Combustion and Flame 177 (2017) 24–36

Contents lists available at ScienceDirect

Combustion and Flame

journal homepage: www.elsevier.com/locate/combustflame

Scaling combustion recession after end of injection in diesel sprays

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ARTICLE INFO

Article history:
Received 1 July 2016
Revised 14 September 2016
Accepted 30 November 2016
Available online 4 January 2017

Keywords:
Diesel engine
Unburned hydrocarbons
Fuel injection rate shaping
Flame lift-off
End-of-injection

ABSTRACT

While soot and NOx emissions tend to be lower for partially-premixed compression ignition (PPCI) strategies compared to more conventional conditions, a common theme amongst PPCI strategies are the excessive unburned hydrocarbons (UHC) that originate from overly lean mixtures near the nozzle due to end-of-injection entrainment. The focus of this work is on combustion recession, which governs the outcome of near-nozzle UHC and has been identified as a process that is strongly influenced by end-of-injection transients in addition to in-cylinder thermodynamic conditions and injection parameters. Combustion recession is the process whereby the initially lifted reaction zone retreats back towards the nozzle following end-of-injection thus consuming UHC that would otherwise remain near the nozzle and persist into the expansion stroke. In an effort to link end-of-injection combustion transients to ambient thermodynamic conditions and injector parameters, a scaling methodology to predict the likelihood of combustion recession in diesel sprays was developed. This methodology relates ignition timescales during steady injection to mixing timescales after end-of-injection. Reasonable agreement between the predicted scaling and measured combustion recession data is shown over a very wide range of ambient conditions, injector parameters, and end-of-injection transients. The success of this scaling suggests that combustion recession is autoignition dominated, heavily influenced by injector design, and that the mixing-limited vaporization assumption can be extended to the study of end-of-injection phenomena. This work also suggests that combustion recession is a more robust parameter for correlation to UHC than ignition dwell.

1. Introduction

Modern diesel engine strategies seek to meet emissions regulations with minimal aftertreatment by utilizing a wide range of in-cylinder strategies. Broadly categorized as Low-Temperature Combustion (LTC), these in-cylinder strategies may inject fuel into in-cylinder gases that are relatively cooler, less dense, or contain less oxygen (due to large amounts of exhaust gas recirculation (EGR)) compared to more conventional diesel conditions. These in-cylinder strategies may also include changes to the fuel injection schedule/system, such as multiple injections, higher injection pressures, smaller orifices, or even different fuel blends. Excellent reviews of LTC subtopics, such as Homogenous Charge Compression Ignition (HCCI) [1], Reactivity Controlled Compression Ignition (RCCI) [2], and Partially Premixed Compression Ignition (PPCI) [3] are available in the literature. These LTC conditions largely feature a positive ignition dwell, where ignition begins after the end of injection, but LTC conditions with negative ignition dwell, where ignition occurs during injection, can also be generated [4]. Application of the current work is best aligned with PPCI, where ignition is more closely coupled to the injection event compared to HCCI or RCCI. While soot and NOx emissions tend to be low, a common theme amongst PPCI strategies are excessive unburned hydrocarbons (UHC) that originate near the nozzle, which have been attributed to end-of-injection transients [5].

The focus of this work is on combustion recession, which governs the outcome of near-nozzle UHC, and is strongly influenced by end-of-injection transients, in addition to in-cylinder thermodynamic conditions and injection parameters [6–9]. Combustion recession is the process whereby the initially lifted reaction zone retreats back towards the nozzle immediately following end-of-injection, thus consuming UHC that would otherwise remain near the nozzle and persist into the expansion stroke. Besides the problem of UHC, knowledge regarding the state of near-nozzle mixtures following the end of injection can be valuable. For example, knowledge of the state of the gases into which subsequent injections will penetrate can aid the design for multiple injection strategies. Subsequent injections could encounter one of three scenarios: they could penetrate into (i) combustion products, (ii) partially reacted species or (iii) very lean unreacted fuel-air mixtures, and the particular scenario is dependent on the timing and

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http://dx.doi.org/10.1016/j.combustflame.2016.11.021
0010-2180/

existence of combustion recession. Subsequent injections are unlikely to interact with liquid from the first injection because vaporization occurs very quickly, less than 100 µs after the end of injection, and dwells shorter than 100 µs are not practical [10]. The outcome of fuel dribble, which is low momentum fuel leaving the injector orifice and/or sac after injector needle closing, is also affected by the presence of combustion recession. If combustion recession occurs, fuel dribble will penetrate into hot oxygen-depleted combustion products and may form soot, while if combustion recession does not occur, the dribbled fuel could also not ignite and further contribute to UHC emissions. Although swirl, bowl design, and even jet-jet interaction will influence the path of jet combustion products in an actual engine, which have been given some treatment in the literature [11], a fundamental study that characterizes combustion recession over a wide range of in-cylinder thermodynamic conditions, injection parameters, and end-of-injection transients has not yet been performed.

Some progress has been made in this regard, however, where existing line-of-sight, high-speed, broadband chemiluminescence data taken in a quiescent spray chamber were compiled to understand the effects of in-cylinder thermodynamic conditions (temperature, oxygen concentration), injection parameters (injection pressure), and fuel (dodecane, diesel, gasoline, and n-heptane) [7]. In general, combustion recession was found to be promoted for higher temperatures, higher oxygen concentrations, lower injection pressures, and higher reactivity fuels. However, this work lacked the effect of ambient gas density, nozzle orifice diameter, or different end-of-injection transients. Koci et al. observed similar trends with respect to temperature, oxygen concentration, and injection pressure, but was also able to vary the end of injection transient, often referred to as *ramp-down*, with the aid of a modified Hydraulic-Electric Unit Injector (HEUI) [8]. From their line-of-sight, high-speed imaging of electronically-excited hydroxyl, OH*, they found that combustion recession was promoted with longer ramp-down durations, i.e. slower end-of-injection transients. By simultaneously imaging CH*/soot luminosity, they also found that combustion recession could be accompanied by soot under certain combinations of in-cylinder thermodynamic conditions, injection parameters, and end-of-injection transients. We will refer to this temporal and spatial overlap of soot with combustion recession as *soot recession* in the remainder of this work. *Soot recession* has been, historically, the main observation from previous studies with optical engines on end-of-injection combustion behavior, e.g., from the work of Espey and Dec [12], Singh et al. [13], as well as Bobba et al. [14]. Koci et al. showed that combustion recession could occur without soot though, demonstrating three possibilities of near-nozzle mixtures following end-of-injection [8]. Our most recent work has identified another possibility in that combustion recession might occur partially, or in separated, distinct pockets [9]. Therefore, four regimes exist and are referred to as the following: (i) *soot recession*, (ii) *complete combustion recession*, (iii) *partial combustion recession*, and (iv) *no combustion recession*. An example movie of each regime is given in the Appendices and is viewable in the electronic version of this manuscript.

This study seeks to develop a database for conditions that exhibit these four regimes following the end of injection in diesel-like sprays under conditions where combustion and injection overlap (negative ignition dwell). This work is performed in a quiescent spray chamber without the complications of in-cylinder flows, thus providing a baseline for which combustion recession can be characterized. Line-of-sight, high-speed diagnostics that are sensitive to combustion chemistry, soot, as well as liquid/vapor boundaries are employed. A scaling methodology is presented that predicts the likelihood of combustion recession, based on comparing timescales for joint mixing-chemistry processes that lead to ignition in steady injection sprays to mixing timescales following end-of-injection. Validation of a recently developed reduced-order model, which is based on a dense turbulent gas-jet, is also presented [6].

2. Experimental setup

2.1. Spray chamber and injection system

Combustion experiments were performed in a continuous flow-through type spray chamber with three optical access ports on the sides and one on top [9]. This chamber is capable of maintaining a nominally-quiescent ambient gas environment from atmospheric temperature and pressure up to 950 K and 100 bar. A nitrogen separator is used to simulate exhaust-gas recirculation and is capable of dilution down to 0.05% O_2. Based on previous temperature measurements and the estimated region of influence for single axial sprays used in this study, the ambient temperature is within +1% to −1.5% of the target temperature [9]. The temperature uniformity within the spray chamber is important to keep in consideration because combustion recession has been shown to be highly sensitive to ambient temperature [7].

Previous work has identified the end-of-injection transient as an important factor regarding the outcome of combustion recession. To control the end-of-injection transient, a unique injection rate-shaping system was designed. This system quickly modulates the pressure supplied to the fuel injector by charging or discharging its fuel supply lines. The charging valve opens prior to the injector in order to create a constant high-pressure source. The injector is then energized and the flow rate of fuel resembles the first phase of a normal injection. Shortly thereafter, the charging valve is closed at nearly the same instance as the discharging valve is opened. The fuel pressure that supplies the injector quickly decays as the volume upstream empties. This rate shaping technique emulates existing systems, e.g. HEUI injectors, where injection rate-shaping is accomplished via internal pressure modulation. More details on the injection rate-shaping system can be found in Ref. [9].

Two end-of-injection transients (fast and slow) were executed for each nozzle diameter, d_0, and injection pressure, P_{inj}, used in this work. The two injectors used are part of the Engine Combustion Network [15] and provided by Bosch. Each common rail injector is solenoid-actuated and features a single, hydro-ground, axially-drilled hole with nominal k-factor = 1.5. The smaller of the two nozzles (90 µm) is from the Spray A injector set (injector #211020) while the larger (186 µm) is part of the Spray D set (injector #209133). Injection rate profiles for each are shown in Fig. 1, where the injection velocity, U_0, was obtained via rate-of-momentum measurements, with a measured steady injection area contraction coefficient of 0.91 and liquid fuel (n-dodecane) density of 699 kg m^{-3}. Then, each profile was normalized by its steady injection velocity and is shown after the start of ramp-down (ASORD). The fast ramp-down (RD) profile is nearly linear and has the same characteristic timescale of velocity decrease [16], $\alpha = U_0/(dU_0/dt) \approx 100$ µs, regardless of injection pressure and nozzle diameter. The normalized slow RD profiles are also nearly identical to one another, independent of injection pressure and nozzle diameter, but they are not linearly decreasing like the fast RD, i.e. there are two distinct slopes. Thus, it is difficult to quantify a single characteristic timescale of velocity decrease for the slow RD profile. Shown later, the procedure illustrated in Fig. 6 will be used to find an equivalent timescale, based on a single linear velocity decrease, for the slow RD profiles used in this work.

2.2. Optical diagnostics

The objective of characterizing combustion recession over a wide range of operating conditions, combined with the short time