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A study of the effect of post injection on combustion and emissions with premixing enhanced fueling strategies ☆

Marko Jeftić *, Ming Zheng

Department of Mechanical, Automotive, and Materials Engineering, University of Windsor, 401 Sunset Avenue, Windsor, Ontario N9B 3P4, Canada

HIGHLIGHTS

- Early post injections increased the exhaust gas temperature and the engine IMEP.
- The use of butanol significantly reduced the NOx and the smoke emissions.
- Neat butanol enabled earlier post injection timing without a smoke emission penalty.
- Early post injections advanced the combustion phasing of the butanol main injection.
- Slightly delayed post injections increased H_2, reactive light HC, and methane.

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ABSTRACT

An empirical investigation was carried out in a compression ignition engine to characterize the effect of the post injection timing on the post injection power production, the exhaust temperature, and the exhaust gas composition. Due to the potential emission reduction benefits of alternative fuels, numerous fuel injection strategies were investigated, including direct injection diesel, dual fuel diesel and ethanol, dual fuel diesel and butanol, and direct injection butanol. For all of the tested fuel injection strategies, the results indicated that the engine power output, the exhaust gas temperature, and the exhaust gas composition were very sensitive to the post injection timing. For producing additional power output, a relatively early post injection timing was the most suitable and the power output gradually declined when the post injection timing was delayed. A relatively early post injection timing was also preferable for raising the exhaust gas temperature. For generating highly reactive species, such as hydrogen and reactive light hydrocarbons, the results suggested that an intermediate post injection timing was the most suitable. Furthermore, a late post injection timing was the least desirable due to a very low contribution to power output, a minimal increase in the exhaust gas temperature, and a very low amount of reactive species in the exhaust gas. In general, the alternative and dual fuel injection strategies resulted in reduced nitrogen oxide emissions, reduced smoke emissions, and reduced exhaust gas temperatures compared to the traditional diesel fuel injection. For the alternative and dual fuel tests, it was found that an early post injection was able to reduce the hydrocarbon and carbon monoxide emissions relative to the quantity without a post injection.

1. Introduction

The reduction of vehicle emissions, particularly the emissions of nitrogen oxides (NOx) and particulate matter (PM), remains an important engineering challenge and the enforcement of progressively more stringent emission regulations has compelled lean-burn engine manufacturers to research and develop advanced in-cylinder and after-treatment emission reduction technologies [1–4]. In-cylinder technologies, such as exhaust gas recirculation (EGR) and advanced fuel injection strategies, can reduce the formation of NOx and PM emissions from lean-burn engines but they can also lead to an increase in the unburned hydrocarbon emissions and a reduction in the fuel economy [5,6]. The use of emission after-treatment system can reduce some of the burden of in-cylinder emission reduction and it can allow engine manufacturers to calibrate the engine to operate at conditions more suitable for improved fuel efficiency while using the after-treatment to fill the gap in satisfying the emission regulations.

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* Corresponding author. Tel.: +1 (519) 253 3000x4789.
E-mail address: jeftic2@uwindsor.ca (M. Jeftić).

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Nomenclature

ATDC	after compression top dead center
BMEP	brake mean effective pressure
BSFC	brake specific fuel consumption
BTDC	before compression top dead center
CA	crank angle
CA[50]	crank angle of 50% heat released
CAI	California Analytical Instruments
CI	compression ignition
DI	direct injection
DPF	diesel particulate filter
EGR	exhaust gas recirculation
FSN	filter smoke number
FTIR	Fourier transform infrared spectroscopy
HCCI	homogeneous charge compression ignition
HRR	apparent heat release rate
IMEP	indicated mean effective pressure
NI	National Instruments
LHV	lower heating value
LNT	lean NOx trap
NOx	nitrogen oxides
p	pressure (Pa)
PCCI	premixed charged compression ignition
PM	particulate matter
ppmV	parts per million by volume
Q	heat (J)
SCR	selective catalytic reduction
THC	total hydrocarbon
V	volume (m^3)
γ	heat capacity ratio

After-treatment systems can be complex and can include multiple devices such as a diesel oxidation catalyst, a diesel particulate filter (DPF), a lean NOx trap (LNT), or selective catalytic reduction (SCR) [7–9]. Each of these devices require specific temperatures and exhaust gas composition for optimal performance. SCR and LNT systems typically require reactor temperatures in the range of 250–400 °C for maximum NOx conversion efficiency [10–12]. Temperatures above 500 °C may be periodically required by DPFs for regeneration purposes [13]. Furthermore, the presence of reactive species like hydrogen can enhance the performance of after-treatment devices [14,15]. However, lean-burn engines can have a wide range of exhaust gas temperatures and exhaust gas compositions which may lead to conditions which are not suitable for after-treatment devices.

To assure suitable exhaust conditions for after-treatment devices, an in-cylinder post injection or a fuel injection directly into the exhaust can be used. Disadvantages of an exhaust injection include the requirement of additional hardware, such as exhaust injectors and fuel lines, and that it cannot contribute to engine power output. Thus, this study attempted to characterize the ability of a post injection to generate suitable conditions for after-treatment systems. In particular, the effect of the post injection timing on the post injection combustion, the exhaust gas temperature, and the exhaust gas composition was investigated.

Similar studies have been previously carried out but those studies were mainly focused on direct injection (DI) of diesel fuel [16,17]. In this study, the post injection characterization tests were performed with traditional and alternative fuel strategies due to the potential emission benefits of alternative fuels. Oxygenated alternative fuels, such as ethanol and butanol, can be used in a dual fuel application with diesel to enable premixing enhanced combustion and can be an attractive option for the reduction of PM and NOx emissions in lean-burn compression ignition engines [18,19]. In addition, it is possible to utilize port injection of pure butanol to allow for homogenous charge compression ignition (HCCI) which could further reduce the particulate matter emissions. For this reason, three different fuels were used in this study: ultra-low sulfur diesel, n-butanol, and ethanol. The study investigated the post injection characteristics with traditional fuel injection of direct injection diesel but also with dual fuel and alternative fuel injection strategies as will be described in Section 3.2.

2. Literature review

Post injection and alternative fuel studies in compression ignition engines have been previously done by many researchers [16–33]. Numerous diesel post injection studies have been carried out to determine the effects of the post injection on soot emissions [20–25]. Researchers have indicated that a significant reduction of soot emissions can be achieved with an early post injection [21,25]. Hotta et al. attributed the smoke reduction to increased turbulence caused by the injection of the post fuel and to increased in-cylinder temperatures caused by the combustion of the post injection [21]. In a different study, Nimodia et al. indicated that the reduced soot emissions can be accompanied by increased brake specific fuel consumption (BSFC) [25]. The same authors demonstrated that the exhaust gas temperature can be significantly increased by increasing the quantity of the post injection fuel [25]. The authors of [20] showed that a two-staged bowl piston and a twelve hole double-row nozzle were beneficial for reducing the carbon monoxide, the total hydrocarbon (THC), and PM emissions with a close-coupled post injection when high EGR rates were used. For constant BSFC and NOx levels, Hardy and Reitz indicated that only a slight reduction in PM emissions was achieved with a close-coupled post injection and that the PM reduction was attributed to improved mixing of the in-cylinder gases caused by the momentum of the post injection fuel [22].

Desantes et al. provided insight with regards to the differences between a close-coupled post injection and a post injection more remote from the main injection [23]. It was explained that a post injection which was close-coupled with the main injection was effective for the reduction of PM emissions due to increased acceleration of the final stages of combustion and it was further noted that a smaller close-coupled post injection was more suitable for increasing the acceleration [23]. However, if the post injection was more remote from the main injection then there was a split flame [23]. It was concluded that a small and remote post injection did not affect the PM emissions and that any PM reduction was simply due to the shortening of the main injection [23]. Furthermore, if the post injection was remote and relatively large then it was possible for the post injection to produce additional PM, especially if the post injection timing was relatively early and if the in-cylinder temperature was relatively high [23]. Research has shown that the particle size distribution was sensitive to the dwell time between the main and the post injection [24]. It was acknowledged that the particle count of the nucleation mode particles was reduced and that the particle count of the accumulation mode particles was increased when a close-coupled post injection was used [24]. The same trends were observed with a single post injection and with a double post injection [24]. For diesel partially premixed charge compression ignition at high loads (BMEP of 16.5 bar), de Ojeda et al. indicated that a post injection, in combination with a pilot and a main injection, was useful for soot reduction [27].

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