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Split fuel injection and Miller cycle in a large-bore engine

Matteo Imperato *, Ossi Kaario, Teemu Sarjovaara, Martti Larmi

Aalto University, Finland

HIGHLIGHTS

- High premixed combustion peak is reduced with pilot injection.
- Split injection in large bore engines increases engine efficiency.
- Pilot injection with high Miller rate can reduce NOx up to 60%.
- NOx reduction of 42% could be obtained without decrease in engine efficiency.

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ABSTRACT

The upcoming emission legislation for sea-going vessels issued by the international marine organization requires drastic reduction in nitric oxides. A well-known approach for meeting these requirements is to reduce the in-cylinder temperature prior to combustion by using the so-called Miller cycle. However, the mere use of this technique presents the actual limits due to long ignition delay, which occurs when the compression temperature is very low. As a consequence, premixed combustion develops quickly, increasing the local temperature in the combustion chamber and favoring NOx formation. Splitting the fuel injection into a small pilot and a main injection can reduce the magnitude of the premixed combustion and the local in-cylinder temperatures. The work presented here is divided in two parts and is novel by being the first systematic study of split injection combined with Miller cycle in large-bore engines. In its first stage, an extensive study of the injection dwell with two intake valve closings and three timings of the main injection are analyzed. In the second stage, both injection events are shifted later in the power stroke with fixed injection dwell. Overall, the pilot injection reduced the ignition delay but dropped the peak of the premixed combustion only with the most advanced intake valve closing. This improved fuel economy, but provided no advantages as far as emissions are concerned. In addition, while increasing injection dwell reduced NOx emissions, it also increased fuel consumption. The highest achieved NOx reduction was close to 60%, with a small drawback in fuel economy.

1. Introduction

The emission limits for ships' diesel engines are becoming constantly stricter. In 2016, a new regulation, which reduces nitric oxides (NOx) emission by 80% – compared to 2001 level – for large-bore compression–ignition (CI) engines [1], comes into effect. Therefore, the development of new solutions and technologies for reducing emissions is mandatory, in order to fulfil the stringent demands of the legislation. However, the engine performance should not be negatively affected by the new adopted configurations.

NOx formation occurs in the combustion chamber when the local gas temperature is high [2]. An effective way to reduce the combustion temperature in CI engines is the so-called Miller cycle [3]. This can be realized by closing the intake valve before bottom dead center (BBDC), so that the effective compression ratio is lower than the effective expansion ratio. Thus, the compression in-cylinder temperature and the eventual combustion temperature decrease. Miller cycle has been theoretically studied [4], and it is

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Abbreviations: °CA, crank angle degree; ATDC, after top dead center; BBDC, before bottom dead center; BDC, bottom dead center; BMEP, brake mean effective pressure; BTDC, Before Top Dead Center; CI, compression–ignition; CO, carbon oxide; HR, heat release; HRR, heat release rate; IMEP, indicated mean effective pressure; IVC, intake valve closing; LTO, low temperature oxidation; MI, main injection; NDIR, non-dispersive infrared; NOx, nitrogen oxides; NTC, negative temperature coefficient; PI, pilot injection; SFC, specific fuel consumption; SOMI, start of main injection; SOPI, start of pilot injection; TDC, top dead center.

* Corresponding author at: Department of Mechanical Engineering, Aalto University, 5 Puumiehenkuja, Aalto 00076, Espoo, Finland.

E-mail address: matteo.imperato@aalto.fi (M. Imperato).

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widely used in automotive [5,6], heavy-duty [7,8] and large-bore engines [9].

The Miller cycle approach is based on the correlation between NOx formation and the flame temperature. The approach states that, with reduced flame temperature, NOx emissions are expected to be lower [2,10]. As mentioned, the NOx formation kinetics is strongly temperature-dependent. However, recent investigation has reported several cases where the flame temperature correlation fails to capture the trend of NOx emissions for diesel combustion. A study demonstrated that at low load [11] increasing the Miller rate increases NOx close to the reference value with standard valve timing. In addition, it was shown that ignition delay becomes very long with advanced Miller rate, and the consequent high in-cylinder pressure fluctuations result in increased NOx values, despite the low in-cylinder temperature at ignition [12]. In addition, because of the lower compression temperature a higher Miller rate increases the ignition delay. Kyrtatos et al. [13,14] tested very advanced Miller timing in a large-bore medium-speed engine and observed that a longer ignition delay – due to lower in-cylinder temperature – allowed more fuel being mixed prior to ignition, leading to a greater magnitude of premixed combustion. Moreover, the long ignition delay let the spray penetrate further, enhancing air entrainment and resulting in an overall leaner premixed combustion that could favor NOx formation. This might also result in unstable combustion and high cycle-to-cycle variation of the in-cylinder pressure, which could compromise the engine's proper function and performance [12].

The amount of the premixed combustion may be correlated with the formation of NOx. Generally, a high peak of premixed combustion results in high NOx outcomes. Musculus [15] realized optical measurements in a diesel engine and found contradicting trends. It was reported that, reducing the intake temperature, NOx initially decreased and then increased monotonically with premixed combustion. Consistently, it was found that, for operating conditions with large premixed ratios, retardation of injection eventually led to an increase of NOx after reaching a minimum. It was concluded that large portions of premixed combustion generally led to faster combustion, with high increase in cylinder pressure early in the engine cycle. Thus, the reactants entering the diffusion flame are compressed to higher temperatures, leading to higher flame temperatures (compression heating).

Split injection has been widely used in diesel engines for reducing both NOx and soot [16–18]. Injecting a small pilot dose with advanced intake valve closing (IVC) can trigger the combustion earlier before top dead center (BTDC), reducing also the ignition delay of the main injection. This is expected to reduce the magnitude of the premixed combustion and NOx. Brückner et al. [19] studied the influence of fuel pilot injection and Miller cycle in a heavy-duty diesel engine running at 1000 rpm and demonstrated that the pilot injection decreased the peak of the premixed combustion, reducing further NOx only in conditions of very low in-cylinder temperature.

Pilot injection has not been extensively studied in marine engines. On a two-stroke marine engine, Andreadis et al. [20] tested pilot injection, achieving a NOx reduction of 15% and also a slight improvement in the engine economy. However, the study did not investigate any influence of Miller timing combined with split injection. Nonetheless, systematic studies of the use of the Miller cycle and split injection in large-bore engines cannot be found in the literature. The present research was carried out with a single-cylinder large-bore four-stroke mediumspeed research engine [21,22]. Former achievements include 40% NOx reduction at partial load, adopting Miller cycle [23]. Recently, split injection and Miller cycle running at partial load with 1500 bar injection pressure and with a pilot injection fuel fraction of 25% were attempted for the first time [11]. In those runs, pilot injection timing was tested either very close or very far from the main injection. Hence, the influence of the split injection on the combustion characteristics was not completely understood.

The novelty of this research consists of testing split injection and Miller, running with low fuel injection pressure, and investigating the combustion behavior at regular injection dwell steps. The main aim was to reduce the ignition delay when running with advanced Miller rate and to study the effect of the injection strategy on the combustion process and performance outcomes, especially that of NOx. The present study is divided in two parts. In the first part, different injection dwells are tested. Then, with a fixed dwell, the injection events are retarded to reduce the NOx amount, while attempting to fulfil the upcoming legislation requirements.

2. Material and methods

2.1. Experimental setup

A single-cylinder large-bore CI medium speed engine was employed in this research: its main components were designed to withstand in-cylinder pressure of 30 MPa running and mean piston speed of 12 m/s [22,24]. The engine was connected to an electric motor, which also allowed running in the motored mode. In addition, the gas exchange valves were controlled by electro-hydraulic valve actuators (EHVA) instead of the traditional mechanical camshaft, providing high flexibility in valve timing [25] for the gas exchange phase. Moreover, the fuel system permitted changing of injection pressure, duration and timing. An external charge-air supply plant and an exhaust gas throttle valve controlled the boundary conditions: the maximum allowed intake air pressure was 10 bar. The parameters of injection, valve timing and ancillary systems could be freely set and remotely monitored [21].

A schematic of the engine is shown in Fig. 1. The charge air is processed by the compressor (C); then, it is cooled, dried and heated before going through the flow meter. The air reservoirs reduce the pressure fluctuations and the intake pressure is regulated by a control valve. The engine (E) is connected to the electric motor (M). The exhaust gas pressure is controlled by the throttle valve, and exhaust gas samples are diverted to the emission analyzers and to the smoke meter (AVL 415).

The engine was equipped with Kistler in-cylinder pressure sensor 6045AU20 connected to the Kistler charge amplifier 5064. An Emerson Micromotion ELITE CMF100 flow meter was employed for charge air measurement, and an Emerson Micromotion ELITE CMF025 flow meter for the measurement of fuel mass flow before the engine. The emission measurement system was composed of different analyzers for each gas. NOx emissions were measured with an ECO Physics CLD822Sh analyzer. Soot emissions were measured as filter smoke number (FSN) by an AVL 415 smoke meter. A non-dispersive infrared (NDIR) absorption analyzer by Sick was employed to measure carbon oxide (CO). The emission probes were located in the exhaust pipe five meters from the cylinder head

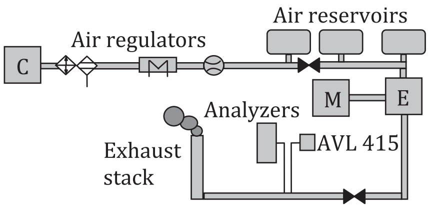

Fig. 1. Schematic of the engine test bed.