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Full Length Article

Post-injection strategies for gasoline compression ignition combustion under high load conditions: Understanding the role of premixed, main, and post-injections in soot mitigation and load extension

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ABSTRACT

Engine experiments and computational fluid dynamics modeling (CFD) were used to isolate and understand the role of premixed, main, and post-injections in soot mitigation and load extension for high-load GCI operation. Results showed that for all the three injection strategies soot emissions increased with increasing load. For the post-injection cases, soot emissions increased as the dwell time between the main and the post-injection increased. However, adding load through post-injections resulted in higher soot emissions compared to the baseline injection strategy irrespective of the SOI timing of the post-injection. Premixing a portion of the main injection fuel reduced the soot emissions for the post-injection cases, but they remained higher compared to the baseline injection strategy. The CFD modeling showed that the post-injection cases resulted in lower soot formation when compared to the baseline injection strategy. However, the increased injection durations at high-load conditions resulted in soot being formed late in the cycle from the post-injection where the temperatures dropped rapidly, slowing down the soot oxidation rates. This resulted in higher net soot production for the post-injection cases compared to the single long main injection cases. This temperature effect on soot emissions was enhanced, as the post-injection SOI timing was delayed, resulting in increased soot emissions with increasing dwell time. Premixing a portion of the main injection fuel reduced the soot emissions for the post-injection strategies, as the well-mixed premixed fuel combusts without forming any soot. When a similar study was repeated under low- and mid-load conditions using the validated CFD model, post-injections showed a benefit with a maximum reduction in soot of ~62% compared to the baseline strategy. This was because, similar to the high-load conditions, the fuel from the post-injection was targeted at a different region in the combustion chamber relative to the main injection, which provided better access to the oxygen to both the main and the post-injections. However, compared to high-load conditions, since the duration of the main and the post-injection is shorter, it allowed the SOI timing of the post-injection to be advanced closer to TDC without overlapping with the main injection. The advanced post-injection timing, combined with the shorter duration of the post-injection, resulted in the fuel being delivered sufficiently early in the cycle. This provided enough residence time in the high-temperature regions to oxidize the soot formed from the post-injection completely, resulting in reduced soot emissions compared to the case without the post-injection.

1. Introduction

Gasoline-compression-ignition (GCI) combustion [1–3] has received a lot of interest in recent years due to its potential to achieve simultaneous reduction in soot and NOx emissions. Additionally, the projected demand for transportation fuels [4] shows that the demand for heavier fuels (e.g., diesel fuel) is expected to continue to increase, while gasoline demand is expected to decrease or remain constant. The GCI engines have the potential to address this projected transportation fuel imbalance.

Strategies with GCI use light fuels like gasoline [5–7], naphtha [8–10], etc., in a compression ignition engine. Unlike diesel fuel, these

Abbreviations: AHRR, apparent heat release rate; ATDC, after top dead center; BDC, bottom dead center; CFD, computational fluid dynamics; CRIN, common rail injector; EGR, exhaust gas recirculation; ERC, Engine Research Center; EVO, exhaust valve opening; FSN, filter smoke number; FTIR, Fourier transform infrared; GCI, gasoline compression ignition; GRI, Gas Research Institute; IMEP, indicated mean effective pressure; IVC, intake valve closure; PAH, polycyclic aromatic hydrocarbon; PID, proportional integral derivative; RNG, re-normalization group; SOI, start of injection; TDC, top dead center

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lighter fuels have a low cetane index, which allows for early cycle injections and higher fuel premixing (dilute mixture), which enables GCI strategies to achieve high efficiencies with low NOx and soot emissions. However, operation under high-load conditions (~20 bar indicated mean effective pressure (IMEP)) becomes challenging, as the chemistry timescales drastically reduce due to the high in-cylinder pressures under such operating conditions. The reduced chemistry timescales make it difficult to control the peak pressure rise rate [11,12], thereby constraining the load that can be added through the premixed fuel.

A recent study by Kavuri et al. [13] has shown that GCI operation under high-load (~20 bar IMEP) conditions is feasible, but it requires high levels (~55%) of exhaust gas recirculation (EGR) near a stoichiometric global equivalence ratio to control the peak pressure rise rate (PPRR). This made the strategy highly unstable for fluctuations in intake pressure and EGR. Furthermore, the high EGR requirement places a heavy burden on the air handling equipment, which makes the strategy highly impractical.

Paz et al. [14] investigated high-temperature GCI operation at reduced EGR rates (< 30%) with a strategy of mixing-controlled conventional diesel combustion but with gasoline fuel. Due to the high fuel stratification resulting from the mixing-controlled injection, the peak pressure rise rate was well controlled despite operating at a reduced EGR rate. However, combustion at locally rich equivalence ratio's and high temperatures resulted in the classical tradeoff between soot and NOx emissions. They compared conventional diesel combustion and GCI strategies under high-load conditions and found that operating with a relaxed NOx constraint at NOx emission levels suitable for production applications (~10 g/kg-fuel) yields significantly lower soot emissions (~1 filter smoke number (FSN)) at a higher efficiency (~42%) relative to conventional diesel combustion (~3 FSN, 40%) operation for similar levels of NOx emissions (~10 g/kg-fuel). However, even with gasoline fuel, soot emissions were ~1 FSN, which remains higher than acceptable levels for no soot after-treatment.

Past research [15–17] in mixing-controlled strategies has shown post-injections to be a viable mechanism to reduce soot emissions. There are several explanations in the literature on how post-injections reduce soot emissions. Several authors [18–20] have explained that the soot reduction is due to enhanced mixing where the post-injection mixing with oxygen brings fresh oxygen to the soot from the main injection, causing the overall soot oxidation to improve. Other authors [21–23] have found that the increased temperatures from the combustion of post-injections enhance the oxidation of soot formed from the main injection. Some authors [24–26] have found that the dwell time between the main and post-injections affects how effective the post-injections are in reducing soot. Closely coupled post-injections with minimal dwell time between the main and post-injections were found to be the most effective at reducing soot. A combination of the enhanced mixing and increased combustion temperature due to the post-injection was found to be the reason for soot reduction from closely coupled post-injections.

To better understand the effects of post-injections, O'Connor and Musculus [27] performed an experimental study where the load was increased by increasing the duration of the post-injection while keeping the duration of the main injection and the start of injection (SOI) timing of the main and post-injections constant. The fuel mass in the main injection was fixed to achieve a load of 4 bar IMEP, and the post-injection duration was varied to achieve a load range of 4–8 bar IMEP. The results from this study were compared with the baseline case, which had no post-injection, where a similar load range was achieved by varying the duration of the main injection. They found that, for a small increase in post-injection duration, a significant soot reduction (~30%) is seen compared to the baseline injection strategy at a similar load. However, as the load that was added with the post-injection increased beyond a cut-off value, the soot levels of the post-injection strategy approached the baseline soot levels. This indicates that the benefits of the post-injection disappear as the load that is added through the post-injection increases. However, in this study, there was no premixed fuel, and the study was done at a fixed SOI timing of the post-injection.

In another study where a majority of the fuel (~75%) was premixed, Kavuri et al. [28] found that load can be increased using post-injections without causing a soot penalty if the SOI timing of the post-injection is sufficiently late (~20° aTDC) in the expansion stroke. In this study, performed at a mid-load condition of 13 bar IMEP, a premixed charge of gasoline (early cycle injection) was used to achieve a premixed compression ignition combustion event and a mixing-controlled injection of gasoline was added near top dead center (TDC) to act as a load extension injection. They investigated the effects of the load extension injection SOI timing, EGR, and injection pressure on soot emissions using a combination of experiments and computation fluid dynamics (CFD) modeling. The results showed a strong effect of oxygen concentration for injection timings near TDC. However, as the load extension injection timing was delayed beyond 20° aTDC, the CFD model, which was well validated with experiments, showed that soot formation becomes independent of oxygen concentration and becomes solely dependent on temperature. Hence, despite having locally rich mixtures during combustion, the late post-injections do not form soot because the combustion temperatures are not high enough to facilitate soot formation.

Despite the variety of studies done investigating the use of post-injections to reduce soot emissions, most of these studies were done at low- to mid-load conditions. The current study adds to this research by investigating the use of post-injections to reduce soot emissions under high-load conditions in the range of 16–20 bar IMEP. A combination of experiments and CFD modeling will be used to isolate and understand the role of premixed, main, and post-injections on soot emissions. The effect of SOI timing and injection duration of the post-injection on soot emissions will also be investigated.

2. Methods

2.1. Experimental setup

The engine used is a single cylinder version of a Cat® C-15, 15-L six-cylinder engine. Table 1 shows the engine and injector specifications. The C-15 is typical of a heavy-duty-size class diesel engine with a bore of 137 mm and a stroke of 171 mm, yielding a displacement of 2.5 L per cylinder. For high-pressure, direct-injection of gasoline fuel, a Bosch common rail injector (CRIN II), which has six 250-μm holes with included angles of 130° is used.

Fig. 1 shows the laboratory setup. A compressor and drier located outside the lab supplies dry intake air to the test cell. The proportional integral derivative (PID)-controlled intake air heaters precisely control the temperature of the charge entering the engine. Large (265 L) surge tanks ensure stable intake and exhaust pressure. The PID-controlled valves control the intake and exhaust pressure and EGR rate. Emissions measurements in the intake and exhaust are performed with a Fourier transform infrared (FTIR) spectrometer (Nicolet Model CQ1319-100).

Table 1
Engine and injector specifications.

Engine specifications	
Displacement [L/cylinder]	2.5
Bore x stroke [mm]	137 × 171
Compression ratio [–]	16.4:1
Intake valve closure [° aTDC]	−154°
Exhaust valve opening [° at top dead center]	113°
Gasoline injector – Bosch CRIN II	
Number of holes	6
Hole diameter [mm]	0.250
Included spray angle [°]	130°
Injection pressure [bar]	500–2000