Visual Characterization of a Pilot-Ignited Direct-Injection Natural Gas Combustion

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About the projects

A convertible thermodynamic/optical engine at CERC is being used to understand what happens inside an engine cylinder with a direct-injected diesel and natural gas fuel system that can lower the greenhouse gas emissions in heavy-duty trucks by 10-15%. The thermodynamic engine configuration models conventional combustion and is used for measurements like air/fuel flow, emission, and torque while the optical engine configuration is paired with imaging techniques that visualize the flame. These visualization techniques show high temperature regions, flame temperature and soot concentrations in the cylinder that were used to develop a conceptual model of direct-injected natural gas combustion.

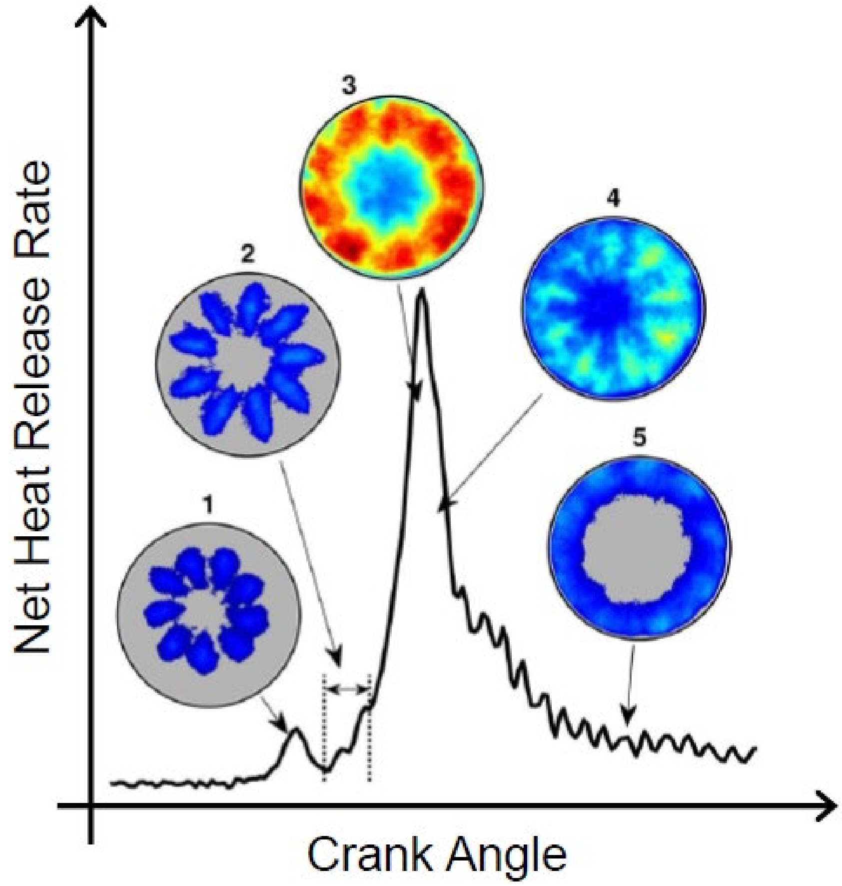

Figure 1. Visualization of conceptual combustion model from HPDI combustion using OH-CL*

For more details of this project, visit:

- Westport Fuel Systems (*link*)
- Profile of Dr. Patrick Kirchen (*link*)
- Parametric study of pilot-ignited direct-injection natural gas combustion in an optically accessible heavy-duty engine (*link*)
- Pyrometric imaging of soot processes in a pilot ignited direct injected natural gas engine (*link*)

Project Summary:

Heavy-duty trucks are the primary form of freight transportation in the country, helping to move food products and manufactured goods to market. Heavy-duty trucks rely mostly on diesel compression ignition engines which contribute a significant and growing amount of greenhouse gas (GHG) emissions leading to the development of natural gas (NG) as a transport fuel. Vehicles that use NG can have GHG emissions that are 10-15% lower compared to those using diesel, in addition to fewer particulate matter and NOx emissions. The lower GHG emissions from NG compared to diesel are contingent on low methane emissions, as it has a global warming potential at least 28-times greater than CO2. Methane emissions are typically higher in port-injected engines where the premixed NG charge can become trapped in crevice volumes or be quenched because of slow flame speeds. However, methane emissions can be effectively reduced in configurations where NG is injected directly into the engine cylinder.

Project Summary:

Westport Fuel Systems specializes in fuel systems including a high-pressure direct-injection (HPDI) system that uses NG at pressures above 200 bar and a concentric dual needle to feed a diesel pilot and NG into the cylinder, resulting in non-premixed combustion. HPDI typically has a lower knock tendency and lower methane emissions compared to premixed combustion, although there is more potential for particulate emissions. Understanding in-cylinder combustion of HPDI systems has involved conventional engines or numerical simulation, but few studies have used imaging to characterize combustion.

To better understand the in-cylinder combustion process, a convertible thermodynamic/optical engine at UBC is being used develop a conceptual model of HPDI by using injection strategies like different injection pressures, relative injection timing, and injection duration. The thermodynamic engine configuration models a conventional engine, allowing for continuous operation as well as measurement of air/fuel flowrate, exhaust emissions, and brake torque. In contrast, the optical configuration uses a Bowditch piston and a quartz window for optical access, although it requires skip-fired operation to avoid damage to the quartz and has a different piston geometry. Although the differences between the thermodynamic and optical engine configurations may impact combustion, the heat release rate is similar in both. The optical access was used for visualization techniques like OH*-chemiluminescence (OH*-CL) to detect high-temperature reaction zones and with two colour pyrometric imaging to measure flame temperature and in-cylinder soot concentration. The imaging techniques helped to develop a conceptual model of HPDI combustion in 5 stages explained below, alongside Figure 1, which includes OH*-CL images and the heat release rate:

1. *Pilot Autoignition*: Pilot autoignition after diesel injection and subsequent heat release.
2. *NG ignition*: Interaction of NG with radicals and high temperature from pilot initiates NG combustion, shown by NG ignition in the same area where pilot OH* radicals are present. NG conversion and jet momentum cause the flame to grow radially. Some NG penetrates past the reaction zone and mixes with air near the cylinder wall.
3. Rapid, distributed partially premixed NG combustion: As the flame reaction zone extends to the cylinder wall, the premixed NG combusts, resulting in faster flame speeds and the peak heat release rate. Ongoing NG injection adds momentum to the partially premixed zone, although the flame reaction becomes increasingly mixing controlled.
4. Non-premixed combustion: Ongoing NG injection as the flame reaction zone moves upstream along the jets towards the injector. The high-intensity OH*-CL near the NG jets suggests that the flames are mixing-controlled.
5. Late-cycle oxidation: NG injection ends, leaving the remaining fuel and partial oxidation products to oxidize. OH*-CL shows late-cycle oxidation occurring near the cylinder wall.