

Conceptual Investigation of the Origins of Hydrocarbon Emissions from Mixing-Controlled, Compression-Ignition Combustion

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ABSTRACT

Experiments conducted with a set of reference diesel fuels in an optically accessible, compression-ignition engine have revealed a strong correlation between hydrocarbon (HC) emissions and the flame lift-off length at the end of the premixed burn (EOPMB), with increasing HC emissions associated with longer lift-off lengths. The correlation is largely independent of fuel properties and charge-gas O_2 mole fraction, but varies with fuel-injection pressure. A transient, one-dimensional jet model was used to investigate three separate mechanisms that could explain the observed impact of lift-off length on HC emissions. Each mechanism relies on the formation of mixtures that are too lean to support combustion, or "overlean." First, overlean regions can be formed after the start of fuel injection but before the end of the premixed burn. Second, during the mixing-controlled burn phase, longer lift-off lengths could increase the mass of fuel in overlean regions near the radial edge of the spray cone. Third, after the end of injection, a region of increased entrainment and mixing upstream of the lift-off length could cause late-injected fuel to become overlean. The model revealed a correlation between the lift-off length at EOPMB and overlean regions from the mixing-controlled burn that closely matched experimentally observed trends. HC emissions associated with overlean regions produced either before the end of the premixed burn or after the end of injection did not correspond as well to the experimental observations.

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INTRODUCTION

Hydrocarbon (HC) emissions from compression-ignition engines have not historically been of paramount concern, and research has focused on emissions of particulate matter (PM) and nitrogen oxides (NO_x), which are more problematic with respect to mixing-controlled combustion. However, tighter exhaust-emissions standards and the development of alternative combustion strategies have contributed to intensify interest in diesel HC emissions. Many studies have investigated emissions associated with alternative, low-temperature combustion (LTC) modes (e.g., [1,2]), and the results have shown that HC emissions can be problematic. However, strategies that produce a large extent of global premixing during the ignition delay may not be suitable at moderate to high engine loads, due to excessive heat-release rates, challenges with controlling combustion phasing, and elevated emissions of soot and NO_x . Mixing-controlled combustion strategies that are focused on enhancing only the extent of local premixing may be more attractive for high-load operation. One example is leaner lifted-flame combustion (LLFC) [3,4], which seeks to create mixtures that are leaner at the lift-off length than conventional diesel combustion, to attenuate or prevent soot formation. It is noted, however, that considerable further development is required to achieve sustained LLFC operation at high loads (e.g., [4]).

Early investigations of the origins of HC emissions from compression-ignition engines [5,6] identified numerous potentially important mechanisms. These include overmixing before the premixed burn under long ignition-delay conditions, late-cycle fuel-rich regions resulting from undermixing, wall impingement and quenching, and fuel emptying from injector sac and nozzle hole volumes. In their study, Greeves et al. concluded that a major cause of HC emissions was "fuel premixed to leaner than lean-limit conditions" [5]. Yu et al. also identified overmixing of regions beyond the lean limit of combustion to be a primary source of HC emissions [6]. These observations are often tied to ignition delay (and thus fuel cetane number), because longer ignition-delay times contribute to increased mixing of injected fuel and charge gas.

Recent experimental data have revealed that, under mixing-controlled combustion conditions, HC emissions levels can be directly linked to flame lift-off lengths measured at the end of the premixed burn phase [7]. These data might be viewed as a further indication that HC emissions primarily result from overmixing during the ignition-delay period. However, alternative mechanisms to be presented in this paper appear to better explain the experimental results.

In this study, a simplified jet-mixing model is used to conceptually evaluate the potential importance of three HC emissions mechanisms that correspond to different phases of mixing-controlled, compression-ignition combustion. The relative significance of each mechanism is assessed by comparing the model results to trends observed in the experimental data.

SUMMARY OF EXPERIMENTAL DATA

The modeling study described in this paper was motivated by experimental work conducted by the authors and previously reported in Reference [7]. The experiments were carried out in a single-cylinder, heavy-duty engine, modified to provide optical access to the combustion chamber. A common-rail fuel injector with a two-hole tip was used to minimize the effects of interactions between adjacent jets. The engine was operated at 1500 rpm and constant start-of-combustion timing, achieved by adjusting the start of injection as necessary based upon fuel ignition delay. Two fuel-injection pressures (80 and 180 MPa) and three charge-gas dilution levels (21, 18, and 16 mol% O₂) were investigated. Engine load was kept constant at each fuel-injection pressure, with gross indicated mean effective pressures (gIMEP) of 1.72 and 2.91 bar for the 80- and 180-MPa injection pressures, respectively. These loads correspond to loads obtained with the baseline fuel at a fixed, 3.5-ms indicated duration of injection. Throughout this paper, experimental data and model results will be identified based upon fuel injection pressure (80 or 180 MPa); however, the reader should note that these identifiers uniquely represent two different loads as well (i.e., 1.72 and 2.91 bar gIMEP, respectively). In all of the engine runs, more than 80% of the heat release occurred during mixing-controlled combustion.

The fuels evaluated were a #2 ultra-low-sulfur diesel certification fuel, plus four of the nine diesel fuels designed by the Coordinating Research Council's Fuels for Advanced Combustion Engines (FACE) Working Group [8]. The certification fuel (CF) served as a baseline fuel, with the FACE fuels providing varying properties with respect to cetane number (CN), aromatics content, and 90% distillation temperature (T90), as illustrated in Figure 1. FACE Diesel Fuels 1, 2, 6, and 8 were evaluated, and are referenced in this paper using the nomenclature "F#" (e.g., F1 for FACE Diesel Fuel 1). Table 1 summarizes the design properties for CF and the four tested FACE fuels. Additional test-fuel properties and distillation curves can be found in Reference [7].

With respect to HC emissions, the experimental data revealed that the lower CN fuels (F1 and F2) produced higher indicated HC emissions than the moderate and higher CN fuels (CF, F6, and F8), as shown in Figure 2. A trend with fuel-injection pressure was also observed, with lower injection pressures (lower loads) producing higher indicated HC emissions. In addition, increasing charge-gas dilution (decreasing mol% O₂, or X_{O2}) was associated with higher HC emissions. These latter two effects were attributed to the lower in-cylinder temperatures associated with the lower injection pressure and higher dilution cases.

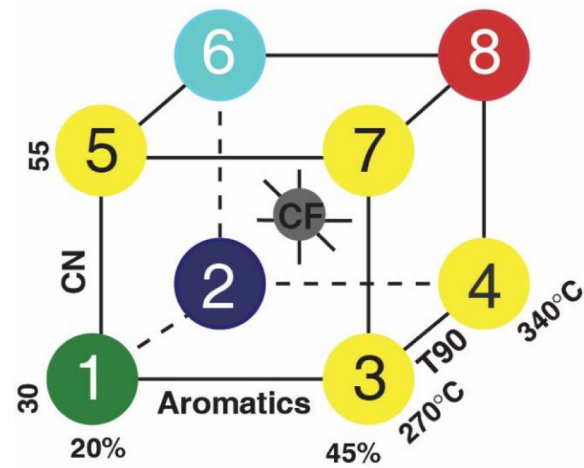


Figure 1. Certification fuel (CF) and FACE diesel fuels F1, F2, F6, and F8, shown with respect to fuel design properties. Numerical values shown are approximate; see Table 1 for measured values.

Table 1. Experimental test-fuel properties and relative values compared to the baseline certification fuel (CF) [7].

Fuel Property and Value (relative value compared to CF)			
Fuel	Cetane Number	Aromatics Content [mass %]	T90 [°C]
CF	43.3	29.7	310
F1	30.3 (↓ Lower)	26.6 (↓ Lower)	284 (↓ Lower)
F2	28.4 (↓ Lower)	23.3 (↓ Lower)	346 (↑ Higher)
F6	53.7 (↑ Higher)	21.5 (↓ Lower)	339 (↑ Higher)
F8	49.5 (↑ Higher)	44.4 (↑ Higher)	342 (↑ Higher)

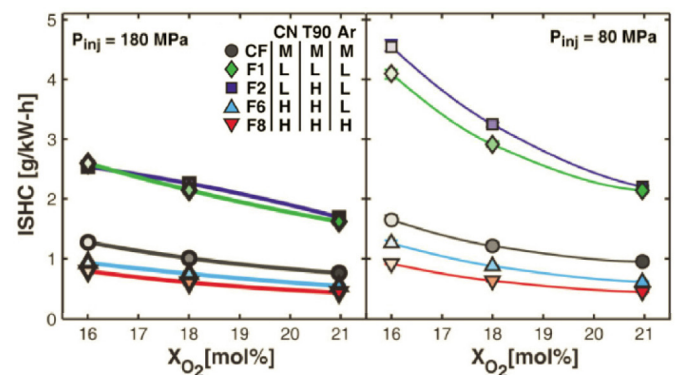


Figure 2. Indicated specific hydrocarbon (ISHC) emissions as a function of intake-O₂ mole fraction (X_{O2}) for experimental test-fuels at fuel injection pressures of 180 MPa (left) and 80 MPa (right) [7].

When the experimental data are viewed as presented in Figure 2, no clear relationship emerges between HC emissions and measured fuel or engine parameters, though CN appears to play an important role. Subsequent analysis showed a strong correlation between HC

emissions and the flame lift-off length, H , measured at the end of premixed burn (EOPMB). Lift-off lengths were determined via chemiluminescence imaging, and represent the axial distance between the fuel-injector orifice outlet and the position where the standing premixed ignition zone stabilizes during mixing-controlled combustion [7,9, 10, 11]. As shown in Figure 3, within each fuel-injection pressure, the HC emissions index (EIHC) scaled with H at EOPMB, regardless of fuel or dilution level. Note that in Figure 3, HC emissions are presented in terms of an emissions index [g/kg fuel] rather than an indicated value [g/kW-h] to facilitate later comparison with model results. Nevertheless, the trends shown are nearly identical regardless of whether the emissions index or indicated emissions are plotted, as engine load scaled directly with the mass of fuel injected.

The strong correlation observed in Figure 3 suggests that the mechanism(s) driving HC emissions levels are heavily influenced by the lift-off length at the end of premixed burn. Three mechanisms were identified that might explain the experimental trends, and were evaluated using a simplified non-vaporizing, non-reacting jet-mixing model.

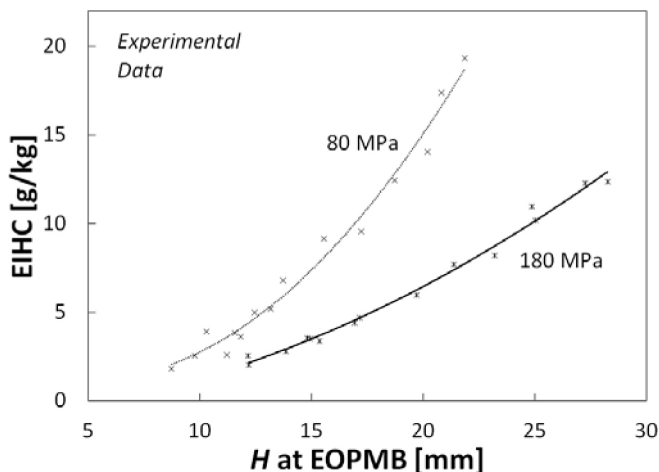


Figure 3. Experimental data suggest a strong link between HC emissions index (EIHC) and the lift-off length (H) at the end of the premixed burn (EOPMB). Figure shows data for all tested fuels and dilution levels.

MODEL DESCRIPTION AND PARAMETERS

The computational model used is a one-dimensional, non-vaporizing jet-mixing model developed by Musculus and Kattke [12] and based upon work by Naber and Siebers [13]. Full details regarding the model may be found in the referenced papers; only a brief summary of the model will be provided here.

The model is based upon a control-volume analysis, with control volumes established along the jet axis (Figure 4). The model solves the transient, conservation of mass and momentum equations for the control volumes established, based upon seven simplifying assumptions:

1. The jet is non-vaporizing.
2. The flow is incompressible.
3. Turbulent and molecular viscous forces can be neglected.

4. Momentum diffusion can be neglected (only momentum convection is considered).
5. Forces due to the axial pressure gradient are negligible.
6. The jet spreading angle is constant.
7. Radial velocity profiles are as suggested by Abramovich [14]:

$$\frac{u}{u_c} = \left[1 - \left(\frac{r}{R}\right)^\alpha\right]^2 \quad (1)$$

with a uniform profile at the nozzle ($\alpha=\infty$) that evolves downstream into a fully-developed, Gaussian-like profile (with $\alpha=1.5$). In Eq. 1, u_c represents the velocity at the centerline ($r=0$) and R is the jet radius.

In Figure 4, θ is the jet-spreading angle, and z and z' are axial coordinates relative to the nozzle and the virtual origin, respectively, with $z_0 = z' - z$. The model was implemented with control volume widths of 0.05 mm, a computational domain extending to $z = 100$ mm, and time steps of 20 μ s.

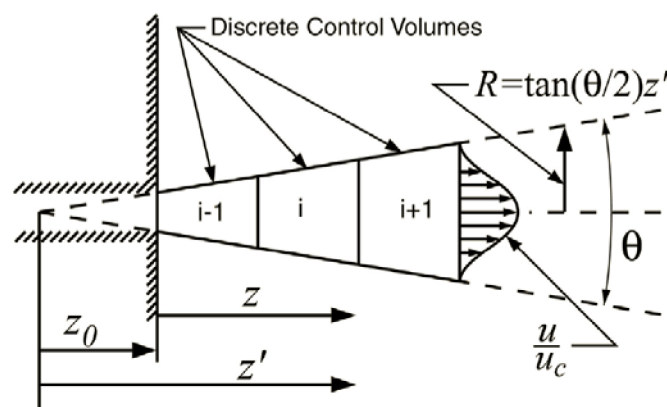


Figure 4. Schematic of one-dimensional, discrete control volumes (adapted from [12]).

While the lift-off length at EOPMB was most directly tied to HC emissions, evaluation of the potential HC emissions mechanisms using the model required H data spanning from EOPMB to end of injection (EOI). In preparing lift-off length data to use for the model runs, significant similarities were identified within two separate test-fuel groups. As shown by the experimental data in Figure 5, all fuels produce concave-up trendlines when H is plotted with respect to time or crank angle degree. However, for CF, F6, and F8, H generally increased with time, while for F1 and F2, the H values first measured were larger than those measured later during combustion. Lift-off length magnitudes were also clustered according to these groups, with CF, F6, and F8 producing shorter lift-off lengths. In terms of the test-fuel design parameters, the fuel groups can be categorized as medium and high CN fuels (CF, F6, and F8), and as low CN fuels (F1 and F2). To limit the number of model runs necessary, lift-off length data were developed at each injection pressure for these two fuel groups only, rather than for each of the five individual fuels. These lift-off lengths were defined by a curvefit to the relevant experimental data, and assumed to be similar (in shape) across different dilution levels. A scaling factor was used in the model to evaluate the effects of higher or lower H values.