

Applying Advanced CFD Analysis Tools to Study Differences between Start-of-Main and Start-of-Post Injection Flow, Temperature and Chemistry Fields Due to Combustion of Main-Injected Fuel

Randy Hessel, Rolf D. Reitz, and Zongyu Yue
Univ. of Wisconsin

Mark P. B. Musculus
Sandia National Laboratories

Jacqueline O'Connor
Pennsylvania State University

ABSTRACT

This paper is part of a larger body of experimental and computational work devoted to studying the role of close-coupled post injections on soot reduction in a heavy-duty optical engine. It is a continuation of an earlier computational paper. The goals of the current work are to develop new CFD analysis tools and methods and apply them to gain a more in depth understanding of the different in-cylinder environments into which fuel from main- and post-injections are injected and to study how the in-cylinder flow, thermal and chemical fields are transformed between start of injection timings.

The engine represented in this computational study is a single-cylinder, direct-injection, heavy-duty, low-swirl engine with optical components. It is based on the Cummins N14, has a cylindrical shaped piston bowl and an eight-hole injector that are both centered on the cylinder axis. The fuel used was n-heptane and the engine operating condition was light load at 1200 RPM.

The in-cylinder processes investigated are typical and include fuel injection and the subsequent growth of a largely non-combusting fuel-rich vapor jet, pre-mixed burn followed by sharp reductions in fuel and oxygen concentrations, limited air entrainment that coincides with a transition from pre-mixed burn to mixing-controlled burn, and the end of main-injection, after which many in-cylinder processes tend back toward their pre-injection values. What distinguishes the work is the ability to use the newly developed tools and methods so that the aforementioned in-cylinder processes of interest can be linked in a quantifiable and visual way.

CITATION: Hessel, R., Reitz, R., Yue, Z., Musculus, M. et al., "Applying Advanced CFD Analysis Tools to Study Differences between Start-of-Main and Start-of-Post Injection Flow, Temperature and Chemistry Fields Due to Combustion of Main-Injected Fuel," *SAE Int. J. Engines* 8(5):2015, doi:10.4271/2015-24-2436.

INTRODUCTION

One in-cylinder strategy of current interest for reducing engine-out soot emissions from diesel engines while maintaining fuel efficiency is the use of close-coupled post injections. Post injections are small injections of fuel that follow a conventional main fuel-injection, and they are "close coupled" if the dwell between injections is relatively short (typically a few crank angle degrees). Our recent experimental [1] and computational [2] studies of close-coupled post-injections focused on identifying the contributions of both soot formation and soot oxidation to engine-out soot as affected by post-injection duration. Within the introductions of those previous works are detailed background information, including extensive references and motivations for using post-injections. To avoid duplicating that

background information, only a summary relevant to the continuing work is provided here. For more details and background on post-injections, the reader is referred to the previous works [1, 2].

The experimental measurements and computational predictions showed important differences between the effects of short and long post-injections on engine-out soot. For short post injections, i.e., post injections that are less than 500 μ s in duration, soot formed from the post-injection fuel can oxidize quickly, such that it does not add to engine-out soot. In addition, short post-injections can increase the rate of combustion of fuel from the main-injection pulse, thereby reducing the contribution of main-injection fuel to soot formation. Hence, the short post-injections not only do not add to engine-out soot, but they can reduce the engine-out soot by further reducing the contribution to soot from the main injection. By contrast, long post-injections, those

greater than 500 μs , form much more soot than short post-injections, and much of it is not oxidized during the cycle. And, even though long post-injections increase the rate of combustion of main-injection fuel, this effect does not sufficiently offset the increased soot produced by the long post-injection. These two factors led to an increase of engine-out soot with long post-injections.

Since the earlier works the authors have pursued three more areas of research related to post injections. The first is development of an analysis method that more clearly separates soot contributions from the main- and post-injection fuel to the total soot. The visualization and quantification of soot formed and oxidized as distinct quantities proved to be very beneficial in furthering the understanding of the role of post injections on engine-out soot [2]. While helpful, it did not provide a clear way to visualize and quantify the main and post injections as distinct entities. That capability has since been developed as a computational fluid dynamics (CFD) analysis tool, the “species tracking tool.” This analysis tool allows tracking of any species, not just soot, as originating from the main- or from the post-injection pulse. Using the tool, the effect that post-injections have on soot that formed from the main-injection, separate from effects on post-injection soot, have been directly quantified and visualized.

Preliminary findings also show that fuel injected during short post-injection pulses is predicted to burn essentially to completion [3, 4]. Therefore, for those cases, the small amount of unburned fuel that exists at exhaust valve opening (EVO) originates from the main-injection and not from the post-injection. Additionally, the species tracking tool shows that the majority of soot that exists at EVO originates from fuel that was injected during the main-injection, further confirming earlier conclusions of the same [2]. Additionally, when comparing the amount of EVO soot that originates from the main-injection pulse of the short post-injection case, to the total EVO soot from the main-injection-only case, there is a 25% soot reduction. Analysis suggests that the total EVO soot reduction is mostly due to a reduction in soot formation from the main-injection pulse of the short post-injection case as opposed to an increase in soot oxidation.

The second area of research is transitioning the newly developed CFD analysis capabilities to a CFD code with detailed chemical kinetics and a semi-detailed soot model [5]. In a constant-volume chamber simulation, both short and long post-injections decreased main-injection soot, and long post-injections even more than short post-injections. The constant-volume simulations also showed that, if given enough time, long post-injections can reduce total soot at the end of the simulation even more than short post-injections. These findings are opposite to that observed in the engine, which implies that the limited time available for combustion in the engine is important for post-injection performance. In the engine, by EVO, short post-injections can reduce the total soot, but long post-injections have not had sufficient time to do so.

The third area of research is the topic of this paper. The species tracking tool was designed to investigate the details of how the main and post injections interact, with a primary goal of gaining a clearer understanding of how post injections can be designed to maximize soot reduction. In our initial attempts to gain this understanding, it became clear that the in-cylinder conditions created by the main-

injection, and into which the post-injection is introduced, are of critical importance. It is not only the design of the post-injection that is important, but also the residual environment created by the main-injection.

The in-cylinder environment encountered by the post-injection is very different from that of the main or a single injection, which is characteristic of the majority of diesel combustion studies to date. The in-cylinder conditions that the post-injection pulse sees are, in large part, established by the main-injection. To characterize the in-cylinder environment created by the main-injection with the desired level of detail, the analysis tools that were developed earlier in this project were employed but in different domains. Here, the domains are called the vapor-jet and the burning-jet, and they have specific definitions in the context of this paper (see Definitions section). Certainly, vapor-jets and burning-jets are not new concepts. But, in this paper, their clear definition and their usefulness as domains for visualization and quantification provide insights into the transient processes that generate the in-cylinder conditions at the start of the post-injection.

The quasi-steady-state findings from this analysis agree quite well with well-established knowledge in the area of direct-injection combusting jets [6]. An intended value of this work is the ability to visualize and quantify combustion and emissions quantities on the jets in a transient framework so that the way in which the in-cylinder conditions at the start of post-injection are generated can be well understood. This paper also lays the foundation for a follow-up paper that will focus specifically on the post injections so that the differences in the way combustion and emissions evolve as a result of the post-injection can be compared directly with the way the processes evolve as a result of the main-injection.

The general layout of the paper is as follows. The engine and model setup and operating conditions are given, terms relevant to this paper are defined and the in-cylinder environments at start of main-injection, SOI_{main}, and start of post-injection, SOI_{post}, are compared. Events during main injection are then broken up into four phases in crank angle space. A subsection is devoted to describing processes that are predicted to occur in each phase. The paper concludes with a summary.

ENGINE AND OPERATING CONDITION

This section describes the engine that is modeled, along with details sufficient to describe its operation over the crank angle range of interest to this study, i.e., from intake-valve-closure to start-of-post-injection. More details of the experimental test facility are available elsewhere [1].

Engine and Injector

Experiments are conducted on a Cummins N14-based, single cylinder, heavy-duty, low-swirl optical engine. Engine and injector characteristics are listed in [Tables 1](#) and [2](#), respectively. Injection rates were measured using an impingement-based meter [1]. The piston has a centrally located, optically accessible, glow plug in the piston bowl. The injector is also centered on the cylinder axis and has

eight holes evenly spaced azimuthally. Although the engine provides optical access for imaging and laser diagnostics [1], no optical data are included here, so the optical access is not described.

Operating Condition

The operating condition is at 1200 rotations per minute (RPM), 18% intake oxygen by volume and slightly boosted (Table 3). The engine is skip fired, nine motored cycles per fired cycle, to reduce thermal stresses on optical components. As such, real exhaust-gas recirculation (EGR) is not available for dilution. Instead, the intake charge is diluted with excess nitrogen until the intake oxygen is 18% by volume. Engine load of main-injection fueling is 5 bar gross indicated mean-effective pressure (gIMEP).

MODEL SETUP

This section describes the combustion chamber geometry, models used, initial and boundary conditions, and model assumptions.

Model Geometry

The engine has a centrally mounted injector with eight equally spaced holes, which yields an 8-fold rotational symmetry about the cylinder axis. Hence, to achieve higher spatial resolution for a given number of computational cells, the combustion chamber is modeled with a representative 45° sector, and symmetry assumptions are applied to account for the whole combustion chamber. With this simplification, asymmetries due to valve recesses in the head and material differences due to optical window placement are ignored.

The computational domain includes the piston/liner crevice starting at the piston's top surface and extending down to the top ring's top surface. No ring gaps are modeled, so flow does not exit the computational domain via the crevice and no blowby model is used. Crevice depth is adjusted to match motored pressure. The benefit of adjusting crevice depth, as opposed to adjusting squish height to match motored pressure is that the measured top-dead-center (TDC) squish height can be retained, which should provide better estimates of in-bowl flow structures due to squish flows. Since the crevice is far from spray and combustion, altering its dimensions has minimal impact on soot estimates.

Combustion chamber geometry and mesh resolution are summarized in Table 4. The resolution is typical for diesel simulations using CFD solvers like KIVA, although the crevice resolution is relatively coarse. The coarseness does not adversely affect soot results and too much crevice refinement can increase run time substantially.

Sub-Models

Net soot, also referred to simply as soot in this paper, is the difference between the mass of soot formed and oxidized. While a variety of advanced chemistry and soot models are available to model soot formation and oxidation [e.g., 7], the current models are selected to be consistent with other recent CFD modeling done on this project [2].

Some of the more important sub-models used in this study are listed in Table 5 and model details are available elsewhere [8]. The CFD solver is a version of the Los Alamos National Laboratory KIVA3V

code [9], enhanced with sub-models developed at the University of Wisconsin-Madison Engine Research Center [8]. Ignition is modeled with the Shell model [10] and combustion with the Characteristic Time Combustion model [11].

The soot-formation rate is given by the single-equation Hiroyasu model [12]:

$$\frac{dM_{sf}}{dt} = A_f M_{fv} P^{0.5} \exp\left(-\frac{E}{RT}\right) \quad (1)$$

In Eq. 1, M_{fv} is fuel vapor mass (g), P is pressure (bar), and T is temperature (K), all of which are calculated by other KIVA3V-ERC sub-models and supplied to the soot sub-model as formation-equation input values on a per-cell basis. R is the universal gas constant, while A_f (700 bar⁻¹g⁻¹) and E (12500 cal/mole) are user-supplied model parameters that represent the pre-exponential term and soot activation energy respectively [13].

Table 1. Engine characteristics.

Engine base type	Cummins N-14, DI diesel, 4 stroke
Swirl ratio	0.5 (estimated, air rpm/crankshaft rpm)
Bore	139.7 mm
Stroke	152.4 mm
Connecting rod length, mm	304.8 mm
Geometric compression ratio	11.2:1
Bowl width	97.8 mm
Bowl depth	15.5 mm

Table 2. Injector characteristics.

Fuel Injector	Delphi DFI-1.5 (light duty)
Fuel injector type	Common-rail, solenoid actuated
Cup (tip) type	Mini-sac
Number of holes & arrangement	8, equally-spaced
Spray pattern included angle	156°
Nominal orifice diameter	0.13 mm

Table 3. Operating conditions.

Engine Speed	1200 RPM
Engine Load	5 bar gIMEP
Intake O ₂ (volume / mass basis)	18 / 20 %
Fuel Pressure	1200 bar
Nominal TDC Motored Density	16.6 kg/m ³
Nominal TDC Motored Temperature	900 K
Intake Pressure	1.61 bar
Intake Temperature	381 K
Mass of fuel per main injection pulse	70 mg
Start of main injection, CAD	-10.14
Duration of main injection, °CA	16.4

Table 4. Model dimensions and mesh resolution.

Geometry	Dimension, mm	Number of cells along the dimension	mm/cell
Bowl radius	48.88	20	2.4
Bowl depth	15.5	12	1.3
Crevice radial extent	1.67	4	0.42
Crevice depth	34.51	6	5.75
Squish radial extent (bowl lip to crevice)	19.3	12	1.6
Squish height @ TDC	5.6	10	0.56

The soot oxidation rate is predicted by the Nagle-Strickland-Constable model [14] :

$$\frac{dM_{so}}{dt} = \frac{6Mw_c}{\rho_s D_s} M_s f(T, Po_2) \quad (2)$$

In Eq. 2, Mw_c is carbon's molecular weight (12.001 g/mole), M_s is soot mass (g), and ρ_s and D_s are user supplied values for soot density (2 g/cm³) [13] and soot diameter (25 nm) respectively. The cell gas temperature, T , and oxygen partial pressure, Po_2 , are provided by functional relationships [8]. The soot-formation sub-model supplies the soot mass to the oxidation model. Hence, all the dependencies mentioned for the formation model are also dependencies of the oxidation model, as is local oxygen concentration.

Initial and Boundary Conditions

Model in-cylinder initial conditions at intake valve closure (IVC) and surface temperature boundary conditions are listed in Table 6. Surface temperatures were not measured directly and are instead estimates based on measured coolant temperatures. Table 6 also lists average measured intake manifold pressure and temperature for reference. As mentioned in the Operating Conditions section, the engine is skip-fired and dilution is with excess nitrogen.

The simulations start at IVC, at which point in-cylinder pressure, temperature, and species concentrations need to be specified. Here, all are treated as uniformly distributed throughout the computational domain. Hence, the entire domain starts at the same thermodynamic state. By contrast, in a real engine, the thermodynamic state at IVC is not uniform, which can lead to differences in heat transfer between simulations and experiments, even early in the compression stroke. In an attempt to compensate for the net effect of non-uniformities present in the IVC state of the experiments, the simulation pressure is matched to measured pressure at a later position in the compression stroke (−90 CAD) rather than at IVC. Measured and model IVC pressures differ by only 0.01 bar (Table 6).

Swirl is also initialized at IVC in the simulations as solid-body rotation about a swirl axis coincident with the cylinder axis. Here, tangential velocity increases almost linearly with increasing radial distance from the axis, then tails off toward zero at the liner, owing to the no-slip condition. An axial velocity distribution is also assigned at IVC, where bowl and piston nodes receive the IVC piston velocity and velocities above the piston and bowl are linearly interpolated to zero at the firedeck.

DEFINITIONS

Iso-Surface

In 3D computational domains, most variables, like temperature, vary in magnitude throughout the domain. An iso-surface identifies points within the domain where variables have a particular value. For example, an iso-surface of 1000 K will identify all points within the combustion chamber where the temperature is 1000 K. Iso-surfaces often result in a series of connected points that form arbitrary zero-thickness geometrical shapes. The shapes may be connected or disjoint and they typically change shape and location with time.

Table 5. Models used in this study.

CFD solver	KIVA3V-ERC
Ignition	Shell
Combustion	CTC (Characteristic Time Combustion)
Spray breakup	KH-RT (Kelvin-Helmholtz/Rayleigh-Taylor)
Turbulence	RNG k-epsilon
Soot formation	Hiroyasu
Soot oxidation	Nagle-Strickland-Constable

Table 6. Initial conditions at IVC and surface temperatures.

Pressure, bar	1.65 (measured intake/IVC values 1.61 / 1.64)
Temperature, K	378 (measured intake temperature is 381 K)
Swirl ratio	0.5
O ₂ volume/mass fractions	0.18 / 0.20
N ₂ volume/mass fractions	0.82 / 0.80
Liner and head temperature, K	373
Piston temperature, K	398

Iso-Volume

An iso-volume is similar to an iso-surface, except an iso-volume represents a range of values, rather than a single value. For example, an iso-volume can be defined to represent the region of space occupied by gases that range in temperature from 950 to 1050 K. Where iso-surfaces normally have zero-thickness, iso-volumes typically add width to such surfaces. As with iso-surfaces, iso-volumes typically change shape and location with time.

HRR, Heat Release Rate

HRR is calculated as the chemical energy released from all reactions. Specifically, the specific internal energy is summed over all species of each cell at the beginning and end of the subroutine where reactions are solved. The difference is the heat release for that time step. For consistency with experimental measurements, the predicted heat release is accumulated in ¼ crank degree increments and divided by the crank angle increment in order to calculate a rate. Note that it is

important to be consistent when selecting a crank angle increment to use for rate calculations, because using different increments can result in different magnitudes and in slight changes in phasing of peak values. When the distribution of HRR is visualized on cells, its units are J/deg/cm³. Total HRR is the sum of HRR over all cells and is given in units of J/deg.

Burning-Jet

In this paper, the burning-jet is defined as an iso-volume. The range of this iso-volume starts in regions of the computational domain where HRR is the highest. Locations of monotonically decreasing HRR are then added to the iso-volume until 90% of all heat release is included within the iso-volume. Hence, regions where HRR is relatively low are not included in the burning-jet. The choice of stopping the iso-volume at 90% of total heat release instead of 100% is because the 100% level extends the jet periphery far out into where fuel concentrations are very low, such that most of the combustion chamber is encompassed. Though it is a subjective threshold, the 90% level provides a visually meaningful burning-jet boundary.

In constructing the burning-jet, the local magnitude of HRR is determined on a cell-by-cell basis. Each cell has a predicted HRR value in units of J/deg/cm³ and all cells are sorted from highest to lowest HRR according to their value. Multiplying by cell volume then converts cell HRR values to J/deg.

Vapor-Jet

In this paper, the (fuel) vapor-jet is defined as an iso-volume. The range of this iso-volume starts in regions of the computational domain where fuel-vapor concentration is the highest. Locations of monotonically decreasing concentration are then added to the iso-volume until 90% of all fuel vapor is included in the iso-volume. Regions where concentration is relatively low are not included in the vapor-jet. Much like the burning jet, the 90% threshold provides a visually meaningful vapor-jet boundary. The vapor-jet typically overlaps with the burning-jet, as is seen in many of the images contained herein.

PHI

PHI represents the “mixture-fraction” equivalence ratio. In the absence of reaction, the mixture fraction equivalence ratio is identical to the more commonly used fuel-based equivalence ratio. Unlike the conventional fuel-based equivalence ratio, which can change value when chemical reaction occur, the mixture-fraction equivalence ratio is unaffected by reaction. Therefore, the mixture-fraction PHI is not an indicator of the progress of combustion. The mixture-fraction equivalence ratio is calculated as:

$$PHI = \frac{(2 \cdot C + 0.5 \cdot H)}{O} \quad (3)$$

Here, C, H and O are the number of carbon, hydrogen and oxygen atoms from all species local to the calculation, including reactants, products, and intermediates. For example, C₇H₁₆ contributes 7 carbon and 16 hydrogen atoms, CO₂ contributes 1 carbon and 2 oxygen atoms, etc.

In this document, when visualized objects are colored by PHI, the PHI calculation is done on each computational cell that contributes to the visualization. When PHI is reported as a value on an iso-volume, then it is a mass-average value, weighted by the computational cell masses of each cell that makes up the iso-volume.

Soot

For this computational study, soot is groups of carbon atoms that originate from fuel molecules. The only units used to quantify soot in this paper are mass units, mg, when soot is integrated over particular volumetric regions, and soot volume fraction, when viewing soot distributions.

Phase Initiation and Termination

In the following, four phases are defined. Phases are used to divide the main-injection event into crank angle intervals for detailed analysis. During each phase the injected fuel transforms the in-cylinder environment in particular ways that can contribute to soot formation and oxidation. The start of each phase is identified when a slope change is observed in a number of the process curves over a narrow crank angle range. The process whose curve changes slope first is the process said to initiate the phase and its slope change defines the phase initiation time. A phase is defined to terminate when the next phase is initiated. Phases are discussed in greater detail in the Results section.

Phase I

Phase I covers the time from the start of main injection, SOI_{main}, to the start of pre-mixed burn. SOI_{main} initiates Phase I. Phase I is characterized by growth of a largely non-combusting vapor-jet with a rich core. Growth includes penetration in radial and axial directions, and in the accumulation of fuel vapor and O₂ masses within the vapor-jet.

Phase II

Phase II follows Phase I in crank angle space. It is initiated by the pre-mixed burn and terminates when O₂ flowrate toward the vapor-jet reaches a near-steady value. Phase II is characterized by an increasing pre-mixed burn rate, followed by the start of a rapid consumption of fuel vapor and O₂ from the periphery of the vapor-jet. Soot starts to accumulate as the end of Phase II is approached.

Phase III

Phase III follows Phase II in crank angle space. It is initiated when O₂ flowrate toward the vapor-jet reaches a near-steady value and terminates when the injector starts to close. Phase III is characterized

by the transition of many flow and combustion quantities from highly transient to quasi-steady. Soot on the other hand, increases steadily during Phase III.

Phase IV

Phase IV follows Phase III in crank angle space. It is initiated when the injector starts to close. Phase IV is characterized by a slowing HRR, a rapid reduction in fuel vapor mass and a leaning out of the vapor-jet. In cases where there is a post injection, Phase IV terminates at SOIpost. When there is no post injection, Phase IV terminates at exhaust-valve opening.

RESULTS

This section describes processes that are predicted to occur from SOI_{main} to SOI_{post}. Line graphs are used to describe the processes and renderings of CFD results are added to supplement the graphical information.

The Results section layout is as follows. The general format of line graphs used in this section is introduced. Then, quantities calculated over the whole cylinder are discussed. Next, the velocity, temperature and species fields at SOI_{main} and SOI_{post} are compared. The subsection addresses the first major goal of the paper, and that is to draw distinctions between the environments into which the main- and post-injections are injected.

The subsequent subsections use the previously-defined phases to analyze the processes that are predicted to occur from SOI_{main} to SOI_{post}. One subsection is dedicated to each phase. These subsections address the second major goal of the paper, and that is to analyze in detail how the main injection transforms the in-cylinder environment to its state at SOI_{post} and how each phase contributes to the accumulation of soot.

Line Graphs used in this Paper

Line-graph characteristics are provided in this subsection. Some line-graph curves are light colored and have been overlaid on dark background-curves to make them easier to see on white paper. Dashed lines also have dark background-curves so the curves remain contiguous, thus facilitating visualization of each step in a process.

Vertical axis tick labels are color coded with the curves. To keep the graphs more legible, a limited number of tick marks are labeled. Because the tick marks are evenly spaced, values at non-labeled tick marks can be easily determined. In the analysis, there is little mention of the actual magnitudes of the graphed quantities. Instead, what is considered to be more important are the phase relationships between the curves.

There is a second horizontal axis at the top of each graph. It indicates time after start of main injection. The axis is not used as part of the analysis in this paper; it is included only for reference. Phases are also identified at the top of graphs when relevant and phases are accentuated with shaded backgrounds.

In-Cylinder Average Values

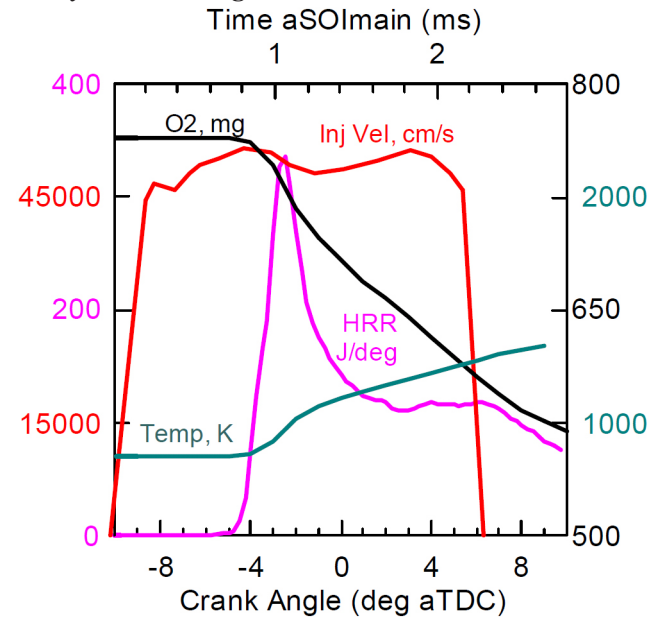


Figure 1. Red: Injection velocity, cm/s; Magenta: 90% of total heat release rate, J/deg; Black: total in-cylinder molecular oxygen, mg; Green: mass average in-cylinder temperature, K.

Main-injection is the impetus for the majority of the processes discussed herein (Figure 1, red curve). It starts at about -10 deg. after TDC (aTDC), increases sharply, levels off, then decreases sharply, ending at about 6 deg. aTDC forming a top-hat-like shape. After a delay period, pre-mixed burn begins (HRR, magenta), the total amount of molecular oxygen in the cylinder decreases (O_2 , black), and the in-cylinder mass-average gas temperature begins to rise (Temp, green).

The pre-mixed burn transitions to a mixing-controlled burn, and reaches a quasi-steady burn rate shortly after TDC (HRR, magenta). More details regarding the pre-mixed to mixing-controlled burn transition are provided later in the Results section. In whole-cylinder terms, and of the quantities plotted in Figure 1, HRR and injection velocity are the only quantities that reach quasi-steady values. In the coming sections, a number of other quantities are predicted to reach quasi-steady values as well.

Note that the heat release rate plotted in Figure 1 (HRR, magenta) is calculated on the burning-jet, rather than throughout the cylinder. This choice was made so that HRR is presented consistently in all of the graphs in this paper. Recall from the burning-jet definition that it contains 90% of all heat released over any given crank angle increment. Therefore, the burning-jet HRR can simply be scaled up to find the total HRR.

When going through the next subsections, where values are mostly calculated on the burning-jet and on the vapor-jet, the reader might find value in referring back to Figure 1 to compare how the perhaps new and perhaps unfamiliar quantities compare with familiar ones given in this subsection.