

Post Injections for Soot Reduction in Diesel Engines: A Review of Current Understanding

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ABSTRACT

This work is a technical review of past research and a synthesis of current understanding of post injections for soot reduction in diesel engines. A post injection, which is a short injection after a longer main injection, is an in-cylinder tool to reduce engine-out soot to meet pollutant emissions standards while maintaining efficiency, and potentially to reduce or eliminate exhaust aftertreatment. A sprawling literature on post injections documents the effects of post injections on engine-out soot with variations in many engine operational parameters. Explanations of how post injections lead to engine-out soot reduction vary and are sometimes inconsistent or contradictory, in part because supporting fundamental experimental or modeling data are often not available. In this paper, we review the available data describing the efficacy of post-injections and highlight several candidate in-cylinder mechanisms that may control their efficacy. We first discuss three in-cylinder mechanisms that have been frequently proposed to explain how post injections reduce engine-out soot. Thereafter, to provide a foundation for interpretation of past research, we briefly review basic soot formation and oxidation chemistry, and soot/fluid processes in fuel sprays and engine flows. Next, we provide a comprehensive overview of the literature on the efficacy of post-injections for soot reduction as a function of engine operational parameters including injection duration and dwell, exhaust-gas recirculation, load, boost, speed, swirl, and spray targeting. We conclude by identifying major remaining research questions that need to be addressed to help achieve a design-level understanding of the mechanisms of soot reduction by post injections.

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INTRODUCTION

Exhaust soot is a heavily regulated emission for diesel engines [1, 2, 3], and while effective aftertreatment systems have been developed for its mitigation, in-cylinder soot reduction techniques remain attractive alternatives to reduce or eliminate the aftertreatment burden. One commonly used and potentially very effective in-cylinder solution for soot reduction is the use of post injections. A post injection is a shorter injection that follows the main fuel injection. While post injections have been used for a variety of reasons, including management of exhaust aftertreatment [4, 5, 6] and reduction of unburned hydrocarbons at low temperature combustion conditions [7, 8], here, we focus on post injections for the engine-out soot reduction. This work is a technical review of past research and a synthesis of current understanding on post injections for soot reduction in diesel engines.

The literature on post injections for soot reduction begins in force in the early 1990's, coinciding with the development and implementation of injection systems capable of multiple

injections per cycle. Early pump-line-nozzle fuel-injection system designs were incapable of multiple injections [9]. For those designs, pressure dynamics in the relatively long lines, including the pressure-wave transit time (lag) and reflections, would have made multiple injections difficult to control even if they were made possible by pump design. Later unit injector designs, whether hydraulically or mechanically actuated, shortened the length of the high-pressure fuel delivery to the nozzle, thereby allowing more precise control of injection rate. With electronic controls, both the timing and duration of injection could be controlled independently, paving the way for multiple injections. Likewise, electronically controlled common-rail systems can also deliver multiple injections. Multiple injection actuation for early electronically controlled unit and common rail injectors was relatively slow, with rise/fall times (time between beginning/end of injection to the steady-state level) of 300-500 microseconds (e.g., [10, 11]), which limited how closely the injections could be placed. Modern common-rail injection systems can achieve rise/fall times around 100

microseconds, and similar dwell between injections (e.g., [12, 13]).

These modern technologies have allowed for more complicated, multiple-injection schedules to be implemented for a variety of purposes, including soot reduction with post injections. Most of the studies discussed in this review used standard common-rail injectors, although other injector technologies can certainly be used with multiple-injection schedules. Further advances in injector technology, such as direct-acting piezoelectric-driven injectors [12] and injection pressure control [14], could potentially lead to better post-injection performance for soot reduction.

There is a large literature on post injections for engine-out soot reduction for both light-duty and heavy-duty engines over a wide range of engine operating conditions. Experimental studies have measured the changes in post-injection efficacy with changes in injection schedule, exhaust-gas recirculation (EGR), load, boost, speed, swirl, and spray targeting, among others. These measurements include both engine-out soot and in-cylinder soot using optical/laser diagnostics. Complementary computer modeling predictions also provide insight into potential in-cylinder processes affecting post-injection performance.

Despite the large number of studies that have investigated how post injections can reduce soot emissions, there is little consensus within the literature about how, or even how well, post injections work. To help frame a detailed discussion on how various engine operational parameters affect engine-out soot reduction by post-injections, we first review three explanations for soot reduction with post injections that have been offered in the literature.

Enhanced mixing

Several studies have presented the explanation that post injections reduce engine-out soot by enhancing mixing within the cylinder [15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29]. Ultimate soot yield depends on a balance between formation and oxidation (discussed in more detail in the following section), and enhanced mixing could conceivably affect formation and/or oxidation. Many authors have hypothesized that enhanced mixing increases oxidation of soot from the main injection [15, 16, 19, 25, 28]. In these explanations, enhanced mixing by the post injection brings fresh oxygen to the soot from the main injection, enhancing oxidation of this soot while simultaneously burning the post-injection fuel.

It is difficult to isolate mixing from other effects of post injections, but one unique study from Konno *et al.* [30] attempts to do so by using an unconventional post injection. In their experiment, a “combustion chamber for disturbance” (CCD), a small auxiliary combustion chamber located above the firedeck and connected to the main combustion chamber via a small, straight nozzle, provided an additional injection of combustion products into the cylinder. The CCD is akin to a prechamber of older indirect-injection diesel engines,

though in this case the main fuel was still delivered by direct injection. The purpose of the CCD was to provide a high-velocity post-jet of combustion products after the main injection. Their results showed that over a large range of CCD injection dwells (varied by changes in injection time), engine speeds (800-1200 RPM), excess air ratios (between 1 and 4), and CCD jet diameters, the CCD injection reduced engine-out soot. Soot reduction was greatest at the highest CCD jet momentums, from which Konno *et al.* concluded that the increased mixing and/or turbulence introduced by the jet enhanced soot oxidation. This was also supported by the accelerated combustion observed in the apparent heat release rate (AHRR) with the use of the CCD jet. Konno *et al.* indicated that the combustion products of the CCD jet likely played a smaller role in combustion chemistry than in a conventional post injection, but the enhanced mixing and/or turbulence that resulted from the use of a CCD jet certainly affected the combustion process and oxidation of soot. Even so, a definitive conclusion about post-injection mixing effects on oxidation has not been established.

Whereas many studies have pointed to mixing as a way to enhance oxidation, the computer model predictions of Yun *et al.* [22] predicted that increased mixing can suppress soot formation from the main injection if the post jet interacts with the burning fuel from the main injection. Three-dimensional Reynolds-averaged Navier-Stokes (RANS) computational fluid dynamics (CFD) simulations using KIVA, examples of which are shown in Figure 1, predicted that the post injection redistributes the fuel from the main injection, creating a more well-mixed fuel/air distribution with smaller and less fuel-rich soot-forming zones. In these tests, the main-injection duration was shortened when a post injection was added to maintain constant load.

The predicted increase in mixing from the post injection is evident in Figure 1, which shows contours of equivalence ratio for a single injection (left) compared to main-plus-post injection (right). In the single-injection case, a large region of high equivalence ratio (maximum near 3.5) resided in the bowl, whereas the maximum equivalence ratio in the main-plus post-injection case was approximately 2.7, and the fuel was more evenly distributed in both the bowl and the squish regions. Additionally, this work showed that this fuel redistribution mechanism could be particularly important at high rates of exhaust gas recirculation (EGR) where oxygen is limited and mixing is crucial to soot reduction. While these modeling results pointed to a post-injection mixing effect on soot formation for this engine and operating condition, experimental data that isolates the post-injection mixing effect on formation is limited and not yet conclusive.

Light-duty, 0.48 liter/cyl
1500 RPM, 3 bar IMEP
50% EGR, 65°C, 134 kPa intake
n-heptane, common rail, 1350 bar P_{rail}

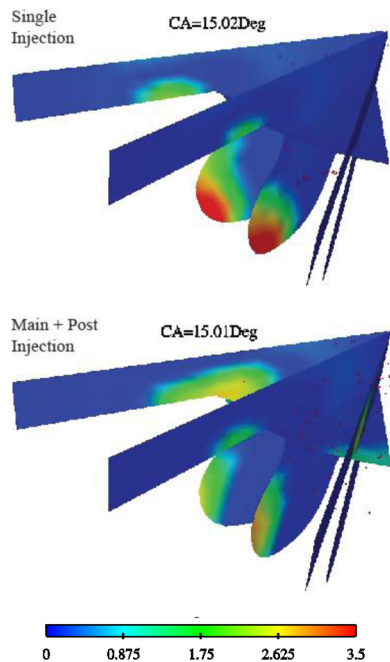


Figure 1. Predicted contours of equivalence ratio for a single main injection (top) and for a main plus post injection (bottom) from KIVA simulations. [22].

Increased temperature

Other studies have argued that as the post-injection fuel burns, the increased temperature from the additional heat release can enhance the oxidation of soot from the main injection, thereby reducing engine-out soot [15, 27, 31, 32, 33, 34, 35, 36]. This is a difficult explanation to support experimentally, as accurate measurements of in-cylinder temperatures in diesel combustion are challenging, even in optically accessible engines. Two-color soot pyrometry [37] can provide some information about soot temperature, though the uncertainties are considerable. One example is the work by Bobba *et al.* [15], which measured soot temperature in the squish region where much of the post-injection fuel burned after a relatively long dwell time between the end of the main injection and the start of the post injection. An example of these results is in Figure 2.

Higher soot temperatures were measured in the squish region when the post injection was present, as evidenced by the peaks in temperature during the burn of the post injection in Figure 2. The engine-out soot decreased with the post injection at these conditions, suggesting that temperature may play a role. Similar effects of increased temperature in the squish region were predicted in a computational effort by Hotta *et al.* [19]. While engine-out soot reduction by post-

injections can be correlated to increased in-cylinder temperature, these studies also acknowledged the importance of mixing and/or targeting of the post jet.

Heavy-duty, 2.34 liter/cyl
1200 RPM, 9-10 bar IMEP
12.7% O_2 , 116.5°C, 276 kPa intake
Certification #2 Diesel, common rail, 1600 bar P_{rail}

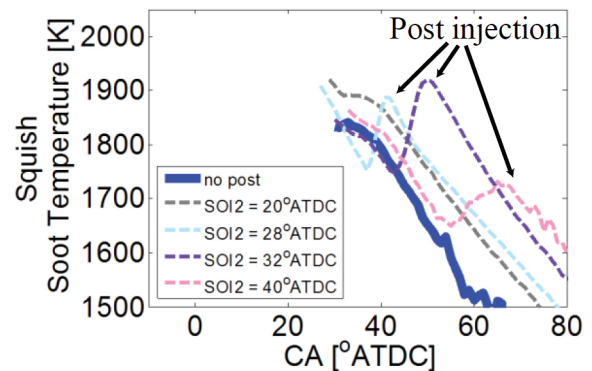


Figure 2. Soot temperature in the squish region showing a rise in temperature during the burn of the post injection. Copyright © SAE International. Reprinted with permission [15].

Injection duration effects

Finally, a smaller number of studies have noted that soot formation is related to the duration of each injection [28, 38, 39, 40, 41, 42]. Researchers have attributed the engine-out soot reduction to a lack of soot formation in the post injection and/or a non-linear decrease in soot formation with injected fuel mass in the shortened main injection. This mechanism is most often referenced in studies with close-coupled post-injection schedules, where the dwell between the end of the main injection and the beginning of the post injection is very short. An example is work by Desantes and coworkers [39, 40], in which they discussed a “split-flame” concept, pictured in Figure 3. In this concept, it was posited that the fuel from the main injection and the post injection burned separately without any interaction, and the reduction in exhaust soot stemmed from splitting the fuel delivery into multiple injections.

Another common concept related to injection duration effects, proposed by Han *et al.* [38], is the concept of “jet replenishment.” Based on computer model simulations, these authors concluded that soot formation is dependent on injection duration, not just total quantity of fuel delivered to the engine per cycle. This was because as the injection duration increases, the model predicted that the head of the jet, a fuel-rich region where much of the soot is produced [43], was replenished by fresh fuel along the centerline of the jet for as long as the injection was sustained. The longer the injection, the more fuel was delivered to this head region.

creating a larger fuel-rich mixture that supported more soot formation.

Light-duty, 0.47 liter/cyl
2000 RPM, 4 bar IMEP
0% EGR, 150 kPa intake
Diesel, common rail, 610 bar P_{rail}

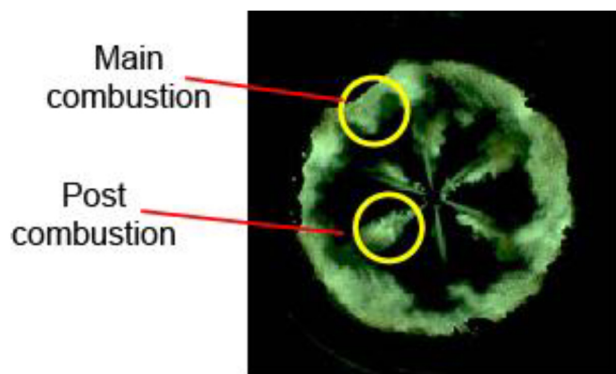


Figure 3. “Split flame” visualization showing separate combustion events from the main combustion and the post injection. Copyright © SAE International. Reprinted with permission [40].

This mechanism also agrees with the idea that splitting a given amount of fuel into shorter injections reduces the overall soot formed as a result of the change in mixture formation due to jet replenishment. While injection duration can be correlated to in-cylinder and/or exhaust soot, the importance of this effect relative to other potential mixing and thermal effects has not been established.

Despite the large number of studies on post injections, little consensus exists as to how the three mechanisms above, and perhaps others, act to reduce soot in diesel engines. Before even considering the question of the mechanism(s) of soot reduction by post injections, the degree to which post-injections reduce or even increase soot varies by nearly an order of magnitude in each direction in results presented in the literature. The inconsistency in engine-out soot results is evident in [Figure 4](#), which shows a compilation of data from ten post-injection studies. Here, the ratio of engine-out soot with a post injection to that without a post injection is plotted against the start of post injection. Note that [Figure 4](#) is not from a single controlled study, but rather a compilation of data; operating conditions such as main injection scheduling/duration, post-injection duration, load, speed, and EGR are not held constant across these studies.

The somewhat even distribution of data above and below unity in [Figure 4](#) indicates that post-injection efficacy is not universal, but rather highly sensitive to the engine and/or operating condition. This dependence will be discussed at length, using the studies shown in [Figure 4](#) among many others, in the third section of this paper.

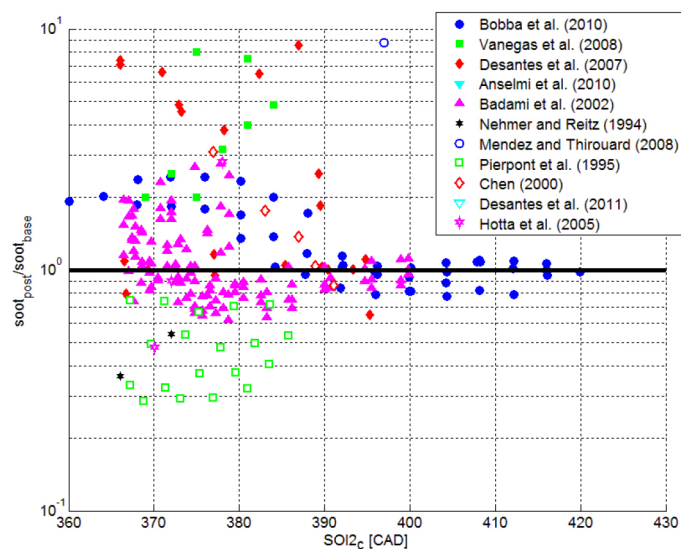


Figure 4. Ratio of engine-out soot with a post-injection to that without a post injection versus timing of the post injection for ten studies in the literature [10, 15, 16, 17, 19, 20, 25, 32, 40, 44, 45].

Though each of the soot-reduction mechanisms described above is certainly plausible, insufficient evidence exists to quantify the relative importance among the mechanisms for different operating conditions. As such, this manuscript aims to provide an overview of the state of post-injection research and clearly define what we as a community do and do not know about post injections for soot reduction.

The paper is organized as follows. This introductory section concludes with an overview of some important terminology that will be used in the discussion of post injections for soot reduction. Next, we provide an overview of soot formation and oxidation processes in diesel engines. This begins with an overview of soot chemistry that is pertinent to diesel combustion situations. We use this foundation to build an understanding of soot formation in diesel jets, based on significant research in both computational studies and experimental work in spray facilities and in optical diesel engines. We close the soot formation/oxidation overview by discussing the role of engine flow fields on soot formation and oxidation, and how post injections may interact with these flow features to reduce engine-out soot. The third section presents a review of the effects of various engine operating parameters (injection scheduling, EGR, load, boost, speed, swirl, and spray targeting) on post-injection soot-reduction efficacy as reported in the post-injection literature. Finally, we pose several remaining research questions that remain unanswered.

Terminology

Before we delve into a discussion of the technical aspects of post injections, it is helpful to define terminology that will be used throughout this paper. Though not an exhaustive list, the following definitions explain terms that are found

throughout the literature, yet may not be precisely defined among studies.

Post injection

A particular multiple-injection schedule where a quantity of fuel is allocated into separate portions such that the second injection duration is much shorter than the first, or main, duration. The specific cutoff for which the second injection is small enough relative to the main injection to constitute a post injection rather than a generic split injection is not well defined, but a maximum of approximately 20% of the total fuel in the post injection is consistent with most existing self-described post-injection studies.

Split injection

A general multiple-injection schedule where a quantity of fuel is split into separate portions. The individual split injections are often described by the percentage of the total fuel that each contains. Studies often explore effects of split injections through parameter sweeps with the allocation of fuel shifted between two injections, such as from 10% in the first injection and 90% in the second injection, to 90% in the first and 10% in the second injection. Hence, split-injections are broad category of multiple injections, of which post-injections are a subset.

Close-coupled

An injection scheme where the dwell between the end of one injection and the beginning of the next injection is short, such that combustion phasing for the second injection is still favorable for thermodynamic efficiency. Some studies have shown considerable engine-out soot reduction for post injections that are late in the expansion stroke, but the combustion phasing degrades the thermodynamic efficiency. Such late-injection schemes would not be characterized as close-coupled. The threshold for characterizing a post-injection schedule as close-coupled is not well defined, but dwells of at most a few crank angle degrees are typical.

An alternate definition for “close-coupled,” found in certain literature and common in industry, implies that all post injections intended for in-cylinder soot reductions are considered “close-coupled.” According to this alternative definition, post-injections that are used for exhaust aftertreatment management are not close-coupled. This aftertreatment-based definition is very different than the efficiency-based definition of close-coupled used here.

SOI_C, DOI_C

Commanded injection-schedule start of injection (SOIC) and duration of injection (DOIC). These descriptions differentiate the commanded injection schedule, i.e., the pulses sent to the drive electronics, from the actual injection schedule, i.e., when fuel is actually emerging from the injector nozzles. Injector dynamics, rail dynamics, and other system issues can lead to significant differences between the

commanded injection schedule and the actual injection schedule.

OVERVIEW OF SOOT PROCESSES IN DIESEL ENGINES

Soot Formation and Oxidation Chemistry

As briefly reviewed above, the post-injection literature proposes three overall mechanisms by which engine-out soot might be reduced by the addition of a carefully selected post injection: enhanced mixing, increased temperature, and injection duration effects. The action of all three mechanisms ultimately involves soot formation and oxidation rates, and depends on in-cylinder fluid-mechanical and chemical kinetic processes. The literature on soot formation and oxidation chemistry is vast and still evolving, and it is beyond the scope of this work to include all of the fundamental details. Instead, in this section, we provide an engineering-level overview of a few important aspects of in-cylinder soot formation and oxidation chemistry. In the sections to follow, the soot formation and oxidation processes will be applied to more practical aspects of in-cylinder processes, with discussion of many example studies from the post-injection literature from which some insight into post-injection effects on soot formation and oxidation may be gained.

The evolution of the in-cylinder soot yield results from a battle between the chemical processes of formation and oxidation. The relative rates of these two processes, each of which is comprised of several complicated steps, are highly sensitive to ambient conditions, particularly temperature and equivalence ratio. These conditions are non-uniform and constantly changing during the highly unsteady event of diesel combustion. The discussion here provides a brief overview of some of the key aspects of basic soot chemistry, followed by a brief discussion of how soot chemistry can be applied to diesel combustion. For a more detailed discussion of soot formation and oxidation, the effects of engine operating conditions, and the process of soot formation and oxidation in diesel engines, see for instance the review by Tree and Svensson [46].

Soot formation can be considered, in general, as a five-step process that starts with fuel and ends with fully formed soot agglomerates [47, 48, 49, 50, 51]. The five general steps are summarized in Figure 5 [46]. The first step, pyrolysis and/or fuel decomposition, involves the splitting of fuel molecules into smaller molecules such as acetylene and resonantly stabilized radicals (e.g., propargyl). These smaller molecules serve as building blocks for soot precursors [49, 52], which include polycyclic aromatic hydrocarbons (PAH). Nucleation, the transition of gas-phase precursors to particles, creates the starting point for subsequent soot particle growth. Nucleation occurs at flame temperatures above 1300 K [53].

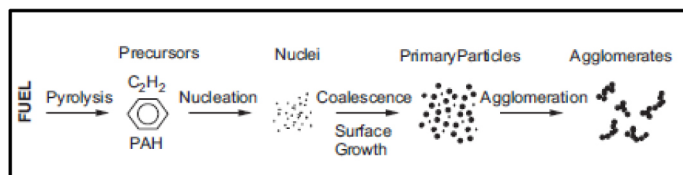


Figure 5. Process of soot formation in flames [46].

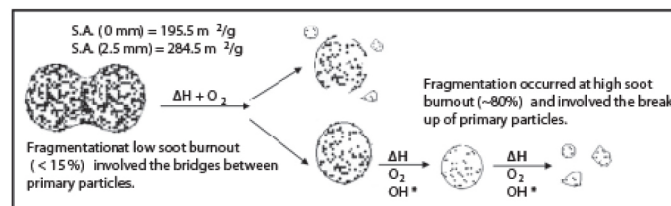


Figure 6. Soot oxidation pathways through fragmentation and subsequent surface oxidation [57], with high soot-burnout pathway on the bottom and low soot-burnout pathway on the top.

After the nucleation site has been created in a relatively high-temperature zone, the soot particle mass increases through surface growth, coalescence, and agglomeration, all of which may happen simultaneously. These later processes may proceed at lower temperatures than the initial precursor synthesis and nucleation steps, and indeed, they often happen away from high-temperature zones. The progress rates of the soot formation processes, from fuel decomposition and precursor synthesis to nucleation, coalescence, and agglomeration, increase with the concentration of the reactants involved, such that other factors being equal, more fuel-rich mixtures generally form soot more quickly.

At any time during this process, soot formation can be stymied by the presence of oxidizing species, typically O, O₂, and especially OH. Several investigations of soot oxidation chemistry have been undertaken at atmospheric conditions with a variety of fuels, from methane to heavier hydrocarbons such as ethylene, m-xylene, and n-dodecane [54, 55, 56, 57, 58]. These investigations outline two pathways of soot oxidation. In fuel-lean mixtures, O₂ and OH pathways of soot oxidation are important. OH molecules are highly reactive at the surface of soot particles [54, 56]. These surface reactions form CO, a molecule that does not participate in any further soot-formation reactions [46]. Simultaneously, O₂ molecules, more plentiful at fuel-lean conditions, are not as reactive at the surface, and instead penetrate into the internal soot structure, causing internal burning and subsequent fracturing of the soot molecules [56, 57, 58]. Simultaneous measurements of soot particle diameter and number density confirm that prior to bulk burnout of soot, the number density increases significantly due to the fracturing of large molecules. Late in the soot burnout process, soot molecules of all sizes are oxidized through OH surface pathways [58]. A schematic of this process is shown in the bottom portion of Figure 6, taken from Ref. [57].

At fuel-rich conditions, results vary regarding the impact of the soot-fracturing by the O₂ pathway [57, 58]. Experiments performed with ethylene fuel did not observe the soot fracturing pathway, but instead saw the dominance of the OH oxidation pathway at all particle sizes through the flame [58]. In the same experiment, however, soot produced with heavier hydrocarbon fuels such as m-xylene and n-dodecane, did undergo a fracturing process in addition to the OH burnout [57]. The reasons for these differences are unclear.

Additionally, the extent to which soot burns, termed the “soot burnout” [57], determined the sites of the fracturing in these studies. In low-burnout conditions (less than 15% soot oxidation), fracturing occurred predominantly at the “bridges” connecting primary soot particles, as shown in the upper oxidation path in Figure 6. For high soot-burnout (greater than 15% of soot oxidation), there was further fracturing of primary particles by O₂ molecules as well as OH oxidation at the surface, shown in the bottom path in Figure 6.

Many empirical soot models, especially those applied to diesel combustion modeling, do not account for these detailed nuances of soot oxidation chemistry. As described in the review of soot models by Kennedy [59], commonly used soot models use non-physical shortcuts for estimating soot oxidation rates. These include calculating soot oxidation rate as a function of the concentration of only O₂, and modulating soot oxidation rate to scale with soot formation rate. As described above, these empiricisms do not account for the multiple pathways for soot oxidation and the different roles of O₂ and OH. Several more detailed mechanisms, however, account for oxidation by both O₂ and OH at different types of carbon sites [60, 61, 62].

This more detailed understanding of soot formation and oxidation chemistry may help to improve the understanding of post-injection processes in diesel engines.

Chemical-Kinetic Modeling of Diesel Soot Formation/Oxidation

The dependence of soot formation and oxidation processes on both mixedness and temperature can be illustrated through chemical kinetic simulations of many of the processes described above. Figure 7 shows the predictions of one such simulation [63], with soot yield as a function of mixture equivalence ratio and temperature. The closed reactor simulations used detailed soot formation and oxidation kinetics at each combination of equivalence ratio and temperature, at a pressure of 60 bar, typical of TDC conditions in diesel engines. The soot yield is the net formation after a simulation time of 2 milliseconds, which is a relevant timescale for diesel engines. Note that not all conditions are practically accessible in diesel combustion.

i.e., both high temperature and high equivalence ratio (top-right portion) generally do not occur simultaneously.

Figure 7 shows that according to detailed soot formation and oxidation modeling, net soot formation is positive within a peninsula, over a range of temperatures and above an equivalence ratio (ϕ) threshold near $\phi=2$. Moving across the peninsula from left to right, soot formation in fuel-rich mixtures does not begin until the temperature is sufficiently high, and the net soot formation initially increases with increasing temperature. Eventually, increasing temperature reduces soot formation rates while increasing oxidation rates, so that the soot yield peaks and then decreases at higher temperatures [63]. In the equivalence-ratio direction, soot yield increases monotonically moving upward as the mixtures become more fuel rich, owing to the increasing concentration of reactants, as described above.

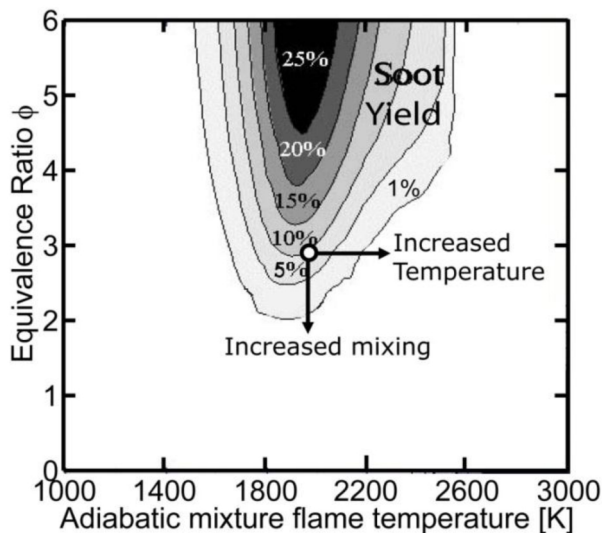


Figure 7. Closed-reactor simulation of soot formation in ϕ -T coordinates. The simulation was constant temperature, for n-heptane at a pressure of 60 bar and a reaction time of 2 ms. Soot contours are soot yield, the percentage of fuel carbon formed into soot. (The final, definitive version of Figure 7 has been published in the *International Journal of Engine Research*, 3(4), August, 2002 by SAGE Publications Ltd., all rights reserved. © [63].)

Soot Formation and Oxidation in Diesel Jets

While the ϕ -T plot of Figure 7 lends insight into soot formation/oxidation tradeoffs under static conditions, conventional diesel combustion occurs in a dynamic in-cylinder environment with considerable spatial and temporal variation of temperatures and mixing states. Hence, the balance between soot formation and oxidation processes also varies considerably throughout the chamber and during the combustion event. Nevertheless, current understanding of the

structure and evolution of diesel spray combustion provides a framework upon which the soot formation and oxidation processes described above may be applied to gain insight into net soot production in diesel jets. The conceptual model of conventional diesel combustion proposed by Dec [43] provides a description of the reacting diesel jet structure and soot formation and oxidation processes. Figure 8 shows an illustration from the model during the “quasi-steady” period of diesel-jet combustion, which occurs between autoignition and the end of fuel injection.

During the quasi-steady period, and in the absence of interactions with in-cylinder surfaces, the characteristic features of the reacting jet remain essentially unchanged, even as the jet continues to penetrate into the combustion chamber during the fuel injection event. As shown in Figure 8, the high-pressure liquid-fuel spray emerges from the injector and entrains hot ambient gases as it penetrates into the combustion chamber. At some downstream location, the entrained gases provide sufficient thermal energy to vaporize all of the fuel. Downstream of this “liquid length,” fuel exists only in the vapor phase.

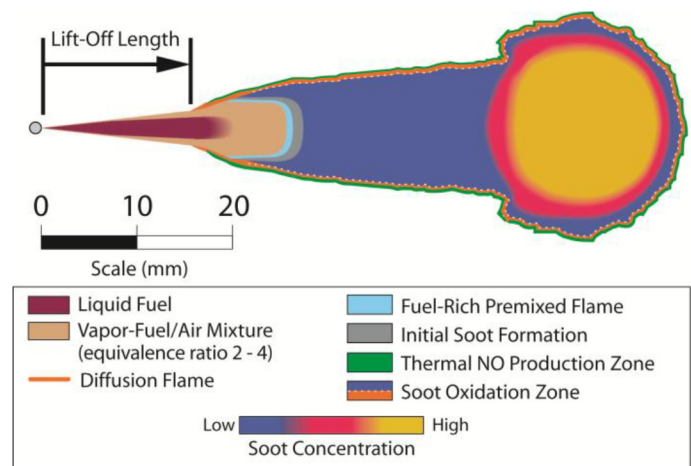


Figure 8. Conceptual model of diesel combustion during the quasi-steady period. Copyright © SAE International. Reprinted with permission [43].

Diesel spray flames are typically lifted, such that significant exothermic reactions occur only downstream of some flame lift-off length (see annotation in Figure 8). Downstream of the lift-off length, the diesel jet is surrounded by a diffusion flame. A fuel-rich, partially-premixed reaction-zone also resides across the interior of the jet near the lift-off length [64], and the downstream jet interior contains the hot products of the premixed reaction zone, as well as entrained products from the diffusion flame. It is within these hot, fuel-rich mixtures in the jet interior that soot formation occurs for diesel jets, as depicted in Figure 8. One of the key species for soot oxidation, OH, exists primarily in the hot diffusion flame surrounding the jet. Hence, in the conceptual model, once