HCCI Combustion in a Diesel Engine using Oxygenated Fuels and Various Operating Parameters – A Review

Gangeya Srinivasu Goteti [1], Tamil Selvan. P [2]

[1] Research Scholar, School of Mechanical and Building Sciences, VIT University, Chennai-600127, India.

[2] Associate Professor, School of Mechanical and Building Sciences, VIT University, Chennai -600127, India.
([1] ggsvas@gmail.com,[2] tamilselvan.p@vit.ac.in)

Corresponding Author: Gangeya Srinivasu Goteti, School of Mechanical and Building Sciences, VIT University, Chennai-600127, India.
E Mail: ggsvas@gmail.com, ph: +91 9849490282.

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Abstract- The growing attention on the environment, revived research interests on the usage of alternative energy sources for diesel engines and to improve the combustion efficiency of the engines. In this regard a new concept of HCCI (Homogeneous Charge Compression Ignition) combustion technology has been considered which promotes highly efficient combustion and produce low emissions and also usage of oxygenated fuels in HCCI engines leads to reduction in emissions like hydrocarbon (HC) and carbon monoxide (CO), since HCCI has increased HC and CO emissions. HCCI offers less pollutant emissions like NO_X and PM. HCCI engine technology is the most adoptable technology for next generation engines to reduce emissions for cleaner environment. This study investigates the effects of the oxygenated fuels, ignition improvers and operating conditions on the HCCI combustion and emissions from it. HCCI combines the characteristics of Spark-Ignition (SI) and Compression Ignition (CI). HCCI engines can operate on gasoline, diesel and most alternative fuels. This paper reviews the parameters involved in HCCI engine technology that fuelled with alternate fuels having high oxygen percentage and also the challenges involved in HCCI combustion.

Keywords: Homogeneous Charge Compression Ignition (HCCI), Oxygenated Fuels, NO_X, PM, HC, CO_2, EGR.

1. Introduction

Compression Ignition engines are the major sources for transportation and for other applications. These engines consume maximum amount of fuel to produce power and emits harmful exhaust gases which include CO, HC, NOx and PM. SI and CI engines use conventional fuels and both have their own drawbacks. The growing concern over the global warming and pollution standards revived research interests on the usage of alternative energy sources for diesel engines using new concept of HCCI/PCCI combustion [18, 19] since it promotes highly efficient combustion and produces lower emissions, usage of oxygenated fuels in HCCI engines also done by researchers now a day's to promote further reduction in emissions like HC and CO which are particularly high in these engines. CI has the advantages like good thermal efficiency and low fuel consumption but suffers from high NOx and PM pollutants due to its heterogeneous combustion and maximum heat release rate during combustion [84, 85]. HCCI concept have the advantage of lesser NOx and PM emissions compared to conventional diesel engines due to its methodology of homogeneous combustion and lower heat release rates during combustion, on the other hand it is obvious that the preparation of homogeneous air- fuel mixture is a crucial for HCCI combustion during the engine operation, especially for direct fuel injection. HCCI mode is suitable for limited load and speed conditions so far, this limits HCCI combustion range and to shift for conventional CI mode continuously in operating conditions.

2. Concept of HCCI

HCCI is the phenomenon of obtaining the fuel and air homogeneous mixer before combustion starts and the mixture auto-ignites as a result of compression stroke which causes the temperature to rise[50]. HCCI is the combustion concept of both SI and CI engines. Here the combustible mixture is drawn to conditions familiar for self-ignition as in conventional CI engines, with homogeneous air fuel mixture as in SI engine. In HCCI mode of combustion, the homogeneous mixture is prepared and self-ignited in a single time throughout the total combustible mixture due to increase in temperature by the stroke of compression and this fact is found by optical diagnostic research methodology[87]. HCCI offers complete combustion due to homogeneous charge. HCCI is a concept which is developed in response to the need of lower NOx and PM emissions and higher efficiency. Reducing HC and CO emissions is much easier in HCCI than reducing NOx and PM from emissions in CI engines. HCCI concept can overcome all the technical issues but requires utmost attention. Regulating the rate of heat release, combustion initiation and homogeneous mixture preparation are major research obstacles in practical implementation of this technology. Comparison of HCCI and CI engines is shown in **Table 1**.

Table1: Comparison between Conventional CI and HCCI

S.No	Comparing Parameters	CI Engine	HCCI Engine
1	Efficiency	High	Equally High
2	PM and NOx emissions	More	Less
3	Ignition Temperatures	1600^0C to 1800^0C	1200^0C to 1500^0C
4	Ignition Period	High	Less
5	Combustible Mixture	Heterogeneous	Homogeneous

Source: References [23, 27, 50, 59]

Figure 1 shows the mode of combustion for HCCI compared with CI and SI engines indicating low temperature combustion without flame front propagation. Flame front creates high temperature regions for NOx formation.

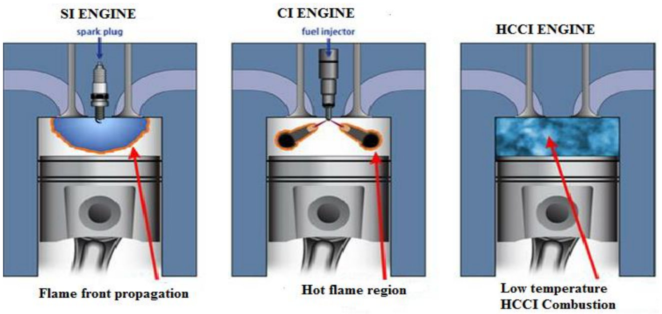

Fig.1: HCCI combustion without Flame front [90]

Two-dimensional images of the chemiluminescence using framing camera for an optically accessible engine fuelled with DME by Lida et al[69], indicating homogeneous and heterogeneous combustion processes by mixing air with fuel in intake manifold is shown in figure 2.

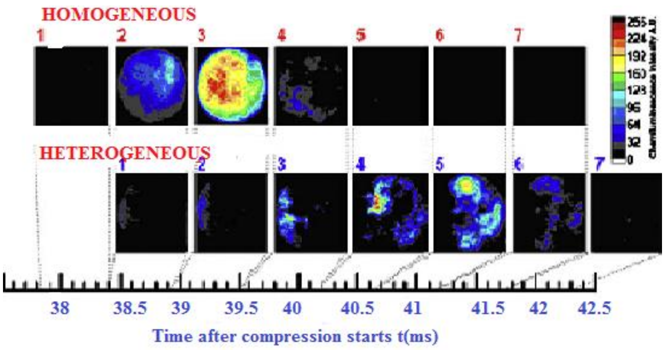

Fig.2: Homogeneous combustion compared to Heterogeneous combustion [69]

3. Use of Oxygenated Fuels

The requirements of specific fuel consumption, torque, power induced and emissions are highly influenced by the chemical composition of the fuel we have supplied. The Oxygenated fuels are suitable conventional fuel alternatives when we are used in advanced combustion concepts like HCCI. Oxygenated fuels commonly used by the researchers for evaluating engine performance and emission characteristics are alcohols and ethyl or methyl esters of biodiesels. The blending of these fuels with conventional fuels will provide necessary oxygen levels for effective combustion and helps to emit CO_2 instead of carbon rich particles like CO and also these fuels are helpful to reduce particulate matter (PM) emissions but care should be taken that the use of more Oxygenated fuels will promote more fuel consumption compared to power output [60]. Blending of these fuels with conventional fuels will also reduce cetane number since oxygenated fuels (alcoholic) have negligible cetane value. Since HCCI emits high HC and CO pollutants, Oxygen enriched fuels promotes complete combustion [45] which in turn results in less pollutants [47], when used in conventional and HCCI engines. The properties of these fuels are closer to conventional fuel properties which in turn make them to use and mix with conventional fuels to run engines which are suitable for alternative fuel combustion [60].

Properties of these fuels are indexed in Table 2.

4. Use of Ignition Improvers

The Ignition improvers are also called as cetane number improvers. The combustion quality of the diesel fuel with other blends could be improved by adding ignition improvers. Diesel fuel blends with improper cetane numbers could cause rough engine operation. The time delay between the injection and spontaneous combustion of the fuel could be decreased by adding ignition improvers by increasing the diffusion rate , which also could minimise the cold starting problems of diesel engines especially at higher altitudes. The NOx emissions could be effectively reduced by adding ignition improvers because of their high latent heat of vapourization and also the ignition improvers could cause reduction in HC emissions because of its high oxygen percentages [86]. Another consideration is also there that decrease in the cetane number improved the ignition delay period which in turn causese reduced smoke emission [88].

So by adding ignition improvers like DEE, DME etc to diesel fuel blends at optimum level only [72] leads to further reduction of emissions by allowing the fuel blends to evaporate immediately and also to maintain the blend cetane value to the required extent.

The properties of ignition improvers permit them to use as fuel additives because of their

- Higher cetane value
- Volatility
- Higher latent heat of vaporization
- Non corrosive nature
- Lower auto ignition temperature
- Miscibility with Diesel

Some of the properties of these ignition improvers compared to Diesel are indexed in Table 3.

5. Review of Literature

Research conducted by Rakesh Kumar Maurya et al [1] on combustion and emission characteristics of HCCI engine fuelled with ethanol showed that the relative air–fuel ratio (2.0–5.0) and intake air temperature(120^0–150^0C) have significant effect on the thermal efficiency, combustion efficiency. NOx emissions are lower than 10 ppm however HC and CO emissions are higher. Morteza Fathi et al [2] conducted experiments on HCCI engine using natural gas and n-heptane with various Exhaust Gas Recirculation (EGR) levels. Heat transfer rate decreases with EGR addition with lower specific fuel consumption, NOx emissions but HC and CO emissions are in increased trend. K Senthil Kumar et al [3] conducted performance test on a Diesel engine using ethanol blended biodiesel. Experimental results reveal that increased inlet air temperatures (40^0 to 60^0 C) and advanced injection timings (12^0, 15^0, 18^0 BTDC) caused in reduction of HC and CO emissions and increased NOx emissions. Javad Rezaei et al [4] investigated the characteristics of HCCI combustion using oxygenated fuels (i.e. butanol and ethanol). The thermal efficiency is higher at higher butanol volumes due to HCCI combustion. Su Han Park et al [5] conducted investigations on HCCI engine by varying the injection of Diesel and DME as 10 mg and 16.4 mg respectively, which showed lesser HC, CO and soot emissions than diesel, and higher NOx emission in DME combustion. K. Mathivanan et al [6] investigated multiple fuel injection strategies on HCCI engine fuelled with diesel. The increased thermal efficiency with reduced HC and smoke emissions were observed with multiple fuel injection strategies compared to those of single point injection. Ahmet Uyumaz et al [7] used the concept of higher intake air temperature with the fuel blend of 20% n-heptane and 80% isooctane with reduced valve lift for trapping exhaust gases. The in-cylinder pressure and heat release rate were decreased with stable HCCI combustion by trapping exhaust gases results in avoid knocking especially at higher loads.Based on above review the summary of details is indicated in Table 4.

6. Strategies to adopt HCCI Combustion

From the above review it has been observed that even though using oxygenated fuels in HCCI engines in some experiments, HC and CO emissions were in increased trend because of drawback of its combustion phenomenon, to avoid that there is a need to regulate instantaneous combustion [45] and also need for to ensure complete combustion. Later there is a need to improve the evaporating capacity of the fuel using ignition improvers and changing of operating conditions like injecting the fuel in pulses using multiple fuel injection strategies. EGR in high fractions [2, 55] increases HC and CO emissions, so there is need to regulate EGR fractions. HC and CO emission gets be reduced by increasing compressions ratios [8]. Premixed combustion and spray atomization also regulates HC and CO emissions [17]. The stratification strategy and by low temperature combustion using small exhaust gas proportions can improve operating ranges to higher loads[50].

Figure 3 shows the ideal combustion region for both HCCI and CI engines for to reduce emissions of UHC, NOx and CO and to reduce soot production[89]. Ideal combustion region is more practical for HCCI engines because of its lower combustion temperatures(1200^0C to1500^0C).

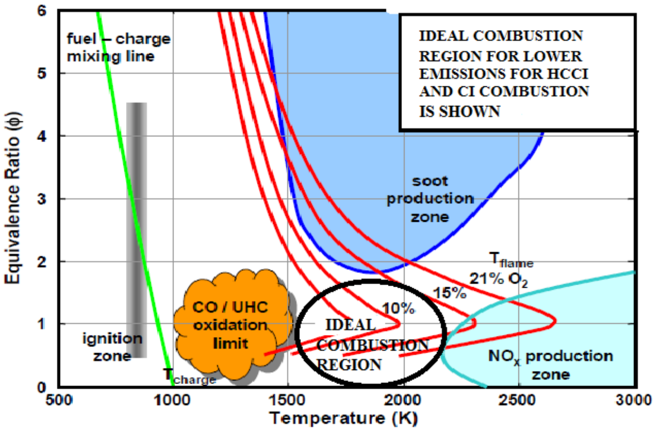

Fig.3: Ideal combustion region for lowest emissions[89]

It has been observed that in addition of using oxygenated fuels, ignition improvers [83,21], changing of some operating conditions for the HCCI engines leads to further reduction of HC and CO emissions. Multiple fuel injection strategies can be used for to improve the performance of HCCI in different operating conditions [70].

The HCCI mixture formation could be achieved by following methods for CI engines

- High intake air temperature
- Exhaust Gas Recirculation
- High equivalence ratios
- High intake pressures and highly delayed combustion timings
- External mixture formation techniques
- Injecting diesel in pulses using multiple fuel injection strategies
- Port injection technique
- Oxygenated fuels with ignition improvers

Source: References [41, 64, 69, 80]

The major challenges for HCCI Combustion includes

- The difficulty in combustion phase control which depends on properties of the mixture and exposure to time temperature history.
- Cold starting problems since operating temperatures of these engines are less compared to conventional engines so there is need for to start with conventional mode.
- Homogeneous mixture preparation which requires homogeniety in combustible mixture that requires elevated intake air temperatures for immediate evaporation and mixing of fuel with air.
- Unburnt hydrocarbons and CO emissions because of lowest operating temperatures of HCCI.

Source: Reference[50]

Table 2: Properties of some Oxygenated fuels compared to Diesel

S.No	Fuel	Molecular Wt. (g/mol)	O_2 (wt %)	LHV(MJ/l)	Stochiometric A/F ratio	Boiling point (^{0}C)
1	Methonol	32.04	0.50	15.8	6.46	64.7
2	Ethonol	46.0	0.35	21.4	8.98	78
3	n hexanol	102.16	0.16	29.3	12.15	175
4	n proponal	60.09	0.27	24.7	10.33	97
5	n-butanol	74.11	0.22	26.9	11.17	118
6	Iso-proponol	60.09	0.27	24.1	10.33	83
7	Iso butanol	74.11	0.22	26.6	11.17	108
8	Diesel	198.4	0	35.06	14.95	125-400
9	Gasoline	111.19	0	30-33	14.58	27-225

Source: References [20, 12]

Table 3: Comparison between properties of DME and DEE with Diesel

S.No	Property (unit)	DME	DEE	Diesel
1	Chemical structure	C_2H_6O	$C_2H_5OC_2H_5$	–
2	Carbon content (mass %)	52.2	64.86	86
3	Hydrogen content (mass %)	13	13.5	14
4	Oxygen content (mass %)	34.8	21	0
5	Liquid density (kg/m^3)	667	713	831
6	Cetane number	>55	>125	39–50
7	Auto ignition temperature (K)	508	433	522
8	Stoichiometric air fuel ratio	9.0	11.1	14.6
9	Boiling point at 1 atm (K)	248.1	307	450–642
10	Lower heating value (MJ/kg)	27.6	33.9	42.5
11	Kinematic viscosity of liquid (cSt)	<0.1	0.23	3

Source: References [21, 22, 17, 61, 93]

Table 4: HCCI Emissions and Performance using various Operating Parameters and Fuel blends

S.No	Blended Fuel	Operating Parameters	Efficiency Parameters	Emissions
1	Ethanol	Higher Relative Air–Fuel Ratio and Intake Air Temperatures[1,13]	Thermal Efficiency, Combustion Efficiencies are High	NOx Emissions are Lower, HC and CO Emissions are Higher
2	Natural Gas and N-Heptane	Exhaust Gas Recirculation[2]	Reduced fuel consumption	Reduced NOx Emissions and Increased HC and CO Emissions
3	Ethanol blended Biodiesel	Increased Inlet Air Temperatures and Advanced Injection [3]	Increased Peak Cylinder Pressures and Heat Release Rates	Reduced CO and HC and Increased NOx Emissions
4	Diesel	Multiple Fuel Injection[6,34]	Thermal Efficiency Increased	The HC and Smoke Emissions are Lower with increased NOx
5	20% N-Heptane, 80% Isooctane	Increased Inlet Air Temperatures, Exhaust Gas Trapping by Reduced Valve Lift [7]	Increased Indicated Thermal Efficiency	Low NOx emissions
6	DME	EGR,Multiple Injection[17,80]	No Change	Lower HC and CO Emissions
7	N-Butane with DME	Conventional Engine[16]	Power Output Improved	Soot and NOx Emissions were Comparable
8	Mixtures of n-heptane and iso-octane	Increased inlet temperature, EGR temperature, equivalence and compression ratio[8]	Reasonable indicated efficiency with increased overall reactivity	Decreased emissions of CO and HC,CO_2 increased
9	70% Ethanol	High intake pressures, high equivalence ratios and highly delayed combustion timing[11]	High power output, low ringing tendency	Low NOx emissions

6. Conclusion

The HCCI concept has the ability to produce lower NOx and PM emissions while maintaining the thermal efficiency near to that of conventional CI engines. The main limitations of HCCI combustion are regulating its rapid combustion or its instantaneous combustion, homogeneous mixture preparation, controlling of HC and CO emissions, rapid pressure rises and knocking at maximum loads. HC and CO emissions can be controlled by blending with oxygenated fuels. Multiple injection strategies have been developed in order to extend the operating load range and to reduce HCCI emissions.

The fundamental concerns to gain HCCI combustion are by varying the mixture ratios for self-ignition, by using multiple injection strategies, varying the ignition delay period and temperatures to which the mixture is exposed, varying the conventional fuels with oxygenated fuel blends and also by using ignition improvers to improve evaporative properties of HCCI fuels and cetane number there by to ensure homogeneous mixture preparation.

HCCI is the advanced clean and complete combustion concept, but there is need for to bridge the gap between the fuel properties and operating parameters to ensure complete HCCI technology and to replace conventional CI system. There is need for to improve its operating range performance at various load and speed conditions. The HCCI concept will become more practical throughout the operating range by switching over to multiple mode combustion processes, by using various operating conditions and by varying fuel properties.

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Nomenclature

DEE	Di Ethyl Ether
DME	Di Methyl Ether
HC	Hydro Carbons
HCCI	Homogeneous Charged Compression Ignition
PCCI	Premixed Charged Compression Ignition
CI	Compression Ignition
SI	Spark Ignition
NO_X	Nitrogen Oxides
PM	Particulate Matter
CO	Carbon Monoxide
CO_2	Carbon Dioxide
ppm	parts per million
EGR	Exhaust Gas Recirculation
LHV	Lower Heating Value
A/F	Air Fuel Ratio
UHC	Un burnt hydrocarbons

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