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THE IMPACT OF INTAKE TEMPERATURE ON AIR ASSISTED FUEL INJECTION HCCI ENGINE

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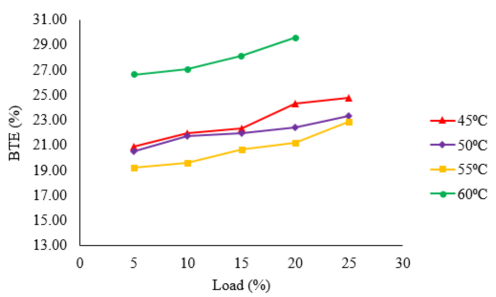
Graphical abstract



Abstract

HCCI combustion is one of the combustion strategy that can help to suppress the emission of NOx and soot in diesel engine. Among the challenges faced are the homogenous mixture preparation, combustion phase and auto ignition control and limited working range. The low volatility of the diesel is one of the hurdle in preparing a homogenous mixture for auto ignition of HCCI engine. The experimental work focus on the impact of intake air temperature on the performance, combustion behavior and emission on HCCI mode. Air assisted injector of 5 bar with port fuel injection method was used on a single cylinder 4 stroke diesel engine. The intake air was heated at different temperatures of 45ºC,50ºC,55ºC and 60ºC. Highest BTE was recorded by intake temperature 60ºC with maximum efficiency of 22.3% at 20% load. Highest fuel efficiency also was showed by intake temperature 60ºC.The working range for intake temperature 60ºC is limited to 20% as beyond that load knocking occurred during combustion. Higher intake temperature increase ignition timing and in-cylinder pressure which contributed the knocking issue. Lowest emission of HC was also observed via intake temperature 60ºC. Intake temperature 45ºC contributed the lowest NOx with value ranging from 8 to 14 ppm but recorded the highest CO with values from 0.18 to 0.41% .

Keywords: Internal combustion, HCCI, air assisted fuel injection, port fuel injection, diesel

Abstrak

Pembakaran HCCI ialah pembakaran suhu rendah yang boleh membantu menahan pelepasan NOx dan jelaga dalam enjin diesel. Antara cabaran yang dihadapi ialah penyediaan campuran homogen, fasa pembakaran dan kawalan pencucuhan automatik dan jarak kerja yang terhad. Kadar pengewapan diesel yang rendah adalah salah satu halangan dalam menyediakan campuran homogen untuk pencucuhan automatik enjin HCCI. Matlamat kajian ini adalah untuk memberi tumpuan kepada kesan suhu udara masuk terhadap prestasi, tingkah laku pembakaran dan pelepasan ke atas pembakaran HCCI. Penyuntik bantuan udara 5 bar dengan kaedah suntikan bahan api port telah digunakan pada enjin diesel 4 lejang silinder tunggal. Udara masuk dipanaskan pada suhu berbeza 45ºC hingga 60ºC. Kecekapan haba brek tertinggi direkodkan oleh suhu pengambilan 60ºC dengan kecekapan maksimum 22.3% pada beban 20%. Walau bagaimanapun, julat kerja untuk suhu pengambilan 60ºC adalah terhad kepada 20% kerana di luar beban itu, ketukan berlaku semasa pembakaran. Pelepasan HC terendah juga diperhatikan melalui suhu pengambilan 60ºC. Pelepasan NOx terendah direkodkan oleh suhu pengambilan 45ºC dengan nilai antara 8 hingga 14 ppm

Kata kunci: pembakaran dalaman, HCCI, Penyuntik bantuan udara, diesel, suntikan bahan api

1.0 INTRODUCTION

Internal combustion engines still primarily depends on the gasoline and diesel as the main fuel for combustion. The researchers and engineers focused primarily on advanced combustion modes such as homogeneous charge compression ignition (HCCI), stratified charge compression ignition (SCCI), and premixed charge compression ignition (PCCI) because of their improved thermal efficiencies and ability to produce significant low levels of NOx and soot emissions.

HCCI is an advanced combustion strategy which combine the efficiency of compression engine and better emission quality of spark ignition engines. The flexibility of fuel in HCCI engine offers an attractive alternative to internal combustion. Figure 1 shows the combustion region of HCCI that sit well beyong the NOx and soot formation. Despite several advantages, HCCI combustion is stil facing several problem.

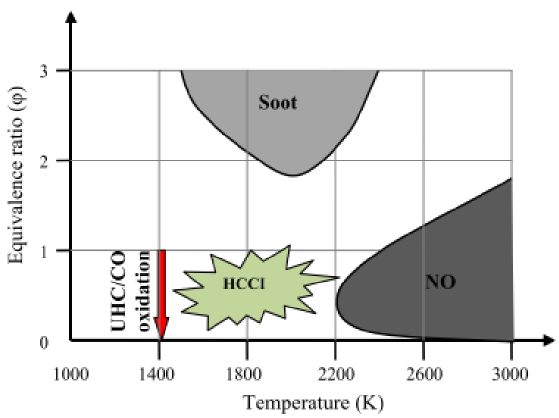


Figure 1 HCCI Combustion [1]

In HCCI, one of the difficulty is to control combustion phasing. HCCI combustion relies on the chemical kinetic reaction of the mixture compared to the spark ignition combustion which relies on spark plug to control the combustion. The combustion phasing are affected by fuel properties,intake temperature,mixture homogenuity amd air to fuel ratio. Limited operation range is another barrier for HCCI because the lack of adequate thermal energy prevents the spontaneous ignition of the mixture. Homogenous mixture preparation is also equally important to prevent mixture inhomogeneity. Optimising the fuel mixture interaction and minimising interactions between the fuel and the walls is essential for attaining optimal fuel efficiency, minimising hydrocarbon (HC) and particulate matter (PM) emissions, and minimising the diluting of oil. High HC and CO as well as cold start are other problems faced by HCCI combustion.

One of the important part in HCCI combustion is the preparation of fuel and air mixture to provide homogenous mixture for combustion. HCCI uses Port fuel injection (PFI) or Early direct injection to allow homogenous air and fuel mixture. PFI and elevating the intake intake air temperature were one of the several methods explored by researches. The intake temperature influences the temperature inside the cylinder. A greater in-cylinder temperature leads to an accelerated pace of chemical reactions. Rakesh and Avinash [2] compared the performance of ethanol and methanol with gasoline fuel. The study was performed on a customised four-cylinder four-stroke engine at various engine speeds using the port fuel injection method together with an intake air pre-heater. Both ethanol and methanol exhibit HCCI properties and can serve as viable alternatives to gasoline.

Hui Xie *et al*. [3] conducted an experiments to investigate the combined effects of residual gas retention and heating of the incoming air . The purpose is to optimise combustion and enhance the efficiency of converting fuel within the operational range of HCCI. Most of the researchers use pre-heater [4], [5], [6] to elevate the intake temperature to assist the auto ignition of the mixture. The evaluation characteristic of HCCI covers the performance, combustion behaviour and emission of the HCCI engine. Brake power, (BP) Brake thermal efficiency (BTE) and Brake Specific fuel consumption (BSFC) are the performance indicator for the engine. In-cylinder pressure and heat release rate (HRR) will show the combustion behaviour. K. Mathivanan *et al*. [7] study the performance and combustion characteristics of diesel fuelled HCCI engine using multiple fuel injection strategies. The study shows the thermal efficiency is greater (15%) with multiple phase fuel injection compared to single pulse injection (11%) at an IMEP of around 3 bar. Performance and emission for HCCI engine has been extensively reviewed by M. Mofiju *et al*. [8], Mingfa Yao *et al*. [9] and Avinash Kumar Agarwal [10].

The implementation of PFI strategy for low volatile fuel such as diesel require extra modification on the setup. Poor volatility of diesel is the primary obstacle in achieving uniform mixing of fuel and air. Fuel vaporiser was used by D.Ganesh [11] to achieve proper HCCI combustion. The study involved the combination of vaporised diesel fuel and air to create a homogenous mixture, which was feed into the cylinder during the intake stroke. The Exhaust Gas Recirculation (EGR) was implemented to regulate the premature ignition of the diesel vapour-air mixture. A. Singh [12] uses diesel vaporiser to investigate the combustion attributes of diesel engine using external mixture formation method.

Air assist injector also has been used to increase the atomization of fuel droplet for better mixture preparation. The development of air assist injector in HCCI combustion was started by B. Leach [13]. An engine that employed residual gas to initiate and regulate Control Auto Ignition combustion was equipped with an air-assisted injection system. Air assist fuel atomization has been improved the hydrocarbon reduction up to 40% at certain engine parameters by G. Saikalis [14]. Y. H Teoh *et al.* [15] study the combustion, performance and emission of premixed kerosene in air-assisted fuel injection system for partial HCCI engine and found that with higher premixed setting, the emission of HC and CO decreased. The impact of air temperature with partial HCCI-DI combination was investigated by Y.H Teoh[16]. Direct injection and air assisted fuel injection was used as variation of premixed ratio and intake temperature applied to the study. It was found that the inlet air temperature had a profound effect on low-temperature reaction and HCCI combustion timing compared premixed ratios.

The combination of air assisted port fuel injection and heated air intake in HCCI combustion has not been extensively explored and provide a great opportunity to improve the homogenous blend of fuel and air.

The objective is to evaluate the impact of intake temperature on the combustion performance of an HCCI engine. The HCCI combustion used port fuel injection method with air assist injector for better atomization of fuel droplet. The experimental was tested on single cylinder diesel engine and run fully on HCCI with few adjustments.

2.0 METHODOLOGY

A single-cylinder Yanmar diesel engine was employed in this study. Table 1 shows the specification of the engine. The engine was coupled to an eddy current dynamometer in order to enable the manipulation of the engine load. The load for this experiment was systematically adjusted, ranging from 5% to 25% as the speed was maintained at 2100 rpm. The fuel usage was measured manually using a burette and a stopwatch. The dynamometer software was used to measure and record the brake power and torque. The Optrand pressure sensor was utilised to measure and record the pressure inside the cylinder on the computer.

Table 1 Specification of the engine

Description	Specification
Make	Yanmar
Model	L48N
Type	Diesel engine
Bore x Stroke	70 x 57 mm
Displacement	0.219 L
Rated Power	3600 rpm
Rated Speed	3.5kW
Fuel Injection timing	16.5° BTDC

Figure 2 depicts the configuration of the experiment. The intake air was pre-heat via intake pipe manifold fitted with coil heater. Thermocouple type K sensor was fitted at the intake pipe to measure the temperature. At the exhaust pipe, another Thermocouple Type K sensor was fitted to measure the exhaust temperature. The air to fuel ratio was measured using Bosch wideband Innovate Motorsport sensor and display through MTX-L digital air/fuel ratio meter. The rotation speed was measured Hall sensor and transmitted to the dynamometer software.

Figure 2 Setup of the port fuel injection air assisted HCCI

Table 2 Synerjet Strata injector specification

Description	Specification
Maximum Pressure	850kPa
Static Air Flow	0.1-2.5 g/sec
Dynamic Air Flow	0.1-0.9 g/sec
Atomization	4 SMD–28 SMD(μm)
Operating voltage	8V-18V

The Synerjet Strata air assist injector is used for the HCCI mode. The air was delivered by a compressor regulated by an air pressure regulator. The emission was examined via the EMS 5002 Portable Gas analyser. The temperature of the intake air was controlled using Watlow temperature controller. The injector properties are given in Table 2. Figure 3 shows the location of air assist injector.

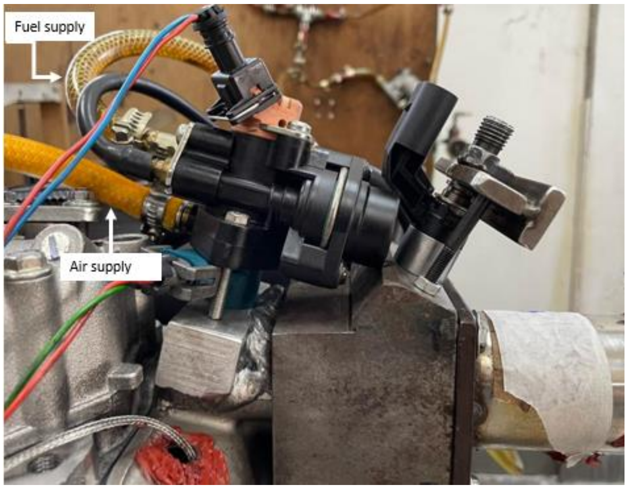


Figure 3 Air assist injector

The air pressure was set at 5 bar using air pressure regulator. The temperature of the intake was adjusted 45⁰C and the engine will start running in direct ignition mode. After the engine has stable, the HCCI combustion will take place by closing the fuel supply manual valve for direct injection. Figure 4 shows the location of the manual valve. Then, the air assisted PFI will supply the atomized fuel to mix with heated air for HCCI combustion. The speed was kept constant at 2100 rpm and the load was gradually increased from 5% to 25%. The same procedure was repeated for 50⁰C,55⁰C and 60⁰C

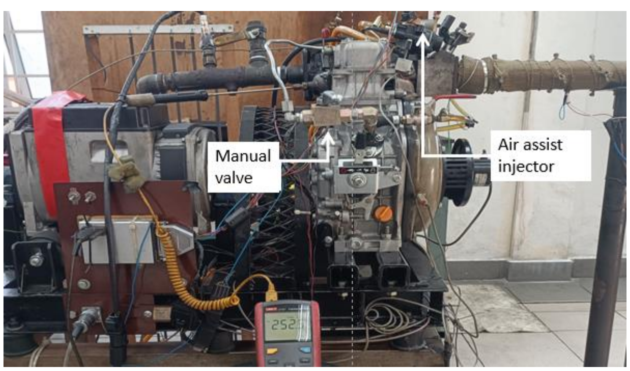


Figure 4 Manual valve and air assist injector location

For this experiment, Petronas diesel Euro 5(B0) was used as fuel. The diesel was obtained from Pandamaran Synergy Petroleum. The physical and thermal properties of diesel fuel were tested as per ASTM standards and results as shown in Table 3.

Table 3 Properties of Diesel

Properties	Method	Unit	Value
Density	ASTM D 4052-11	kg/L	0.8409
Kinematic Viscosity	ASTM D 445-14	mm^2/s	3.650
Heating Value	ASTM D 4737-10	MJ/kg	44.022
Cetane Number	ASTM D 4737-10	-	55

3.0 RESULTS AND DISCUSSION

Performance of an internal combustion is closely related to the efficiency of the engine to covert the chemical energy of the fuel into power. Figure 5 shows the brake thermal efficenct (BTE) variation with the load for different intake temperature. BTE signify the engine ability to convert the chemical energy of the fuel into mechanical output at the crankshaft. Intake temperature 60⁰C shows significantly higher BTE compared to the other intake temperature. The BTE range from 21.3% to 22.3%. HCCI combustion is sensitive to the intake temperature and relies on the auto ignition of fuel and air. Higher temperature accelerates the chemical reactions of air and fuel and shorten the ignition delay. Combination of intake temperature and air assist injector increase the vaporization of the low volatile fuel such as diesel. However, the HCCI combustion could only run until 20% load and the engine suffered knocking at 25% load. Higher temperature helps the auto ignition of the compressed mixture but it also increases the in-cylinder temperature. It causes narrower operating range as HCCI combustion is sensitive to changes on load and speed. S. Gowthaman [17] also shows that the highest thermal efficiency record with inlet temperature of 60⁰C and beyond that temperature will results in knocking. All intake temperature shows increase in BTE as load increases. Intake temperature 45⁰C shows the lowest BTE with reading ranging from 13.9% to 18.3%. Intake temperature 55⁰C and 50⁰C shows almost similar BTE across the subjected load.

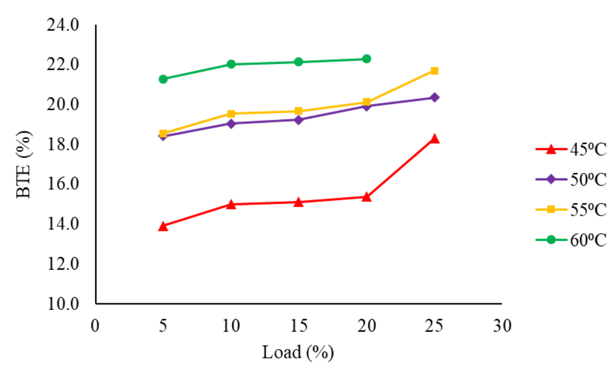


Figure 5 Brake thermal efficiency for different intake temperatures at 5 bar air assist pressure

Figure 6 shows the BSFC variation with different intake temperature. Intake temperature of 60^{0}C shows the lowest BSFC with value ranging from 362.6 g/kWh to 384.2 g/kWh. Higher intake temperature may have improved the fuel atomization which in turn increase the mixture homogeneity. Combustion is more efficient as less fuel is consumed for 60^{0}C. However, the combination of air assist pressure of 5 bar and temperature 50^{0}C and 55^{0}C bar shows lower BSFC compared to 45^{0}C intake temperature. Intake temperature of 45^{0}C shows the highest BSFC with value ranging from 441.6 g/kWh to 587.3 g/kWh. Lower intake temperature uses more fuel for the auto ignition of HCCI combustion. The lambda value decreases as load increases as more fuel is needed to overcome the load. Lambda value signifies the air-to fuel ratio. Throughput the load, the lambda value varies from 5.0 to 2.0. Excess air in lean mixtures provides more oxygen, allowing better dispersion of the fuel droplets.

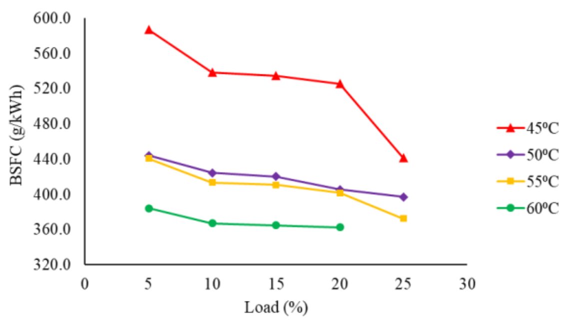


Figure 6 Brake specific fuel consumption for different intake temperatures at 5 bar air assist pressure

Combustion behavior for HCCI mode can be evaluated from the in-cylinder pressure and HRR profile. Figure 7 shows the combustion profile for different temperatures at 10% load. Intake temperature of 60^{0}C recorded the highest pressure of 64.4 bar. The other intake temperature shows a similar in-cylinder profile with intake temperature of 45^{0}C having the lowest peak of 63.3 bar. Observation on the HRR profile shows that the intake temperature 60^{0}C shows the highest HRR after combustion at 2.6 J/ ^{0}CA. Temperature 55^{0}C recorded peak value HRR of 2.4 J/ ^{0}CA. Temperature 50^{0}C and 45^{0}C indicate peak values of 1.9 J/ ^{0}CA and 1.6 J/ ^{0}CA respectively.

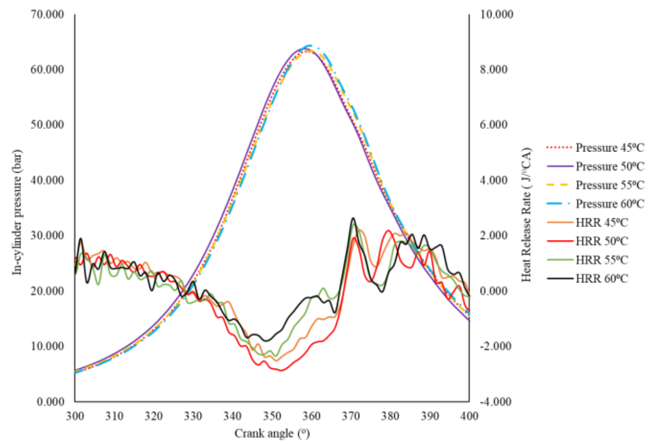


Figure 7 Combustion profile at different temperature at 10% load

At 15% load, intake temperature 60^{0}C and 50^{0}C shows almost similar peak in cylinder pressure of 69.6-69.7 bar as shown in Figure 8. Other intake temperature shows almost similar profile with peak pressure around 68.2 to 68.6 bar. Based on heat release rate profile, all the intake temperatures show three stage ignitions. The typical combustion process for HCCI combustion involves two stage heat release. The initial phase of heat release is attributed to low temperature reactions, where small percentage of heat is release. Subsequently, the second phase of heat release is caused by high temperature reactions[18]. The third heat release shown indicating there are still diffusive combustion where the fuel and air may not mix properly during the first two ignitions. Intake temperature 60^{0}C shows advance heat release during the initial phase. At the combustion stage, the maximum heat release rate still recorded by the intake temperature 50^{0}C with maximum peak of 3.5 J/^{0}CA.

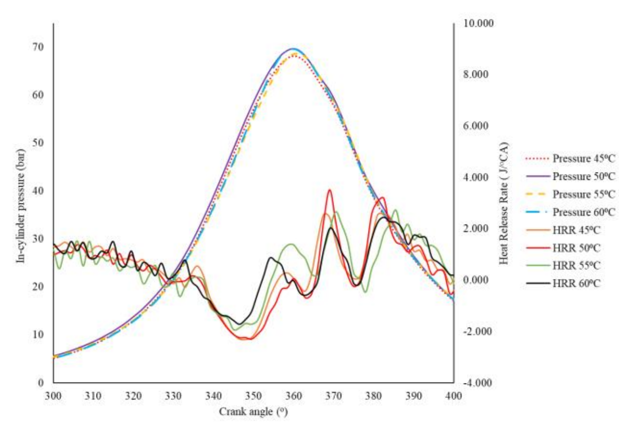


Figure 8 Combustion profile at different temperature at 15% load

Figure 9 shows combustion profile at different temperature for 20% load. Intake temperature 60⁰C shows highest maximum peak pressure of 78.2 bar with 0.2 bar difference with intake temperature 50⁰C.The HRR profile shows significant advance combustion for intake temperature 60⁰C. Highest heat release rate of 5.4 J/⁰CA was recorded around 350 ⁰CA. Can Cinar[19] also demonstrate a higher HRR for increasing intake temperature as HCCI combustion is greatly affected by heating the intake air. The heating of intake air expedited the chemical interactions between oxygen and hydrocarbon molecules. All intake temperatures show three stage ignition and almost the same profile. The three stage ignition also was recorded by Y.Teoh *et al*. [16] in his investigation on the impact of intake air temperature and premixed ratio on partial HCCI-DI engine.

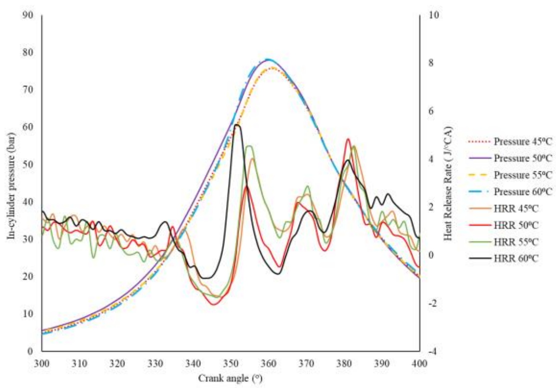


Figure 9 Combustion profile at different temperature at 20% load

The last load applied in the experiment is 25%. The combustion profile at 25% load was shown in Figure 10. Intake temperature 60⁰C shows the highest maximum in-cylinder pressure of 93.6 bar. The pressure profile also shows such an advance ignition which contribute to knocking. The combination of air assisted and intake temperature 60⁰C has shorten the working range HCCI combustion. High intake temperature caused high in-cylinder temperature and with better fuel atomization from the air assisted PFI, the spontaneous combustion occurred too rapid and early. M. Parthasarathy *et al.* [20] found intake air temperature exceeding 100 °C resulted in earlier burning in the middle of the compression stroke due to the gas becoming too hot. Other intake temperatures show in-cylinder pressure below 90 bar and no sign of knocking. The HRR profile of intake temperature 60⁰C also show a significant higher peak value of 17.5 J/⁰CA at 349.5⁰ CA compared to the other temperature. This shows the limitation of using intake temperature of 60⁰C which reduce the operating range due to knocking. Other intake temperature recorded HRR peak values of 12 J/⁰CA and lower.

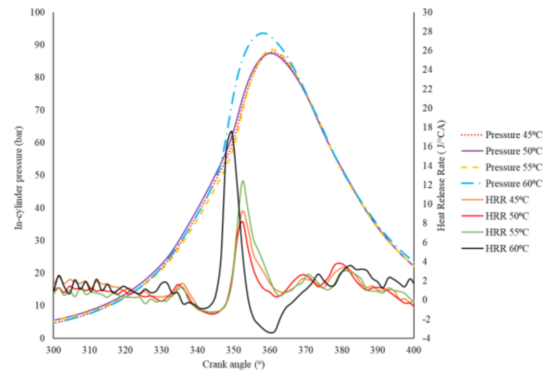


Figure 10 Combustion profile at different temperature at 25% load

The emissions produced by HCCI engines are hydrocarbons (HC), carbon monoxide(CO), nitrogen oxides (NOx), and particulate matter. Figure 11 shows HC and NOx emission at different temperature. Intake temperature of 45⁰C shows the highest HC across all the subjected loads. The HC emission values ranging from 68 to 108 ppm. Lower intake temperature may cause incomplete combustion and poor combustion efficiency. Intake temperature 60⁰C demonstrate the lowest HC emission with value ranging from 45 to 65 ppm which indicate better HCCI combustion compared to other intake temperature. S. Gowthaman [17] also experience similar result with intake temperature 40⁰C also show highest emission of HC. From Figure 8, it can be observed that the highest emission of NOx was contributed by intake temperature 60⁰C. The value of emission ranging from 10 to 14 ppm. Higher intake temperature may have contributed to in cylinder temperature. According to S. Saxena [21], nitrogen oxide emissions, NO and NO_2, are formed through the Zeldovich mechanism by breaking down of the strong triple bond between nitrogen atoms in N_2. High in cylinder temperature will be the activation temperature to this chemical pathway. Hence, intake temperature 45⁰C shows the lowest NOx emission with value ranging from 8 to 14 ppm compared with the other intake temperatures.

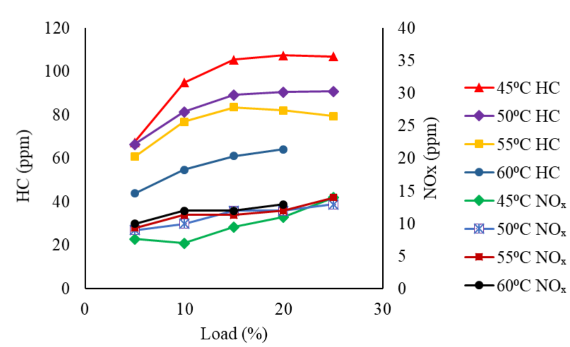


Figure 11 Emission comparison for HC and NOx at different intake temperatures

Carbon monoxide is a significant output from the HCCI engine, exhibiting higher levels of CO emissions in comparison to diesel engine. Figure 12 shows the emission comparison for CO_2 and CO at different intake temperatures. Intake temperature 60⁰C recorded highest emission of CO_2 ranging from 3.1 to 3.4% indicating better combustion as the CO percentage also the lowest with value ranging from 0.1 to 0.4% compared to other intake temperature. The highest CO was recorded temperature 45⁰C with value ranging from 0.18 to 0.41%. CO emission by temperature 55⁰C and 50⁰C recorded value ranging from 0.1 to 0.28% and 0.13 to 0.39% respectively. Complete combustion of hydrocarbon will produce water and CO_2. The lowest CO_2 percentage was contributed by intake temperature 45⁰C with value ranging from 2.1 to 3.3%. Intake temperature 45⁰C,50⁰C and 55⁰C shows decreasing trend after 20% load. Higher HC and CO recorded by the intake temperature 45⁰C due to the incomplete combustion as lower temperature cause the oxidation rates to be slower.

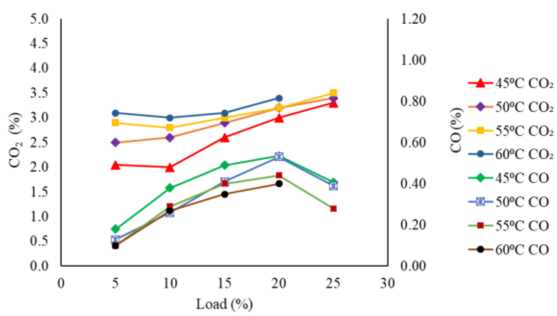


Figure 12 Emission comparison for CO_2 and CO at different intake temperatures

4.0 CONCLUSION

In this study, an external mixture method was employed to create a homogeneous air-fuel mixture. An air-assist injector was installed for port fuel injection, and the intake manifold was heated to several target temperatures. The 60°C intake temperature yielded the highest BTE across all tested loads, with values ranging from 21.3% to 22.3%. Consequently, this temperature also produced the lowest BSFC, ranging from 362.6 to 384.2 g/kWh. Across all intake temperature settings, three-stage ignition was observed at 15% and 20% loads, indicating the presence of diffusion combustion following the high-temperature combustion phase. At 25% load, all temperatures exhibited advanced ignition characteristics, with the peak HRR occurring before TDC. Notably, the 60°C intake temperature resulted in engine knocking at 25% load, with peak in-cylinder pressure exceeding 90 bar. The highest HC emissions were observed at an intake temperature of 45°C, followed by 50°C, 55°C, and 60°C. This trend is attributed to incomplete combustion, as lower temperatures hinder the spontaneous chemical kinetic reactions between the fuel and air. These findings correspond to the lowest BTE being recorded at 45°C compared to the higher temperature settings. The 60°C intake temperature recorded the highest NOx emissions, with values ranging from 10 to 14 ppm. Conversely, the lowest intake temperature setting of 45°C resulted in the lowest NOx emissions compared to all other temperature settings. The highest CO emissions were recorded at an intake temperature of 45°C. As the load increased, CO emissions exhibited a decreasing trend across all settings. Higher intake temperatures shortened the stable operating range of HCCI combustion with the 60°C setting resulted in engine knocking at 25% load. The air-assist system improves atomization and promotes a uniform air-fuel mixture. By utilizing pressurized air to break the fuel into finer droplets, this system reduces the requirement for high-pressure injectors while enhancing the homogenization of the charge. The experiment could be extended to other fuel such as biodiesel. One of the advantages of HCCI combustion is fuel flexibility and the results for this experiment could serve as a reference for other types of fuel.

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Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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