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An Experimental Investigation of Combustion, Emissions and Performance of a Diesel Fuelled HCCI Engine

Akhilendra Pratap Singh, Avinash Kumar Agarwal
Engine Research Laboratory, Department of Mechanical Engineering,
Indian Institute of Technology Kanpur,
Kanpur-208016, India
#Corresponding Author's email: akag@iitk.ac.in

ABSTRACT

Homogeneous charge compression ignition (HCCI) is an advanced combustion concept that is developed as an alternative to diesel engines with higher thermal efficiency along with ultralow NOx and PM emissions. To study the performance of this novel technique, experiments were performed in a two cylinder engine, in which one cylinder is modified to operate in HCCI mode while other cylinder operates in conventional CI mode. The quality of homogeneous mixture of air and fuel is the key feature of HCCI combustion. Low volatility of diesel is a major hurdle in achieving HCCI combustion because it is difficult to make a homogeneous mixture of air and fuel. This problem is resolved by external mixture preparation technique in uses a dedicated diesel vaporizer with an electronic control system . All the injection parameters such as fuel quantity, fuel injection timing, injection delay etc., are controlled by the injection driver circuit. To study the effect of exhaust gas recirculation on combustion and emission behavior, two different EGR conditions (0% and 15%) are investigated. Results show superior emission characteristics of HCCI combustion as compared to conventional CI combustion and gives up to 80% and 50% reduction in NOx and smoke respectively. However HC and CO emissions are slightly higher as compared to conventional combustion. Application of EGR controls the combustion rate significantly and improves emission behavior at a cost of slightly inferior performance.

INTRODUCTION

Performance and environmental requirements of diesel engines are continuously increasing, requiring application of new and advanced technologies along with extensive modification in existing methodologies. DICI (Direct Injection Compression Ignition) and SI (Spark Ignition) engines are two basic technologies with established application in automobiles. SI and CI engines both use fossil fuels and have their own benefits however DICI engines are more popular due to their suitability for medium-duty as well as heavy-duty applications. Both diesel and gasoline engines are large contributors to urban air pollution. In conventional CI engines, large amount of NOx is formed due to high in-cylinder temperatures in flame regions; and smoke is also formed due to low localized temperature zones and presence of localized fuel-rich regions within the combustion chamber. This huge amount of NOx reacts in the atmosphere to form photochemical smog. Particulate matter (PM) emitted from diesel engines increase the incidences of asthma and respiratory problems. Due to adverse health effects of these pollutants, increasingly stringent emission standards in the world are implemented, which require simultaneous reduction of PM and NOx emissions [1].

Homogeneous charge compression ignition (HCCI) is a technique that has been gaining a lot of interest due to simultaneous reduction of both (PM and NO_x) by using homogeneous mixing of fuel-air and compression ignition. Along with this outstanding characteristic, it becomes more attractive due to very high diesel-like efficiencies. In HCCI engines, combustion occurs as a result of spontaneous auto-ignition at multiple points throughout the in-cylinder charge volume . This has been verified by several researchers using optical diagnostic techniques [2-5]. This unique property of HCCI allows the combustion of very lean or dilute mixtures, resulting in relatively lower bulk as well as local combustion temperatures that significantly reduce engine-out NOx emissions. Also unlike conventional diesel combustion, the charge (fuel and air) is well mixed (homogeneous) in HCCI combustion, therefore PM formation and emission is ultra low. From cost point of view, HCCI engines can be made cheaper than conventional diesel engines because HCCI system uses a lower-pressure fuel-injection system. However, the main difficulty in HCCI operation is control of ignition, which in-turn is governed by chemical kinetics. Small variation in control parameters such as temperature, fuel quantity etc. inside the cylinder can make a significant effect on combustion because chemical kinetics is very sensitive to these control parameters. Hence, fuel composition, equivalence ratio and thermodynamic state of the mixture plays an important role in HCCI combustion [6].

Initial efforts for HCCI were made on a gasoline-fueled engine by Onishi et al. with an objective of increasing combustion stability of two-stroke engines [7]. This technology continues to be strongly pursued even today and is named “Active Thermo-Atmosphere Combustion” (ATAC). In this experiment, a significant reduction in engine out emissions as NOx and PM was obtained. On the basis of the results of two stroke engines, Najt and Foster [8] extended the work to four-stroke engines and attempted to gain additional understanding of the underlying physics of HCCI combustion. They performed experiments using 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, which is dominated by CO oxidation. In the experiments, it was noted that HCCI combustion suffers from a lack of control of the ignition process and can be applied within a small timing range. Thring [9] further extended the work of Najt and Foster [8] in four-stroke engines. The experiments were conducted for performance of a HCCI engine operated with a fully-blended gasoline. Experimental results show that the operating regime was restricted to part-load operation, and control of the auto-ignition timing was a critical issue.

After successfully achieving HCCI combustion in gasoline engines, research efforts are turned towards attaining diesel HCCI in 1990’s. Initially, early fuel injection and late fuel injection techniques were attempted for obtaining diesel HCCI, however these techniques resulted in poor mixture quality and inferior combustion. Basic problems related to design and operational parameters related to diesel HCCI were evaluated by Suyin Gan et al. [10]. In the experiments, in-cylinder mixture preparation techniques was used and various experiments were performed under varying operational conditions such as different injection strategies, injection pressures, injection timings, intake air temperatures etc. along with varying design parameters such as piston geometries, compression ratios, swirl etc. It was concluded that the possibility of attaining diesel HCCI combustion exists with various limitations. Main challenge was low volatility of diesel. For resolving this issue, external mixture preparation techniques were developed, in which fuel was injected in the intake manifold, and mixed with hot air to provide premixed homogeneous charge. To achieve this, elevated temperatures are required for significant vaporization of fuel. The other barrier was significant cool-combustion chemistry of diesel, leading to rapid auto-ignition once compression temperatures exceed above 800 K [11]. All above mentioned research efforts showed the potential of early direct injection and late direct injection methodology of HCCI combustion but generally these techniques are suitable for gasoline.

For diesel fuel, external mixture preparation approach is the most advanced concept, which is based on port fuel injection. This technique uses fumigation of diesel at elevated temperatures [12]. Utilization of turbulent flow velocities at intake port to promote mixing makes it potentially strong as compared to others. Ryan et al. applied homogeneous mixture preparation technique and used port fuel injection to supply diesel into the intake air stream. An intake air heater was installed upstream of the fuel injector to preheat the air. Engine compression ratios were varied from 7.5-17 along with the EGR [13]. Concept of external mixture formation was further developed by Gray et al. [14] and they found three key issues for diesel-fueled HCCI. First, very premature ignition and knocking occurred, if normal diesel compression ratios were used. Satisfactory results required compression ratios in the range of 8 to 13, depending on intake air temperature and amount of EGR used. Second, relatively high intake temperatures (135 to 205°C) were required to minimize the accumulation of liquid fuel on surfaces of the intake system. Third, unburned HC emissions were very high. As a result of the poor combustion efficiency, reduced compression ratios and non-optimal combustion phasing, fuel consumption increased by an average of about 28% over normal direct-injection (DI) diesel combustion. However they reported dramatic reduction in emission of NOx. Similar experiments were also conducted by Maurya et al. using gasoline, various alcohols and their blends with gasoline. External mixture formation technique was successfully implemented for a high compression ratio (16.5) engine [15].

Some researchers also explored the possibility of using external methods for combustible mixture formation in the intake manifold [16-17]. Shawn et al. atomized the fuel and then mixed with air to prepare a homogeneous mixture in a diesel atomizer. The effects of various parameters such as EGR, air-fuel ratio, intake air temperature, engine speed etc. on HCCI combustion was investigated by Shawn et al. [18]. It was concluded in this study that EGR is the most promising solution that can control the formation of oxides of nitrogen. In another research carried out by Agarwal et al. [19] also, it was suggested that EGR is an excellent approach to reduce NOx emissions, however it leads to fuel penalty. EGR also affects other important performance and emission parameters such as thermal efficiency, brake specific fuel consumption and smoke. In normal CI combustion, increasing EGR rate leads to higher soot formation and emission. This tends to degrade the lubricating oil due to higher soot contamination and also result in higher engine wear [20]. In most of the recent research efforts related to diesel HCCI, mixture preparation is achieved by using in-cylinder fuel-air mixing techniques, such as very early fuel injection and late fuel injection, leading to formation of partially homogeneous mixtures [10, 21-22].

Present research effort is directed towards development of methodology for formation of homogeneous fuel/air mixture outside the combustion chamber. An electrically heated external mixing device named "diesel vaporizer" has been developed for the formation of homogeneous diesel-air mixture in the intake manifold, outside the engine cylinder. Diesel vapor produced by diesel vaporizer also contain tiny diesel droplets, which mix with intake air and form partly homogeneous combustible mixture. Various engine experiments were performed on diesel HCCI to investigate the combustion, performance and emission characteristics of the HCCI engine under varying EGR conditions. The HCCI experimental results were then compared with the baseline data from an identical diesel engine operating in conventional CI mode.

EXPAERIMENTAL SETUP

The schematic diagram of the experimental setup is shown in figure 1.

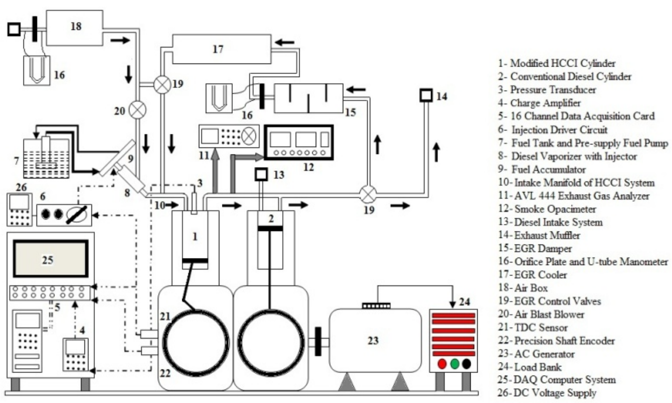

Figure 1: Schematic of diesel HCCI experimental setup

The experimental setup is divided in six basic sub-systems as explained below:

Engine - The experiments were performed on a constant speed, two cylinders, four stroke, air cooled, direct injection diesel engine (Indec PH2). In this engine, one cylinder is modified to operate in HCCI combustion, while the other cylinder works in conventional diesel (CI) combustion mode. The engine is coupled with a single phase 9 kW, 220 volts AC generator. A load bank of 10 kW with a loading steps of 0.5 kW was used for loading the engine generator system. The technical specifications of the test engine are given in Table 1:

Table 1: Technical specification of the test engine

Characteristics	Specifications
Make / Model / Type	Indec/ PH2/ Diesel engine
Injection type	Direct injection
Number of cylinders	Two
Bore/ Stroke	87.3/ 110 mm
Power output/cylinder	4.85 kW @ 1500 rpm
Compression ratio	16.5:1
Displacement/ cylinder	659 cc
Fuel injection timing (SOI)	240 before TDC
Fuel injection pressure	210 kg/cm^2 @1500 rpm
Oil sump capacity	6.8 Liters

Diesel Vaporizer - Homogeneous mixture preparation is the most critical part of the diesel fuelled HCCI combustion. Low volatility of diesel is the main obstacle in formation of homogeneous mixture of fuel and air. In the present investigation, homogeneous mixture of fuel and air was prepared by using an external mixture formation device called "diesel vaporizer", specifically designed for this study.

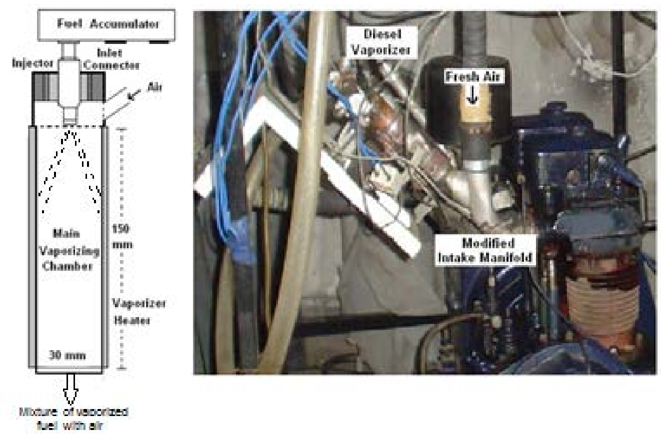

Figure 2: Schematic of diesel vaporizer and its arrangement

Diesel vaporizer contains a main vaporizing chamber made of copper pipe (high thermal conductivity material). Cylindrical surface of this chamber is covered externally by a cylindrical band heater, which provides necessary heat for diesel vaporization. The temperature of this heater is controlled by a PID temperature controller installed on the control panel. The cut-off temperature for the temperature controller was fixed at 160ºC with ± 10ºC. Detailed specifications of the diesel vaporizer are given in table 2.

Table 2: Detailed technical specification of diesel vaporizer

Characteristics	Specifications
Power supply to heater	750 W
Vaporizer diameter	30 mm
Length of vaporizer	150 mm
Warm-up time	6 min
Cut- off temperature	160 ±10ºC
Diesel injection pressure	3.0 bar

Fuel injector sprays the atomized fuel into the diesel vaporizer chamber, which is preheated by the electrical band heater. Fuel droplets absorb heat from chamber walls and vaporize. High velocity air supplied from the blower forces these diesel vapors/ tiny droplets to mix with the intake air. This results in formation of partially homogeneous mixture in the intake manifold, which is supplied to the combustion chamber through the intake valve. Temperature of this homogeneous mixture is considered as the charge intake temperature for the HCCI combustion mode.

Fuel Injection System - In fuel injection system, two separate fuel tanks for both cylinders are used. HCCI fuel tank consists of a pre-supply fuel pump, which delivers pressurized fuel to fuel accumulator (fuel rail). This fuel accumulator is modified for single cylinder system and supplies fuel by an electronically controlled port fuel injector. For controlling the port fuel injector, a dedicated injection driver circuit is designed, which is capable of controlling the injection parameters such as start of injection, injection delay, injection pulse duration and hence injection quantity. It receives input for TDC signal and generates trigger signal for the fuel injector.

Pressure Transducer and Data Acquisition System - A dedicated DAQ system is used to analyze the combustion data followed by characterization of the performance parameters. A data acquisition and analysis program was developed using National Instrument LabVIEW software (V. 8.6). The program allows simultaneous monitoring, processing and recording of various data sets from the engine. This system takes pressure signal as input and delivers combustion parameters such as rate of pressure rise, rate of heat release and engine performance parameters such as IMEP, indicated thermal efficiency and ISFC etc.

Exhaust Gas Recirculation - A part of the exhaust gas from the engine is cooled and recirculated into the combustion chamber. It reduces maximum temperature inside the combustion chamber and thereby reduces NOx emissions. The exhaust gas is highly turbulent and pulsating in nature which creates difficulties in its measurement therefore a damper is used to reduce the exhaust gas pulsations. A U-Tube manometer is used to measure the flow rate of the EGR across a calibrated orifice plate.

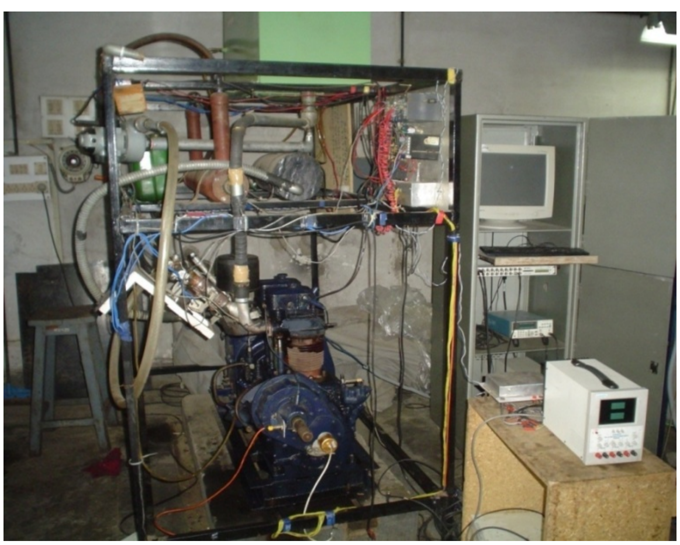

Figure 3: Diesel HCCI experimental setup

Emission Measuring Instruments - For emission analysis, five gas exhaust emission analyzer [Model: 444; make: AVL, India;] is used, which gives the raw concentrations of NO, HC, CO, O_2, and CO_2. The opacity of the exhaust gas is measured by Smoke opacitymeter (Model: 437; Make: AVL, India). The experimental setup is shown in figure 3.

RESULTS AND DISCUSSION

The results of the experiments are presented in the form of combustion analysis, performance analysis and emission analysis in the following sub-sections.

Combustion Analysis

In-cylinder pressure data analysis is the most effective way to analyze the engine combustion behavior because in-cylinder pressure history directly influences the power output, combustion characteristics and emissions of an engine. In the present investigations, in-cylinder pressure data is recorded on a crank angle basis using a high speed data acquisition system. Using this data, P-θ diagram can be drawn, which provides information about the start of combustion, rate of pressure rise, and maximum cylinder pressure. For controlling abnormal combustion due to relatively higher rate of heat release, cooled EGR is used. The combustion data is discussed for medium load condition with and without 15% EGR. The motoring diagrams are also shown for comparison.

P-θ Analysis

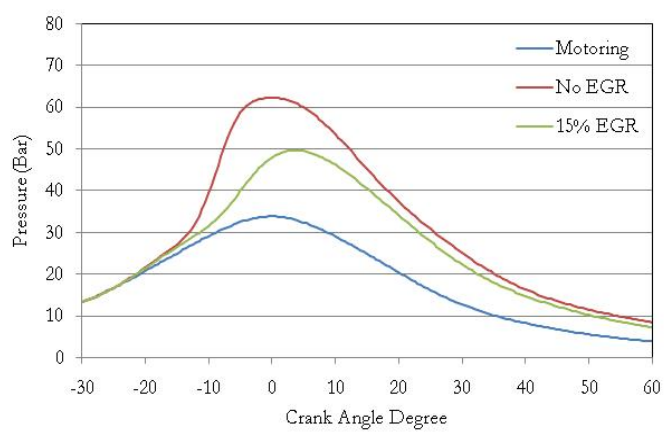

Figure 4: Pressure variation at medium load and EGR

This figure clearly shows the occurrence of auto-ignition (as HCCI combustion) in both cases. Rise in the slope of pressure curve with respect to motoring curve shows the start of combustion. Here early combustion of mixture is controlled by EGR, which retards the start of combustion significantly. Peak cylinder pressure also decrease with increasing EGR rate due to reduction in rate of combustion. It results in delayed combustion due to mixture dilution by inert species of recirculated exhaust gas. As EGR rate increases, level of dilution also increases and hence delay period increases, which shifts pressure curve towards right.

dP-dθ Analysis

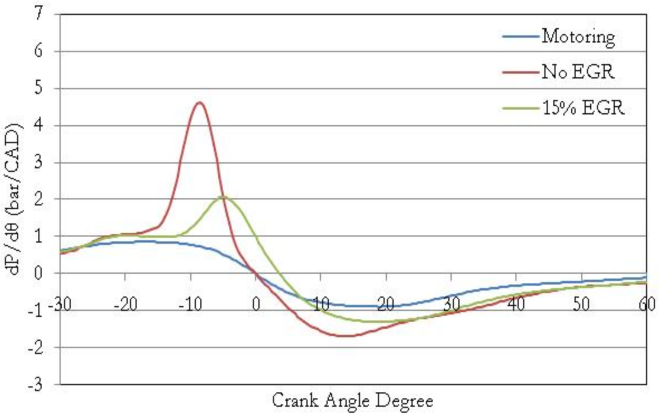

Figure 5: Variation in rate of pressure rise at medium load and EGR

Figure 5 clearly shows that the rate of pressure rise is higher for no EGR condition while introduction of EGR significantly reduces the rate of pressure rise. It happens due to lower rate of combustion with EGR. When diesel-air mixture is rich (no EGR), it favors earlier start of combustion due to dominance of cold chemistry. Similarly diluted mixture (at higher EGR) gives slower rate of combustion due to delayed combustion phenomenon, which shifts pressure rise curve towards ATDC side.

dQ-dθ Analysis

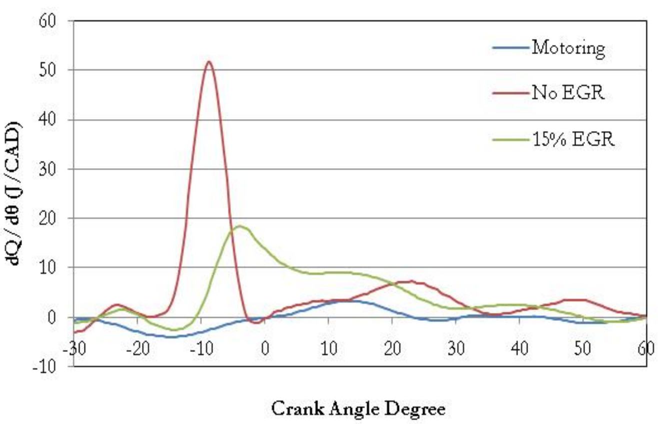

Figure 6: Variation in rate of heat release for medium load and EGR Heat release analysis is another characterization tool for the combustion behavior of HCCI combustion mode. HCCI heat release pattern is different as compared to conventional modes due to occurrence of combined phenomenon of simultaneous ignition of homogeneous mixture using compression (SI and CI). HCCI leads to simultaneous combustion inside the whole of combustion chamber hence total combustion duration reduces, which leads to higher rate of heat release (ROHR). This affects aspects of safety and structural integrity of the engine. Figure 6 clearly shows that the rate of heat release in HCCI combustion mode is quiet high. In HCCI combustion, EGR is used for controlling the rate of heat release. EGR reduces the mixture reactivity by the adding several non-reactive gaseous species. Generally a large fraction of heat is absorbed by the combustion products (mainly CO_2), which are recirculated in the exhaust gas. Hence higher EGR conditions provide lesser reactivity, which reduces ROHR. In HCCI combustion of diesel with EGR, two-stage combustion can be observed from the heat release diagrams (Figure 6). Heat release curve posses two peaks, which are in low temperature heat release region and high temperature heat release region [22-24].

Cumulative Heat Release Analysis

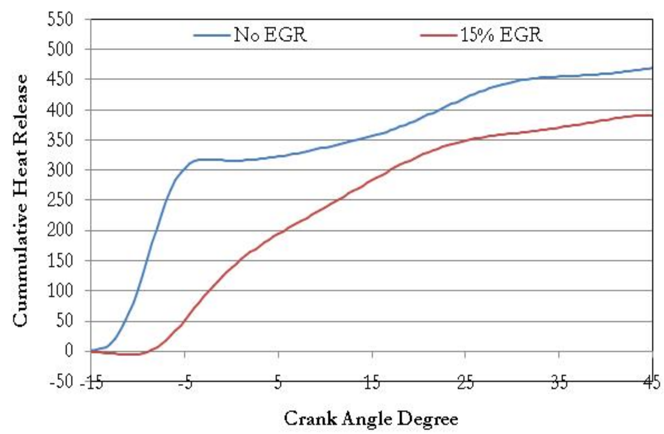

Figure 7: Cumulative heat release curves at medium load and EGR

Figure 7 clearly shows that no EGR condition gives larger cumulative heat release as compared to 15% EGR condition. It happens mainly due to absorption of energy by the colder exhaust gas constituents. EGR contains a large fraction of CO_2 and other high heat capacity gases, which absorbs large part of the combustion generated heat energy and hence reduce the cumulative heat release. Phenomenon of delayed combustion can also be seen in this cumulative heat release curve. Increasing EGR reduces the slope of cumulative heat release curve.

Mass Burn Fraction Analysis

Figure 8 shows the spontaneous combustion characteristics of the HCCI engine operating under two different EGR conditions. At no EGR condition, 40% of the fuel burns in early stages of combustion, while remaining fuel burns in the later stages of combustion. When EGR is introduced, rate of reaction slows down, which reduces the mass burn fraction in the early stages of combustion.

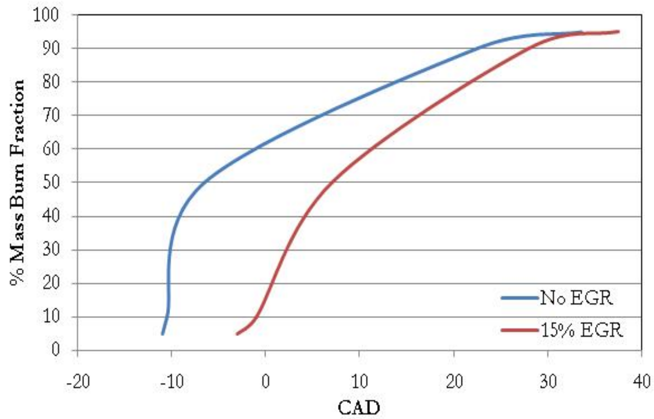

Figure 8: Percentage mass burn fraction at medium load and EGR

Performance Analysis

Important performance parameters analyzed in the experiments are exhaust gas temperature, indicated thermal efficiency and indicated specific fuel consumption. Each parameter is described separately in following sections. The experiments were carried out all loads with 15% EGR and without EGR and compared with baseline diesel engine operating in conventional CI combustion mode.

Exhaust Gas Temperature Analysis

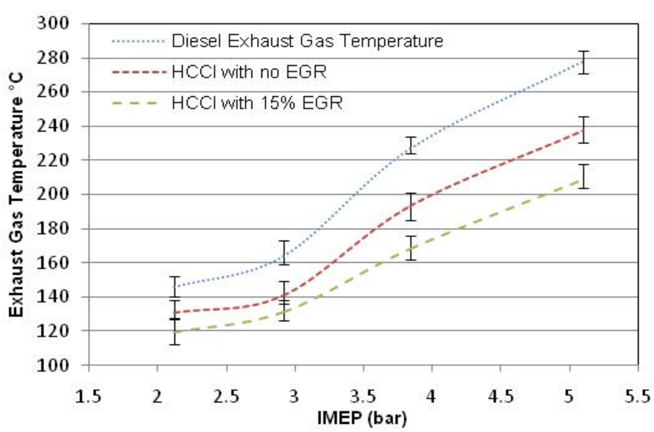

Figure 9: Exhaust gas temperature in HCCI combustion and EGR

Exhaust gas temperature provides qualitative information about the bulk peak temperature prevailing inside the combustion chamber. Injected fuel quantity, rate of EGR and injection timing are few important factors, which affect the exhaust gas temperature. In HCCI combustion, exhaust gas temperature is significantly lower than conventional diesel combustion (CI) due to homogeneous charge combustion. Exhaust gas temperature increases with increasing engine load due to presence of richer combustible mixture, while it decreases with increasing EGR due to mixture dilution. At higher EGR conditions, non-reactive inert gaseous species such as CO_2 and water vapors, which have relatively higher heat capacity compared to other constituents of the exhaust gas, absorb the combustion generated heat and reduce the bulk in-cylinder temperature. At higher loads, EGR becomes less effective due to relatively larger increment in bulk in-cylinder temperature. Heat produced during higher load conditions is significantly higher as compared to heat absorbing capacity of the non-reactive gaseous species.

Indicated Specific Fuel Consumption Analysis

In the experiments, performance of the two different cylinders based on conventional as well as HCCI combustion mode is compared by their indicated thermal efficiency. This study is based on in-cylinder combustion analysis (IMEP) and hence all performance parameters are compared in reference condition. Results show that conventional diesel combustion delivers slightly higher indicated thermal efficiency as compared to HCCI combustion.

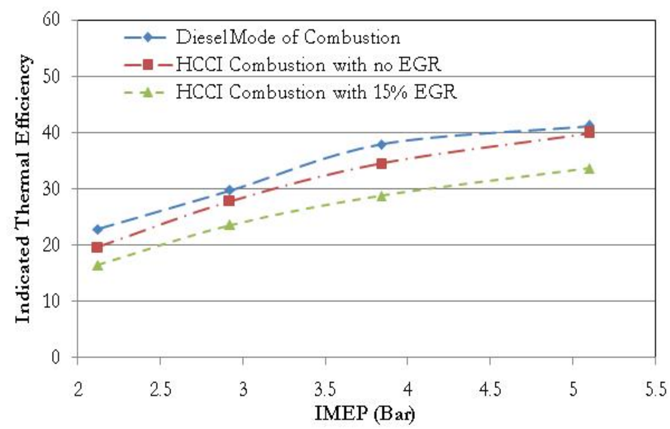

Figure 10: Indicated thermal efficiency in HCCI combustion and EGR

Figure 10 clearly shows slight reduction in indicated thermal efficiency with increasing EGR rates. As EGR rate increases, rate of combustion further decreases, which causes lower in-cylinder temperature (Figure 9). This lowering of in-cylinder temperature increases the emission of unburned fuel in the exhaust, (figure 12), therefore it also reduces indicated thermal efficiency.

Indicated Specific Fuel Consumption Analysis

Figure 11 shows the variation in ISFC with respect to indicated mean effective pressure i.e. engine load. It can be seen that ISFC decreases with increasing load. It happens mainly due to improved combustion of relatively richer combustible mixture at higher temperature. Diesel combustion mode shows slightly lower ISFC as compared to HCCI. As the EGR percentage increases in HCCI combustion, ISFC increases due to reduction in-cylinder combustion temperature. This is because of mixture dilution by EGR, which leads to relatively slower combustion.

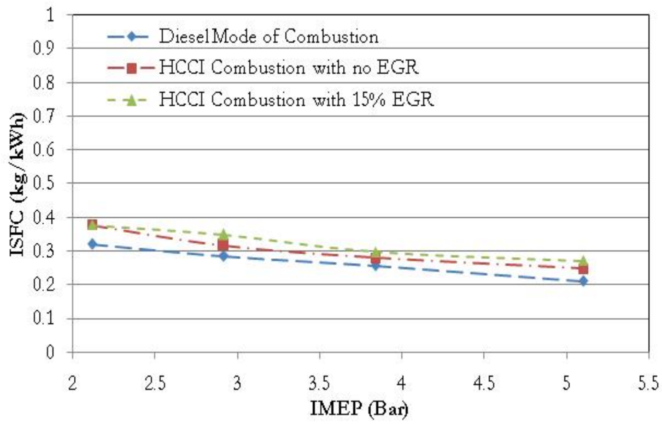

Figure 11: Indicated specific fuel consumption in HCCI combustion and EGR

Emission Analysis

In this section, mass emission analysis of exhaust gas has been performed. It describes the variation in mass emission of different species (NOx, HC, CO and smoke) in exhaust gas. The experiments were carried out all loads with 15% EGR and without EGR and compared with baseline diesel engine operating in conventional CI combustion mode.

CO Emission

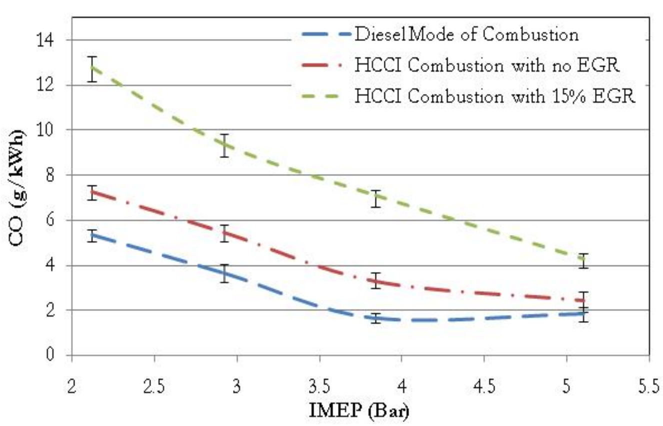

Figure 12: Carbon monoxide in HCCI combustion and EGR

Figure 12 gives a comparison between CO mass emission for conventional CI and HCCI combustion modes. Higher CO emission is found as one of the major drawbacks of HCCI combustion. Like HC emissions, major factor which contributes to higher CO emission is low combustion temperature due to combustion of relatively leaner homogeneous mixture. At lower peak combustion temperatures, intermediate combustion product CO cannot be fully oxidized to CO_2. Level of CO emission decreases with increasing IMEP due to relatively higher combustion temperatures at higher loads. Mass emission of CO in HCCI combustion is much higher as compared to CI combustion mode. Higher EGR levels, which are required for combustion control in HCCI combustion further reduce the peak in-cylinder temperature.

HC Emission

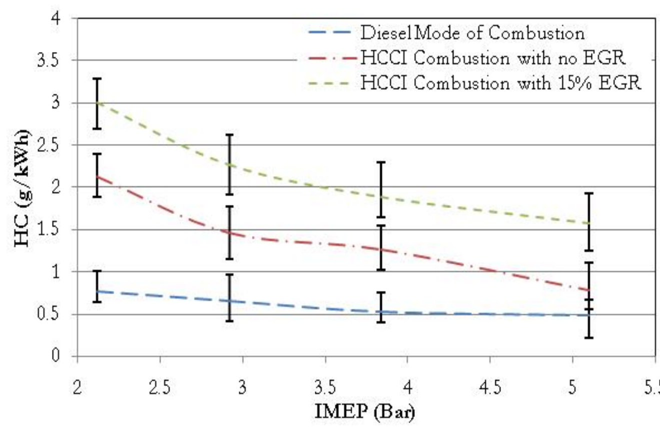

Figure 13: Unburned hydrocarbon in HCCI combustion and EGR

Figure 13 shows the HC mass emission from the HCCI combustion at various EGR conditions along with CI combustion. HC emissions in CI combustion mode are significantly lower than HCCI mode. It happens mainly due to relatively incomplete combustion of fuel at lower peak cylinder temperature and homogeneous combustion of lean mixture. Sizeable amount of homogeneous mixture remains trapped in crevice volume closer to cylinder walls, which is emitted in the exhaust stroke in case of HCCI combustion, leading to higher HC and CO emissions. This source of emission is practically absent in conventional CO combustion mode. Increasing EGR percentage enhances the HC emission level due to two reasons. First is that the recirculation of some unburned HC with exhaust gas leads to reduction in overall HC emissions. Second is the reduction in peak in-cylinder combustion temperature, which leads to increase in HC emissions. Overall effect of increasing EGR on HC profile shows the enhancement in mass emission of HC for all IMEP conditions. At higher IMEP, combustion temperatures are relatively higher, which promote the re-burning of HC present in the cylinder and when the data is converted to mass emission, the BSHC values reduce.

NOx Emissions

Nitric oxide (NO) and nitrogen dioxide (NO_2) are the most harmful pollutants emitted by diesel engines, and are grouped as NOx. High in-cylinder temperature and presence of atmospheric nitrogen in the fresh intake air are the two favorable conditions required for NOx formation. Mainly NOx formation takes place during post-combustion reactions, when localized temperatures due to heterogeneous combustion exceed the critical temperature for NOx formation and molecules of oxygen and atmospheric nitrogen start combining.

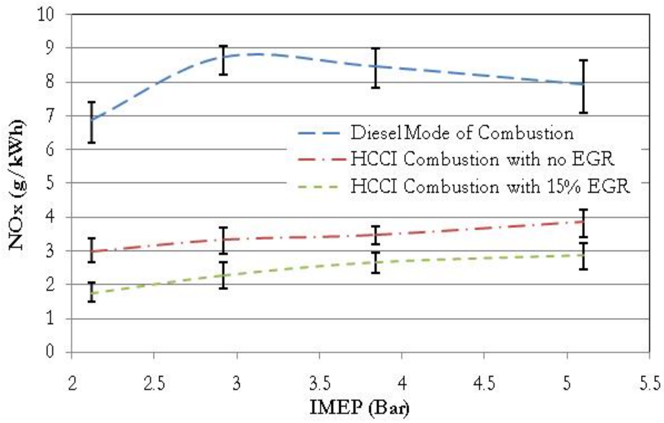

Figure 14: Oxides of nitrogen in HCCI combustion and EGR

In case of HCCI combustion, homogeneous charge gives a uniform combustion and hence bulk temperature is limited, which delivers ultra-low NOx. Introduction of EGR gives positive results and further reduces NOx level due to reduction in temperature.

Smoke Opacity Analysis

Low smoke emission is another important advantage of HCCI combustion. Level of smoke is an indirect indicator of PM and soot emission level in the exhaust. Diesel particulates consist of combustion generated carbonaceous material, with high boiling point organic species condensed and absorbed onto its surface. Generally smoke is measured in terms of smoke opacity. Smoke/ particulate formation is directly affected by the mixture quality and its combustion. Non-homogeneous mixture undergoing heterogeneous combustion gives higher smoke/ particulate formation due to presence of localized fuel-rich zones, while homogeneous charge gives better smoke characteristic.

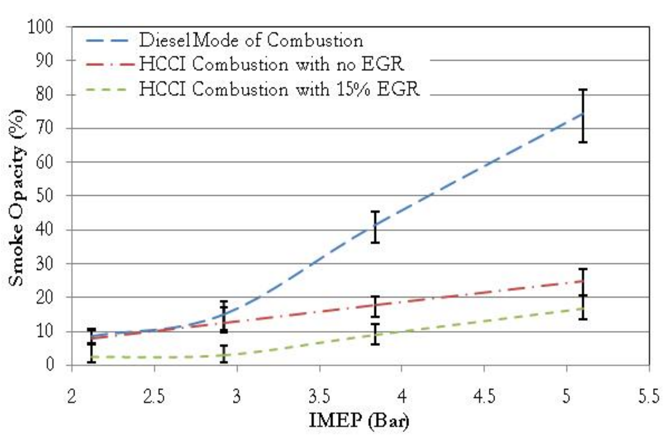

Figure 15: Smoke opacity in HCCI combustion and EGR

Figure 15 clearly shows significantly lower smoke levels for HCCI combustion mode as compared to CI combustion mode. It is mainly due to complete absence of fuel-rich zones because of homogeneous mixing of air and fuel. Smoke opacity increases with increasing engine load in both CI as well as HCCI combustion mode however the rate of increase is much higher in CI as compared to HCCI combustion mode. Application of EGR further reduces smoke level in HCCI combustion.

CONCLUSIONS

This research study explores the potential of achieving HCCI combustion using diesel as fuel in a constant speed decentralized power generating engine. Due to its low volatility, diesel is difficult fuel to premix with intake air. External mixing concept appears a feasible option for achieving diesel HCCI in which an electrically heated diesel vaporizer was developed and used for homogeneous charge preparation. Experiments were performed at different air fuel ratios for investigation of combustion, performance and emission characteristics with 15% EGR and without EGR. It is found that diesel HCCI combustion is highly sensitive to EGR. External charge preparation technique gives improved homogeneity of the mixture as compared to other methods, which improves the combustion results and delivers normal combustion event. With increasing EGR rate, delayed combustion takes place. Indicated thermal efficiency of HCCI is slightly lower than CI combustion, which is compensated by its superior emission characteristics. Indicated specific fuel consumption is slightly higher in case of HCCI combustion as compared to CI combustion. Mass emissions of HCCI combustion mode are significantly better than CI combustion mode. NOx and PM emissions are simultaneously reduced in HCCI combustion. Reduction in NOx is due to the lower peak in-cylinder combustion temperature (local and global). PM emissions are also significantly lower in HCCI combustion due to homogeneous combustion of lean mixture and absence of fuel-rich zones in the combustion chamber. HC and CO emissions were however found to be higher in HCCI combustion as compared to CI combustion. It was mainly due to lower bulk cylinder temperature and trapping of homogeneous air-fuel mixture in crevice volumes and dead volumes in combustion chamber. CO and HC emissions increase with increasing EGR rates because of further reduction in peak in-cylinder temperature; however they can easily be controlled by using simple exhaust gas after-treatment devices.

REFERENCES

1. Mose F.X., Sams T. and Cartellieri W., “Impact of Future Exhaust Gas Emission Legislation on the Heavy Duty Truck Engine”, Society of Automotive Engineers (SAE), Paper No. 2001-01- 0186, 2001.

2. Furutani M, Ohta Y, Komatsu K., "Onset Behavior of Low-Temperature Flames caused by Piston Compression", JSAE Rev 1993; 14(2):12–8, 1993.

3. Iida N., "Combustion Analysis of Methanol-Fueled Active Thermo-Atmosphere Combustion (ATAC) Engine using a Spectroscopic Observation", SAE Paper 940684; 1994.

4. Aoyama T, Hattori Y, Mizuta J, Sato Y., "An Experimental Study on Premixed Charge Compression Ignition Gasoline Engine", SAE Paper 960081; 1996.

5. Mancaruso E., Vaglieco B.M., "Optical Investigation of the Combustion Behaviour inside the Engine Operating in HCCI Mode and using Alternative Diesel Fuel", Experimental Thermal and Fluid Science 2010; 34: Page 346–35, 2010.

6. Mingfa Yao, Zhaolei Zheng and Haifeng Liu, "Progress and Recent Trends in Homogeneous Charge Compression Ignition (HCCI) engines", Progress in Energy and Combustion Science, Volume 35, Issue 5, October 2009, Pages 398-437.

7. Onishi S., Jo S.H., Shoda K., Jo P.D., Kato S., "Active Thermo-Atmosphere Combustion (ATAC) – A New Combustion Process for Internal Combustion Engines", Society of Automotive Engineers (SAE), Paper No.790501; 1979.

8. Najt, P. M. and Foster, D. E., "Compression-Ignited Homogeneous Charge Combustion," Society of Automotive Engineers (SAE), Paper No. 830264; 1983.

9. Thring R.H., "Homogeneous–Charge Compression Ignition (HCCI) engines", Society of Automotive Engineers (SAE), Paper No. 892068; 1989.

10. Suyin Gan, Hoon Kiat Ng, Kar Mun Pang, "Homogeneous Charge Compression Ignition (HCCI) Combustion: Implementation and Effects on Pollutants in Direct Injection Diesel Engines", Applied Energy, Vol. 88, 559-567, September 2011.

11. Dec J.E., Kelly-Zion P.L., "The Effects of Injection Timing and Diluents Addition on Late-Combustion Soot Burnout in a DI Diesel Engine Based on Simultaneous 2-D Imaging of OH and Soot", Society of Automotive Engineers (SAE), Paper No. 2000-01-0238; 2000.

12. Stanglmaier R. and Roberts C., "Homogeneous Charge Compression Ignition (HCC): Benefits, Compromise and Future Engine Applications", Society of Automotive Engineers (SAE), Paper No. 1999-01-3682; 1999.

13. Ryan III T.W., Callahan T.J., "Homogeneous Charge Compression Ignition of Diesel Fuel", Society of Automotive Engineers (SAE), Paper No. 961160; 1996.

14. Gray III A.W., Ryan III T.W., "Homogeneous Charge Compression Ignition of Diesel Fuel", Society of Automotive Engineers (SAE), Paper No. 971676; 1997.

15. Rakesh Kumar Maurya, Avinash Kumar Agarwal, "Experimental Study of Combustion and Emission Characteristics of Ethanol Fuelled Port Injected Homogeneous Charge Compression Ignition (HCCI) Combustion Engine", Applied Energy, Vol. 88, 1169-1180, April 2011.

16. Nakagome K, Shimazaki N, Niimura K, Kobayashi S., "Combustion and Emission Characteristics of Premixed Lean Diesel Combustion Engine. In: International Congress & Exposition", SAE Paper No 970898; 24–27 February 1997.

17. Hasegawa Roy, Yanagihara Hiromichi, "HCCI Combustion in a DI Diesel Engine", SAE Paper No 2003-01-0745; 2003.

18. Shawn M. M., Guezennec Yann, Rizzoni Giorgio, "Mixed-Mode Diesel HCCI with External Mixture Formation", DEER 2003 Newport; August 2003.

19. Avinash Kumar Agrawal, Shailendra Sinha, Mritunjay Kumar Shukla, Shrawan Singh "Effect of EGR on the Exhaust Gas Temperature and Exhaust Opacity in an Experimental Diesel Engine", SADHANA (Indian Academy of Science proceedings in engineering sciences), Vol. 29, Part 3, June 2004, pp 275-284.

20. Shrawan Kumar Singh, Avinash Kumar Agarwal, Mukesh Sharma, "Experimental Investigations into Lubricating Oil Tribology of EGR Operated Engine", Applied Thermal Engineering, Vol. 26, No. 2-3, pp 259-266, February 2006.

21. Myung Yoon Kim, Chang Sik Lee, "Effect of a Narrow Fuel Spray Angle and a Dual Injection Configuration on the Improvement of Exhaust Emissions in a HCCI Diesel Engine", Fuel Vol. 86, 2871–2880, 2007.

22. Miguel Torres Garcı, FranciscoJose Jimenez-Espadafor Aguilar,Tomas Sanchez Lencero, "Experimental Study of the Performances of a Modified Diesel Engine Operating in Homogeneous Charge Compression Ignition (HCCI) Combustion Mode versus the Original Diesel Combustion Mode", Energy Vol. 34, 159–171, 2009.

23. Pucher G.R., Gardiner D.P., Bardon M.F., Battista V., "Alternative Combustion Systems for Piston

Engines Involving Homogeneous Charge Compression Ignition Concepts – A Review of Studies Using Methanol, gasoline and Diesel Fuel”, Society of Automotive Engineers (SAE), Paper No. 962063; 1996.

24. Furutani M., Ohta Y. and Komatsu K., “Onset Behavior of Low-Temperature Flames Caused by Piston Compression”, JSAE Rev 14 (2) (1993), pp. 12–18.

DEFINITIONS, ACRONYMS, ABBREVIATIONS

HCCI: Homogeneous Charge Compression Ignition

CIDI: Compression Ignition Direct Ignition

NOx: Oxides of Nitrogen

PM: Particulate Matter

CO: Carbon Monoxide

HC: Hydrocarbon

EGR: Exhaust Gas Recirculation

ATDC: After Top Dead Center

BTDC: Before Top Dead Center

CONTACT INFORMATION

Dr Avinash K Agarwal
Associate Professor and Devendra Shukla Research Fellow
Department of Mechanical Engineering
Indian Institute of Technology Kanpur
Kanpur-208016 India
Email: akag@iitk.ac.in
Home Page: www.iitk.ac.in/erl
Tel: +91 512 2597982 (O)
FAX: +91 512 2597982, 2597408 (O)

ABOUT THE AUTHORS

Akhilendra Pratap Singh (akhips@iitk.ac.in) is doctoral research student under the supervision of Dr. A K Agarwal. He has completed his M.Tech. program in mechanical engineering from IIT Kanpur under the supervision of Dr A K Agarwal in 2010. His areas of current interest are HCCI Combustion and control, instrumentation, combustion and emission control of IC engine, alternative fuels.

Dr. Avinash Kumar Agarwal (akag@iitk.ac.in) is currently faculty of mechanical engineering at IIT Kanpur since March 2001. His areas of current interest are combustion phenomenon study in IC engines, automotive emission control, biodiesel development and characterization, laser diagnostic techniques, PIV, lubricating oil consumption reduction, lubricating oil tribology, development of micro sensors, and alternative fuels for diesel engines.