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The Impact of Air Pressure on Performance, Combustion Behavior, and Emissions of An Air-assisted Port Fuel Injection HCCI Engine

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ABSTRACT

Low-temperature combustion is achieved through homogeneous charge compression ignition (HCCI), which lowers the emission of nitrogen oxides (NOx) associated with diesel engines. HCCI combustion faces various obstacles, including combustion phasing, high hydrocarbon (HC) emissions, a limited operation range, and homogeneous mixture preparation. This research aims to compare the influence of air pressure in an air-assisted injector on performance, combustion behavior, and emissions. The experiment was conducted at an intake temperature of 50°C, speed of 2100 RPM and air pressures of 3,4 and 5 bar. Intake air was heated in an intake pipe heater, and an air regulator regulated the air pressure. An air assist pressure of 5 bar resulted in the highest brake thermal efficiency, ranging from 20.5% to 23.3%. For brake-specific fuel consumption, an air pressure 3 bar produced higher values ranging from 410.8 g/kWh to 500.8 g/kWh. The in-cylinder pressure for 3,4 and 5 bar pressure exceeds 80 bar at 25% load. Air pressure of 4 bar recorded the lowest HC, ranging from 50 to 75 ppm. For NOx emission, 3 bar air pressure showed the lowest levels, ranging from 8 to 12 ppm across the tested loads. The highest carbon monoxide (CO) percentage was recorded at 5 bar air pressure at 20% load with a CO value of 0.53%. At 20% and 25% load, the combustion profile displayed a three-stage ignition process, indicating the occurrence of diffusive combustion.

Keywords: Air assisted, diesel, fuel injection, HCCI, internal combustion engine, port fuel injection

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INTRODUCTION

Internal combustion has been dominated by spark ignition (SI) and compression ignition technology (CI) technologies. In traditional SI engines, the spark plug ignites the homogeneous charge of fuel-air. In compression ignition (CI) engines, the combustion is facilitated by the high compression of the homogenous charge of fuel and air mixture inside the combustion cylinder. The depletion of fossil fuels and growing environmental concerns have prompted research to find alternative fuels for sustainable energy solutions. Experimental research on biodiesel by several researchers (Zheng & Cho, 2024; Engine, 2023; Khujamberdiev & Cho, 2023; Zheng & Cho, 2023; Khujamberdiev et al., 2023) shows that castor oil and swine oil can be mixed with diesel without the need for major engine modifications. Various combustion technologies have been developed to enhance internal combustion in both spark ignition and direct injection engines, with particular attention paid to improving the fuel and air mixture. More researchers are involved in the study of advanced combustion to improve engine efficiency and emissions in internal combustion. Premixed charge compression ignition (PCCI), reactivity-controlled compression ignition (RCCI) and homogeneous charge compression ignition (HCCI) are some of the advanced combustion modes based on the conventional CI and SI technologies. The PCCI combustion mode uses two fuels with different reactivity injected at the intake port and the cylinder. RCCI also uses a dual-fuel injection method, and the ignition timing is controlled by changing the ratio of these two fuels. Figure 1 shows the different combustion modes in internal combustion. One of the combustion technologies that has attracted significant interest is HCCI. HCCI combines spark ignition and compression advantages for better combustion performance. The air-fuel mixture is premixed and compressed at high pressure to auto-ignite the charge in the HCCI engine (Pandey et al., 2018).

Managing combustion phasing in HCCI combustion is challenging. In traditional SI engines, spark timing controls combustion, while in CI engines, the fuel injector controls the injection. In HCCI, the fuel and air mixture are homogenously premixed before combustion with auto-ignition depending on factors such as intake temperature, mixture

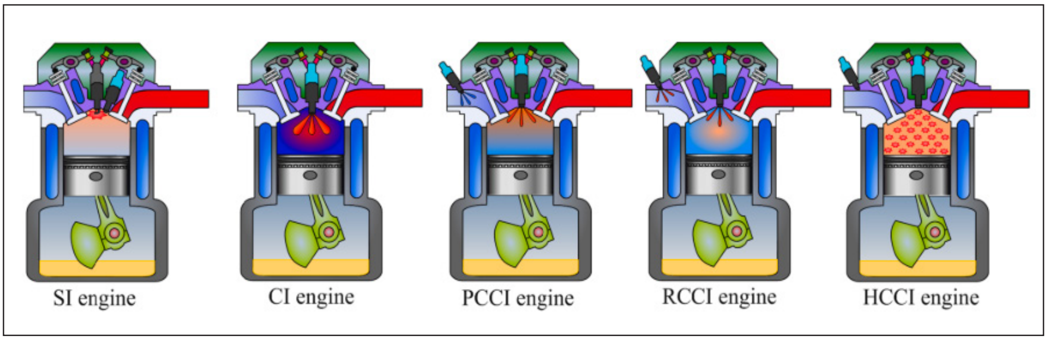

Figure 1. Combustion mode in internal combustion engine (Duan et al., 2021)

homogeneity, compression ratio, fuel properties and more. High unburned hydrocarbon (UHC) and carbon monoxide (CO) emissions, cold start issues, and homogenous mixture preparation are some of the obstacles in HCCI (Yao et al., 2009).

The HCCI engine is associated with the low-temperature combustion (LTC) method. A higher degree of dilution minimizes combustion temperature and prolongs the ignition delay. This extended ignition delay reduces homogeneities in the reactant mixture and allows the fuel to evaporate, which in turn reduces the production of nitrogen oxides (NO_X) from locally hot zones and soot from locally fuel-rich zones (Kumar & Rehman, 2016).

Two mixing strategies can reduce the local fuel regions. The strategies for mixture preparation are either in-cylinder direct injection or external mixture, as shown in Figure 2.

Effective mixture preparation and avoiding wall wetting are critical for improving fuel economy, lowering hydrocarbon (HC) and particulate matter (PM) emissions, and preventing oil dilution. Fuels with low volatility, such as diesel, are challenging for HCCI combustion. Elevated intake air temperature or fuel atomizer is used for better fuel and air mixture formation. Port fuel injection (PFI) is one of the external mixture formation methods used to create a better homogenous mixture of fuel and air, improving combustion effectiveness. Ganesh and Nagarajan investigated HCCI combustion of diesel fuel using PFI with a fuel vaporizer. Experiments were performed both without EGR and with varying percentages of EGR. Low NOx and smoke emissions were obtained, with fuel consumption 12% higher than the standard diesel operation when the engine was operated with 30% EGR (Ganesh & Nagarajan, 2010). The performance comparison of diesel and biodiesel in HCCI mode was investigated by Singh et al. (2014) using the PFI strategy. It was discovered that combustion is more stable in biodiesel HCCI than diesel HCCI because of the lower heat release rate (RoHR) rate in biodiesel. Fuel adaptability is one of HCCI's benefits. Maurya and Agarwal (2014) examined the performance, combustion, and emission characteristics of an HCCI engine powered by ethanol and methanol and compared the results to baseline gasoline fuel. Experiments were performed on a modified HCCI engine operating at varying intake air temperatures and relative air fuel ratios using ethanol and methanol as fuels. Compared to ethanol and methanol, gasoline requires higher

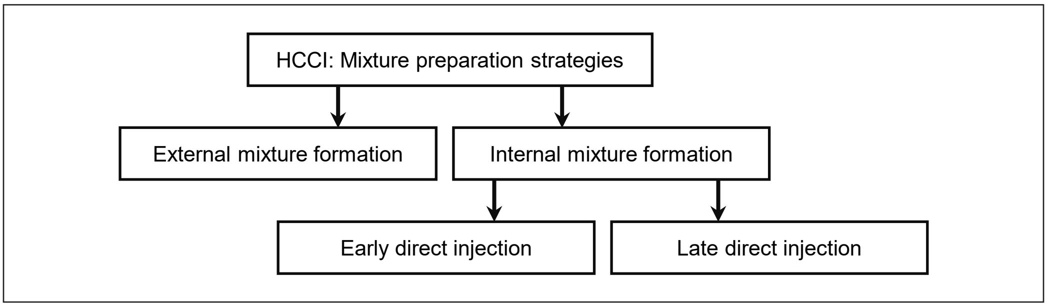

Figure 2. Strategies for mixture preparation (Bendu & Murugan, 2014)

engine speeds and intake temperatures. Port injection pressure has a considerable impact on the performance and emissions of an HCCI engine (Gowthaman & Gobikrishnan, 2021) used fuel injection pressure of 2,3 and 4 bar to study fuel penetration and mixing quality in an HCCI engine. The HCCI engine operating at 3 bar exhibits superior brake thermal efficiency (BTE) values under all loading conditions and produces approximately 10% more power than a normal diesel engine. Increasing the air intake temperature also helps the auto-ignition of the HCCI combustion, as studied by Dhileepan et al. (2023), Teoh et al. (2021) and Parthasarathy et al. (2020).

Most researchers have used fuel vaporizers for low-volatility and high-viscosity fuels to facilitate mixture formation. One of the less common methods involves using air assistance for external formation. Early studies on air-assisted injection have focused on the spray and atomization characteristics of the injector (Wu et al., 2020; Kourmatzis et al., 2013; Fan et al., 2014; Das & Dent, 1994). Cathcart and Zavier (2000) studied the basic characterization of Orbital's pressure air-assisted, spray-guided combustion system, considering the effect of in-cylinder charge motion, injected gas composition and injection pressure. The studied combustion system has demonstrated the potential to operate more stratified with reduced fuel consumption and emissions at a nominal injection pressure of 6.5 bar gauge. Two-phase injectors in constant volume chambers and optical engines have been studied using laser diagnostic and computational fluid dynamic techniques by Boretti et al. (2007). The characteristics of air-assisted fuel injection in a constant volume space have also been explored by Wu et al. (2019). Kerosene was used under different gasoline direct injection (GDI) engine conditions. As the chamber pressure increased from 0.5 bar to 3.5 bar, the penetration decreased because of air and fuel interface differential pressure reduction and resistance to penetration.

Previous studies have concentrated on the direct injection performance and characteristics of air-assisted fuel injectors (Saikalis et al., 1993; Jin et al., 2004; Leach et al., 2005). The application of air-assisted injection has been extended to homogenous charge compression ignition-direct injection (HCCI-DI) combustion. A homogenous mixture of fuel and air is prepared upstream of the intake manifold, known as PFI. This method avoids the wall wetting on the cylinder walls. Air-assisted injection can replace the high-pressure PFI injection used by many researchers. Teoh et al. (2021) investigated the impact of premixed ratio and intake temperature on combustion behavior in a partial HCCI-DI diesel engine. Significant advancement in the start of combustion, along with higher HC and CO emissions, was observed along with the pressure rise when the premixed ratio was increased. An increase in intake temperature improved the HC emissions but contributed to higher CO and NOx being released.

This study aims to assess the influence of air assist pressure in a single-cylinder HCCI engine on its performance, combustion behavior, and emissions. Three different air pressure settings, 3, 4 and 5 bar, are evaluated. The fuel and air are mixed via port fuel injection using a low-pressure pump and air compressor.

MATERIALS AND METHODS

Experimental Setup

A single-cylinder, four-stroke direct injection (DI) diesel engine was employed in this study. The technical specifications of the diesel engine are shown in Table 1. The engine was connected to an eddy current dynamometer, allowing the engine load to be varied. In this experiment, the load varied from 5% to 25%. Fuel consumption was recorded manually using a burette and a stopwatch. Brake power and torque were recorded using dynamometer software. The in-cylinder pressure was measured with an Optrand pressure sensor and recorded on a computer using customized software.

Figure 3 shows the setup of the diesel engine. The engine was fitted with an intake pipe with a coil heater. The intake manifold was equipped with a Type-K thermocouple sensor, while the exhaust temperature was measured using another Type-K thermocouple sensor. The air-to-fuel ratio was measured using a Bosch wideband Innovate Motorsport sensor, displayed through MTX-L digital air/fuel ratio gauge. The rotational speed was measured with a

Table 1
Technical specification of the engine

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

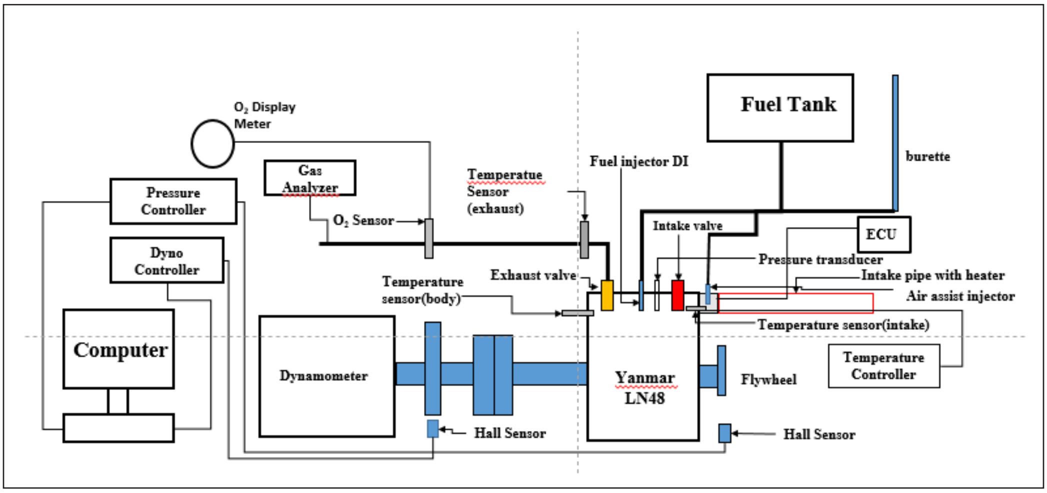

Figure 3. Setup of the port fuel injection air-assisted HCCI

Hall sensor and fed to the dynamometer software. The intake manifold was fitted with a Synerjet Strata air assist injector, supplied using a compressor via an air pressure regulator. The injector properties are given in Table 2. Emissions were analyzed using the EMS 5002 Portable Gas analyzer. Figure 4 shows the experimental engine setup.

Diesel is supplied via direct injection at the beginning of the experiment. Once the engine is stable, the manual valve supplying fuel for the direct injection is closed, and fuel is supplied through PFI using an air assist injector in HCCI mode. The settings of the air assist injector were configured through Tuner Studio software (Figure 5). Figure 6 shows the air assist injector with fuel injector and rail. The air temperature intake was

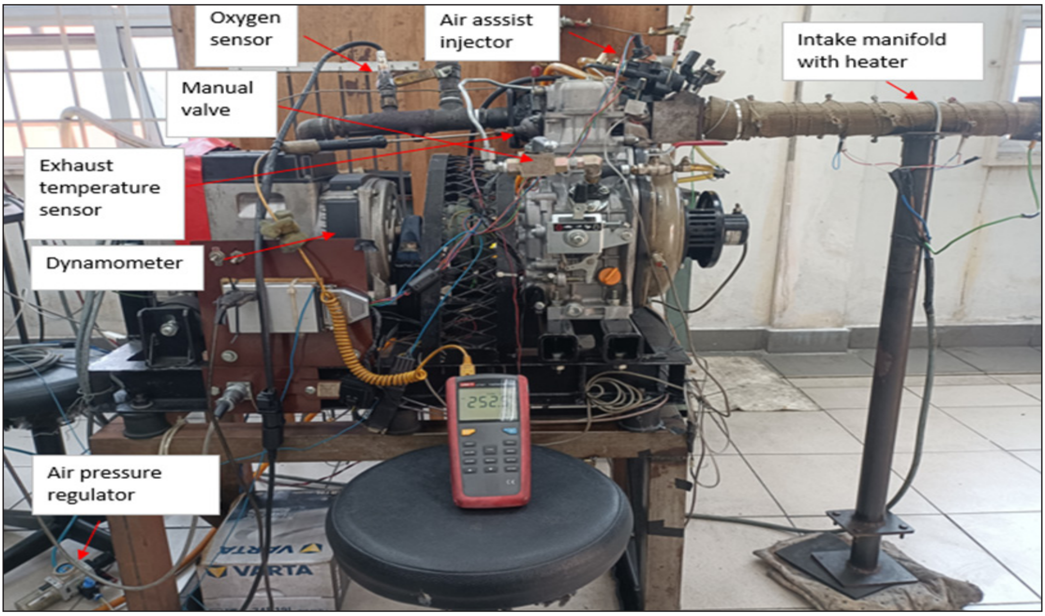

Figure 4. Experimental setup of air-assisted HCCI engine

Figure 5. Tuner Studio software for the air assist injector

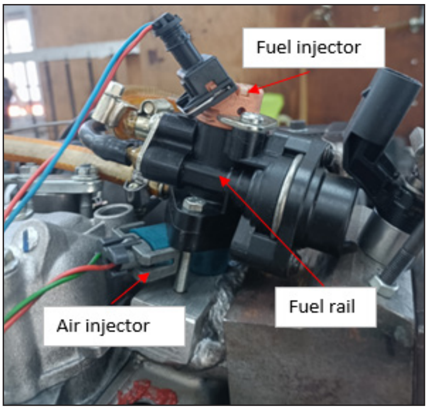

Figure 6. Air assist injector

controlled using Watlow series 988 temperature controllers. Air pressure varied at 3, 4 and 5 bar via the air pressure regulator. The intake temperature was set at 50°C, and the load was adjusted to 5%,10%,15%,20% and 25% at 2100 rpm. Table 3 shows the parameter settings for the experiment. All recorded power, in-cylinder pressure, and emission readings were repeated three times for each air pressure setting to ensure consistency.

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

Fuel Properties

For this experiment, Petronas diesel Euro 5(B0) was used as the fuel. The diesel was obtained from Pandamaran Synergy Petroleum. The physical and thermal properties of diesel fuel were tested according to American Society for Testing and Materials (ASTM) standards, and the results are presented in Table 4.

Table 3
Experimental parameter settings for HCCI

Description	Specification
Air assisted pressure	3, 4 and 5 bar
Load	5, 10, 15, 20 and 25%
Intake temperature	50°C
Speed	2100 rpm
Mode	PFI

Table 4
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

RESULTS AND DISCUSSION

Effect of Air Pressure on Engine Performance

Figure 7 shows brake power variation with increasing load. At a 5% load, the brake power for all air assist pressures showed no significant difference, varying from 0.63kW to 0.66kW. As the load increased, the brake power for 5 bar rose higher than that for 3 and 4 bar pressure. The brake power at 5 bar air assist pressure increases by 63.7%, with values ranging from 0.66kW to 1.82kW as the load increases from 5% to 25%. As load increases, brake power increases as more fuel is supplied for combustion. The 4 bar air pressure brake power range is from 0.66kW to 1.67kW. An air pressure of 3 bars recorded the lowest brake power, ranging from 0.63kW to 1.59kW. At 25% load, brake power of 1.59kW, 1.67kW and 1.82 kW were recorded for air pressure of 3,4 and 5 bar, respectively.

BTE variations with varying air assist pressure are shown in Figure 8. An air assist pressure of 5 bar demonstrates a higher BTE compared to 3 and 4 bar air pressure, with BTE values ranging from 20.3% to 23.3% as load increases. Air assistance at 3 bar shows the lowest BTE across all load conditions compared with the other pressure, with values ranging from 16.3% to 19.7%. The 4-bar air assist pressure shows BTE values ranging from 16.5% to 20.5%. At 25% load, the air assist pressure of 5 bar shows an 18.3% improvement compared to 3 bar. The significant improvement in BTE percentage shows that higher pressure of air assistance substantially affects the performance of HCCI combustion. The atomization of diesel fuel was improved with the introduction of higher air-assisted pressure.

Figure 9 compares brake-specific fuel consumption (BSFC) for all air pressure settings. At a low load of 5%, the air pressure of 5 bar demonstrates the lowest BSFC of 398.9 g/kWh compared with 3 and 4 bar air pressure, which shows values of 500.8 g/kWh and 494.5 g/kWh, respectively. As load increases, the BSFC for 5 bar air pressure shows a significant difference compared to the 3 and 4 bar, with values ranging from 398.9 g/kWh to 347.5 g/kWh. For 3 bar air pressure, BSFC varies from 500.8 g/kWh to 410.8 g/kWh. For 4 bar, the BSFC decreases from 494.5 g/kWh to 365.1 g/kWh as the load increases from 5% to 25%. Mixture preparation has a significant effect on fuel efficiency. For HCCI operation, proper mixing of air and fuel is necessary to form a homogeneous charge. Thus, 4 and 5-bar air pressure shows better BSFC as the fuel disintegrates into smaller droplets, enhancing air and fuel mixing.

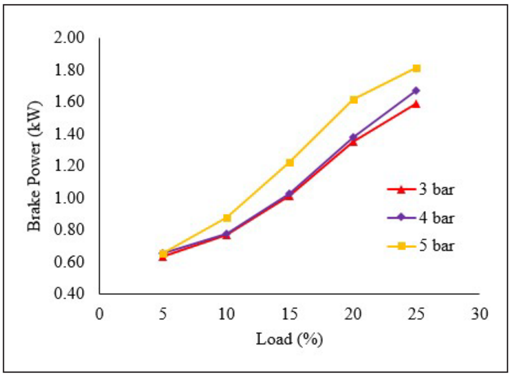

Figure 7. Brake power variation with varying air assist pressure

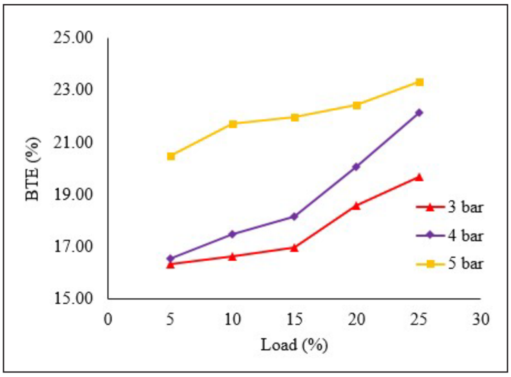

Figure 8. Brake thermal efficiency variation with varying air-assisted pressure

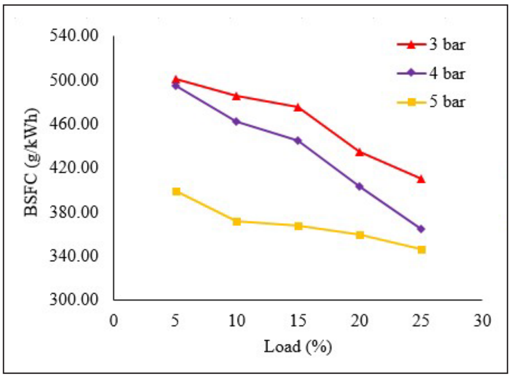

Figure 9. Brake-specific fuel consumption with various air assist pressure

Effect of Air Pressure on Combustion Characteristics

The combustion behavior of an internal combustion can be observed through the in-cylinder pressure and heat release rate(HRR) profile. Canova et al. (2007) performed an experimental study on an HCCI engine with a fuel atomizer to observe the cylinder pressure and net heat release against the crank angle. One of the indicators of combustion behavior in HCCI combustion is HRR analysis, which is determined using the cylinder pressure data illustrated by Equation 1 (Ganesh & Nagarajan, 2010).

$$\frac{dQ}{d\theta} = \frac{\gamma}{\gamma - 1} * P * \frac{dv}{d\theta} + \frac{1}{\gamma - 1} * v * \frac{dP}{d\theta} \qquad [1]$$

The combustion process for HCCI diesel uses a two-stage heat release. A small percentage of the total energy (7%–10%) is released during the first stage of heat release, which is caused by low-temperature reactions (LTR), and a larger fraction is released during the second stage, which is caused by high-temperature reactions (Hasan & Rahman, 2016).

Figure 10 displays the in-cylinder pressure and HRR profile for a 5% load. The air pressure 3 bar recorded a maximum in-cylinder pressure of 60.9 bar, which is lower than the 4 and 5 bar air pressures. The 4 and 5 air pressures recorded maximum in-cylinder pressures of 62.8 bar and 63.1 bar, respectively. The pressure profile of 4 and 5 bars also indicates earlier combustion compared to the 3-bar air pressure. The HRR profiles for 4 and 5 bars are almost similar, showing no significant difference.

As the load increases to 10%, the in-cylinder pressure and HRR also increase compared to the 5% load, as illustrated in Figure 11. The maximum in-cylinder pressure recorded by the 3, 4 and 5 bar air pressure settings is 62.4 bar, 64.2 bar and 65.8 bar, respectively.

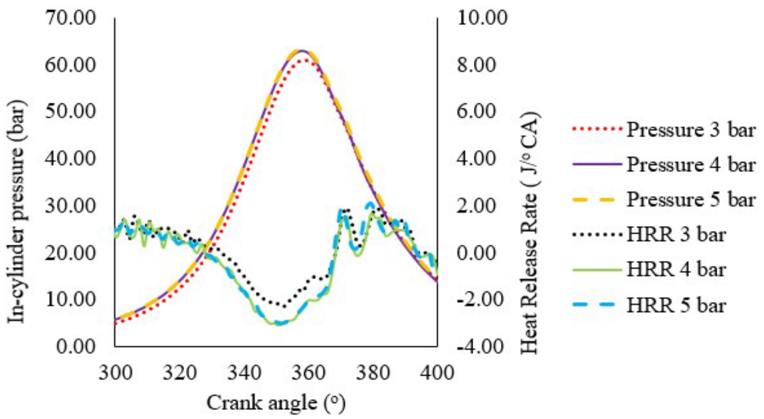

Figure 10. HRR profile and cylinder pressure at 5% load

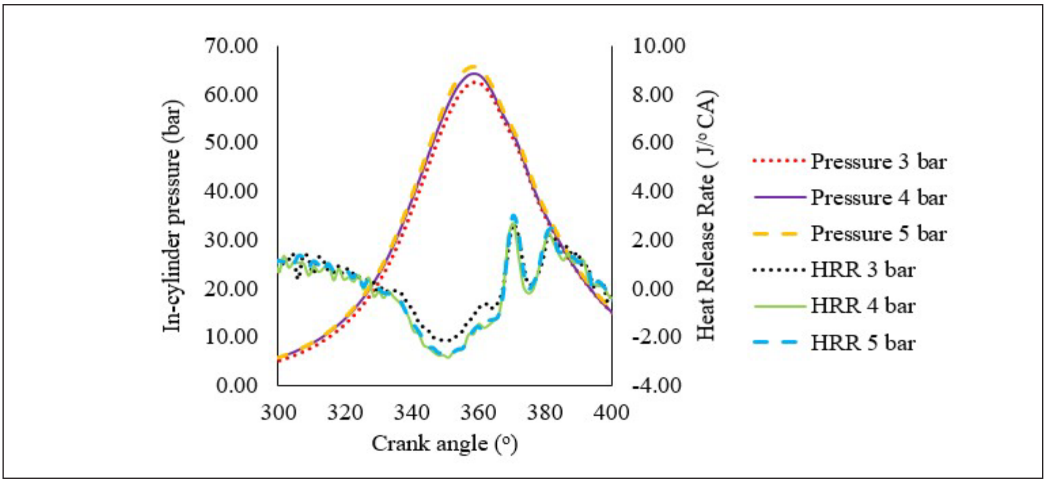

Figure 11. HRR profile and cylinder pressure at 10% load

The HRR profile shows a similar pattern as the 5% load. The HRR profile for 5% and 10% load displays two-stage ignition with almost identical combustion timing.

From Figure 12, the maximum cylinder pressure increases to 67.2 bar, 70.3 bar and 69.7 bar for air pressures of 3, 4 and 5 bar, respectively, as the load increases to 15%. The HRR generally increases for all pressure settings as more fuel is required, resulting in a lower lambda λ value. An additional spike around the Top Dead Centre (TDC) indicates that early combustion occurred compared to the 5% and 10% load.

At 20% load, the combustion phase for all air pressure is almost similar, although the maximum cylinder pressure for 3 bar air pressure recorded at 75.2 bar is lower compared to 4 and 5 bar settings. Maximum cylinder pressure for 4 and 5 bars are 79.4 bar and 78.8 bar, respectively. The maximum HRR has increased beyond 4.0 J/°CA for 4 and 5-bar air pressure, as shown in Figure 13. The HRR profile exhibits a significant three-stage ignition, with the highest peak occurring after the combustion stage. It suggests that diffusive combustion is still taking place, indicating that the fuel and air may not have mixed properly during the first stage of ignition.

Figure 14 displays the in-cylinder pressure and HRR of the HCCI engine at its maximum load. The in-cylinder pressure values have exceeded 80 bar for all air pressure settings. The maximum cylinder pressures for 3, 4 and 5 bars are 88.0 bar, 89.1 bar and 87.5 bar, respectively. Higher pressures lead to a knocking problem, a significant problem in HCCI combustion. Operating at loads higher than 25% may cause substantial noise and vibration, potentially damaging the engine. The initial spike in the HRR rate also increases significantly, indicating that early combustion has occurred. In an HCCI engine, the volumetric ignition of full charge causes rapid HRR, which could result in knocking combustion (Chaudhari & Deshmukh, 2019).

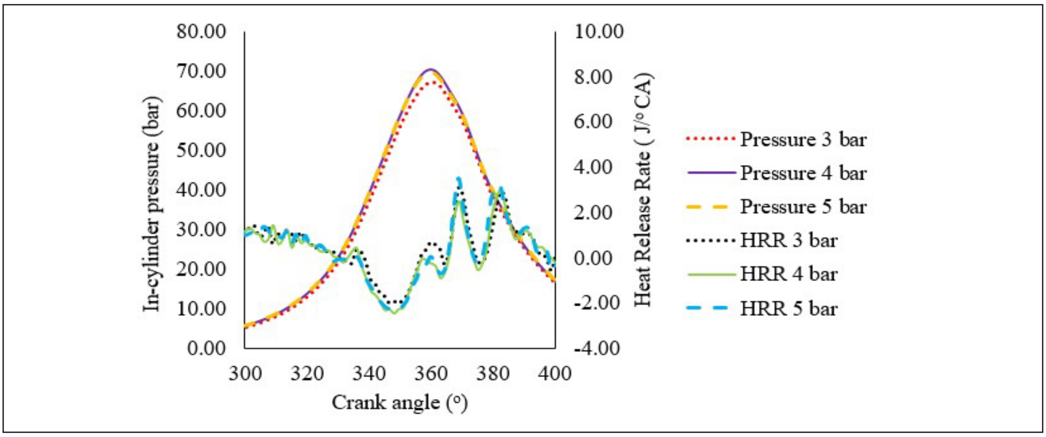

Figure 12. HRR profile and cylinder pressure at 15% load

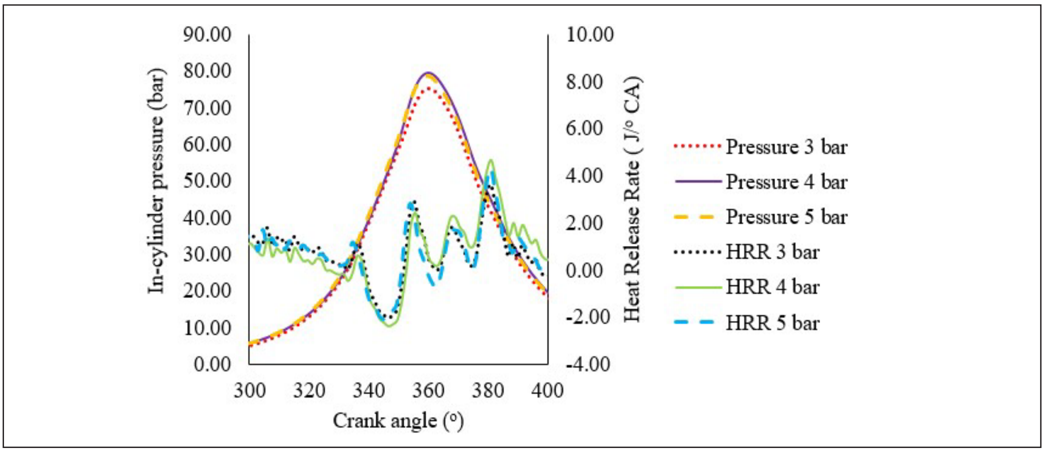

Figure 13. HRR profile and cylinder pressure at 20% load

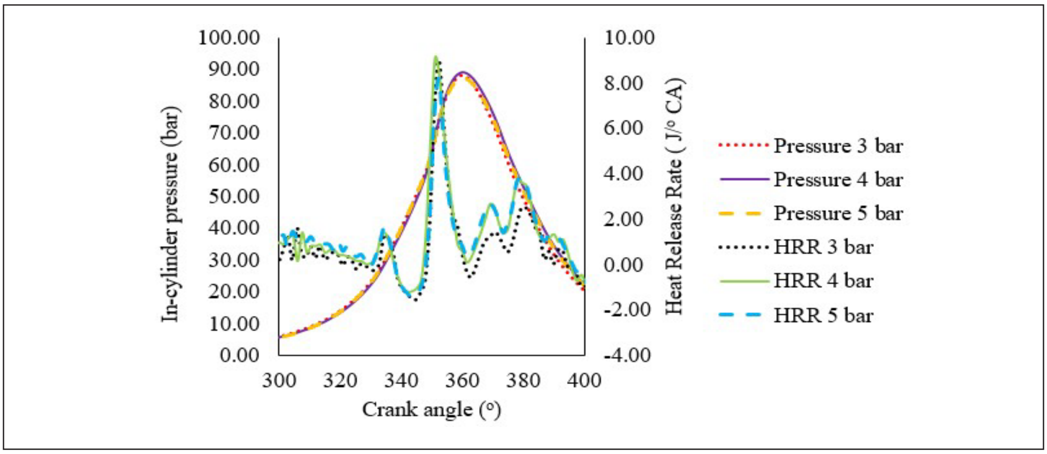

Figure 14. HRR profile and cylinder pressure at 25%

Effect of Air Pressure on Emission

HCCI allows minimal nitrogen oxide and soot emissions. Introducing oxidation catalysts into the fuel can enable low carbon monoxide emissions and unburned hydrocarbons in HCCI engines. HCCI may be a viable alternative to diesel for achieving low urban and global pollution levels due to its cleaner emissions (Saxena & Bedoya, 2013). Figure 15 shows the emission of HC and NOx. The air pressure of 4 bar recorded the lowest HC emissions, ranging from 50 to 75 ppm, compared with 3 and 5 air pressure. For 3-bar air pressure, HC values ranged from 50 to 79 ppm, while the 5-bar air pressure recorded values ranging from 44 to 91 ppm. Higher HC levels are a consequence of incomplete combustion. 3 bar air pressure shows poor mixture formation, contributing to higher HC.

For NOx emission, an air pressure of 3 bar showed the lowest ppm ranging from 10 to 12 ppm throughout the tested load compared with 4 and 5 bar air pressures. The 4-bar air pressure recorded NOx values ranging from 11 to 17 ppm, while the 5-bar air pressure showed NOx emissions ranging from 15 to 21 ppm. NOx emissions are formed by the reaction between nitrogen and oxygen at high temperatures and pressures during the combustion process in an engine cylinder (Pandey et al., 2012). Based on the HRR profile, the 5-bar air assist generally exhibits higher peaks, which contribute to higher NOx emission.

The gas analyzer also recorded the emission of carbon dioxide (CO_2) and CO, and Figure 16 compares the different air pressures used. The fuel-air equivalence ratio determines CO emissions from internal combustion engines. As shown in Figure 16, CO emission, the 4-bar air pressure recorded the lowest CO emissions, ranging from 0.11% to 0.45%. The highest CO percentage was recorded by the 5-bar air pressure at 20% load with a value of 0.53%. The percentage range of CO for all air assist pressure is almost similar, as Gowthaman and Gobikrishnan (2021) reported. The highest emission of CO_2

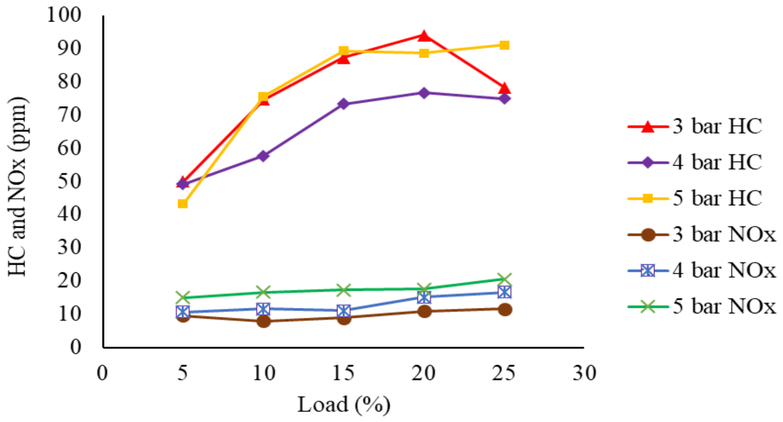

Figure 15. Emission comparison for HC and NOx for various air pressures

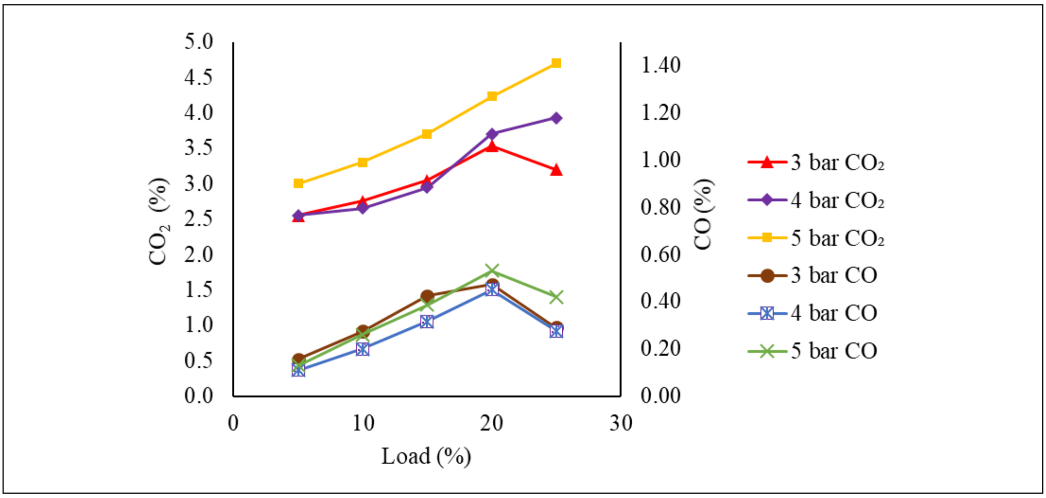

Figure 16. Emission comparison for CO and CO2 for various air pressure

was recorded by 5 bar air assists with values ranging from 3% to 4.7%. The 4-bar air assist pressure showed CO_2 values ranging from 2.6% to 3.9%.

CONCLUSION

In general, all air pressure settings (3, 4 and 5 bar) can be used to run the combustion in HCCI mode. The load can be varied from 5% to 25% without any significant knocking during combustion. The engine performance, combustion behavior and emissions have been successfully analyzed. Based on the investigation, the following conclusions can be drawn:

- BTE increases as load increases for all air pressure settings. The 5-bar air pressure recorded the highest efficiency, ranging from 20.5% to 23.3%. In contrast, the 3-bar air pressure shows the lowest BTE compared to the 4 and 5-bar air pressure settings, recording values from 16.3% to 19.7%. Fuel is atomized better with 5 bar air pressure and mixed homogenously with air, leading to more efficient combustion.
- The BSFC decreases as load increases for all air pressure settings. The 5-bar air pressure demonstrates the lowest BSFC, ranging from 346 g/kWh to 399 g/kWh. The highest BSFC was recorded by the 3-bar air pressure setting, ranging from 411 g/kWh to 501 g/kWh.
- As load increases, in-cylinder pressure also rises for all three air pressure settings. At load 5% and 10%, all pressure settings exhibit two-stage ignitions, and at load 15%, 20% and 25%, a stage ignition is recorded. At 25%, the in-cylinder pressure exceeds 80 bar, which can contribute to knocking if more load is applied.
- Higher HC emissions were observed for the 3 and 5-bar air pressure settings. The 4-bar air pressure recorded the lowest HC emission, ranging from 50 ppm to 75

ppm. The 3-bar air assist recorded the lowest value for NOx emission, ranging from 8 ppm to 12 ppm.

- The 5-bar air assist recorded the highest CO2 emissions, ranging from 3% to 4.7%, indicating high combustion efficiency. In contrast, the 4-bar air pressure exhibited the lowest carbon monoxide (CO) emissions compared to the 3-bar and 5-bar settings, with emissions ranging from 0.11% to 0.28%.

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