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GREEN ENERGY FOR ENVIRONMENTAL SUSTAINABILITY

Emissions from homogeneous charge compression ignition (HCCI) engine using different fuels: a review

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Abstract

The main objective of this paper is to review the emission characteristics of homogeneous charge compression ignition (HCCI) engines using different fuels and additives. Additionally, the impacts of various operating conditions on HCCI engine emissions are also analyzed. There is a demand faced by the engine and car manufacturers for high fuel efficiency and low emission from both consumers and the government. HCCI is an alternative internal combustion technology that is more efficient and cleaner than traditional combustion techniques. In this engine, fuel and oxidiser (typically air) are entirely mixed and compressed to the point of auto-ignition. It is a new combustion concept that provides high efficiency and resolves high nitrogen oxide (NOx) and particulate matter (PM) emissions simultaneously. Conventional diesel engine emits NOx around 2000–2500 ppm which is a primary concern; however, when diesel is used in HCCI engine, it reduces NOx to only 70–400 ppm. Furthermore, natural gas cannot be used as fuel in the conventional engine but can be used in HCCI engine. It helps reduce NOx emission even below 10 ppm. This paper reviews several works done by researchers on HCCI engines to reduce their emissions and benefit future research.

Keywords HCCI engine · Fuel · Additive · Emission · Pollution · Environment

Introduction

Spark ignition (SI) and compression ignition (CI) engines are the most widely used ground transportation engines these days. Even though both engines are reciprocating in nature, they are still different in fuel economy, power efficiency, and emissions. SI (petrol) and CI (diesel) engines use fossil fuels and contribute largely to air pollution in urban areas. A large quantity of NOx is formed in the conventional type of IC engines because of high temperature inside the cylinder. Smoke is formed within the combustion chamber due to localized fuel-rich regions and localized low-temperature zone. Photochemical smog is formed due to this NOx's reaction with atmospheric gases (Hussaini et al. 2016). PM emitted from diesel engines causes various respiratory problems like asthma, chronic obstructive pulmonary disease (COPD), lung cancer, and many more. Many emission standards are being implemented due to such adverse effects on human health because of these pollutants. They require the reduction of pollutants like PM and NOx emissions (Ohur and Kariuki 2014).

A new combustion system is required to minimize the emission level from conventional internal combustion (IC) engines. HCCI is a technique that is becoming more popular because of its capability of reducing PM and NOx emissions simultaneously by using compression ignition of the homogeneous fuel-air mixture. It is a form of IC engine in which oxidizer (mainly air) is thoroughly mixed with fuel and compressed to the point of auto-ignition. Energy released from this exothermic reaction is transformed in an engine in work and heat like other combustions. HCCI combines characteristics of conventional petrol engines and diesel engines (Janathanan et al. 2016).

HCCI engine gives improved thermal efficiency and very less emissions. It can be implemented by modifying either

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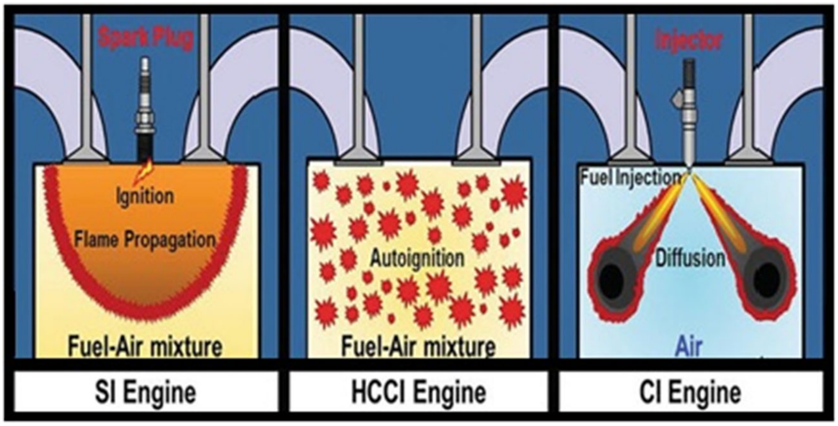

Fig 1 Comparison of SI, HCCI, and CI engines

spark ignition or compression ignition engine using any fuel type for combination. Air-fuel mixture is kept lean in HCCI engines. It automatically ignites in different locations and burns volumetrically without recognizable flame propagation. In HCCI engine, fuel delivery is essential for the controlled combustion process.

HCCI engine is a four-stroke IC engine that works similarly to SI and CI engines. Fuel is injected into each cylinder, and air is introduced into the cylinder through a separate air intake manifold during suction stroke. Fuel and air are mixed perfectly. Temperature starts increasing inside the combustion chamber due to compressed air-fuel mixture during the compression stroke. As sufficient heat is accumulated for combustion, ignition takes place without any use of a spark plug. The combustion in an HCCI engine is a lean and low temperature process (unlike SI and CI engines), and its energy is released across the entire combustion chamber. Complete air-fuel mixture is burned and produces a similar amount of power (as SI or CI engine) by using lesser amount of fuel and releasing very few emissions. At the end of the power stroke, an exhaust stroke is initiated. Still, exhaust valves close before all of the burned gases can be evacuated, trapping some amount of latent heat of combustion. This heat is preserved, and small amount of fuel is injected inside the combustion chamber through the inlet valve for pre-charging before the next intake stroke begins (Mulane and Limaye 2016) (Fig. 1).

Lean combustion in HCCI increases the fuel efficiency by 15% over the conventional SI engine. It has lower emissions (especially NOx) than a conventional CI engine. Fuel is burned quicker and at a lower temperature which reduces heat energy losses. Also, the overall engine noise, vibration, and harshness are lower than conventional engines. HCCI engine does not require any external aid to initiate the combustion process. A variety of fuels can be used in the HCCI engine, which also helps in reducing emission losses. Low-pressure fuel injection system is used, and a spark plug is also not required, making manufacturing cheaper. Also, it has the least throttle losses (Hasan and Rahman 2016).

Although HCCI has an advantage over conventional engines in terms of thermal efficiency and NOx emission, its combustion has many difficulties. Combustion in HCCI engines is achieved by controlling the pressure, temperature, and composition of the air-fuel mixture to ignite itself when the piston reaches top dead centre (TDC). It is more complex than a direct control mechanism like a fuel injector in the CI engine or a spark plug in the SI engine, which controls ignition timing. High cylinder pressure in HCCI needs more robust engine construction, which makes it expensive. Otherwise, there is a risk of explosion due to high energy produced during power stroke. Also, it has limited power and a small torque range compared to SI engine. Although it has less NOx emission, high hydro-carbon (HC) and carbon monoxide (CO) emissions are compared to the SI engine. HCCI engine has weak cold start capability, and difficulty is also faced in preparing homogeneous charge mixture (Venkataramana 2013).

Conventional fuels like petrol and diesel are the main causes of emissions from automobiles. It is understood that HCCI technology offers better fuel economy and emissions control; however, it is not confident that these engines will deliver these characteristics inexpensively. Continued advancement is necessary to bring it into the daily production of the vehicle. These challenges must be overcome for the mass production and implementation of HCCI engines in the daily production of the vehicle. This paper reviews several works done by researchers on the HCCI engine to reduce its emission. Prospective fuels for HCCI engines to get minimum emission are also discussed. This compilation will be beneficial for carrying out future research in this field.

Emissions from HCCI engine

Natural gas

Yao et al. (2006) performed a study to find controlling strategies of HCCI combustion fuelled with methanol and dimethyl ether. Experiments were performed on a single-cylinder–modified direct-injection diesel engine which was water-cooled. NOx emissions were observed very low for the HCCI engine at 1400 rpm, and 0.64 MPa indicated mean effective pressure (IMEP) and varying die-methyl ether (DME) and exhaust gas recirculation (EGR). Till 10% EGR, NOx emission was around 30 ppm. At higher EGR like 25%, 40%, and 65%, NO_X emission was very less, even less than 10 ppm. NOx emission increases sharply when knocking occurs up to 70 ppm. HC and CO emissions in HCCI engine were analyzed at 1400 rpm and 0.44 MPa IMEP and varying DME and EGR. On increasing EGR rate from 0 to 65%, keeping DME at around 62%, HC and CO emission was around 0.3–0.4%. DME was increased to around 74%; HC emissions reduced to less than 0.15%, and CO emissions reduced to less than 0.1%. Exhaust gas recirculation and dimethyl ether have a considerable effect on the performance and emission of HCCI engine.

He et al. (2013) studied the combustion characteristics and emission characteristics of an HCCI engine fuelled by n-butanol. Experiments were performed on a four-stroke single-cylinder gasoline engine equipped with variable valve lift (VVL) and variable valve timing (VVT) devices on both the valve intake and exhaust. It was observed that for 1500 rpm, 63° CA after top dead centre (ATDC), and 0.26 MPa IMEP, NOx emission was 40–60 ppm whereas for 2000 rpm, 43° CA ATDC and 0.158 MPa IMEP, it was 10–20 ppm. Very less amount of NO emission was observed as compared to other conventional engines. Methanol emission was around 15–16 ppm for 1500 rpm and 13 ppm for 2000 rpm; however, ethanol emission was 345–360 ppm for 1500 rpm and 270–300 ppm for 2000 rpm.

Maurya and Agarwal (2010) performed experiments to study the combustion and emission characteristics of HCCI combustion engine running on ethanol. A four-stroke two-cylinder engine was used, which was naturally aspirated, air-cooled, and bowl-shaped combustion chamber. Direct injection diesel engine was modified for experiments. An experiment was performed at 1500 rpm, and intake air temperature of fuel was maintained between 120 and 150°C to analyze different emission parameters. HC emission was 200–400 ppm at 120 °C for a range of "λ" value from 2 to 3.5. However, at 150 °C, it was 175–225 ppm for a range of "λ" value from 3 to 5. CO emission ranges from 0.1 to 0.8% for different temperatures and different "λ" values. NOx emission for all the temperatures was found to be less than 10 ppm. Results show that NOx emissions are lower than 10 ppm for all stable operation points; however, HC and CO emissions were higher.

Tsolakis et al. (2007) studied the exhaust gas fuel application of reforming in diesel and HCCI engines fuelled with biofuels. They explained the exhaust gas fuel-reforming benefits by adding simulated reformed gas to a diesel engine which was fuelled by the mixture of 50% ultra-low sulfur diesel and 50% rapeseed methyl ester, referred to as B50. They also used a HCCI engine that uses bio-ethanol. It was observed that at 4.5 bar IMEP and 2.6 "λ", exhaust gas composition was 0.01% CO, 12.6% O_2, 4.76% CO_2, and 5.02% H_2O. Also, as the percentage by volume of EGR increases from 0 to 20%, NOx emission is reduced from 700 to 400 ppm, and on increasing reformed EGR (REGR) by same, NOx emission reduced from 700 to 650 ppm for fuel injection at standard 22° BTDC. As fuel injection is retarded to 19° BTDC, NOx emission is found to be 700–550 ppm. At 6.1 bar IMEP and 2.14 λ, exhaust gas composition was 0.01% CO, 10.8% O_2, 6.3% CO_2, and 6.4% H_2O. NOx emission decreased from 1050 to 600 ppm for EGR and 1050 to 800 ppm for REGR.

Olsson et al. (2001) worked on a dual-fuel turbocharged HCCI engine. A 6-cylinder truck engine was modified for dual fuel turbocharged HCCI engine operation. Ignition timing was controlled by using two different fuels, ethanol and n-heptane. A study was done to demonstrate high load operation of a HCCI engine. As the load was increased at high speed, HC emission reduced from 10 to 8 g/kWh, and at low speed, it was around 6–7 g/kWh. The same trend can be seen in CO emission also. At high speed, CO emission reduced from 90 to 20 g/kWh on increasing the load; and at low speed, CO emission was around 10–15 g/kWh. It was observed that NOx emission increases with an increase in load; however, even at the highest load condition of 16 bar break mean effective pressure (BMEP), NOx was less than 4 ppm (0.063 g/kWh).

Again Olsson et al. (2003) performed experiments to study the cooled EGR effect on emissions and performance of turbocharged HCCI engine. A six-cylinder D12 truck engine was modified for this study. Ethanol and n-heptane port fuel injection was used. For the closed-loop combustion control, cylinder pressure sensors were also used. It was observed from the experiment that, for intermediate loading of 11.5 bar, HC emission reduces from 40 to 20g/kg_{fuel} when EGR is increased from 0 to 60%; and for intermediate loading of 7.5 bar, HC emission reduces from 25 to 10 g/kg_{fuel}. Maximum CO emission is 22 g/kg_{fuel} for both 11.5 and 7.5 bar load conditions and reduces to around 10 g/kg_{fuel} on increasing EGR rate. Observing for NOx emission at 11.5 bar, it was found that it ranges between 0.02 and 0.07 g/kWh. When a turbocharger is used at 1600 rpm and 11 bar BMEP, NOx emission for no EGR condition is between 15 and 25 ppm and for 45% EGR, NOx ranges between 20 and 35 ppm.

Polat (2015) performed experiments to study engine performance, combustion, and emission characteristics of HCCI engine using diethyl ether blend and ethanol. Four-stroke single-cylinder HCCI engine with port injection was used. Mixture of diethyl ether and ethanol was used in the experiment in the ratio like 30% ethanol–70% diethyl ether (E30/D70), 40% ethanol–60% diethyl ether (E40/D60), 50%

ethanol–50% diethyl ether (E50/D50), and 100% diethyl ether (DEE). Observations were taken at a fixed speed of 1200 rpm. For E30/D70 mixture, if inlet temperature was fixed at 353 K and "λ" is increased from 1.5 to 3, CO emission reduced from 0.09 to 0.07% and HC emission reduced from 230 to 180 ppm. However, on fixing "λ" at 2 and increasing temperature from 333 to 393 K, CO emission reduced from 0.05 to 0.07%, and HC emission reduced from 330 to 240 ppm. For E40/D60 mixture, on increasing λ from 1.46 to 2.25 at same 353 K, CO emission reduced from 0.08 to 0.05%, and HC emission reduced from 290 to 220 ppm. But on fixing "λ" at 2 and increasing temperature from 333 to 393 K, CO emission reduced from 0.14 to 0.1%, and HC emission reduced from 425 to 360 ppm. For E50/D50 mixture, if inlet temperature was fixed at 353 K and "λ" is increased from 0.8 to 1.6, CO emission reduced from 0.15 to 0.11%, HC emission reduced from 340 to 300 ppm, and NOx emission ranges between 94 and 40 ppm. But on fixing "λ" at 1 and increasing temperature from 333 to 373 K, CO emission reduced from 0.22 to 0.16%, HC emission reduced from 460 to 400 ppm, and NOx emission increased 75 to 117 ppm. For DEE, if inlet temperature is fixed at 353K and increased "λ" from 1.59 to 2.85, CO emission reduced from 0.065 to 0.04% and HC emission reduced from 190 to 140 ppm.

Ying et al. (2009) performed a comparative study of emission and combustion characteristics of HCCI engine and HCCI-DI engine. A four-stroke single-cylinder naturally aspirated direct injection diesel engine fuelled with dimethyl ether was used for the experiment. Observations were taken for different values of "*r*" which was ratio of the mass consumption rate of port aspirated DME fuel and total mass of fuel. For 18% "*r*" ratio, NO_X emission increases from 150 to 350 ppm on increasing BMEP, and as "*r*" ratio is increased to 1, NOx emission decreases to almost 10 ppm. Maximum NOx emission was found to be 700 ppm for direct injection compression ignition (DICI) engine. Maximum HC emission reduced from 1080 for 100% "*r*" ratio to 300 ppm for 18% "*r*" ratio at low load condition. As load is increased, HC emission was further reduced to 500 ppm for 100% "*r"* ratio and almost 0 ppm for other "*r*" ratio values. On increasing load from 0.05 to 0.35 MPa BMEP, CO emission reduced from 2.2 to 0.1% for 100% "*r*" ratio. But for 18%, 26% and 33% "*r*" ratio, CO emission increases on increasing the load. As EGR was increased from 0 to 12%, NOx emission reduced from 50 to 20 ppm for 33% "*r*" value and from 72 to 60 ppm for 26% "*r*" value. HC emission increased from 350 to 450 ppm for 26% "*r*" value and from 440 to 520 ppm for 33% "*r*" value. CO emission increased from 0.2 to 0.35% for 26% "*r*" value and from 0.45 to 0.6% for 33% "|*r*" value.

Yap et al. (2005) experimented with studying exhaust gas fuel reforming on HCCI engine operation worked on natural gas. Modified single-cylinder SI engine was used for compression ratio from 10.5 to 15 at 1500-rpm engine speed. CO emission increased with REGR addition was observed during emission characteristics. CO emission is 0.16% for 10% H_2 in 5% REGR, 0.18% for 15% H_2 in 5% REGR, and 0.06% for HCCI combustion without H_2 supply. Similarly, HC emission also increased with the addition of H_2 in REGR. HC emission increased to 210 ppm if 15% H_2 was supplied with 5% REGR and 200ppm at 10% H_2 with 5% REGR. But NO_X emission decreases on supplying H_2 with REGH. NO_X emission reduced to 300 ppm if 15% H_2 was supplied with 5% REGR and 500 ppm at 10% H_2 with 5% REGR compared to 800 ppm for no EGR condition.

Maurya and Agarwal (2014) modified a four-cylinder four-stroke engine and experimented with different engine speeds by preparing homogeneous charges using port fuel injection. Air-fuel mixture was auto ignited by air preheater intake in the combustion chamber. Heat release curve for calculating combustion parameters was used. NOx emission was below 10 ppm till 1800°C of mean cylinder temperature, but after that, it boosts to 70–90 ppm; however, in conventional mode, NOx emission ranges around 2000–2500 rpm. Highest CO emission was observed to be 55 g/kWh for methanol. However, it was lower in the case of gasoline-fuelled engine. It was found that HC emission was reduced by advancing the combustion timing. The highest HC emission was 18.4 g/kWh at the lowest engine load for gasoline in HCCI mode.

Mack et al. (2009) investigated heat release rates, intake temperatures, engine operating limits, and exhaust emission parameters for the engine operating with 40%, 60%, 80%, 90%, and 100% ethanol-in-water mixtures. It was observed that HC emission was above 1000 ppm for E60/W40 mixture, between 400 and 600 ppm for E80/W20 mixture, and less than 200 ppm for 100% ethanol fuel. Similarly, CO emission was also highest for E60/W40 mixture going maximum to 1400 ppm and least for 100% ethanol fuel around 500 ppm. Also, NOx emission for 100% ethanol fuel was around 0.5–4 ppm; and for E60/W40 mixture, it was 4–8 ppm. It was concluded that CO, HC, and NO emissions increased, but O_2 emission decreased with increasing water content in fuel.

Gharehghani (2018) investigated three fuels: natural gas, ethanol, and methanol, for finding load limits vis-a-vis proper operating range for each type of fuel. A single-cylinder variable compression ratio diesel engine of 507cc volumetric capacity was used for experiments. In this study, for stable HCCI operation, a high load limit was defined by the knock phenomenon and low load limit by combustion stability. CO emission for natural gas ranges between 1.5 and 6.5 g/kWh, whereas for ethanol and methanol, CO emission ranges between 0.7 and 5.8 g/kWh, which was less than natural gas. Similarly, HC emission for natural gas was around 0.8–4.2 g/kWh, whereas for ethanol and methanol, it ranges between 0.35 and 4.9 g/kWh. NO_X emission for natural gas was around 0.02–0.12 g/kWh, whereas for ethanol and methanol, it was around 0.06–0.26 g/kWh and 0.05–0.45 g/kWh, respectively.

Therefore, ethanol and methanol could be used for the lean mixture (low loads) and lower intake temperatures. In contrast, natural gas should be used for HCCI for the rich mixture (high loads) and higher intake temperatures. Methanol is also usable even for ultra-lean mixtures. Emissions from HCCI for Natural Gas are mentioned Table 1.

Diesel

Singh and Agarwal (2012) performed an investigational experiment on emission, combustion, and the HCCI engine performance worked on diesel. Experiment was performed on an engine of two cylinders in which one cylinder was modified to operate on HCCI technique. In contrast, other cylinder was operated on conventional CI engine mode. Combustion, emission, and performance characteristics were analyzed with 15% EGR and without EGR. As data of emissions are checked, it was found that maximum CO emission in diesel engine is 5 g/kWh, whereas for HCCI engine, it is 7 g/kWh; and on using 15% EGR in HCCI engine, CO emission further increases to 13 g/kWh. Also, the maximum HC emission in diesel engine is 0.75 g/kWh, whereas for HCCI engines, it was 2.1 g/kWh; and on using EGR in HCCI engine, HC emission further increases to 3 g/kWh. On the contrary, NOx emission in diesel engine was 8.9 g/kWh and for HCCI engine, it decreased to 3.9 g/kWh; and if 15% EGR was used in HCCI engine, NOx emission further decreases to 2.9 g/kWh. CO and HC emission increases in HCCI engine, whereas NOx emission decreases compared to diesel engine emissions.

Gowthaman and Sathiyagnanam (2016) experimented with analyzing the various effects of inlet air temperature and fuel injection pressure on performance and emission behavior of HCCI engine worked on diesel. Inlet air temperature was varied from 40 to 70°C, and injection pressure in the port fuel injector is varied from 4 to 5 bar. It was observed that at 4 bar, the maximum NOx emission of the conventional diesel engine is 980 ppm, and for HCCI engine worked on diesel, it was 520 ppm at 60 °C inlet air temperature. For higher pressure fuel injection of 5 bar, NOx emission for diesel remained the same, but for HCCI engine, it increased to 650 ppm. Also, if BMEP was increased, NOx emission increases. If inlet temperature of HCCI engine was increased by 40 °C, 50 °C, and 60 °C, a rise in NOx emission can be seen by 2%, 5%, and 9%, respectively. HCCI engine, operating at 4-bar injection pressure and 50 °C inlet temperature, emits smoke density maximum of 32 HSU (Hatridge Smoke Unit), whereas conventional diesel engine emits smoke density ranging between 36 and 73 HSU. If inlet temperature of HCCI engine is increased by 40 °C, 50 °C, and 60 °C, rise in smoke emissions can be seen by 2%, 4%, and 5%, respectively. HC emission in the case of the diesel engine is 50 ppm and HCCI engine was around 100 ppm. CO emission in diesel engines is 0.2%, and HCCI engine was around 0.34–37%. As the inlet temperature increases from 40 to 60 °C, HC and CO emissions reduce at all load conditions.

Table 1 Emission values for natural gas

Emission parameters Authors	NO_X	HC	CO	CO_2	O_2	H_2O
Yao et al. (2006)	0–70 ppm	0.15–0.3%	0.1–0.4%	-	-	-
He et al. (2013)	10–60 ppm	13–360 ppm	-	-	-	-
Maurya and Agarwal (2010)	0–10 ppm	175–400 ppm	0.1–0.8%	-	-	-
Tsolakis et al. (2007)	550–1050 ppm	-	0.1%	4.76–6.3%	12.6–10.8%	5.02–6.4%
Olsson et al. (2001)	0–0.63 g/kWh	6–10 g/kWh	10–90 g/kWh	-	-	-
Olsson et al. (2003)	15–35 ppm	10–40 g/kg	10–22 g/kg	-	-	-
Polat (2015)	40–117 ppm	140–460 ppm	0.04–0.22%	-	-	-
Ying et al. (2009)	10–350 ppm	300–1080 ppm	0.1–2.2%	-	-	-
Yap et al. (2005)	10–800 ppm	100–210 ppm	0.04–0.18%	-	-	-
Maurya and Agarwal (2014)	0–90 ppm	6.7–18.4 g/kWh	55–74 ppm	-	-	-
Mack et al. (2009)	0.5–8 ppm	100–1100 ppm	500–1400 ppm	-	10–19 ppm	-
Gharehghani (2018)	0.02–0.45 g/kWh	0.8–4.2 g/kWh	0.7–6.5 g/kWh	-	-	-

Shi et al. (2005) experimented with studying the effect of internal and external exhaust gas recirculation on the emission from the HCCI engine. Four-stroke single-cylinder, water-cooled, and naturally aspirated diesel engine was used. For internal EGR, at 1500 rpm, if IMEP is increased from 0.3 to 0.4 MPa, NO emission is less than 20 ppm at 10° CA valve overlap. If valve overlap changes to −20° CA valve overlap, NOx emission increased from 30 to 150 ppm. A drastic increase in NOx emission was observed at 40° CA negative valve overlap, and it reached 1100 ppm at 0.4 MPa IMEP. Maximum smoke opacity was observed at 0.4 MPa IMEP, and its value is 6.5% for 40° CA negative valve overlap, 6% for 20° CA negative valve overlaps, and 16% for 10° CA valve overlap. For External EGR, NOx emission in diesel engine was found to be approximately 360 ppm, but in the HCCI engine, NOx emission was reduced to 150 ppm at 0% EGR. As EGR rate is increased to 50%, NOx emission was further reduced to even less than 10 ppm. Maximum smoke opacity of 50% was observed for diesel engines at 40% EGR rate. In HCCI engine, smoke opacity was reduced to 10–30%. Maximum CO emission of diesel engine was 0.15% which was less than HCCI engines which produce CO emissions of 0.4%.

Singh and Agarwal (2016) examined HCCI combustion by using four test fuels. These test fuels are diesel, diesoline (15% v/v of gasoline with diesel), diesohol (15% v/v of ethanol with diesel), and diesosene (15% v/v of kerosene with diesel). A two-cylinder engine in which one cylinder operated on HCCI technique while the other on conventional compression ignition mode was used for experimentations. Compression ratio of HCCI cylinder was kept at 16.5. Analysis was also done for different air-fuel ratio.

CO emission was observed to be less than 10 g/kWh till "λ" value of 3.75 for all the fuels, but after 3.75, CO emission of diesohol increased rapidly to 50 g/kWh at "λ" 4.5 and 81 g/kWh at "λ" 5.25. CO emission for diesel, diesoline, and diesosene increased to 15 g/kWh, 20 g/kWh, and 19 g/kWh, respectively, at "λ" 4.5; and at "λ" 5.25, it further increased to 70 g/kWh, 65 g/kWh, and 80 g/kWh, respectively. HC emission also showed similar trend. Till "λ" 3.75, HC emission remained between 4 and 8 g/kWh and at "λ" 5.25, it increased to 12–20 g/kWh for all fuels. Maximum NOx emission found at "λ" 1.5 with a value of 2 g/kWh for diesosene, 1.5 g/kWh for diesel, 1.45 g/kWh for diesoline, and 1.2 g/kWh for diesohol. As "λ" value increased to 2.25, NOx emission reduced to 1.25 g/kWh for diesosene, 0.3 g/kWh for diesel, 0.45 g/kWh for diesoline, and 0.15 g/kWh for diesohol. If "λ" is further increased to 3.75, 4.5, or 5.25, NOx emission reduces to even less than 0.3 g/kWh. They figure out that addition of volatile additives like gasoline, kerosene, and alcohols to baseline diesel improved the emission characteristics in HCCI combustion, mainly up to medium range of loads. At higher range of loads, diesoline, and diesosene showed a higher knocking tendency when compared to diesel and diesohol.

Singh et al. (2014) experimented with studying the combustion, emission, and performance characteristics of the HCCI engine working on biodiesel using external mixture formation techniques. Experiments were performed on a four-stroke two-cylinder air-cooled direct injection diesel engine generator set which was run at a constant speed. One was operated in HCCI combustion mode out of two cylinders, while the other was operated on conventional CI combustion mode. Diesel and its various blends like B20 and B40 were used. Experiments were performed for different air-fuel ratio "λ" like 2.1, 2.7, 3.7, and 5.6. It was observed that CO and HC emissions were reduced by reducing the "λ" values or EGR rate. For diesel, maximum CO emission was 25 g/kWh for "λ" 5.6 and 30% EGR. For lower "λ" values of 3.7, 2.7, and 2.1, CO emission was less than 10 g/kWh. At "λ" 5.6 and 30% EGR, CO emission for B20 was 125 g/kWh; and for B40, it was 120 g/kWh. On reducing EGR to 0%, CO emissions reduced to 10 g/kWh for B20 and 85 g/kWh for B40. HC emission for diesel and B20 fuel ranges between 0 and 7.5 g/kWh for all values of λ and all EGR rates. But for B40 fuel, HC emissions were found to be 29 g/kWh for 30% EGR, 23 g/kWh for 15% EGR, and 25 g/kWh for 0% EGR at 5.6 "λ". For other values of "λ", HC emission ranges between 5 and 10 g/kWh. NOx emission was highest for diesel fuel at 2.1 "λ" around 33 g/kWh and 0% EGR, 23 g/kWh for 15% EGR, and 12 g/kWh for 30% EGR. As "λ" was increased to 5.6, NO

Table 2 Emission values for diesel

Emission parameters Authors	NO_X	HC	CO	CO_2
Singh and Agarwal (2012)	2–4 g/kWh	0.75–3 g/kWh	3–13 g/kWh	-
Gowthaman and Sathiyagnanam (2016)	10–600 ppm	50–100 ppm	0.05–0.37%	-
Shi et al. (2005)	10–1100 ppm	-	0.4%	-
Singh and Agarwal (2016)	0.15–2 g/kWh	4–20 g/kWh	10–80 g/kWh	-
Singh et al. (2014)	0–33 g/kWh	5–30 g/kWh	10–135 g/kWh	-
Patel and Yadav (2017)	10–120 ppm	22–120 ppm	0.01–0.09%	-
Mohanamurugan and Sendilvelan (2011)	20–500 ppm	20–140 ppm	0.1–0.3%	0.5–6.5%

Table 3 Emission values for petrol

Emission parameters Authors	NO_X	HC	CO
Hyvönen et al. (2003a, b)	-	70–110 g/kg	100–700 g/kg
Hyvönen et al. (2005)	0.3–0.65 g/kg	15–140 g/kg	20–40 g/kg
Hyvönen et al. (2003a, b)	0.2–0.37 g/kg	80–150 g/kg	80–550 g/kg

emission became almost negligible. Similar output was observed for B20 fuel also. For B40 fuel, NO emission was almost 0 for all vales of λ and EGR rates.

Patel and Yadav (2017) experimented with improving biodiesel and CNG-fuelled HCCI engine performance and emission characteristics. Experiments were carried out on a four-stroke single-cylinder high-speed water-cooled diesel engine which is coupled with an eddy current dynamometer. Thermocouples were fixed to measure temperatures. Gaseous emissions such as CO, HC, and NOx were measured using the exhaust gas analyzer connected to the exhaust pipe. It was seen that HC emission for all types of fuel increases with an increase in load. HC emission ranges between 42 and 76 ppm for diesel, 44 to 78 ppm for B5, 30 to 50 ppm for B10, 22 to 44 ppm for B15, and 80 to 120 ppm for CNG. On checking for NOx emission, it was least for CNG and ranges between 10 and 20 ppm. NOx emission for diesel and B10 first increases from 80 to 110 ppm if load was increased from 0 to 20% and then it decreases to 90 ppm at 40% and further increased to 120 ppm at 80%; and if load was increased to 100%, NOx emission decreased to 110 ppm. For B5, NOx emission increases from 30 ppm at 0% to 85 ppm at 100% and for B15, NOx emission increases from 70 ppm at 0% to 110 ppm at 100%. CO emission for diesel increases from 0.04% vol at 0% load to 0.09% vol at 100% load. Least CO emission was found for B15 fuel around 0.01–0.02% vol. For B5, B10, and CNG fuel, CO emission ranges between 0.02% vol and 0.08% vol. Hence, the best fuel for getting lease HC and CO emission is B15 and for getting the least NOx emission is CNG.

Mohanamurugan and Sendilvelan (2011) performed experiments to study the emission and combustion characteristics of different fuels in the HCCI engine. A four-stroke indirect injection diesel engine was used. Different modes of fuel injection were applied from the primary injector and pilot injector. HC emission decreases with an increase in load for HCCI mode while increasing load for conventional mode. Maximum HC emissions at 100% load for diesel and biodiesel were 110 ppm and 60 ppm, respectively. For diesel: diesel, biodiesel: biodiesel, diesel: biodiesel, biodiesel: diesel, diesel: petrol, and biodiesel: petrol, maximum HC emissions were 35, 25, 45, 140, 85, and 90 ppm. NOx emission for all modes increases with an increase in load. NOx emissions were around 500–550 ppm for conventional mode, much higher than for HCCI mode, around 300–400 ppm. CO emission was constant at 0.1% for all loads in the HCCI engine except in diesel: petrol mode. In diesel: petrol mode, CO emission was 0.3% for 0–20% load and 0.2% for 40–100% load. For diesel and biodiesel conventional mode, first increases to 0.5% and 0.4% till 40% load and then decreases to 0.3% and 0.2% at 100% load condition. Emission values for diesel are summarized in Table 2.

Petrol

Hyvönen et al. (2003a, b) experimented with studying the multi-cylinder HCCI engine operating range using the variable compression ratio. A 5-cylinder, 1.6-L engine with a variable compression ratio (VCR) range of 8:1 and 14:1 in the original was used. Its piston was modified to get VCR range of 9:1 and 21:1 and called it P21 piston. They compared the result with an earlier test of an HCCI engine having VCR range 9:1 and 17:1 and called it P17 piston. It can be seen that CO emission reduced by around 85% from 700 to 100 g/kg as the speed is increased from 1000 to 5000 rpm. Also, HC emission was reduced by around 35% from 110 to 70 g/kg as the speed increased from 1000 to 5000 rpm.

Furthermore, Hyvönen et al. (2005) performed a comparative study on operating conditions of HCCI engine using spark ignition and without using spark ignition. A 5-cylinder, 1.6-dm^3 engine having a variable compression ratio (VCR) ranging between 10:1 and 30:1 was used for the experiment. Approximately, standard valve timings were used, except the inlet valve closing, 10 crank angle degrees (CAD) earlier. NOx emission level was between 0.3 and 0.65 g/kg_{fuel} (4–8

Table 4 Emission values for LPG

Emission parameters Author	NO_X	HC	CO	CO_2
Kannan et al. (2020)	5–10 g/kWh	15–135 g/kWh	0.0443–0.4 g/kWh	5–11 g/kWh

Table 5 Emission values for different fuels

Emission parameter Fuel	NO_X	HC	CO	CO_2	O_2	H_2O
Natural gas	0–800 ppm Yao et al. (2006) Olsson et al. (2003) Maurya and Agarwal (2014)	10–1100 ppm He et al. (2013) Polat (2015) Mack et al. (2009)	0.04–2.2% Yao et al. (2006) Ying et al. (2009) Yap et al. (2005)	4.76–6.3% Tsolakis et al. (2007)	12.6–10.8% Tsolakis et al. (2007)	5.02–6.4% Tsolakis et al. (2007)
	0–0.45 g/kWh Olsson et al. (2001) Gharehghani (2018)	0.8–18.4 g/kWh Olsson et al. (2001) Maurya and Agarwal (2014)	1–90 g/kWh Olsson et al. (2001) Gharehghani (2018)			
Diesel	10–1100 ppm Shi et al. (2005) Patel and Yadav (2017)	20–140 ppm Gowthaman and Sathiyagnanam (2016)	0.01–0.4% Shi et al. (2005) Patel and Yadav (2017)	-	-	-
	0.15–33 g/kWh Singh and Agarwal (2012) Singh and Agarwal (2016)	0.75–30 g/kWh Singh et al. (2014) Singh and Agarwal (2016)	3–135 g/kWh Singh and Agarwal (2012) Singh and Agarwal (2016)			
Petrol	0.2–0.65 g/kg Hyvönen et al. (2003a, b) Hyvönen et al. (2005)	70–150 g/kg Hyvönen et al. (2003a, b) Hyvönen et al. (2005)	20–700 g/kg Hyvönen et al. (2003a, b) Hyvönen et al. (2005)	-	-	-
Liquefied petroleum gas	5–10 g/kWh Kannan et al. (2020)	15–135 g/kWh Kannan et al. (2020)	0.0443–0.4 g/kWh Kannan et al. (2020)	5–11g/kWh Kannan et al. (2020)	-	-

ppm) in this test. NOx emission level is almost 0.1 g/kg_{fuel} (1–2 ppm) higher in spark-assisted HCCI combustion than normal HCCI emission at all air-fuel ratios. Engine out NOx emission increased as the air-fuel decreases. Unburned HC increased from 50 to 60 g/kg_{fuel} to a maximum of about 130–140 g/kg_{fuel} at around 60% initial slow heat release fraction and later decreased to stoichiometric 14–18 g/kg_{fuel} level. CO emissions are between 20 and 40 g/kg_{fuel} level.

Hyvönen et al. (2003a, 2003b) experimented on a supercharged HCCI engine to extend its operational range. A 5 cylinder 1.6-L engine with a variable compression ratio ranging between 9:1 and 21:1 was used for the experimentations. HC and CO emission decreased when throttle was provided. HC emission ranges between 100 and 150 g/kg at 1000 rpm and 80–100 g/kg at 2000 rpm. If catalyst is added, specific HC emission was reduced to less than 5 g/kWh. CO emission ranges between 100 and 450 g/kg at 1000 rpm and 80–550 g/kg at 2000 rpm. If the catalyst was added, specific CO emission was observed to be even less than 2 g/kWh. However, NOx emission increases on providing throttle. It increases from 0.2 to 0.37 g/kg at 2000 rpm. At 1000 rpm, NOx emission decreases from 0.25 to 0.2 g/kg. Emissions for Petrol fuel are compiled in Table 3.

Liquefied petroleum gas (LPG)

Kannan et al. (2020) performed a study to analyze LPG-fuelled diesel engines using HCCI combustion technique. Effect of preheating of intake air on emission of LPG-fuelled HCCI engine was analyzed under varying load conditions. Tests were conducted in an HCCI engine modified from single-cylinder diesel engine. Port fuel induction method was used to prepare a homogeneous charge. For the same load, HC and CO emissions were higher in the LPG-fuelled HCCI engine, whereas NOx and CO_2 emissions were lower than the conventional diesel engine. HC emission for diesel engine remained below 10 g/kWh, whereas for LPG, it reduced from 135 to 15 g/kWh on increasing the load. CO emission for diesel engine was below 0.1 g/kWh, whereas for LPG, it reduced from 0.4 to 0.0443 g/kWh on increasing the load. NOx emission for diesel engine increased from 13 to 35.14 g/kWh for diesel engines, and for LPG, it ranged between 5 and 10 g/kWh. CO_2 emission of diesel engine was between 14 and 16 g/kWh, and for LPG-fuelled HCCI engine, it reduced from 11 to 5 g/kWh on increasing the load. Emissions from HCCI engines for LPG are summarized in Table 4.

Conclusion

Finally, emissions from HCCI engines for different fuels are summarized in Table 5.

Following are concluding remarks based on a critical review of emissions from HCCI using different fuels:

- NOx emission in HCCI engine is less than a conventional diesel engine, almost 1:10th the emission.
- Different fuels can be used in HCCI engines, and NOx emission is the least of HCCI engines worked on natural gas than diesel, petrol, or LPG.
- NOx emission is 90–95% lesser for natural gas-fuelled HCCI engine than diesel, petrol, or LPG, which will significantly help in reducing the environmental pollution.
- NOx emission increases by almost 0.17 g/kg_{fuel} as inlet pressure decreases by 0.4 bar. Also, NOx emission increases by 0.1 g/kg_{fuel} on an increment of speed by 1000 rpm.
- HC emission for natural gas-fuelled HCCI engine is 50–60% less than diesel or LPG, whereas CO emission is 90–95% less for LPG–fuelled HCCI engine.
- Exhaust gas recirculation also helps in reducing the NOx emission by around 300–400 ppm; however, HC and CO emission increases by 100–200 ppm.
- Advancing the combustion timing reduces the HC emission. If load increases in HCCI engine, HC emission gets reduced.

This review will be helpful for the researchers doing further studies on HCCI engine. Research can be done to solve various challenges involved in the implementation of HCCI engine in real life. Various performance parameters can also be analyzed.

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Data availability Here, critical analysis has been done with reference to earlier research work. This is a kind of comprehensive review. Hence, there is no data used.

Declarations

Ethics approval and consent to participate Not applicable

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References

Gharehghani A (2018) Load limits of an HCCI engine fuelled with natural gas, ethanol, and methanol. Elsevier Ltd Fuel 239(2019):1001–1014. https://doi.org/10.1016/j.fuel.2018.11.066

Gowthaman S, Sathiyagnanam AP (2016) Effects of charge temperature and fuel injection pressure on HCCI engine. Elsevier Ltd. Alexendria Engineering Journal 55:119–125. https://doi.org/10.1016/j.aej.2015.12.025

Hasan MM, Rahman MM (2016) Homogeneous charge compression ignition combustion: advantage over compression ignition combustion, challenge and solution. Renew Sust Energ Rev 57:282–291

He BQ, Yuan J, Liu MB, Zhao H (2013) Combustion and emission characteristics of a n-butanol HCCI engine. Elsevier Ltd Fuel 115(2014):758–764. https://doi.org/10.1016/j.fuel.2013.07.089

Hussaini SY, Lahane S, Patil NG (2016) Analysis of performance and emission characteristics of homogeneous charge compression ignition (HCCI) Engine. Procedia Technology 25(2016):854–861

Hyvönen J, Haraldsson G, Johansson B (2003a) Operating range in a multi cylinder HCCI engine using variable compression ratio. Society of Automotive Engineer JSAE 20030178, SAE 2003-01-1829

Hyvönen J, Haraldsson G, Johansson B (2003b) Supercharging HCCI to extend the operating range in a multi-cylinder VCR-HCCI engine. SAE Technical Paper Series 2003-01-3214

Hyvönen J, Haraldsson G, Johansson B (2005) Operating conditions using spark assisted HCCI combustion during combustion mode transfer to SI in a multi-cylinder VCR-HCCI Engine. SAE Technical Paper Series 2005-01-0109

Janathanan K, Pandian V, Dhandapani M, Kanagara K (2016) A performance, combustion and emission study on HCCI engine: trends and innovations. SAE Technical Paper 2016-28-0013

Kannan S, Mahalingam S, Srinath S, Sivasankaran M, Kannan S (2020) An experimental study in HCCI combustion of LPG in diesel engine. 37:3625–3629. https://doi.org/10.1016/j.matpr.2020.09.774

Mack JH, Aceve SM, Dibble RW (2009) Demonstrating direct use of wet ethanol in a homogeneous charge compression ignition (HCCI) engine. Energy 34(2009):782–787. https://doi.org/10.1016/j.energy.2009.02.010

Maurya RK, Agarwal AK (2010) Experimental study of combustion and emission characteristics of ethanol fuelled port injected homogeneous charge compression ignition (HCCI) combustion engine. Elsevier Ltd. Appl Energy. https://doi.org/10.1016/j.apenergy.2010.09.015

Maurya RK, Agarwal AK (2014) Experimental investigations of performance, combustion and emission characteristics of ethanol and methanol fuelled HCCI engine. Elsevier Ltd Fuel Processing

Technology 126(2014):30–48. https://doi.org/10.1016/j.fuproc.2014.03.031

Mohanamurugan S, Sendilvelan S (2011) Emission and Combustion Characteristic of Different Fuels in a HCCI Engine. International Journal of Automotive and Mechanical Engineering ISSN 1985-9325 (Print) ISSN 2180-1606 (Online) 3:279–292

Mulane SA, Limaye SD (2016) Homogeneous charge compression ignition (HCCI) engine technology – a review. INPRESSCO E-ISSN 2277–4106, P-ISSN 2347–5161

Ohur EO, Kariuki SM (2014) Effect of car emission on human health and the environment. Int J Appl Eng Res 9(21):11121–11128

Olsson JO, Tunestal P, Haraldsson G and Johansson B (2001) A turbo charged dual fuel HCCI engine. SAE Technical Paper Series 2001-01-1896

Olsson JO, Tunestal P, Ulfvik J, Johansson B (2003) The effect of cooled EGR on emissions and performance of a turbocharged HCCI engine. SAE Technical Paper Series 2003-01-0743

Patel DS, Yadav M (2017) Experimental study to improve the performance and emission characteristics of HCCI engine using blends of bio-diesel and CNG. IRJET e-ISSN: 2395-0056 p-ISSN 2395-0072

Polat S (2015) An experimental study on combustion, engine performance and exhaust emissions in a HCCI engine-fuelled with diethyl ether–ethanol fuel blends. Elsevier Ltd Fuel Processing Technology 143(2016):140–150. https://doi.org/10.1016/j.fuproc.2015.11.021

Shi L, Cui Y, Deng K, Peng H, Chen Y (2005) Study of low emission homogeneous charge compression ignition (HCCI) engine using combined internal and external exhaust gas recirculation (EGR). Elsevier Ltd Energy 31(2006):2665–2676

Singh AP, Agarwal AK (2012) An experimental investigation of combustion, emissions and performance of a diesel-fuelled HCCI engine. Society of Automotive Engineer Paper No. 2012-28-0005

Singh AP, Agarwal AK (2016) Diesoline, diesohol and diesosene-fuelled HCCI engine development. Journal of Energy Resources Technology. https://www.researchgate.net/publication/302870619

Singh G, Singh AP, Agarwal AK (2014) Experimental investigations of combustion, performance and emission characterization of biodiesel-fuelled HCCI engine using external mixture formation technique. Sustainable Energy Technologies and Assessments 6(2014):116–128. https://doi.org/10.1016/j.seta.2014.01.002

Tsolakis A, Megaritis A, Yap D (2007) Application of exhaust gas fuel reforming in diesel and homogeneous charge compression ignition (HCCI) engines fuelled with bio-fuels. Elsevier Ltd. Energy 33(2008):462–470

Venkataramana P (2013) Homogeneous charge compression ignition (HCCI) engine. International Journal of Engineering Research & Technology (IJERT) ISSN: 2278-0181, Vol. 2 Issue 2

Yao M, Chen Z, Zheng Z, Zhang B, Xing Y (2006) Study on the controlling strategies of homogeneous charge compression ignition combustion with fuel of dimethyl ether and methanol. Elsevier Ltd 85(2006):2046–2056

Yap D, Peucheret SM, Megaritis A, Wyszynski ML, Xu H (2005) Natural gas HCCI engine operation with exhaust gas fuel reforming. Elsevier Ltd International Journal of Hydrogen Energy 31(2006): 587–595

Ying W, Li H, Jie Z, Longbao Z (2009) Study of HCCI-DI combustion and emissions in a DME engine. Elsevier Ltd Fuel 88(2009):2255–2261. https://doi.org/10.1016/j.fuel.2009.05.008