of combustion a) λ=3.1 b) λ=2.9 c) λ=2.6 d) λ=2.4

4. Conclusion

The effects of HCCI combustion mode in a DI diesel engine by varying intake air temperature and λ value were investigated using palm oil biodiesel and conventional diesel fuel. The tests were performed with different palm oil-blend at 5%, 10%, 15%, and 20% at a constant speed of 2700 rpm and λ = 3.1, 2.9, 2.6 and 2.4 conditions. No common references were found on the HCCI combustion fuelled palm oil biodiesel hence the original results here presented, obtained through a wide set of experimental tests was carried out. The result obtained covers a certain lack of literature and demonstrate that HCCI combustion fuelled with biodiesel can be achieved with remarkable advantages in terms of both efficiency and environmental impact. The following conclusions were obtained:

- The peak in-cylinder pressure increases in low-temperature combustion by increasing POB. The pattern of in-cylinder pressure was more stable for blending ratio of 5% - 10% of palm oil-blend. This is due to different autoignition characteristics of palm oil biodiesel
- Experiment was performed at different air-fuel mixture from λ = 3.1 to λ = 2.4 As the mixture becomes richer, the peak in-cylinder pressure and rate of heat release increase due to a higher rate of combustion. Start of combustion is very sensitive to λ.
- The in-cylinder pressure decreases in the case of higher amount of biodiesel in the testing fuels, combustion intensity for biodiesel fuel is

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lower which affects the heat release rate whereas the High intake temperature trigger the combustion means speed up the auto-ignition proses of fuels.

- The brake specific fuel consumption (BSFC) of the HCCI engine is higher than the conventional DI diesel engine. The rate of fuel consumed by the HCCI engine is depending on intake temperature and λ. The rate of fuel consumption is decreased with lower λ while increasing the intake air temperature. The intake air temperature of 90°C operated at λ =2.4 has lower BSFC at 0.273 kg/kW h. This is almost close to the conventional diesel engine.
- Brake thermal efficiency (BTE) of the HCCI engine depends on the amount of fuel consumption and heat energy released from the combustion process. At intake temperature of 90°C with λ =2.4, the HCCI engine consumed less amount of fuel and generated high efficiency compared to other conditions. However, the BTE in HCCI is lower than the CIDI mode due to lack of volumetric efficiency.
- The result yielded shows that the HCCI has lower NO_x emissions compared to CIDI. By increasing the amount of biodiesel will increase the NO_x emissions, however it is still lower than that of CIDI. This is due to more oxygen contents in biodiesel.
- The emissions of HC and CO were reportedly higher in many literatures when the engine operates in HCCI mode. The same pattern occurred in this study, where the emissions of HC and CO were higher than that of CIDI mode. However, it was found that, the HC and CO were improved (decrease) in HCCI mode when increasing the POB content. The emission of CO_2 also decreased when the amount of POB increased.
- The emission levels for all gases (HC, CO, CO2 and NOx) were sensitive to operating conditions of different intake temperature and λ. By increasing the intake temperature, the emissions of HC and CO_2 were increased, while emission of CO was decreased. By increasing the λ, on the other hand, the emission of HC and CO_2 were decreased, while the CO was increased.

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