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Research Paper

Low temperature combustion strategy in an off-highway diesel engine – Experimental and CFD study

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HIGHLIGHTS

- Investigations are conducted on low temperature combustion (LTC) concept.
- Experiments and CFD analysis are conducted on a compression ignition engine with LTC concept and also to optimize the engine parameters to reduce the nitric oxides emissions.

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ABSTRACT

Today, low temperature combustion (LTC) is one of the promising options to meet future emission norms in diesel engines. In this study, the LTC concept is adopted to an existing off-highway diesel engine, by using high quantity of cooled exhaust gas recirculation (EGR), high fuel injection pressures and retarded fuel injection timings, to reduce nitric oxides (NOx) and smoke emissions to meet the off-highway TIER-4 final emission norms. The experiments are performed at 33, 55 and 80% loads to reduce the NOx emissions to the level of 75% of the base engine (target level) and the smoke emissions to the level of the base engine (target level). In addition, a CFD analysis has also been carried out to understand the combustion phenomenon in the LTC mode. From the experimental results, it is found that, the NOx emissions are possible to reduce to the level of 75% of the base engine, at all the three loads. At 33 and 55% loads, the smoke emissions are possible to reduce below the target level; whereas, at 80% load, they are at about 3.7 times more than the target level. Finally, it is proposed that, the existing diesel engine can be operated in the LTC mode up to about 60% load. Beyond this load, a significant increase in the smoke emissions are observed in the LTC mode, hence conventional CI mode is proposed.

1. Introduction

Globally, diesel engine emission regulations demand for substantial reduction in emissions and currently stringent emission regulations like EURO-6, TIER-4 final, etc., are met with costly exhaust after treatment devices viz., diesel oxidation catalyst, diesel particulate filter, and selective catalytic regeneration. However, these have following disadvantages: (i) increase in manufacturing cost, (ii) increase in fuel consumption, (iii) catalyst poisoning, (iv) increase in operational cost, and (v) increase in complexity of the engine. Therefore, it is viable to look for strategies to reduce pollutant formation at the in-cylinder level. In this direction, one of the promising option is the low temperature combustion (LTC) concept, by which both NOx and soot formation can be reduced simultaneously.

The LTC is the combustion occurring at temperatures preferably below 2100 K (not much favourable temperature for NOx and soot formation). The LTC can be achieved in two ways: first, by reducing combustion temperature using pre-mixed lean fuel-air mixtures. This strategy involves early fuel injection to achieve the premixed lean mixture. But, for this strategy, controlling the start of combustion and rate of pressure rise are major challenges. Second, by reducing combustion temperatures by using the combination of a large quantity of EGR, low compression ratio and late fuel injection, etc., [1,2]. Here, the start of combustion is directly controlled by the start of fuel injection like in CI combustion and can overcome major challenges of the first strategy. In this strategy, at low loads, most of the fuel is burned in the pre-mixed combustion phase. Whereas, at medium and high loads, most of the fuel is burnt in the mixing-controlled combustion phase [1,2]. In this

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study, the second strategy is used and in further discussion referred to as the LTC.

The basis for the LTC came from the study of Kamimoto et al. [3]. They are the first ones to study the influence of the combination of in-cylinder temperature and equivalence ratio (ER) on the emissions in a CI engine using temperature-equivalence ratio (T-Ø) plots. They suggested that the local combustion temperature should be kept below about 2200 K to avoid the formation of NOx at low equivalence ratios. However, at high equivalence ratios, they suggested to further reduce the combustion temperatures to avoid the soot formation. They also found that, if the combustion temperature was kept below about 1650 K, both the NOx and soot formation could be completely avoided regardless of the equivalence ratio. Later, Ciajolo et al. [4] studied the effect of in-cylinder temperature on the soot formation. They found that, at high flame temperatures, polycyclic aromatic hydrocarbons (PAHs), which were considered as soot precursors, oxidized instead of forming the soot. They also found that, the maximum soot concentration occurred at the intermediate combustion temperatures, which were ideal for both the formation of PAH and their transformation into soot particles. Akihama et al. [5] did a simulation study to investigate the rich smokeless diesel combustion based on the findings of Kamimoto et al. [3]. They used high quantity of cooled EGR to lower the combustion temperature. This reduction was sufficient to avoid both the soot and NOx formation regions on the standard temperature versus equivalence ratio plots.

Initially, Kimura et al. [6] experimentally investigated the late injection LTC concept using high quantity of cooled EGR, retarded fuel injection timing, high swirl and high fuel injection pressure. They called this strategy as the modulated kinetics (MK) concept. Here, the main requirement was to make the ignition delay period to be equal to or more than the period of fuel injection duration. When the ignition delay was prolonged, smoke level was suppressed even when the mixture equivalence ratio was closer to stoichiometric value. However, the major challenge was to extend the load range because of the increase in equivalence ratio at higher loads with higher EGR rate. Later many researchers explored the late fuel injection LTC concept using high EGR in combination with high fuel injection pressure, low compression ratio, low intake charge temperature, more number of fuel injector holes, high fuel flow rate, high intake air swirl, optimum piston bowl geometry and LTC-CI dual mode operation, etc. [7–15].

Currently, by using the conventional CI engine configurations, by optimizing the operating parameters, the LTC operation is possible up to the BMEP of about 6 bar [16]. However, by modifying the base engine to operate in the LTC mode, it is possible to extend the BMEP up to about 10 bar (modern diesel engine's BMEP range is about 12–20 bar). Therefore, to cover the entire range of BMEP, it is required to operate the engine in a combination of LTC and conventional CI modes [16]. But, with the modified configuration of the engine, operating the engine in both the modes is challenging. Therefore, a feasible approach is to operate the engine in the LTC for low and medium loads (up to about 7 bar). At higher loads, operate the engine in the conventional CI mode with conventional engine configuration. This type of operation can reduce the overall engine out emissions, which in turn help downsizing of the after-treatment system.

In the present study, experiments are conducted by operating the existing off-highway three-cylinder diesel engine in the LTC and the conventional CI combustion mode. In order to achieve the LTC, the engine is operated using a high quantity of EGR, high fuel injection pressure and late fuel injection timing. Here, all the experiments are conducted at a constant engine speed of 2100 rev/min., with three loads of 33, 55 and 80% of the base CI engine. In addition, a CFD study is also carried out to understand the phenomenon of the LTC at 55% load conditions. Finally, the suitable load range for the LTC and the CI mode of operation is suggested. To meet TIER-4 emission norms, with less expensive after treatment system, at every load, the NOx emissions should be reduced to the target level which is 75% of the base CI engine. Also, smoke emissions should be reduced to that level of that of the base CI engine.

2. Experimental setup and procedure

2.1. The engine, measurement systems and the test setup

In this study, a three-cylinder, water-cooled, direct injection (DI) turbocharged diesel engine is used for conducting experiments. The detailed engine specifications are shown in Table 1. The engine is coupled to an eddy current dynamometer (SAGE AG250) to control and measure the torque and speed of the engine. The engine speed and load are varied by adjusting the fuel injection quantity through engine control unit (ECU) based on the demand of load. The air to the turbocharger is conditioned using an air conditioner which supplies the air at a temperature of about 24 °C and a relative humidity of 50%. The air flow rate is measured using a turbine type flow meter (Elster Handel). The fuel mass flow rate is measured using the Coriolis mass flow meter (AVL 4210). The AVL fuel conditioner is used to maintain the fuel temperature at about 40 ± 3 °C at the inlet of the engine. In this study, the fuel injection pressure and the start of fuel injection is dynamically varied and measured during testing using the INCA 5.4 software. The ETAS 581 tool kit is used to interface the software to the ECU.

The smoke emissions are measured using the automatic AVL smoke meter (415SE). An exhaust gas analyser working on the principles of FID for HC, NDIR for CO and CLD for NOx respectively is used to measure the exhaust emissions levels. The in-cylinder pressure is measured using the AVL GH13P pressure sensor and crank angles are measured using the AVL crank angle encoder. The AVL INDICOM software is used to acquire pressure and crank angle signals. A mechanical throttle is used to set exhaust back pressure. The EGR system used can provide a maximum EGR flow rate of about 52 and 45%, at 33 and 80% load conditions respectively. The system consist consists of pipe diameter of 35 mm, an electronic flow control valve, a secondary EGR cooler and a venturi at the intake air passage is fitted to the base CI engine. A common rail fuel injection system is used to vary the fuel injection pressure. Figs. 1 and 2 show the schematic and the photograph of the test setup respectively used in this study.

2.2. Experiments and procedure

For all the experiments, the coolant temperature is maintained at about 85 °C which is as per the testing guidelines of the TIER-4 emission norms. The intake charge temperature after mixing the EGR is maintained at about 45 °C and 65 ± 5 °C for base CI and with

Table 1
Specification of the base CI engine.

Engine type	Three-cylinder, inline DI diesel engine
Bore × stroke (mm)	96 × 122
Displacement (cm^3)	2647 (882 cm^3/cylinder)
Aspiration	Turbocharge intercooled (TCI)
Engine cooling	Water cooled
Compression ratio	17.3:1
Combustion chamber type	Re-entrant bowl
Fuel injection system	Bosch – CRDI
CRDI injector	7-hole with Ø 0.14 mm
EGR cooling	Tube and shell type cooler
Intake charge control	Water to air to intercooler
Valve timings	IVO = 10° bTDC; IVC = 35° aBDC; EVO = 35° bBDC; EVC = 8° aTDC