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Effect of EGR in HCCI Mode of Combustion in a Flexible LTC Engine

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ABSTRACT: Low Temperature Combustion (LTC) is an emerging combustion strategy to simultaneously reduce nitric oxides (NO_x) and smoke emissions to near zero level which are the major pollutants from the diesel powered vehicles. Homogeneous Charge Compression Ignition (HCCI) is one of the promising LTC strategy. Although, HCCI strategy has been extensively investigated for more than two decades, investigations on HCCI in a flexible LTC engine is very limited which could enable mixed mode combustion. The present work intends to optimize exhaust gas recirculation (EGR) concentration to address the major limitation in HCCI combustion in terms of narrow load range. To improve the external mixture preparation in HCCI engine, a high pressure common rail injection system is used in the intake manifold for preparing homogeneous mixture. Experiments are initially conducted in an unmodified single cylinder diesel engine under conventional combustion mode to set the baseline reference data. Then the engine is modified as a flexible LTC engine which can run in any LTC mode including HCCI. With an existing engine compression ratio of 17.5, it is possible to run in HCCI mode only upto 20% of rated load, beyond that engine knocks severely. The major reason behind this is found to be a very early ignition at this higher compression ratio. To achieve higher loads the engine compression ratio is reduced to 15 and EGR is utilized upto 56%. With these modifications the engine operating load range in HCCI is extended upto 40% of rated load. Near zero nitric oxide and smoke emissions are obtained in HCCI mode, however the brake specific fuel consumption and unburned emissions are found to be higher as compared to conventional combustion.

KEYWORDS: HCCI, LTC, EGR, Compression ratio, Emissions

NOMENCLATURE

HCCI	Homogeneous Charge Compression Ignition
LTC	Low Temperature Combustion
EGR	Exhaust Gas Recirculation
bmep	Brake Mean Effective Pressure
NTC	Negative Temperature Coefficient
NO _x	Oxides of Nitrogen
CO	Carbon Monoxide
THC	Total Hydrocarbons
FSN	Filter Smoke Number

I. INTRODUCTION

The HCCI mode of combustion is achieved by compressing premixed fuel, air and recycled combustion products until the mixture auto ignites. As a result, ignition occurs simultaneously at multiple locations inside the combustion chamber. Thus, HCCI combines the favourable features of conventional spark ignition (SI) and compression ignition (CI) engines in terms of premixing fuel-air well before ignition and maintaining a higher compression ratio for thermal efficiency benefits. However, unlike SI and CI engines, HCCI eliminates the use of spark plug and fuel injector in the cylinder head.

HCCI combustion differs from that of SI combustion owing to the absence of flame front and devoid of localized high temperature zones. Because of overall lean mixture and lower temperatures, fuel economy is better in HCCI owing to lower heat losses. Combustion is induced inside the engine cylinder once the ignition temperature of 800 K is reached [1]. As the combustion starts, temperature and pressure would increase but are found to be well below that required for

the formation of nitric oxides [1]. Besides combustion duration is much shorter than in CI engines and thus, results in lower heat losses and higher thermal efficiency [1]. Further, it reduces overall vehicle cost owing to low pressure fuel injection system requirements and elimination of after treatment control requirements. Since the combustion temperatures remains low due to diluted homogeneous air and fuel mixtures, NO_x and PM emissions decrease significantly compared to SI and CI engines.

Adapting Variable Compression Ratio (VCR) and exhaust gas recirculation (EGR) are some of the strategies that could help to achieve better HCCI combustion and address its challenges in terms of precise combustion timing control and lower operating load range [3]. HCCI engines are highly fuel flexible and can operate with gasoline, diesel and also, alternative fuels [15]. Most of the engines adopt HCCI in a mixed combustion mode, wherein, upto mid load conditions HCCI is utilized, while at higher loads the engines switch to conventional SI or CI mode of operation. Further, the engines start with conventional SI or CI mode before switching to HCCI mode for idle and low to part load operation.

II. METHODOLOGY

The base engine is a Kirloskar make, single cylinder air-cooled diesel engine whose technical specifications are provided in Table 1. To operate the engine under HCCI mode, suitable modifications are done in the intake and exhaust manifold. Subsystems such as air pre heater, fuel vaporizer, cooled EGR and a common rail injection system are fabricated and assembled in the intake/exhaust manifold to implement HCCI combustion.

Parameter	Specification
Displacement	662 cm ³
Stroke	110 mm
Bore	87.5 mm
Compression ratio	17.5:1
Rated output	4.4 kW at 1500 rpm
Rated speed	1500 rpm
Cooling system	Air cooled

TABLE 1: TECHNICAL SPECIFICATION OF TEST ENGINE

EGR System

A provision has been made in the exhaust manifold to re circulate exhaust gas (EGR) to the intake manifold to dilute the intake charge and thereby increase ignition delay and improve fuel-air mixing. It also provides control over combustion phasing in HCCI. When EGR is used the exhaust gas coming out of the engine is cut off from the main exhaust blower and is drawn through a separate blower (refer Figure 1) designed to pump the exhaust gas. As the exhaust gas pressure is normally lower in the test engine which is of single cylinder, naturally aspirated type, a separate blower is required to maintain the required flow of exhaust gas into the intake system. The exhaust blower is coupled with a motor whose speed is controlled using an auto transformer to vary the flow rate. The main control valve is placed far from the engine so that back pressure can be eliminated. The exhaust gas from the blower is split into two paths to handle hot and cold EGR. For the cold EGR, a custom designed shell and type heat exchanger is utilized. To cool the exhaust gas water is fed into the shell side of the cooler by using a 0.5 HP motor. Thermocouples are placed at the inlet and outlet of the cooler to measure the temperatures of cooling water.

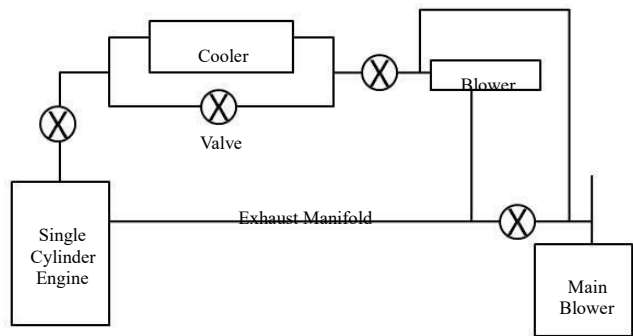


FIGURE 1: EGR LOOP

Parameter	Specification
Tube	11mm OD
Tube material	Admiralty Brass
Number of tubes	9
Tube sheet	Carbon steel
Baffle	SS304 – 3mm thick
Number of baffles	6
Tie rod	SS304 – 6mm diameter
Number of tie rods	4
End cover	MS
Shell side port	1” socket
Cover side port	1-1/2” socket
Overall size	100mm diameter x 1450mm long

TABLE 2: TECHNICAL SPECIFICATION OF COOLER

III. COMPARISON OF HCCI COMBUSTION WITH AND WITHOUT EGR

The engine performance and exhaust emissions trends in HCCI at 20% and 40% load with and without EGR are presented and discussed next. The optimal EGR concentration at 20% and 40% load conditions are found to be 12.5 and 48.5 respectively.

Combustion Analysis

The heat release rates are compared between conventional and HCCI combustion in Figure 2. A distinct low temperature heat release is observed in HCCI indicating that the combustion mode is of low temperature combustion (LTC). Between the low temperature and high temperature heat release, there is a negative temperature coefficient (NTC) regime in HCCI. Further, unlike in conventional combustion, there is no diffusion phase heat release in HCCI combustion.

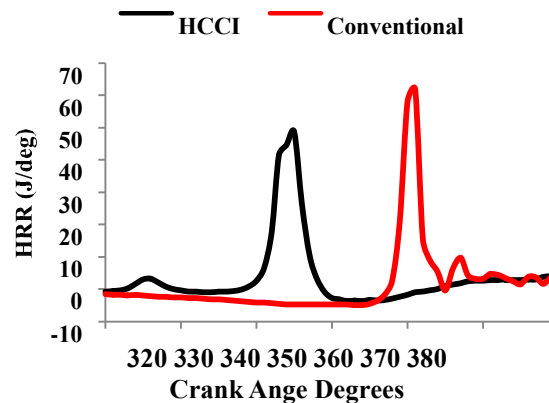


FIGURE 2: VARIATIONS OF HEAT RELEASE RATE IN CONVENTIONAL AND HCCI AT 20% LOAD

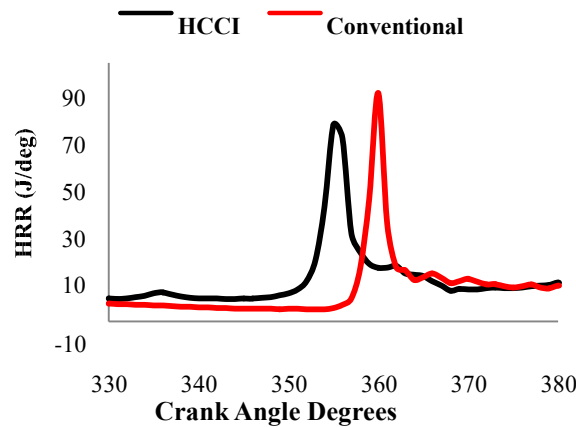


FIGURE 3: VARIATIONS OF HEAT RELEASE RATE IN CONVENTIONAL AND HCCI AT 40% LOAD

Performance Analysis

Figures 4 and 5 compares bsfc and brake thermal efficiency in HCCI with and without EGR. It is observed that the bsfc reduces and brake thermal efficiency increases with the addition of EGR. Thus, it is inferred that the addition of EGR helps in achieving optimal combustion phasing wherein negative work is reduced and occurrence of peak pressures happen after TDC of compression stroke. This results in higher brake thermal efficiency and lower bsfc with EGR.

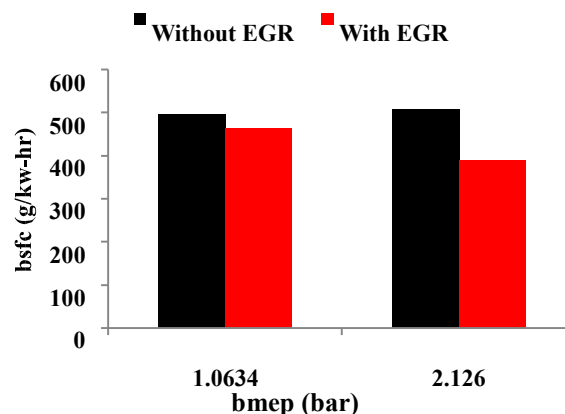


FIGURE 4: COMPARISON OF BSFC WITH AND WITHOUT EGR

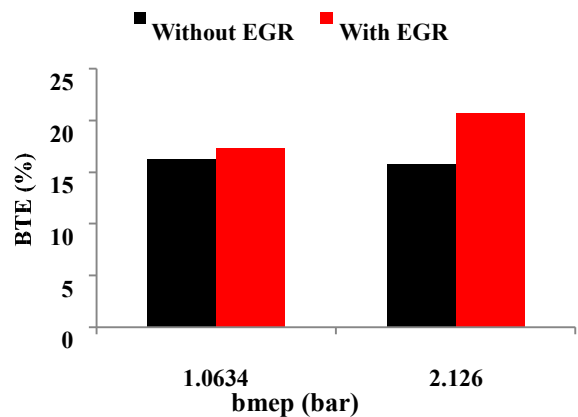


FIGURE 5: COMPARISON OF BTE WITH AND WITHOUT EGR

Emission Analysis

The engine out exhaust emissions such as NO_x, Smoke, CO and THC are compared with and without EGR in HCCI in Figures 6 to 9. It is observed that CO emissions decrease with EGR addition primarily due to a better combustion phasing favoring more complete combustion. The NO_x emissions decreases with EGR addition owing to lower in-cylinder temperatures due to higher specific heat of its inert constituents, THC emissions increase slightly for the same reason. The smoke emissions decreases with EGR addition especially at higher loads, owing to prolonged ignition delay resulting in better mixture preparation.

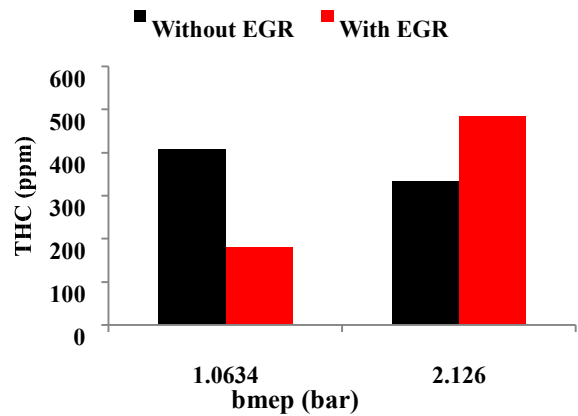


FIGURE 6: COMPARISON OF THC EMISSIONS WITH AND WITHOUT EGR

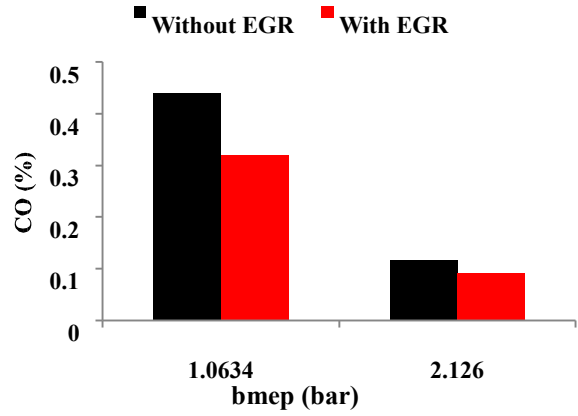


FIGURE 7: COMPARISON OF CO EMISSIONS WITH AND WITHOUT EGR

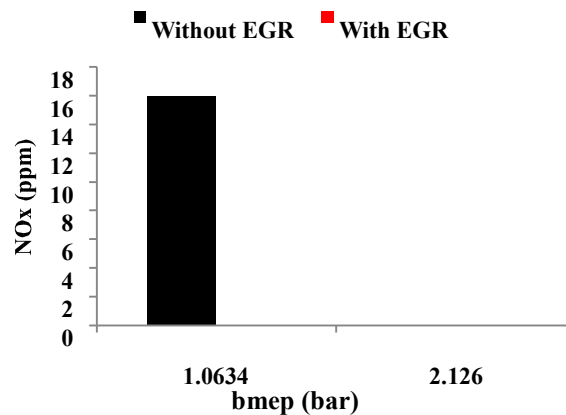


FIGURE 8: COMPARISON OF NO_x EMISSIONS WITH AND WITHOUT EGR

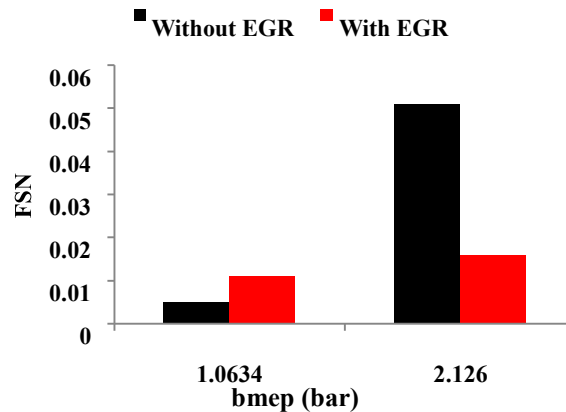


FIGURE 9: COMPARISON OF SMOKE EMISSIONS WITH AND WITHOUT EGR

IV. CONCLUSIONS

In the present research work, effects of optimizing EGR concentration on the performance and emission characteristics of a HCCI engine is investigated. The combustion, performance and emission parameters are compared between HCCI combustion mode with and without EGR at rated speed, varying load conditions. The important conclusions reached from this work are as follows:

- The appearance of distinct low temperature heat release and the absence of diffusion phase combustion are observed from the heat release rate plots of HCCI combustion at all the load conditions with the addition of EGR.
- By utilizing cooled EGR, the operating regime of HCCI is found to be extended upto 60% of full load primarily by avoiding very early ignition timing and un optimal combustion phasing.
- The addition of EGR to the intake charge in HCCI helps in achieving better combustion phasing and thereby increases brake thermal efficiency and reduces exhaust emissions.

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