High-Speed Characterization of Transient Injection Events in an Engine

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Objectives & Motivation

Advanced combustion strategies incorporating equivalence ratio stratification, multiple injections, and LTC (low temperature combustion) techniques, as well as small CI engines use short injection durations where a significant portion of the injection has a transient rate-of-injection. The quasi-steady scaling relationships previously developed in the literature are not expected to hold up under these conditions. This work serves to investigate the following points:

- Develop reliable diagnostic methods for acquiring liquid fuel, vapor, and combustion data simultaneously in the engine
- Effects of the initial transient on jet development and deviation from quasi-steady scaling laws
- Quantify transient jet effects on the injection transient and subsequent combustion

Transient Jet Overview

Compression ignition (CI) direct injection (DI) internal combustion engines use a fuel delivery process composed of a liquid fuel jet that vaporizes and mixes with hot-in-cylinder gases, governed by a complicated set of thermodynamic and fluid mechanics. These jets are characterized by their liquid length, jet (combined liquid and vapor regions) penetration length, dispersion angle, and lift off length (after the start of combustion).

Engine Operating Conditions

A set of engine thermodynamic conditions bounding those typically used in modern small displacement diesel engines are being tested. A range of injection parameters resulting in varying initial transient events with varying properties are also being tested.

Image Processing

Optical measurement techniques have been a key tool in jet measurements, both in engines and in constant-volume combustion chambers. Experimental results from optical tests are used to provide a non-intrusive means for gaining a physical understanding of and developing relationships for jet characteristics.

Although all jets undergo the transients of turn-on and turn-off as seen in Figure 2, the effects of these regions have been largely assumed to be negligible on eventual quasi-steady development in the literature [1-4] for long injection durations.

Existing Parameter Scaling - Development of quasi-steady scaling - Penetration

- Liquid Length

- Dispersion Angle

- Observation from accelerating jets

Engine & Diagnostic Operation

The primary experimental apparatus used for the measurements is composed of a single in-line optical engine paired with an optical imaging system, data acquisition system, and fuel injection system:

1. Internal combustion engine
2. Optics and imaging system

The high-speed optical imaging system used for the work to date is capable of imaging the entire injection event in the cylinder while maintaining sufficiently high temporal resolution to resolve the initial fuel injection transient.

Engine Operating Conditions - Injection Parameters

Table 1: Measurement Matrix

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>SOI Timing</td>
<td>-114 to +3 mm IS</td>
</tr>
<tr>
<td>IC Density</td>
<td>10, 20, 30 kg/L</td>
</tr>
<tr>
<td>Intake Temperature</td>
<td>-5, 0, 10°C</td>
</tr>
<tr>
<td>Intake Pressure</td>
<td>500 kPa</td>
</tr>
<tr>
<td>Intake Injection Pressure</td>
<td>750 to 1500 kPa</td>
</tr>
</tbody>
</table>

Engine Operating Conditions - Engine Conditions

Table 2: Parking Matrix

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Engine</td>
<td>Ford F150 5.4L (331 CID)</td>
</tr>
<tr>
<td>Speed</td>
<td>1,000 to 2,500 rpm</td>
</tr>
<tr>
<td>Load</td>
<td>0 to 20 lb-ft, 32% load</td>
</tr>
<tr>
<td>Air Density</td>
<td>0.074 to 0.088 kg/L</td>
</tr>
<tr>
<td>EGR</td>
<td>0, 25, 50, 100%</td>
</tr>
</tbody>
</table>

Engine Operating Conditions - Injection Pressure

Figure 11: Distribution curves for tested fuels (PPS-P & PPI-P curve not tested)

The jet and liquid-length measurements showed expected results with respect to the fuel volatility. The diesel fuel, with its higher boiling point curve, has a longer stabilized liquid length than the jet fuel blends. The time dependency of the penetrations vary significantly from those predicted by quasi-steady scaling relationships, however.

Conclusions & Future Work

It is evident from the current preliminary results that the jet penetration evolution is strongly impacted by the initial RDI transient. As combustion strategies become more complicated through series of multiple short injections, and the necessity exists for extremely precise injection parameters for CFS purposes to match and predict experimental conditions as closely as possible, the relevance of the understanding of accelerating jets increases. Transient RDI cause time variations in jet dispersion and penetrations not expected from quasi-steady scaling.

Additional analysis is planned to further investigate these effects:

- Comparison of results with those from a 1-D transient model (using both an quasi-steady injection profile and the ROI from the current tests)
- Temporal dependencies to be made to existing scaling laws to account for deviations during RDI transient
- Comparisons to results from accelerating single-phase jets

References


Figure 1: Graphical representation of a direct injection compression jet engine

Figure 2: ROI profile of typical small diesel engine common rail injector

Figure 3: ROI profile of ‘top-hole’ style injections used in much of the existing literature [1-4]

Figure 4: Targeted-in-cylinder thermodynamic parameters for measurements

Figure 5: Liquid, background subtracted, and threshold image overlaid with a corresponding OH chemiluminescence image

Figure 6: Optical engine used in optical measurements

Figure 7: High-speed optical imaging used in optical measurements of in-cylinder flames

Figure 8: Optical engine used in measurements

Figure 9: Graphical representation of the paths followed by the light for imaging the short injection durations

Figure 10: Distribution curves for tested fuels (PPS-P & PPI-P curve not tested)

Figure 12: Liquid and jet penetration for DI fuel at injection pressure of 138 MPa

Figure 13: Liquid and jet penetration for DI fuel at injection pressure of 77.5 MPa

Figure 14: Jet velocity and density measurements for tested ROI.

The differences in jet evolution for various transient RDI are more clearly visible in this plot comparing the injection velocity (derivative of penetration) and ROI derivative. Initially, the two ROIs display significantly more complex behavior than what is predicted by simple quasi-steady scaling, then approaching the steady scaling prediction at long times. Also, it is important to note the strong correlation between the ROI and the jet velocity.