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Effect of after injections on late cycle soot oxidation in a small-bore diesel engine

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ABSTRACT

After injection, for which a short fuel injection follows the main injection, is proved to be effective in reducing soot emissions in diesel engines. The present study aims to better understand this in-cylinder soot reduction mechanism of after injection with a particular emphasis on its efficacy in a small-bore diesel engine in which more significant flame-wall interactions could cause different behaviour compared with extensively studied heavy-duty diesel engines in the literature. With the main injection only case as a baseline, two after-injection cases of close-coupled and long-dwell timings have been investigated in a single-cylinder common-rail optical engine. Various optical/laser-based imaging diagnostics have been performed including line-of-sight integrated chemiluminescence imaging of OH*, planar laser-induced fluorescence of hydroxyl (OH-PLIF), planar laser-induced incandescence of soot (PLII) and transmission electron microscope (TEM) imaging of thermophoretically sampled in-flame soot particles to visualise the spatial and temporal evolution of high temperature reaction and soot as well as particle structure. The results indicate that both after-injection strategies introduce a secondary heat release that leads to additional bulk gas temperature rise and thereby promoting the late-cycle soot oxidation. However, the efficacy is found to be dependent upon the after-injection timing. The OH-PLIF and PLII images show that the close-coupled after-injection induces additional high-temperature reaction and soot formation due to high ambient gas temperature. The new reaction occurs near the jet–wall impingement point, which is well separated from the main combustion zone as the main fuel jet travelled along the bowl wall due to significant jet–wall interactions. Although the main and after-injection soot are decoupled, soot morphology analysis based on TEM images suggests that the close-coupled after-injection does enhance the oxidation of main combustion-generated soot particles through the breakdown of large soot aggregates at elevated temperatures and with increased OH radicals. In comparison, both OH-PLIF and PLII images show no visual evidences of decoupled after-injection combustion for the long-dwell case due to insufficient temperature as the additional reaction occurs later in the expansion stroke. However, the increased OH radicals and breakdown of soot aggregates in the main combustion region are evident in OH-PLIF and TEM images. Overall, the close-coupled after-injection adds more soot but induces a higher degree of oxidation for the main combustion-generated soot particles. By contrast, the promotion of soot oxidation is less significant for the long-dwell after-injection but it produces no extra soot.

1. Introduction

While diesel engines are favoured for fuel economy and high torque delivery, adverse impacts of soot emissions on the environment and human health have proposed strict regulations, which pose significant challenges to engine developers [1–3]. Although after-treatment systems, such as diesel particle filters (DPF), can help limit soot emissions below the regulatory limit, the back-pressure issues and increased costs are unavoidable [4]. Therefore, the in-cylinder reduction of soot is crucial, which has been achieved using high-pressure common-rail fuel delivery systems [5,6] capable of multiple fuel injections [7–9]. One of the widely used multi-injection strategies is after injection, which injects a small amount of fuel after the main injection event for the

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reduction of soot emissions [10–12]. Typically, additional injection right after the main injection is termed after-injection for its expected promotion of late-cycle soot oxidation [13–20] whereas a similar injection executed very late in the expansion stroke or early exhaust stroke is called post injection for its DPF regeneration purposes [21–23]. However, post injection is often used for its broader meaning that includes the role of after injection [10]. In the present study, the small amount of fuel injection immediately following the main injection is consistently called after-injection.

Previous studies reported that the benefits of after-injection are attributed to a mixing mechanism that leads to enhanced oxidation of in-cylinder soot particles [13–16]. Notably, one paper showed that the after-injection fuel jet craves out the main combustion soot to cause reduced equivalence ratio in the region, and correspondingly the higher oxidation rate of main combustion soot during the late-cycle burn-out phase [13]. On the other hand, some studies proposed a thermal mechanism as the increased in-cylinder temperature from the additional heat release promotes the oxidation of soot particles [15,17–20]. While most studies focused on enhanced oxidation leading to a soot reduction, some studies showed that the reduced soot is due to the suppressed soot formation [24–28]. This is primarily caused by decreased injection duration of the main injection—i.e. splitting effects [25]. For the single-main injection, the fuel jet head is replenished by the sustained fuel injection leading to locally fuel-rich mixtures and thus high soot formation [29], which can be suppressed by splitting the single injection into the main and after injection.

In implementing after-injection, the injection timing, more specifically the dwell in between the start of after-injection and the end of main injection, is considered as a key parameter [17,26,27,30–34]. Some studies reported that a short-dwell or close-coupled after-injection strategy is more effective in soot reduction than a long-dwell strategy [14,17,24,27,34]. This was explained by higher ambient gas temperature [24,27,30,33] and injection momentum fed into the main soot [13,15,17,25,26] and thereby increasing after-injection-induced soot oxidation [14,17]. However, others showed that the higher ambient gas temperature [27] and the entrainment of combustion products of the main combustion [24,32,35] lead to increased soot formation in the after-injection fuel jet when the close-coupled strategy was applied. There are reported cases with the increased soot formation rate outperforming the increased soot oxidation rate and as a result, the overall soot emission of the main/after-injection is higher than the single-main case [26,27,30]. In comparison, a long-dwell after-injection strategy could cause soot oxidation with no additional soot production due to lower ambient-gas temperature [26] and the reduced chance for the after-injection jet to the main flame interaction [17,26,27]. Specifically, the main soot is out of the after-injection jet path and thereby avoiding the entrainment of hot combustion products [26,35]. However, as the two combustion events are decoupled, the aforementioned effects on soot oxidation are reduced [24,25] and the primary cause of the decreased soot emissions is the fuel splitting for reduced soot formation [10,27,28].

From the literature, it is clear that the soot reduction mechanism associated with after-injection is not one directional but depends strongly on the timing. Another important consideration is the engine size as the way that the main soot interacts with the after-injection jet will be significantly different to that in large-bore, heavy-duty engines upon which most of the previous investigations were performed [13,36,37]. Recent diesel engine technology changes have caused flame-wall interactions to play a key role in diesel combustion. For example, the injection pressure has been increased considerably, leading to higher jet momentum [38–41]. At the same time, with downsizing trends, particularly in the automotive market, the wall is now closer to the injector. The increased swirl flow in small-bore, high-speed diesel engines further complicates the flame development [36]. All these factors can make a significant impact on the soot reduction mechanism of the after-injection. Therefore, it is necessary to re-evaluate the effect of after-injection on soot reduction in a small-bore engine for automotive applications.

Table 1
Engine specifications and operating conditions.

Displacement	497.5 cm^3
Bore	83 mm
Stroke	92 mm
Compression ratio	15.5 (geometric)
Engine speed	1200 rpm
Swirl ratio	1.4
Wall (coolant) temperature	363 K
Intake air temperature	303 K
Fuel [ref]	Methyl decanoate
Lower heating value	37.7 MJ/kg
Cetane number	47–53 [49]
Injector type	Common-rail (Bosch CP3)
Number of holes	1
Nozzle type	Hydro-grounded, K1.5/0.86
Nozzle diameter	134 µm
Included angle	150°
Rail pressure	100 MPa
Main injected fuel mass per hole	11.5 mg
Main injection signal duration	1.2 ms
Main injection signal timing	11°CA bTDC
After injection signal timing	Close-coupled after injection: 13°CA aTDC Long-dwell after injection: 25°CA aTDC
After injection fuel mass per hole	2.8 mg
After injection signal duration	0.3 ms

The present study fills this gap by investigating the in-cylinder soot reduction mechanism of after-injection and how it is impacted by injection timing variations in a small-bore, single-cylinder optical diesel engine. Planar laser-induced imaging of soot incandescence (PLII) and planar laser-induced fluorescence imaging of OH (PLIF) [37–42] have been performed to analyse the spatial and temporal evolution of soot and high-temperature reaction regions in the presence of after injections. In addition, the thermophoretic sampling of soot particles and analysis using a transmission electron microscope (TEM) [43–47] has been conducted for various in-bowl locations so that the structural change of soot particles due to after injections is visualised during both the main-injection-induced and after-injection-induced combustion. The laser-based images of soot and OH, together with TEM images of soot particles, are used to provide full details of soot growth and oxidation and their variations due to after injections executed at different injection timings.

2. Methodology

2.1. Optical engine setup and operating conditions

The imaging diagnostics and in-bowl soot sampling experiments were performed in a single-cylinder, small-bore optical diesel engine modified from a conventional 2-l, four-cylinder diesel engine. The simplified schematic of the optical engine configuration is shown in Fig. 1. Engine specifications and selected operating conditions are summarised in Table 1. The engine has a displacement volume of 497.5 cm^3 with 83 mm bore and 92 mm stroke. The optical access of the engine is made possible through a piston top quartz window, a cylinder liner quartz window, and a 45° reflection mirror located within the void section of the extended piston. The piston top quartz window provided a field-of-view of 43 mm in diameter of the bottom view of the combustion chamber. For the access of the excitation laser sheet when the piston is at top dead centre, a 35-mm wide portion of the piston bowl was removed resulting in a cut-out section in line with the cylinder liner