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Effect of post injections on mixture preparation and unburned hydrocarbon emissions in a heavy-duty diesel engine

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ABSTRACT

This work explores the mechanisms by which a post injection can reduce unburned hydrocarbon (UHC) emissions in heavy-duty diesel engines operating at low-temperature combustion conditions. Post injections, small, close-coupled injections of fuel after the main injection, have been shown to reduce UHC in the authors' previous work. In this work, we analyze optical data from laser-induced fluorescence of both CH_2O and OH and use chemical reactor modeling to better understand the mechanism by which post injections reduce UHC emissions. The results indicate that post-injection efficacy, or the extent to which a post injection reduces UHC emissions, is a strong function of the cylinder pressure variation during the post injection. However, the data and analysis indicate that the pressure and temperature rise from the post injection combustion cannot solely explain the UHC reduction measured by both engine-out and optical diagnostics. The fluid-mechanic, thermal, and chemical interaction of the post injection with the main-injection mixture is a key part of UHC reduction; the starting action of the post jet and the subsequent entrainment of surrounding gases are likely both important processes in reducing UHC with a post injection.

1. Introduction

In this work, we explore the use of post injections – close-coupled, short injections after the end of the main fuel delivery – to reduce unburned hydrocarbon (UHC) emissions from heavy-duty diesel engines operating at low-temperature combustion (LTC) conditions. This multiple-injection technique has shown some promise in previous studies [1], but the in-cylinder mechanisms by which post injections reduce UHC emissions are still unclear. Understanding the chemical and physical processes driving UHC emissions reduction using post injections is an important step toward increasing the viability of LTC strategies in heavy-duty diesel engines.

LTC operation has the potential to reduce engine-out pollutant emissions, including soot and NO_x. Recently reviewed by Musculus et al. [1] and investigated for applications in both light-duty [2–6] and heavy-duty [7–10] engines, LTC uses a combination of greater dilution and premixing of reactant mixtures compared to conventional diesel combustion [11] to suppress formation of NO_x and soot. One common method of dilution is exhaust gas recirculation (EGR), which introduces high-heat-capacity species such as CO_2 and H_2O into the cylinder, reduces the flame temperature, and thereby slows the chemical kinetics of thermal NO_x formation. Reduced temperatures at LTC conditions can also decrease soot formation rates, but the lower oxygen concentration simultaneously yields an overall more fuel-rich charge, which can promote soot formation if pre-combustion mixing is not also modified. LTC strategies enhance pre-combustion mixing by injecting fuel at point in the cycle where the ignition delay is long compared to conventional diesel fuel-injection timings. In this way, the fuel and air are allowed more time to mix, resulting in mixtures that are less fuel-rich at ignition than for conventional diesel combustion, such that there is much less opportunity for soot formation. This can be achieved by injecting fuel either earlier [10,12] or later [6,13] than the conventional diesel fuel-injection schedule. With greater quantities of fuel premixing prior to combustion, peak heat-release rates can be excessive for LTC conditions at high load, so LTC conditions are generally limited to low load.

Creating this long-ignition-delay, highly dilute mixture before combustion can have undesired consequences on combustion efficiency. Previous studies [14,15] have quantified fuel/air mixing at these conditions, showing that during the long ignition delay certain portions of the mixture can become too lean to ignite, resulting in lower combustion efficiency and increased UHC emissions. Toluene planar laser-induced fluorescence and Rayleigh-scattering mixing studies performed in both an optical engine and optical spray vessel by Musculus et al. [15] measured equivalence ratio

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fields after the end of injection, showing rapid reduction in equivalence ratio near the injector nozzle. Shortly after the end of the injection, within approximately 1 CAD or 139 μs, the regions near the injector tip are leaner than regions further downstream. This characteristic of the distribution persists for the rest of the measured cycle, with more fuel-rich mixtures at greater distances from the injector. This rapid reduction in equivalence ratio near the injector is driven by advection and enhanced mixing that arises from the reduction of flow through the nozzle approaching the end of the injection. Changes in mixing, or entrainment, during rapid velocity variations at the nozzle have been measured in turbulent gas jets by several authors [16–19]. For diesel jets, Musculus and coworkers [20–22] showed how charge temperature and density as well as the profile of end-of-injection transient affect the evolution and propagation of large-scale structures downstream in the jet to increase entrainment. Recent experimental measurements of mixing in a single diesel jet have confirmed the "entrainment wave" during and after the end of injection [23]. A number of studies have connected this enhanced entrainment mechanism to the formation of overly-lean regions near the injector after the end of injection at LTC conditions [1,14,15,24]. Although enhanced mixing is a critical feature of LTC conditions for avoiding fuel-rich regions that form soot, some regions can become over-mixed such that the local fuel concentrations are too low to sustain combustion.

Nomenclature

AEI	after end of injection
AHRR	apparent heat release rate
BDC	bottom dead center
CAD	crank angle degree
DSE1	duration of solenoid energizing – main injection
DSE2	duration of solenoid energizing – post injection
EGR	exhaust gas recirculation
Energizing dwell	time between end of main and beginning of post injection
EOI	end of injection
gIMEP	gross indicated mean effective pressure
HR	homogeneous reactor – Chemkin reactor model
Ignition dwell	time between the end of injection and second-stage ignition
Int.	intermediary species – in Chemkin simulation
LTC	low-temperature combustion
P_o	initial pressure – in Chemkin simulation
PLIF	planar laser-induced fluorescence
SOI	start of injection
SSE1	start of solenoid energizing – main injection
SSE2	start of solenoid energizing – post injection
T_{AC}	adiabatic core temperature
TDC	top dead center
T_{FSP}	temperature of first-stage ignition products
T_{mix}	mixture temperature after adiabatic mixing
TSL	two-stage Lagrangian – Chemkin reactor model
T_{SSP}	temperature of second-stage ignition products
UHC	unburned hydrocarbons
UV	ultra-violet

Table 1
Engine and fuel system specifications.

Engine base type	Cummins N-14, DI diesel
Number of cylinders	1
Cycle	4-stroke
Number of intake valves	2
Number of exhaust valves	1[a]
Combustion chamber	Quiescent, direct injection
Swirl ratio	0.5 (approx.)
Bore	139.7 mm [5.5 in.]
Stroke	152.4 mm [6.0 in.]
Bowl width	97.8 mm [3.85 in.]
Displacement	2.34 L [142 in.^{3}]
Geometric compression ratio	11.2:1
Replicated compression ratio	16:1
Fuel injector	Delphi DFI-1.5 (light duty)
Fuel injector type	Common-rail, solenoid actuated
Rail pressure	1200 bar
Cup (tip) type	Mini-sac
Number of holes and arrangement	8, equally-spaced
Spray pattern included angle	156°
Nominal orifice diameter	0.131 mm

[a] In this optically accessible diesel engine, one of the two exhaust valves of the production cylinder head was replaced by a window and periscope (see Fig. 1).

One way to reduce UHC emissions from these overly-lean sources is with the use of close-coupled post injections [24–27]. Initial studies by Chartier et al. [25], Koci et al. [27], Anselmi et al. [26], and Skeen et al. [28] showed promising results for UHC reduction using a post injection at a limited range of conditions. Recent work by O'Connor and Musculus [24] has detailed the sensitivity of UHC reduction by a post injection, termed "post-injection efficacy," to a wide range of injection parameters. Post-injection efficacy was most sensitive to the duration of the post injection and the ignition delay of the mixture after the start of the post injection; post-injection efficacy was relatively insensitive to the main-injection duration as well as the dwell time between the end of the main injection and the beginning of the post injection. The goal of the current work is to better understand the mechanism by which post injections reduce lean-source UHC emissions at LTC conditions.

2. Experimental overview

2.1. Optical engine

The optical engine is a modified version of a single-cylinder Cummins N-series direct-injection, heavy-duty diesel engine. The engine is equipped with a Bowditch piston with an open, right-cylindrical bowl and a flat fused-silica piston-crown window providing imaging access to the bowl, viewing from below. A 30-mm-wide curved window matching the contour of a portion of the piston bowl wall allows laser access into the bowl. Engine and fuel injector specifications are in Table 1 and a schematic of the engine and experiment is shown in Fig. 1. Further details about this engine can be found elsewhere [11,29].

A Delphi DFI 1.5 light-duty, solenoid-actuated common-rail injector with eight equally spaced 131-μm orifices is used for its fast response time and its ability to deliver consistent, close-coupled, short-duration post injections over a range of injection schedules. The fuel is *n*-heptane, which is selected for its low fluorescence upon illumination by ultraviolet (UV) laser-light, while retaining ignition properties typical of diesel fuel.

2.2. Optical engine diagnostics

Several diagnostics are used to investigate the origin of UHC emissions at LTC conditions, including cylinder pressure