Comprehensive Review on Emission Characteristics of Homogeneous Charge Compression Ignition (HCCI) Engine Operated with Renewable Fuels

Praveen A. Harari¹, Santosh Ghorpade², Santosh Bhuimbar³, Amar S. Kekare⁴, Amit Deokar⁵

¹,⁴,⁵Assistant Professor, Department of Mechanical Engineering, SGMCOE, Mahagaon, Gadahinglaj, Maharashtra, INDIA
²Assistant Professor, Department of Mechanical Engineering, JITS, Warangal, Telangana, INDIA
³Assistant Professor, Department of Mechanical Engineering, GSIT, Karwar, Karnataka, INDIA

ABSTRACT

HCCI combustion has been drawing the considerable attention due to high efficiency and lower nitrogen oxide (NOx) and particulate matter (PM) emissions. However, there are still tough challenges in the successful operation of HCCI engines, such as controlling the combustion phasing, extending the operating range, and high unburned hydrocarbon and CO emissions. Massive research throughout the world has led to great progress in the control of HCCI combustion. The first thing paid attention to is that a great deal of fundamental theoretical research has been carried out. First, numerical simulation has become a good observation and a powerful tool to investigate HCCI and to develop control strategies for HCCI because of its greater flexibility and lower cost compared with engine experiments.

Keywords-- HCCI Engine, Combustion, Heat release rate, Ethanol, Exergy, Auto-ignition, Emissions.

I. INTRODUCTION

Automotive industry has been strongly required to develop clean technologies of lower fuel consumption for ambient air quality improvement, greenhouse gas reduction and energy security. As a result, fuels and engines used in transportation have to face two main challenges of improving fuel economy and reducing emissions in a highly competitive economy. Considering continuously stringent emission regulations, as well as increasing shortage of primary energy resources, the development of new highly efficient and environment friendly combustion systems, associated with alternative fuels becomes increasingly important and hence research need to be carried out in this domain. Many research programs are currently being undertaken in the area of developing alternative fuels and new combustion concepts [1]. The exhaust of diesel engines is one of the major contributions to the air pollution problem, such as particulate matter, hydrocarbons, and nitrogen oxides emissions, and so on. Homogeneous charge compression ignition (HCCI) is an alternative operating mode for a diesel engine because it has the potential to reduce both particulate matter and nitrogen oxides emissions while maintaining high fuel efficiency [2]. Homogeneous charge compression ignition (HCCI) combustion is regarded as a promising combustion regime in IC engine applications because of its high efficiency and low emissions. In one version of an engine operating in HCCI mode, well mixed air and fuel are compressed to the point of auto-ignition, without a spark plug or high pressure injection of another fuel [3]. HCCI combustion in gasoline engines can be achieved by increased compression ratio and heating intake air. However, trapping residual gases is one of the most effective ways to raise in-cylinder temperatures, thus reducing the requirement for raising the intake temperature of passenger car gasoline engines [5]. HCCI combustion is highly dependent on the chemical kinetics, mixture composition and the temperature before the auto-ignition. However, there are still some difficulties on HCCI combustion in order to be used in the internal combustion engines. First, auto ignition occurs simultaneously and spontaneously across the combustion chamber. This spontaneous and sudden combustion causes a rapid heat release rate resulting in knocking. In contrast, misfiring problem is seen at lower engine loads. Secondly, CO and HC emissions increase due to leaner mixture and lower combustion temperature in HCCI engines; because CO emissions are strongly affected by combustion temperature. Third one is to control the combustion phasing [6]. The emission reductions are achieved during HCCI combustion by physically separating the injection events from the on set of combustion, thereby ensuring a sufficiently long ignition delay to prepare a lean, nearly-homogenous air–fuel mixture. The temperature reduction is further augmented by diluting the cylinder charge with exhaust gas recirculation (EGR) as well as the use of higher intake
boost pressures. The diesel HCCI combustion is generally implemented with multiple fuel injections during the compression stroke to prepare a near-homogeneous lean cylinder charge [7]. In HCCI combustion, chemical reactions occur simultaneously. HCCI combustion is repeatable and uniform due to the existence of reactive charge mixture in the combustion chamber. HCCI combustion is initiated by the ignition of the charge mixture at multi-points in the combustion chamber spontaneously. The faster heat release is seen compared to the spark ignition [10].

II. HOMOGENEOUS CHARGE COMPRESSION IGNITION (HCCI)

In HCCI combustion concept the fuel and air are mixed before the start of combustion and this mixture is auto-ignited due to the increase in temperature in the compression stroke. In the past decade, many of the I.C. engine researchers have focused their research on homogeneous charge compression ignition (HCCI) combustion concept due to its potential to maintain high part load efficiency and to decrease soot and NOx emissions by burning a lean and homogeneous mixture. In fact, HCCI can be considered as a type of operating mode instead of a type of engine, and both CI and SI engines can be operated in the HCCI mode. In spite of several inherent advantageous features of HCCI combustion, there are some unresolved issues preventing the HCCI engine from being used in commercial engines. The main challenges of HCCI combustion are the difficulty in combustion phasing control, high levels of UHC and CO emissions, limited range of operation, cold starting problem, difficulty in homogeneous mixture preparation, abnormal pressure rise with noise, lacking in prompt response during cycle transient, engine control strategies and systems, cylinder to cylinder variation and the lack of accurate chemical mechanism and precise combustion model. The major challenge with the HCCI combustion mode is that the ignition is completely controlled by the chemical kinetics, and is thus governed by the fuel composition, equivalence ratio and the thermodynamic state of the mixture. There is no external control such as the fuel injection timing used on diesel engines or spark timing used on SI engines. Obtaining the desired level of control during transient operation conditions becomes even more problematic as charge temperatures have to be synchronized properly to the operating conditions with a high repeatability because the speed and load change during rapid transient conditions. In HCCI combustion the gas temperature after combustion can be lower than 1800-1900 K on account of greater dilution of the charge by air or residuals. Therefore, NOx formation in the combustion chamber is reduced. As HCCI combustion use premixed lean mixture, the soot formation during combustion is very low. HCCI combustion of diesel like fuels exhibits a typical two stage heat release. The first stage of the heat release curve is linked with low temperature kinetic reactions, and the time lag between the first and the main heat releases is associated with the “negative temperature coefficient (NTC) regime. This low temperature reaction (LTR), which is a cool flame phenomenon occurs at a temperature below the auto-ignition temperature and creates a two-stage ignition. In the NTC regime, through there is increase in the in-cylinder temperature, the overall reaction rate decreases leading to a lower reactivity of the system. It has been found that the low temperature kinetics chemistry is responsible for knocking in SI engines. Heat release from low temperature reaction depends on the octane number of fuels, the lower is the octane number the more prominent is the heat release. Therefore, for gasoline like fuels (high octane number) the heat release from low temperature reaction is low as compared to diesel like fuels for the same condition [15].

III. LITERATURE SURVEY ON EMISSION CHARACTERISTICS

Nitric Oxide (NOx) Emissions

NOx emissions of HCCI combustion were very low for the lean fuel/air mixture and low temperature combustion. For all stable operation points, NOx emissions were lower than 10 ppm [1]. The nitrogen oxides concentration is slightly higher for the auxiliary fuels injected at 25° BTDC of injection timing than at other injection timings since the fuel carbons burn more completely. With higher premixed ratio less oxygen is inducted in the cylinder. Furthermore, as the premixed ratio increases, less fuel is directly injected and burned under non-homogeneous conditions thereby avoiding the formation of high temperature regions within the combustion chamber. As a result, the nitrogen oxides decrease with an increase in premixed ratio. The nitrogen oxides concentrations are lower with premixed ethanol than with premixed gasoline due to lower gas temperature and less oxygen left. Ethanol has the higher latent heat of vaporization and lower heating value and then there is a lower gas temperature with premixed ethanol. Furthermore, the less oxygen left with premixed ethanol becomes because of more ethanol oxidized within wider flammability limits [2]. The maximum NOx rate of production was almost zero for the temperatures below 1300 K at all equivalence ratios studied. Therefore 1300 K was assumed to be the cutoff temperature of NOx production for that particular study. The NOx production from the thermal mechanism accounts for over 70% for all conditions studied. The N2O intermediate mechanism accounts for up to 25% of the total NOx and was the second most important NOx source. That was attributed to the use of relatively lean mixtures in the examined conditions. Because of the lean condition and no local rich zones from the homogeneous charge, prompt NO mechanism becomes insignificant for those conditions and only accounts for around 5% of the total NOx [3]. The concentration of NO in the exhaust was always less than 25 ppm even at the maximum BMEP of 2.2 bar due to low combustion
temperatures as a result of very lean mixtures. For any given charge temperature, the NO emissions increase with BMEP and that was due to the increase in equivalence ratio which increases the in-cylinder peak temperature. However, in all cases the NO emissions were far lower than conventional engines [4]. NOX emissions can be simultaneously reduced in HCCI combustion, because HCCI engines operate with leaner homogeneous charge mixtures. As NOX emissions were produced at high combustion temperatures, NO formation mechanisms could not occur due to lower end of combustion temperature. That was one of the most important advantage of HCCI combustion. In that study, NO emissions were measured almost zero with all test fuel at each inlet air temperatures. However, NO emissions were only measured as 1 and 2 ppm with n-heptane and B20 at high inlet air temperatures due to knocking. Knocking results higher pressure rise rate and faster combustion. Higher inlet air temperatures increase the tendency of knocking [6]. Unlike diesel HCCI which relies on high intake dilution levels to reduce the NOx emissions, ultra-low emissions of NOx were achieved with n-butanol HCCI combustion without the use of EGR at low to mid-engine loads. While EGR was generally not required for NOX emission reduction during n-butanol HCCI combustion, at higher engine loads, both boost and EGR were required to limit the high pressure rise rates and to modulate the combustion phasing for high thermal efficiency. The load range was extended up to 10 bar IMEP with n-butanol HCCI while maintaining ultra-low NOx emissions with improved performance characteristics compared to diesel HCCI [7]. NO emissions first decreased with the increase of intake air temperature while they tended to increase at high intake air temperatures. Warmer intake air temperatures accelerated the chemical reactions and increased the in-cylinder gas temperature at the end of combustion. Thus, NO emissions increased [10]. During the experiments, almost zero emission of NOx was measured for E30/D70, E40/D60 and DEE test fuels. Therefore, the dramatic reduction was seen on the emissions of NOx for test fuels mentioned on HCCI combustion. The emissions of NOx were only produced for E50/D50 test fuel. The amount of NOx was increased first until the time slightly after the stoichiometric ratio was achieved and then it started to decrease with the increasing lambda for the E50/D50 test fuel [11]. HCCI engine has very low NOx emissions compared to conventional diesel engine due to lean air/fuel charge and low combustion temperature. 4 bar injection pressure and 40°C air temperature HCCI engine resulted in low NOX emissions compared to other conditions operated HCCI engine. The NOX emissions were increased with raising air temperature [14].

IV. HYDROCARBON (HC) EMISSIONS

HC emissions increase when the mixture becomes leaner. Leaner mixture lowers the temperature of the combustion chamber, thus emitting higher hydrocarbons. For constant air-fuel ratio, on increasing intake air temperature, unburnt hydrocarbon emission decreases [1]. The hydrocarbons concentration was slightly lower for the auxiliary fuels injected at 25° BTDC than at other injection timings since the fuel carbons burn more completely. HC emissions increase at high premixed ratios because more fuel escapes from the flammable regions or were trapped in a crevice volume inside the combustion chamber due to a lower maximum temperature of bulk gas. The oxygen self-contained in ethanol assists in burning fuel more completely, so the hydrocarbons concentrations were lower with premixed ethanol than with premixed gasoline [2]. HC emissions decrease with the increase of inlet air temperature. The reason of that reduction was that chemical reactions improve and rapid combustion occurs at high inlet air temperatures. The productions of radicals accelerate with the increase of inlet air temperature and combustion reactions. Moreover, warmer inlet air temperature decreases the cooling effects of homogeneous leaner charge mixture. Minimum HC emissions were measured with n-heptane and B20 compared to other test fuels. When isopropanol was used as an additive fuel, higher HC emissions were obtained especially at lower inlet air temperatures. Apart from n-heptane minimum HC emissions were measured with B20. Autoignition properties were deteriorated and HC emissions were generated when each test fuel was obtained by blending with alcohols. Maximum HC emissions were measured as 440 ppm and 438.88 ppm with P30 test fuel at 313 K and 333 K inlet air temperatures respectively [6]. HC emissions first increased as intake air temperature increased until about 90°C intake air temperature. Higher HC emissions were measured at λ = 0.6. The reason for the increase of HC emissions was low volumetric efficiency owing to lower air flow to the engine at high air intake temperatures. One of the most significant reasons for the increase of HC emissions was richer charge mixture. As the engine operates with the richer mixture the whole fuel cannot be oxidized. In addition, the test engine needs more air in order to complete combustion in the HCCI combustion mode. As a result incomplete combustion occurs. In addition, the flame cannot enter the piston and piston ring crevices. So, the flame goes out especially as the engine operates with leaner charge mixtures [10]. The emissions of HC were decreased with the increasing lambda. The emissions of HC were increased with the increasing ethanol amount in the fuel blends. The highest emission of HC was released for E50/D50 for a richer mixture as compared that for the other test fuels. The higher cetane number and oxygen content of DEE has improved the oxidation reactions resulting in a lower emission of HC. The emissions of HC were decreased with the increasing inlet air temperature [11]. Hydrocarbon emissions from HCCI engine were reduced by improving the inlet air temperature and injection pressure. In general, HC emission from HCCI engine was higher than conventional diesel engine due to lean premixed charge.
leads to partial combustion at certain location in the combustion chamber. 5 bar fuel injection pressure and 60°C inlet air temperature operated HCCI engine resulted in low HC emissions compared to other operating conditions of HCCI engine [14].

V. CARBON MONOXIDE (CO) EMISSIONS

On increasing relative air-fuel ratio, CO increases drastically. That depends mainly on the lower combustion temperature and the later combustion phasing. At the end of combustion, the temperature becomes too low for complete oxidation and high amount of CO was generated [1]. The carbon monoxide concentration is slightly lower for the auxiliary fuels injected at 25° BTDC than at other injection timings since more complete mixing of the air and fuel makes fuel find enough oxygen to react with. CO emissions increase at high premixed ratios because of a lower maximum temperature of bulk gas to react with oxygen incompletely. More oxygen in ethanol assists in burning fuel more completely and the carbon monoxide concentrations are therefore lower with premixed ethanol than with premixed gasoline [2]. Minimum CO emissions were produced with n-heptane because of higher combustion temperature and faster combustion due to knocking. CO emissions decrease with the increase of inlet air temperature, because CO could be oxidized due to higher inlet temperatures. So, CO₂ formation was improved and the amount of CO emissions decreased. Maximum CO emissions were measured at 313 K inlet air temperature for all test fuels. CO emissions increase with the increase of the amount of n-butanol in the test fuel. CO emissions also increase with the increase of the amount of isopropanol except for P40. There was a reduction on CO emissions with P40 test fuel compared to P30 test fuel. B20 and P20 can be easily ignited due to lower octane number such as n-heptane. The auto ignition occurs more difficult with other test fuels. Lower combustion temperature was obtained B30, B40, P30 and P40 according to n-heptane, B20 and P20. Maximum CO emissions were measured as 0.144% with B40, 0.138% with B30 at 313 K inlet air temperature [6]. CO emissions increased with the increase of intake air temperature and then started to decrease at higher intake air temperatures. At high intake air temperatures, the in-cylinder gas temperature increased and chemical reactions improved. Thus, CO was oxidized and CO₂ formed [10]. The increase of lambda causes a reduction of the emissions of CO for all test fuels. The increase on the ethanol amount in the fuel blends has led to an increase in the emissions of CO. The minimum emissions of CO were measured to that of other test fuels due to low ignition temperature and oxygen within its chemical structure. Replacing ethanol with DEE has improved the ignitability of the mixture [11]. HCCI engine has resulted in high CO emissions compared to conventional diesel engine, which could be reduced by raising the inlet air temperature and injection pressure. 5 bar injection pressure and 60°C inlet air temperature operated HCCI engine was shown low CO values for all operating conditions [14].

VI. SMOKE EMISSIONS

The smoke concentration was distinct for various injection timings of auxiliary fuels; in particular, the minimum smoke concentration occurs at 25° BTDC. This phenomenon is because the auxiliary fuel injected into the intake port is slightly later at 25° BTDC than the intake valve opened at 21° BTDC to mix more homogeneously, and then to has less locally high-temperature region. The farther from the open timing of intake valve the auxiliary fuels is injected, the larger the smoke concentration becomes. The smoke concentration decreases with increasing the premixed auxiliary fuels because the mixtures contains less carbon in fuel and are more homogeneous during the compression process than without premixed auxiliary fuel. The smoke concentrations are smaller with premixed ethanol than with premixed gasoline owing to more oxygen and less carbon in fuel [2]. Low smoke density was also the advantage for using HCCI engine, and in that study diesel fuelled HCCI engine resulted in low smoke values between 8 HSU and 24 HSU. 5 bar injection pressure, 40°C inlet air temperature and 4 bar injection pressure, 50°C inlet air temperature operated HCCI engine resulted in low smoke density values [14].

VII. CONCLUSION

HCCI is a combustion concept which has developed over the years in response to the need for lower NOx and soot emissions from DI diesel engines. The earliest HCCI combustion systems introduced in the late 1990s relied on early fuel injection strategies to create the necessary homogeneous mixture by injecting early in the compression stroke. Subsequently, multiple injection strategies have been developed in order to extend the operating load rangeand improve HCCI emissions. Late injection strategies have also been utilized to produce HCCI diesel combustion using high EGR and high swirl to extend ID and promote rapid mixing in the combustion chamber. Further developments in HCCI diesel engines include changes to injector design and injection pressure, piston bowl geometry, compression ratio, intake charge temperature and supercharging or turbocharging. In the short to medium term however, a dual engine system combining conventional diesel combustion for full load conditions and HCCI combustion for medium and low loads remains the most practical implementation in diesel engines. The major drawback of the dual operating mode for car manufacturers is the costs and complexity associated with the development of an engine control management system capable of responding to different operating conditions. In conclusion, whilst HCCI remains a realistic alternative to existing engine combustion technologies to improve emissions, it should
continue to have long term viability as an energy source for both light-duty and heavy-duty diesel vehicles.

REFERENCES


