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Analysis of Performance and Emission Characteristics of a Homogeneous Charge Compression Ignition (HCCI) Engine

Syed Yaser Hussaini[a], Subhash Lahane[a]* , N. G. Patil[a]

[a]*Department of Mechanical Engineering, MIT Aurangabad, 431010, Maharashtra, India*

Abstract

In internal combustion engines, soot-NOx paradox is extremely challenging issue, which remains to be resolved. Homogeneous charge compression ignition (HCCI) is a new combustion concept that gives benefits such as diesel like efficiency and resolves the problem of high level of NOx and PM simultaneously. It gives very high rate of heat release which cannot be easily controlled. The present work deals with development of HCCI engine and performance and emission investigations of combustion on petrol fuelled single cylinder engine. Homogeneous mixture preparation is the most critical part of the HCCI combustion concept. To achieve homogeneous mixture of fuel and air, petrol was used. The mixture was introduced in combustion chamber through carburetor, controlled by throttling, the intake manifold specially fabricated for the engine under consideration. Experiments were performed at variable speed to observe behavior of HCCI combustion. The engine's load carrying capacity was controlled by regulating the air and fuel flow. It was observed that engine could run smoothly at lean air fuel mixture but knocking was noticed at rich air fuel mixture. Compared with base engine, NOx and smoke opacity were observed to be reduced by 78% and 100% respectively with modified engine (HCCI) as compared to base engine.

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Keywords: SI engine; HCCI engine; knocking; NOx emission

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1. Introduction

IC engines have played a key role, both socially and economically, in shaping of the modern world. Their suitability

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* Corresponding author. Tel.: +91-240-2375199; Fax: +912402375275
E-mail address: subhashlahane@gmail.com

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as an automotive power plant, coupled with a lack of practical alternatives, means road transport in its present form could not exist without them. However, in recent decades, serious concerns have been raised with regard to the environmental impact of the gaseous and particulate emissions arising from operation of these engines. As a result, ever tightening legislation, that restricts the levels of pollutants that may be emitted from vehicles, has been introduced by governments around the world. In addition, concerns about the world's finite oil reserves and, more recently, by CO_2 emissions brought about climate change has lead, particularly in Europe, to heavy taxation of road transport, mainly via on duty on fuel. These two factors have led to massive pressure on vehicle manufacturers to research, develop and produce ever cleaner and more fuel-efficient vehicles. CAI/HCCI combustion represents for the first time a combustion technology that can simultaneously reduce both NOx and particulate emissions from a diesel engine and has the capability of achieving simultaneous reduction in fuel consumption and NOx emissions from a gasoline engine [1].

Homogeneous Charge Compression Ignition (HCCI) combustion is radically different from the conventional spark ignition (SI) combustion in a gasoline engine and compression ignition (CI) diffusion combustion in a diesel engine. The combination of a diluted and premixed fuel and air mixture with multiple ignition sites throughout the combustion chamber eliminates the high combustion temperature zones and prevents the production of soot particles, hence producing ultra-low NOx and particulate emissions [2]. Homogeneous Charge Compression Ignition (HCCI) is one of those representative technologies being developed in the field of engine combustion. HCCI engines are expected to have higher efficiency than SI engines due to their high compression ratio and dispensability of throttle valves. Compared to diesel engines, they emit less particulate matters and less NOx because only lean premixed combustion without local fuel-rich zones is present. Due to homogeneous mixture, combustion starts at several points simultaneously inside the combustion chamber instead of just around the fuel injector [3]. This prevents the formation of flame front and reduces the overall temperature (below 1850 K) inside the combustion chamber and hence reduces NOx formation rate as well. HCCI is an alternative piston-engine combustion process that can provide efficiencies as high as compression-ignition, direct-injection (CIDI) engines (an advanced version of the commonly known diesel engine) while, unlike CIDI engines, producing ultra-low oxides of nitrogen (NOx) and particulate matter (PM) emissions [2-3].

Homogeneous charge compression ignition (HCCI) was first identified and studied by Onishi [1]. It involves compressing a homogenous fuel-air mixture until it self-combusts. It differs from diesel combustion because the charge is premixed and only then compressed and it differs from SI combustion because the ignition is spontaneous and not spark-induced. The combustion occurrence depends on chemical kinetics and the compression process [2]. Verified characteristics of HCCI include: 1. Ignition occurs simultaneously at numerous locations within the combustion chamber, 2. Traditional flame propagation advance is absent, 3. There is no need of an external event to initiate ignition, 4. Both rich and extremely lean fuel mixtures may be used, 5. Charge is consumed rapidly, 6. A wide variety of fuels may be used, 7. Essentially, no compression ratio limitations [3-5]. Noguchi et al. [6] performed a spectroscopic analysis on HCCI combustion by experimental work on an opposed piston two-stroke engine. They named the combustion process as "TS (Toyota-Soken) Combustion". From optical investigations, it was noted that ignition took place at numerous points throughout the cylinder and no discernible flame front was observed during combustion. Spectroscopic methods were used to detect the intermediate species and measured high levels of CH_2O, HO_2, and O radicals within the cylinder before auto-ignition. These species are characteristic of low temperature auto-ignition chemistry of larger paraffinic hydrocarbon fuels. After ignition, high concentrations of CH, H, and OH radicals were observed which were indicative of high temperature chemistry during the bulk burn. The measurements technique is presented to visualize the distribution of the in-cylinder mixture by laser induced fluorescence (LIF) and an experimental approach for analyzing the effect of the temperature distribution prior to ignition on HCCI combustion [7]. Olsson et al. [8] modified a 6-cylinder truck engine for turbo charged dual fuel HCCI engine operation. Two different fuels, ethanol and n-heptane, are used to control the ignition timing. The objective of this study is to demonstrate high load operation of a full size HCCI engine and to discuss some of the typical constraints associated with HCCI operation. This study proves the possibility to achieve high loads, up to 16 bar Brake Mean Effective Pressure (BMEP), and ultra-low NOx emissions, using turbo charging and dual fuel.

Najt and Foster [9] extended the work to four-stroke engines and attempted to gain additional understanding of the underlying physics of HCCI combustion. They used a CFR test engine with variable compression ratio and concluded that HCCI auto- ignition is controlled by low temperature (below 1000 K) chemistry and the bulk energy release is controlled by the high temperature (above 1000 K) chemistry dominated by CO oxidation. Correspondingly, it was noted that HCCI combustion suffers from a lack of control of the ignition process and a limited operating range. Combined with the previous work of Onishi [1] and Noguchi [6], it can be concluded that, unlike traditional SI combustion that relies on the flame propagation and diesel combustion and is heavily dependent on the fuel/air mixing, HCCI combustion is a chemical kinetic combustion process controlled by temperature, pressure, and composition of the in-cylinder charge. Onishi [1] worked in order to increase combustion stability of two-stroke engines and this technology continues to be strongly pursued today. It was called 'Active Thermo-Atmosphere Combustion' (ATAC). They found that significant reductions in emission and an improvement in fuel economy could be obtained by creating conditions that lead to spontaneous ignition of the in-cylinder charge. It was reported that stable HCCI combustion can be achieved between low and high load limits with gasoline at a compression ratio of 7.5:1 over the engine speed range from 1000 to 4000 rpm.

From literature review [10-13], it is observed that the new emission standards are very challenging and will require a combination of strategies including: development of advanced combustion systems to reduce engine-out Emissions; development of adequate, reliable, and cost-effective after-treatment systems; and improvements in the coupling between engine and after-treatment-system operation. The problem of HCCI engine like drop in power, speed can be overcome by fuel modification [14]. Polat [15] proposed that die ethyl ether and ethanol are the promising fuel for HCCI engine. The results showed that apart from adopting higher compression ratios and boost pressures use of high swirl ratios is observed to be contributing to a large extent in enhancing the rates of heat transfer which would lead to significant reduction in in–cylinder temperatures suitable for low NOx emission formation in HCCI mode [16]. HCCI is an attractive advanced combustion process that offers the potential for substantial simultaneous reduction of both NOx and PM, while still providing high diesel-like efficiencies. In HCCI engines, combustion occurs as a result of spontaneous auto-ignition at multiple points throughout the volume of the in-cylinder charge gas. This unique property of HCCI allows the combustion of very lean or dilute mixtures, resulting in low bulk as well as local combustion temperatures that dramatically reduce engine-out NOx emissions. Also unlike conventional diesel combustion, the charge is well mixed, so PM emissions can be very low also. Hence, the present work is aimed at to develop HCCI engine (by modifying the compression ratio, intake air temperature and optimizing fuel delivery of base SI engine using gasoline as operating fuel) to compare the performance and emission characteristics of a base SI and HCCI engine.

Nomenclature

CAI	controlled auto ignition
cc	cubic centimetre
CI	compression ignition
CO	carbon monoxide
HC	hydrocarbon
HCCI	homogeneous charge compression ignition
NOx	oxides of nitrogen
PM	particulate matter
SI	spark ignition

2. Experimental details

The test engine used for this work is a 395 cc, air cooled SI engine (G400AG) manufactured by Greaves Cotton Ltd. The engine used for the work is a lightweight engine for 3-wheeler automotive application. The schematic diagram of experimental setup is shown in Figure 1 (a). The detailed specifications of the engine are given in Table 2. Engine was coupled to an eddy current dynamometer which has the capacity of operating at 70 hp @ 5000 – 10000 rpm.

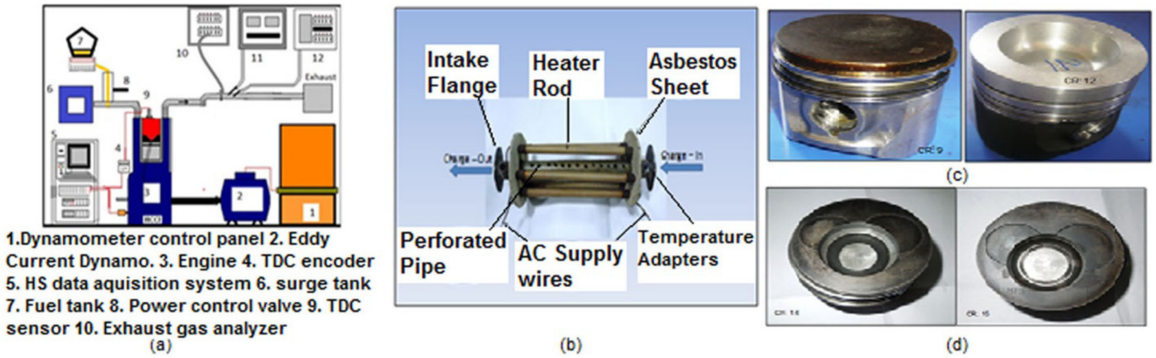

Figure 1. (a) Experimental setup (b) heater with intake manifold (c) Modified piston of CR of 9 and 12 (d) modified piston of CR of 14 and 15

The test engine used for the development of HCCI engine is a single cylinder, 86 mm x 68 mm, 395 cc, four stroke, air cooled, open loop carburetor controlled engine being used in a wide variety of 3 wheeler automotive vehicles. In an IC engine, valve timing is an important design parameter which affects many engine performance parameters. As per valve timing of the engine, the inlet valve opens at 7.5 ºCA before TDC and closes at 25.5° after BDC and exhaust valve opens at 21 ºCA before BDC and closes at 3 ºCA after TDC.

3. Methodology

Utilization of HCCI in internal combustion engines has usually been approached either by converting an existing spark ignition engine to HCCI operation. The selection of the base machine depends upon the purpose and the final goal of conversion. The spark ignition HCCI operation of an existing SI engine would normally retain its petrol operating capacity for need of an assured operational back-up. Another important fact of the first approach is that no major modifications are permissible and therefore, the performance in terms of power and efficiency can at best be comparable to existing petrol operation. The base SI engine can be converted to dedicated HCCI engine with major modifications such as (1) Introduction of intake heater (2) Redesign of piston geometry (3) Changes in carburetor.

Intake heater plays an important role in HCCI engine. It releases heat and heats the intake air to maintain the sufficient temperature of intake air fuel charge for the combustion in combustion chamber. In this work the heater was powered with AC supply for its working. The heater was made using various materials considering minimum rejection of heat to atmosphere. The manufactured heater is shown in Figure 1 (b).

The redesign of the combustion bowl space to provide suitable compression ratio, 9, 12, 14 and 15 in case of HCCI, and to ensure requisite amount of air motion needed for premixed mixture has been carried out. In the present case, flat-piston has been used as shown in Figure 1 (c). The original design being a DI type had a bowl in the piston head as the combustion space as shown in the figure. The bumping clearance was 0.7 mm. In the modified piston, the bumping clearance is 1.0 mm. The squish area has been reduced from 89.3% to 83.1%. The Cylindrical Bowl-in-piston as shown in figure is known to provide radial motion of the charge, which along with the residual swirl and squish successfully creates the required turbulence. These are the original G435AIII diesel engine piston compression ratio 19.3 having same bore as G400AG with different skirt length. The bowl volume is calculated by hit and trail method. So, the appropriate compression ratio is obtained for combustion of HCCI engine. The geometry of the piston is changed / modified with the help of Pro-engineer modeling software. The modified pistons with compression ratio of 14 and 15 are shown in Figure 1 (d).

It has become necessary for the carburetor user to understand the function of each components of the carburetor so that the best performance can be achieved. The carburetor used is a side draught, variable choke mechanically controlled carburetor. The throttle slide has the metering needle attached to it. The pilot system provides a rich mixture at idle and low speeds when not enough air is being drawn through the carburetor to cause the main system to operate. The pilot circuit consists of a pilot jet and airscrew to provide mixture of air and fuel at idle and low speeds. The main system consists of jet needle, needle jet, main jet and main air jet. An air bleed circuit is incorporated in the main metering system. The air bleed aids fuel vaporization by introducing air into the fuel before it enters the air stream through the venture. Tests are conducted with two different main jets viz. MJ 57.5 and MJ 82.5. The main jet with smaller diameter has been used for meeting the lean burn phenomenon of HCCI engine.

4. Results and discussion

According to objective, first of all required modification and instrumentation was done and the experimental setup was completed. For the HCCI setup, a large number of subsystems (intake manifold, fuel induction system and heater etc.) were fabricated and tested separately. This section contains the detailed description of results and discussion based on following parameters:

- Engine performance analysis: This analysis is based on the qualitative performance achieved in HCCI mode and its comparison with base engine performance.
- Emission analysis: This analysis is based on the measurement of CO, HC, NOx and smoke opacity in the exhaust gas. Emission due to HCCI combustion mode and are compared with emission data of base engine in SI mode.

The test conditions for wide open throttle performance of base SI engine, HCCI 82.5 mode and HCCI 57.5 mode is given in Table 1. Engine starting trials were first carried out to decide the position of the intake air heater and the minimum intake air temperature required to start the engine in HCCI mode. Based on the trials, engine started when the intake air heater was placed between the air filter and the carburetor and the air was heated up to 166°C. Depending upon the response of engine other parts were also optimized and staring trials were taken with intake air heater.

Table 1. Test conditions for base SI and HCCI mode

Sr. No.	Parameter	Base SI Mode	HCCI(MJ 82.5) Mode	HCCI(MJ 57.5) Mode
1	Ignition Type	Spark Ignition	Auto Ignition	Auto Ignition
2	Compression Ratio	9	12	12
3	Air Intake	Naturally Aspirated (NA)	NA	NA
4	Intake Air Temperature	Atmospheric Temperature	160°C	160°C
5	Intake Air Heater	No	Yes	Yes
6	Main Jet	90	82.5	57.5
7	Throttle Condition	Wide Open	Wide Open	Wide Open

4.1 Engine performance analysis

The engine performance test under conventional SI mode and HCCI mode were conducted at different speeds for the selected engine. The HCCI mode was operated with two different fuel jets (57.5 and 82.5). The performance curves for power, torque, fuel consumption, brake thermal efficiency and exhaust gas temperature are discussed in this section. The graphical comparison of observed torque between SI and HCCI engine (with two different Main jets of the carburetor) is shown in Figure 2 (a). It can be observed that the engine operating in HCCI mode with small jet has given better torque compared to larger jet which confirms the lean burning phenomenon of HCCI engine. It is also observed that engine is not able to work at high loads and high rpm. The engine speed at maximum torque has dropped from 2300 rpm to 1500 rpm. It may be good for low speed engine application with low / optimum emissions. Similarly, the graphical comparison of observed power between SI and HCCI engine (with two different Main jets of the carburetor) is shown in Figure 2 (b). It can be observed that the engine operating in HCCI mode with small jet has given higher power compared to larger jet which confirms the lean burning phenomenon of HCCI engine. It is also observed that engine is not able to sustain high speed.

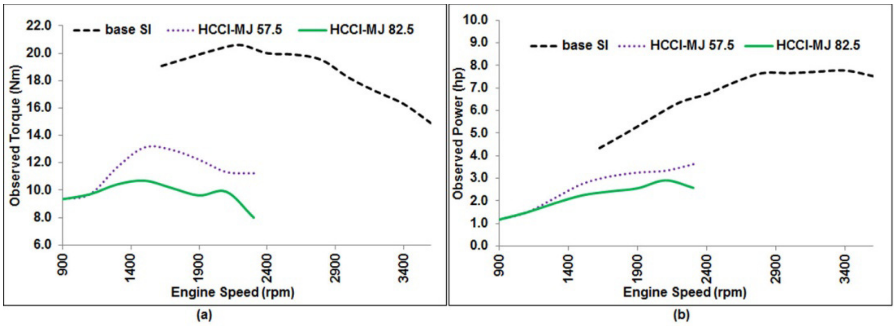

Figure 2. Variation of (a) torque (b) power for base SI and HCCI mode

The variation of fuel consumption of base engine and modified HCCI engine (with two different Main jets of the carburetor) is shown in Figure 3 (a). It is observed that the engine operating in HCCI mode has high fuel consumption than the base engine. Figure 3 (b) represents the brake thermal efficiency comparison of base engine and modified HCCI engine (with two different Main jets of the carburetor). It is observed that the engine operating in HCCI mode has low brake thermal efficiency than the base engine. It may be due to decrease in engine speed in HCCI mode to obtain same power output as in base SI engine. It needs to optimize the power and speed of the HCCI engine to get lower fuel consumption and higher power.

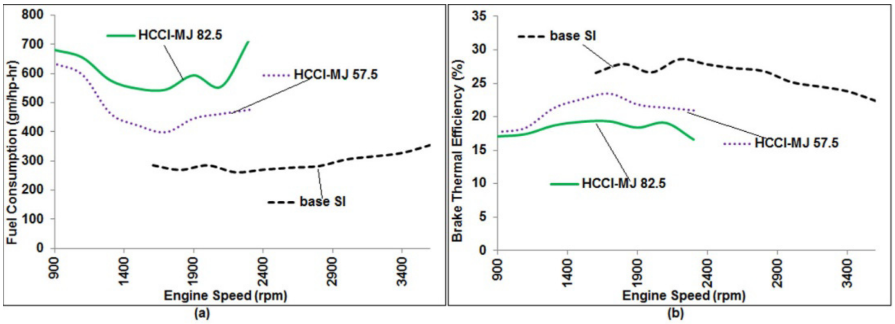

Figure 3. Variation of (a) brake specific fuel consumption (b) BTE for base SI and HCCI mode

The graphical representation of exhaust gas temperature for SI and HCCI engine (with two different Main jets of the carburetor) is shown in Figure 4 (a). It is observed that the engine operating in HCCI mode has comparatively much lower exhaust gas temperature as compared to base engine. This is due to the auto ignition property of HCCI resulting in reduction of NOx in emission which is discussed in next section. Performance with lower size fuel jet is comparatively higher than large size fuel jet which proves the lean burn phenomenon in HCCI. Performance of the HCCI engine can be enhanced by proper optimization and implementing close loop system. Significant reduction of in cylinder temperature results in lower lube oil temperature as well. It is also observed that the auto ignition phenomenon helps in reducing overall NVH of the engine.

4.2 Engine emissions analysis

The emission characteristics describe the engine out emissions like NOx, HC, CO. These parameters were recorded for modified HCCI engine and compared with that of conventional SI mode emissions. Figure 4 (b) shows the CO, HC and NOx emissions of conventional SI mode engine. The CO emission values are in % vol. and HC and NOx emission are in ppm. There is no abrupt change in values of CO with respect to engine speed. HC emission is dependent on the quality of air fuel mixture provided for combustion. The higher values of HC emissions are obtained where the air fuel mixture is rich i.e. at low idle engine speed and at rated power speed. Least value of HC is found at rated torque and speed where the air fuel ratio is stoichiometric. The NOx trend increases with increase in exhaust temperature and hence maximum value of NOx is observed at rated power and least NOx is observed at low idle speed due to low temperature.

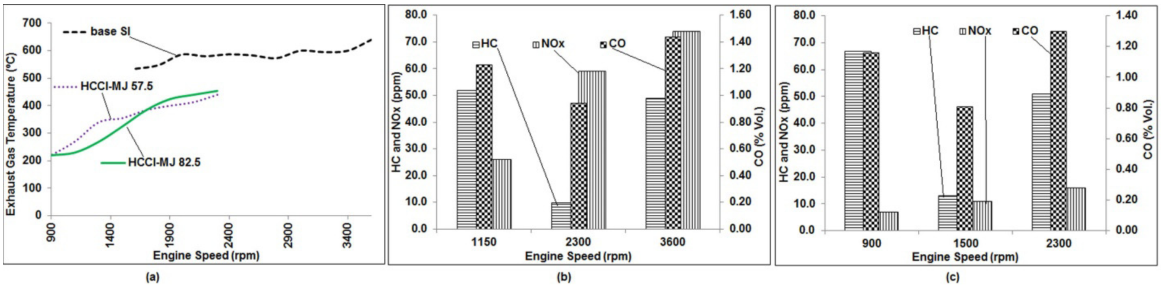

Figure 4. Variation of (a) exhaust gas temperature (b) CO, HC & NOx emission for base SI and (c) emissions for HCCI mode

Nitric oxide (NO) and nitrogen dioxide (NO_2) are the most harmful pollutants emitted by diesel engines. The combination of NO and NO_2 is known as NOx. Usually level of NO in exhaust gas is higher as compared to NO_2. High in-cylinder temperature and presence of atmospheric nitrogen in the fresh intake air are the two favourable conditions for reaction of oxygen with nitrogen to form NOx emission. Mainly NOx formation takes place during combustion when localized cylinder temperatures due to heterogeneous mixture exceed the critical temperature and molecules of oxygen and nitrogen start combining. Mixture quality plays an important role in NOx formation. A homogeneous mixture burns uniformly so that the localized temperature does not exceed up to critical temperature and hence controls level of NOx formation. Introduction of EGR gives positive results for reducing NOx level. Higher EGR percentage reduces rate of combustion hence reduces peak cylinder temperature and pressure. It dilutes the oxygen concentration also, that reduces the availability of fresh oxygen for NOx formation. NOx emission in SI combustion mode and HCCI combustion mode is given in Figures 4 (b) and (c). Difference in NOx levels for both SI combustion mode and HCCI combustion mode is shown in above diagram. This figure shows 80% reduction in NOx emission in case of HCCI combustion compared to CI combustion mode. Level of NOx for HCCI combustion mode is very low as compared to SI combustion mode. It is mainly due to burning of lean homogeneous mixture that gives lower peak temperature of combustion chamber.

HC emission is the measure of incomplete combustion of fuel. The level of unburned hydrocarbons in the exhaust gas is specified in terms of the total hydrocarbon concentration (g/kWh). HC emission in SI combustion mode and HCCI combustion mode is given in above figures. Higher HC emission is one of the drawbacks of HCCI combustion. Level of HC emission in SI combustion mode is lower by 30% as compared to HCCI mode. It happens mainly due to incomplete combustion of fuel at lower peak cylinder temperature due to homogeneous and lean combustion. For HCCI combustion, whole cylinder volume is full of homogeneous mixture of fuel and air, the combustion temperature is low hence more HC is generated because of trapping of lean fuel-air mixture in crevice volume and other dead volumes present in the combustion chamber. Carbon monoxide emission from SI engine is the measure of incomplete combustion. One major factor, which contributes to higher CO emission, is low combustion temperature due to lean mixture. At this lower peak combustion temperature, intermediate combustion product such as CO cannot be fully oxidized into CO_2. As the performance obtained with 57.5 main jet was better than the performance obtained wit 82.5 main jet, therefore emission data in HCCI mode is taken with 57.5 main jet. From the above emission data it can be noted that NOx in HCCI mode is reduced by 78 % at a cost of increase in HC by 30%. As the limit for HC is greater than the limit for NOx therefore the decrease in NOx at a cost of increase in HC is acceptable. There are chances of reduction in HC as well by introducing precise engine management system. CO emissions in SI and HCCI mode are found to be almost same.

5. Conclusions

In the present research work, experiments were carried out on base SI engine and the same engine modified to HCCI mode for analysis of performance and emission characteristics in HCCI mode. Performance with lower size fuel jet is comparatively higher than large size fuel jet which proves the lean burn phenomenon in HCCI. Knocking was observed with high compression ratio but it reduces with decrease in compression ratio. Performance of the HCCI engine can be enhanced by proper optimization and implementing close loop system. Following are the major conclusions drawn from the experimental study.

- Performance in HCCI mode is lower than the SI mode which can be increased by precise controlling of A/F mixture.
- Heating of intake air results in drop of low idle, rated power and maximum torque engine speed.
- In SI mode low idle speed was 1250 rpm whereas in HCCI mode the low idle speed reduced to 900 rpm. The rated power speed in SI mode is 3600 rpm whereas the rated power speed in HCCI mode dropped to 2300 rpm.
- The overall engine noise, vibration and harshness were observed to be reduced in HCCI mode.
- NOx emission decreased by 78% with HCCI mode as compared to base SI engine.
- No significant change was observed in CO emission with base SI and HCCI mode.
- HC emission increased by 30% with HCCI mode as compared to base SI engine.

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