This is the preprint version of the paper.

This version of the publication may differ from the final published version.

Permanent repository link: https://openaccess.city.ac.uk/id/eprint/24454/

Link to published version: http://dx.doi.org/10.1016/j.fuel.2020.118359

Copyright and reuse: City Research Online aims to make research outputs of City, University of London available to a wider audience. Copyright and Moral Rights remain with the author(s) and/or copyright holders. URLs from City Research Online may be freely distributed and linked to.
Spatio-temporal identification of plume dynamics by 3D computed tomography using Engine Combustion Network (ECN) Spray G injector and various fuels

Joonsik Hwang\textsuperscript{a1}, Lukas Weiss\textsuperscript{b}, Ioannis K. Karathanassis\textsuperscript{c}, Phoevos Koukouvinis\textsuperscript{c}, Lyle M. Pickett\textsuperscript{a*}, Scott A. Skeen\textsuperscript{a2}

\textsuperscript{a}Combustion Research Facility, Sandia National Laboratories, Livermore, CA 94550, United States
\textsuperscript{b}Institute of Engineering Thermodynamics FAU Erlangen-Nuremberg, Erlangen, 91058, Germany
\textsuperscript{c}School of Mathematics, Computer Science and Engineering, City, University of London, UK

Abstract

Understanding of plume direction and mixture quality in a combustion chamber is crucial to improve engine performance. While a variety of diagnostics using laser and x-ray facilities have been applied to identify plume direction, most applications require sophisticated experimental setup as well as troubleshooting for light attenuation or scattering issues. In this study, we acquire temporally and spatially resolved liquid volume fraction by three-dimensional tomographic reconstruction of ensemble-averaged extinction images to produce unique information on plume movement and growth in the midst of a multi-plume spray. Measurements were carried out in a constant-flow spray vessel coupled with high-speed Mie-scattering, diffused back-illumination extinction, and schlieren imaging. Four different fuels, a single component iso-octane, a multi-component surrogate with di-isobutylene, a multi-component fuel with olefinic molecular structure, and a 30\% ethanol (e30) blend were injected using Engine Combustion Network (ECN) Spray G injector under ECN G2 (50 kPa absolute), G3 (100 kPa absolute), and G3HT (G3 with 393K ambient temperature) conditions. Planar slices, available from the tomographically reconstructed extinction data, confirmed greater plume-to-plume interaction for the flash-boiling G2 iso-octane condition with an approximately 6° smaller plume direction angle (during steady state) relative to the injector axis, compared to the nozzle drill angle. The G2 condition has a narrower liquid plume width but a longer axial liquid penetration (despite flash-boiling operation), compared to the G3 condition. The olefinic and e30 fuels, which have broader distillation curves including light distillate fraction, exhibited stronger plume growth and eventual complete spray plume collapse and longer time for evaporation. Using the multi-hole 3D dataset, we show that factors that increase plume
growth (such as flash-boiling) also create more interaction between plumes to ultimately reduce the plume direction angle.

**Keywords**: Engine Combustion Network (ECN); Spray G; Flash boiling; Tomographic reconstruction; Plume direction; Plume-to-plume interaction; Projected liquid volume; Spray cone angle

*Contact information:*

Lyle M. Pickett, Tel.:+925-294-2166, e-mail:LMPicke@sandia.gov

Joonsik Hwang, Tel.:+1-925-294-6633, e-mail:joohwan@sandia.gov

**Abbreviations**

<table>
<thead>
<tr>
<th>AMR</th>
<th>Adaptive mesh refinement</th>
<th>PDI</th>
<th>phase Doppler interferometry</th>
</tr>
</thead>
<tbody>
<tr>
<td>CFD</td>
<td>Computational fluid dynamics</td>
<td>PFI</td>
<td>Port fuel injection</td>
</tr>
<tr>
<td>ECN</td>
<td>Engine Combustion Network</td>
<td>PLV</td>
<td>Projected liquid volume</td>
</tr>
<tr>
<td>EGR</td>
<td>Exhaust gas recirculation</td>
<td>PN</td>
<td>Particulate number</td>
</tr>
<tr>
<td>GDI</td>
<td>Gasoline direct injection</td>
<td>RANS</td>
<td>Reynolds averaged Navier-Stokes</td>
</tr>
<tr>
<td>KH</td>
<td>Kelvin-Helmholtz</td>
<td>RT</td>
<td>Rayleigh-Taylor</td>
</tr>
<tr>
<td>LED</td>
<td>Light emitting diodes</td>
<td>SOI</td>
<td>Start of injection</td>
</tr>
<tr>
<td>LES</td>
<td>Large eddy simulation</td>
<td>SPCCI</td>
<td>Spark controlled compression ignition</td>
</tr>
<tr>
<td>LTGC</td>
<td>Low temperature gasoline combustion</td>
<td>TDC</td>
<td>Top dead center</td>
</tr>
<tr>
<td>ON</td>
<td>Octane number</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Nomenclature**

| \( \alpha_p \) | volume fraction of parcel in a cell [a.u.] | \( P_a \) | Ambient pressure [Pa] |
| \( C_{ext} \) | Extinction coefficient [mm\(^2\)] | \( P_v \) | Vapor pressure [Pa] |
| \( d \) | Droplet diameter [mm] | \( \varphi \) | Equivalence ratio [a.u.] |
| \( F/A \) | Fuel to air ratio [a.u.] | \( Re \) | Reynolds number [a.u.] |
| \( I \) | Image frame with spray [a.u.] | \( \rho_f \) | Fuel density [kg/m\(^3\)] |
| \( I_o \) | Averaged background image [a.u.] | \( \tau \) | Optical thickness [a.u.] |
1. Introduction

Gasoline direct injection (GDI) engines have been adopted by the automotive industry over the past few years. Different from conventional port fuel injection (PFI) engines, fuel is injected directly into the combustion chamber, creating charge cooling and higher turbulence. These improvements mitigate knocking tendency and improve engine efficiency. A combination of direct fuel injection with engine technologies such as high-pressure injection, multiple injection strategies, exhaust gas recirculation (EGR) and enhanced air utilization by swirl or tumble motion enable GDI engines to be operated under fuel-lean conditions with even higher efficiency [1-4]. Furthermore, advanced combustion concepts such as low-temperature gasoline combustion (LTGC) and spark-controlled compression ignition (SPCCI) have been considered as next-generation GDI engine technologies [5-6]. These concepts utilize early fuel injection during the intake stroke to form a homogeneous air-fuel mixture, followed by injection during compression to create a stratified charge near the spark plug and stable flame kernel. For this technology to succeed, spray control during all stages in the cycle is of upmost importance. Inappropriate injection parameters and fuel properties cause fuel impingement on the cylinder wall and result in unacceptable particulate matter (PM) emissions [7]. Thus, understanding the direction and ultimate penetration of each liquid plume of the injector under various ambient conditions and fuels is crucial to improve combustion and emission characteristics.

One of the interesting behaviors in a gasoline spray can be found under flash-boiling conditions. Flash boiling occurs at throttled or early-injection conditions when ambient pressure is lower than the saturation pressure. Rapid changes in temperature and the velocity field are accompanied by a bulk conversion of fuel from liquid to vapor during injection. Common observations under flash-boiling conditions are shorter liquid penetration length, enhanced atomization, lower mixture temperature, and large recirculating vortex closer to the injector tip [8-10]. The ratio of ambient pressure to vapor pressure ($P_a/P_v$) has a dominant impact on spray process under flash-boiling conditions, unlike non-flashing sprays where relationship such as Reynolds number ($Re$) and Weber number ($We$) are typically used to summarize spray characteristics [11-13]. A key feature of flash-boiling operation is that vapor
formation commences when pressure decreases as fuel flows through the nozzle, even without any fuel-air mixing or heat transfer, thereby creating a wider radial dispersion of individual injector plumes. Plume dispersion increases with higher fuel temperature or lower ambient pressure (i.e. lower $P_a/P_v$). The larger plume dispersion enhances plume-to-plume interaction and alters velocity and pressure field, which may lead to deflection of the plume direction or complete combinations of plumes and collapse at certain conditions of injection timings. In the previous study of Zeng et al., it was found that sprays from an eight-hole injector with a nominal total spray angle of 60° had a linear increase in liquid spray width as the pressure ratio decreased from 1.0 to 0.3, and finally spray collapse occurred at pressure ratios under 0.3, showing one integrated large plume [14]. Flow analysis using particle image velocimetry (PIV) showed the vortex around spray plumes strengthening under lower pressure cases due to enhanced momentum transfer by interaction between thicker spray plumes and ambient air [15]. Plumes also move towards each other during time, accelerated by a larger pressure difference between the center of the spray and the ambient air [8], and complete collapse occurs under flare flash-boiling conditions.

Fuel properties affect spray mixing over a range of conditions, including flash-boiling operation. As the use of renewable fuels increases, it is important to understand how varying properties affect fuel delivery in either neat fuels or when blended with refinery stock [16]. Properties considered important for limiting liquid impingement upon in-cylinder surfaces include distillation characteristics, heat of vaporization, vapor pressure, surface tension, viscosity and so forth. Over the past decades, many researchers have investigated the effects of fuel properties on spray characteristics summarized by penetration length, spray width, and spray residual time [17-20]. The majority of these studies rely on two-dimensional measurements utilizing Mie-scattering or extinction imaging for spray characterization. The diagnostic approaches are relatively simple and able to provide information about global characteristics of the spray, however, they cannot describe how individual plume motion and growth is affected by fuel properties. Thus, spray analysis in three-dimensional space is essential for a more complete understanding of fuel property influence on plume direction and interaction. Moreover, there is lack of understanding how vapor pressure or shape of distillation curve affect to plume direction and spray collapse. Therefore, in-depth evaluation on the effects of vapor pressure and distillation curve on plume direction and plume collapse is needed.

Numerous non-intrusive optical diagnostics have been applied to investigate the internal motion of plumes and the mixing process, rather than being limited to line-of-sight information. Among the techniques, laser diagnostics were
widely employed. In one example, the peak velocity magnitude in a spray plane measured by phase-doppler interferometry (PDI) was analyzed to represent plume direction movement throughout injection [21]. Planar laser imaging with corrections for multiple-scattering has been performed, however, light attenuation issues still inhibit quantification [22]. On the other hand, x-ray radiography with tomography algorithm reconstruction has been applied to identify individual plume direction [23-24]. X-rays have high penetrating power and negligible scattering to enable data acquisition even in the near-nozzle region, but measurements have been performed only under low-temperature atmospheric ambient conditions at a few planes. A commercial optical patternator (En’Urga Inc, SETscan AP400) using line-of-sight measurements along a plane has been applied to windowed spray chambers at engine-relevant pressures and temperatures including intake-injection as well as late-injection conditions [25]. By rotating the injector in 22.5° increments for a total of eight views over 180° rotation, sufficient data was collected to enable computed tomography along a plane. The technique showed success in identifying major changes in plume position and growth with variation in chamber conditions, including under flash-boiling conditions. However, the technique was limited to only 1 kHz temporal resolution, which is essentially an average over the entire injection event [25]. Further work is needed to identify the plume direction and growth under engine-like conditions with improved temporal and spatial resolution. The techniques described above have drawbacks in terms of complexity in measurement, high-cost in measuring equipment, laborious measurement procedures, or lower spatial and temporal resolution.

In this study a new three-dimensional tomographic reconstruction method using ensemble averaged extinction images was developed to overcome technical issues that conventional diagnostic approaches have. This new method can be applied in the entire spray domain and injection period with a much simpler setup compared to conventional laser or x-ray facilities. High-speed Mie-scattering, diffused back illumination extinction, and schlieren imaging were performed in a constant flow vessel using the Engine Combustion Network (ECN) Spray G injector. The primary objective of this work is to understand plume direction and spatial mixing quality based on tomographically reconstructed spray in three-dimensional space. Four different fuels including single component fuel iso-octane, the multi-component fuel di-isobutylene, olefinic, and e30 blend were applied under flash-boiling and early injection ambient conditions. The tested fuels are considered as promising alternative fuels for conventional gasoline because of high research octane number (RON, 98) and production from renewable sources. Furthermore, large differences in vapor pressure and distillation characteristic between fuels also provide opportunity to investigate their effects on
plume direction and collapse process. Augmenting interpretation of the new experimental data, in this study computational fluid dynamics (CFD) simulations using CONVERGE code were also performed to estimate mixture equivalence ratio effects on vaporization, as these data have not yet been acquired in the experiment.

2. Test method and condition

2.1. Injector and fuels

An ECN-designated Spray G injector (primary injector serial number: AV67-028) was utilized for fuel injection. The Spray G injector is a solenoid driven gasoline direct injector that has nominally axisymmetric eight-holes. The detailed dimensions and specifications are presented in Fig. 1 [26]. The nozzles were designed to have a counterbore shape, which has an inner orifice diameter of 165µm and a step diameter of 388µm. The nozzles were drilled with an angle of 37° from the center axis of the nozzle tip. A standard ECN Spray G electronic injector driver was used to hold an injection profile consistent with previous studies. The electronic command was generated by an external data acquisition system and the signal was delivered to the injector driver.

Four different test fuels, single component iso-octane, multi-component surrogate di-isobutylene, multi-component fuel with olefin molecular structure, and e30 blend fuel were tested and their properties are shown in Table 1. Among the fuels, e30 blend has the highest density, viscosity, and heat of vaporization amongst test fuels. The e30 blend has the lowest energy content due to oxygenated species (30% ethanol). The vapor pressures of olefinic and e30 blends at 90°C are approximately 2.5 and 4 times larger than iso-octane, respectively. The effect of compositional difference between fuels is illustrated in distillation and vapor pressure curves presented in Fig. 2 [27]. Ambient pressure of test conditions are also presented in Fig. 2. The distillation curve of iso-octane is shown as a straight line at the boiling point. A pseudo distillation curve for the di-isobutylene blend is provided, based on the boiling point temperatures of five different species: 1-hexene (4% v/v), n-heptane (12.1% v/v), iso-octane (44.2% v/v), toluene (20.1% v/v), and di-isobutylene (19.6% v/v). The curve remains relatively flat because these species have a relatively narrow range of boiling point temperatures. It is noted that even though the di-isobutylene blend contains species heavier than iso-octane, the vapor pressure is higher because of the existence of light species (1-hexene). On the other hand, olefinic and e30 blends have light and heavy components contributing to a wide range of distillation temperature from 50°C to 200°C. The large amount of light species in olefinic and e30 blends creates higher vapor pressure, and this trend is maintained throughout the temperature range.
2.2. Vessel system and optical setup

Spray test were conducted in a spray vessel at constant pressure and gas flow rate at controlled temperature. The constant-flow spray vessel system has many advantages compared to optical engines or closed (constant-volume) spray chambers: 1) Thermodynamic parameters can be controlled independently in the vessel system. Analysis of spray process at known boundary conditions promotes understanding the effects of each thermodynamic parameter on spray characteristics. 2) The flow-vessel system has a much higher repetition rate than a closed chamber, which must be vented and prepared to a target condition before each injection. 3) The vessel system has much larger optical access than in an optical engine, where the viewing area is limited to a portion of the piston or cylinder liner. This feature facilitates simultaneous imaging for different views and multiple diagnostics. 4) There is less liquid impingement upon surfaces in the spray vessel than in optical engines. With limited space, the spray in optical engines can create wetting on the cylinder wall or piston depending on the ambient condition. On the contrary, the spray vessel has much more spacious volume so the entire spray process can be recorded without wall impingement. Ultimately, the goal of the spray vessel dataset is to provide reliable experimental data with tightly controlled boundary conditions that can be utilized as a validation source for modelling work.

A schematic of the constant-flow spray vessel is presented in Fig. 3. The vessel has an injector port and three optical windows. Quartz windows which have a diameter of 130mm are installed in the three ports for optical access. Internal heaters and an internal optical section are designed to be thermally isolated (with insulation) from the outer pressure vessel. The designed maximum operating pressure and temperature are 150 bar and 1100 K, respectively. Water cooling jackets in the wall, exhaust pipe, and the outer window ports are utilized to cool the pressure vessel, especially under high ambient temperature conditions. Sprays are injected into a continuous nitrogen flow (~0.1m/s) controlled by an electro-pneumatic flow controller. The rate of nitrogen flow is measured by flow meters at the upstream of the vessel and at the exhaust pipe. A customized vacuum pump is used to reach sub-atmospheric conditions in the vessel. The vessel pressure is measured by three different pressure transducers at the vessel inlet line, used for control and appropriate pressure range. The nitrogen flow enters a heating coil surrounded by an insulator piece at the bottom part of the vessel and then moves through a diffuser to enhance uniformity in the velocity and temperature field. To monitor temperature distribution prior to spray events, 24 thermocouples were installed above the diffuser, under the spray, and above the spray region. The vessel region
corresponding to gases that mix with the spray was controlled to a given target temperature. The mixture of injected fuel and nitrogen gas scavenges through the exhaust pipe at the top of the vessel, replaced by a fresh charge of ambient gas before the next injection. Relevant temperature, oxygen concentration, and vessel pressure are digitally recorded.

Two different optical setups were employed in this study. The first setup is for liquid fuel visualization by Mie-scatter extinction and scattering imaging at the side and front views, respectively. The liquid-phase fuel was identified by the diffused back illumination extinction imaging technique shown in Fig. 3. A high-speed green light-emitting diode (LED), Fresnel lens (150mm, f=150mm), engineered diffuser (20°), and band pass filter (center wavelength: 527nm, bandwidth: 20nm, full width-half max: 22nm) were utilized. The engineered diffuser (and collection optics) supplied a homogeneous light field and suppressed beam steering by evaporation or temperature field in the vessel [29]. This imaging technique is designed to collect extinction only by liquid phase fuel, but not from fuel vapor. The recording was extended up to 5ms after the start of injection (SOI) to capture the entire spray development and evaporation process. Normalized by incident light intensity (and other optical parameters), the side-view extinction imaging is quantitative for projected liquid volume (PLV) as explained below. Mie-scatter imaging from the front view was used primarily for visualization of plume-to-plume interaction effects. Here in the first optical setup, extinction and Mie-scattering imaging were carried out simultaneously using two different cameras. The second optical setup is Z-type schlieren imaging to capture the extent of fuel vapor penetration along a line of sight [30]. An effective point source was created using light from a red LED (500ns duration) collected by lens (Nikkor, 50mm f/1.8) and then focused through an aperture (0.6mm diameter). The expanding light collimated by a concave mirror (GSO, 152mm f/6.0) and the parallel rays of light passed through spray region. The parallel light after the spray was then collected by an identical concave mirror, with knife-edge (~50% cut-off) was located at the focal point to enhance sensitivity. Table 2 lists detailed values for optical imaging setup.

2.3. Image processing method

2.3.1. Extinction image and tomographic reconstruction

Extinction imaging is recommended by the ECN community for spray characterization because normalized lighting is more quantitative for liquid fuel concentration compared to side-illumination Mie-scattering imaging. Using the measured optical thickness, droplet size, and extinction coefficient, the projected liquid volume (PLV) along a line
of sight may be provided for direct comparison to CFD results. The optical thickness in a spray region can be calculated based on Beer-Lambert law as equation (eq-1).

\[ \tau = -\ln\left(\frac{I}{I_o}\right) \quad \text{(eq-1)} \]

Where \( I \) is transmitted light intensity with extinction (from droplets) and \( I_o \) is incident light intensity without extinction. The measured optical thickness \( \tau \) may be related to the PLV, which is the integral of liquid volume fraction (LVF) along the cross-stream direction \( y \), as

\[ \text{PLV} = \tau \frac{\pi d^3/6}{c_{\text{ext}}} = \int_{y_\infty}^{y_0} (\text{LVF}) \cdot dy \quad \text{(eq-2)}. \]

Mie scattering and extinction theory is applied in eq-2, along with the simplifying assumption that droplet diameter \( d \) and extinction coefficient \( c_{\text{ext}} \) (which depends upon \( d \)) do not vary along the line of sight. The PLV has units of liquid volume per projected area, or \( \text{mm}^3(\text{liquid})/\text{mm}^2 \), and may be easily calculated from CFD simulations for comparison to experiment. However, the experimentalists must have access to information about \( d \) and \( c_{\text{ext}} \) to estimate PLV. In particular, \( c_{\text{ext}} \) depends upon droplet size, wavelength of light, and collection angle of the receiving optics (e.g. some forward-scattered light is collected). Fortunately, droplet diameter measurements have been performed for Spray G by ECN participants at General Motors and Shanghai Jiao Tong University using phase-doppler interferometry (PDI) [26]. The measurements show an SMD near 7μm with fair uniformity across the plume during injection, which justifies the assumption to use single values for \( d \) (7μm) and \( c_{\text{ext}} \) (78.77·mm\(^2\), from Mie-theory relations using experimental collection angle, wavelength, and 7μm droplet diameter). Note that droplet size measurements were performed only upstream at one axial position (at \( z = 15 \) mm). We make use of these droplet size measurements only during injection because droplets produced upstream during injection constitute the majority of droplets in the domain—they are transported downstream and reside after injection has ended. We will discuss uncertainties associated with the droplet size assumptions throughout the text.

For the macroscopic spray characterization, a threshold for PLV may be chosen to indicate the extent of liquid penetration and width. The ECN recommends thresholds of 0.2·10\(^{-3}\) or 2·10\(^{-3}\) \( \text{mm}^3(\text{liquid})/\text{mm}^2 \) [31]. In this study, the lower threshold value of 0.2·10\(^{-3}\) \( \text{mm}^3(\text{liquid})/\text{mm}^2 \) was applied to process and binarize PLV images according to this threshold value. In the binarized image, liquid penetration length was defined as the farthest axial distance from
the nozzle at the primary view point (0° rotation angle) and the spray liquid width was measured at axial distances of
15mm and 25mm away from the nozzle tip.

Ensemble-averaged PLV data from 300 injections at three different viewing angle were utilized for tomographic
reconstruction. Fig. 4 indicates extinction images at three different views and corresponding PLV images in the
middle. The built-in ‘iradon’ function in Matlab was used for tomographic reconstruction, using a Hamming filter
value of 0.7. It is noted that reconstruction routine creates artifacts in optically thick region so each individual
plumes could not be identified for near nozzle spray (~z=5mm), however, comparison with x-ray data revealed that
it predicts plume center correctly at z=12mm. For the first step, PLV data at a certain location (presented as line in
the PLV images) need to be extracted and placed in a map shown at the bottom of the figure. Because of the limited
injector turns, the data within the viewing angle was interpolated and then the data out of viewing angle was
extrapolated by using the map from 0° to 22.5°. The interpolation and extrapolation were performed by linearly-
weighted averaging. Through this method, a projection map from 0° to 180° is generated for each axial position.
After tomographic reconstruction, a three-dimensional liquid volume fraction distribution is generated at each time
after the start of injection. The detailed description and validation of reconstruction method can be found in [32],
including confirmation of the process using synthetic model data for liquid volume fraction.

2.3.2. Schlieren image

Schlieren images under high-pressure and high-temperature conditions are sensitive to fuel vapor (with a different
refractive index than the ambient), however, non-uniformities in refractive index created by window thermal
boundary layers must also be considered [33]. The problem is especially severe if the window thermal boundary
layer moves during injection, making image normalization at the beginning of injection unsuitable for processing.
However, in the present study an image correction before the start of injection was sufficient to identify the jet vapor
boundary. The image processing routine for schlieren results is shown in Fig. 5(x). First (a), the spray was isolated
from the initial background I₀ by subtracting spray image I from I₀. (b) The vapor envelope was identified by using
the Matlab ‘imgradient’ function, returns the spatial gradient magnitude. (c) The gradient magnitude was binarized
with a certain threshold value and (d) the area inside the vapor boundary (where gradient magnitude is low because
of liquid spray) was filled to create a single, connected vapor boundary (e), produced using the ‘bwperim’ Matlab
function and presented as red line in Fig. 5(e) as a visual check of the process. Vapor penetration length is defined at

10
each time and injection as the distance between the nozzle tip and the farthest axial length on the boundary. (f) A vapor probability map was also derived using results from multiple injections. For 100 injections, the binarized image (d) from each injection and time step was summed to represent the probability percent. The region between 0 to 100 represents a zone of intermittency for low fuel mixture fraction, which can be evaluated with some rigor when compared to CFD.

2.4. Computational setup

Lagrangian parcel spray simulations using CONVERGE (v2.4) were performed to estimate mixing effects (equivalence ratio) on evaporation and overall spray development. The simulation work in this study mainly used default CONVERGE settings for an example Spray G case, so only a brief review of the setup is provided here. The injector specifications for the 8-hole nozzle are given in Fig. 1. The modified settings from the example case were plume cone angle (25°), plume-direction angle (34°), domain size (to enlarge without wall impingement), and turbulence model. Simulations were performed for Spray G conditions using iso-octane as fuel at ambient conditions matching the experiment. Following the Spray G work of Saha et al. [34], Reynolds averaged Navier-Stokes (RANS) standard k-ε model was used instead of the large-eddy simulations (LES) example case. Beginning with blob injection at the size of the nozzle, O’Rourke dispersion, Kelvin-Helmholtz (KH) and Rayleigh-Taylor (RT) models were used to capture turbulent dispersion, primary and secondary breakup, respectively, while the Frossling model is used for evaporation. An injection rate profile provided by ECN was used for the simulation [26]. The simulation time was extended up to 5ms after start of injection (SOI) to match with experimental data. The computational domain and detailed setting for simulation are presented in Fig. 6 and Table 3, respectively.

2.5. Operating conditions

The spray experiments were carried out under ECN Spray G2 (flash-boiling), G3 (early injection), and G3HT (G3 with elevated temperature conditions). As per ECN Spray G standard, an electronic injection command with a duration of 680μs (780μs actual hydraulic duration) was delivered to inject 10mg of fuel with injection pressure of 200 bar. The temperature of injector tip was maintained by a water circulator at 90°C during entire experiments. The ambient temperature was set to 60°C for G2 and G3 condition, but increased to 120°C under G3HT condition. The ambient pressures were 0.5 bar, 1 bar, and 1.18 bar for G2, G3, and G3 HT, respectively. Corresponding ambient densities were 0.5 kg/m³ for G2, and 1.01 kg/m³ for G3 and G3HT conditions. Three different injector viewing
angles were applied and the spray was repeated 300 times per case for extinction imaging. The schlieren imaging was repeated for 100 injections at the primary viewing angle. The experimental conditions are summarized in Table 4.

3. Results and discussion

3.1. Effects of ambient condition on macroscopic spray characteristics

Providing a general overview of the baseline iso-octane sprays, the liquid and vapor envelopes under G2, G3, and G3HT conditions are presented in Fig. 7. Recall that the liquid and vapor results here are derived from ensemble averaging many different injection events. The liquid boundaries determined with PLV threshold of $0.2 \times 10^{-3}$ mm$^3$(liquid)/mm$^2$ are compared according to ambient conditions with vertical lines indicating liquid penetration length in Fig 7(a). Fig. 7(b) shows vapor boundary (dotted) with 20% intermittency and liquid boundary (solid) as defined above. The quantitative comparison of liquid penetration length and liquid width is given in Figs 7(c) and 7(d). Results from the CFD simulation were also analyzed by applying the identical PLV criteria as the experiment, and results for the G2 condition are shown for simplicity.

Analysis of macroscopic spray characteristics shows that the spray under G3HT condition evaporates much faster than G2 and G3 conditions, which is expected because of the higher ambient temperature. Higher ambient density also tends to slow vapor penetration, and results are indistinguishable for G3 versus G3HT. Higher ambient temperature confines liquid to a smaller radial width, which also eventually applies to axial penetration. However, the more remarkable effect is that after liquid penetrates to approximately the same maximum axial position, the time of evaporation to the PLV criteria is much earlier for G3HT (about 2 ms aSOI) compared to that of G3 (about 3.5 ms aSOI). The vapor envelope is similar for either G3 or G3HT conditions. The G2-condition spray shows the longest vapor penetration length, which is expected because of the lower ambient density. Liquid penetration is also the longest, despite the enhancement in vaporization expected for the G2 flash-boiling condition. The spray boundary images and liquid width measurements indicate a transition in spray mixing at some point. While the near nozzle spray outline (refer Fig. 7(a)) under G2 and G3 conditions is similar at 0.5 and 0.8ms, contraction of the spray in radial direction begins under flash-boiling G2 conditions, leading to smaller liquid width than the G3 condition. Factors such as potential for a larger individual plume growth for G2 condition and overall 3D liquid plume movement deserve consideration, and we will discuss these issues after 3D data are presented.
One of the more interesting results from the macroscopic liquid spray parameters is the extended persistence of liquid in both space and time, particularly for the flash-boiling G2 condition with liquid persistence exceeding 3 ms. The long persistence of liquid time under G2 and G3 conditions, even with heated fuel and somewhat elevated gas temperature, is considered significant time scale in an engine system. There is clearly enough penetration distance and time for liquid to impinge upon in-cylinder surfaces during intake injection in an engine. To gain some physical insight into factors affecting vaporization, we perform a thermodynamic analysis for different mixtures (equivalence ratio), guided by CFD simulations for prediction of these mixtures.

Equilibrium-state calculations are performed with liquid and vapor fraction predictions for different mixtures, using standard energy and fugacity balances for liquid fuel and gas initially at the conditions of the experiment. The calculation result shown in Fig. 8 present the equilibrium mixture temperature according to a given equivalence ratio for G2, G3, and G3HT conditions. If the solution is for entirely vapor, a dashed line is indicated. If the solution shows a mixture with both liquid/vapor present, a solid line is used. The transition point is a saturated vapor-liquid equilibrium mixture. If vaporization is driven entirely by mixing, and perfect equilibrium mixtures are formed, no liquid will exist at equivalence ratios less than this transition. While this assumed state is unlikely in a dynamic spray, this very assumption has been applied with encouraging results at diesel conditions at higher temperature and pressure [35]. Fig. 8 shows that the rank ordering for saturated equivalence ratio is in agreement with the experiment in terms of vaporization time. But it also shows that substantial vaporization cooling occurs under all conditions. Fuel initially at 363 K and ambient initially at 333 K cools below 300 K at saturated conditions, and the cooling is more substantial for the flash-boiling condition. Moreover, an equilibrium condition with liquid exists even for flash-boiling conditions. Therefore, it is not surprising to observe liquid for an extended period of time as even equilibrium calculations show a liquid state provided that the mixture equivalence ratio is rich enough.

CFD simulations are utilized to estimate the actual equivalence ratio, in comparison to equilibrium expectations. Fig. 9 shows mixture total equivalence ratio (considering both liquid and vapor) predictions both during and after injection at positions where liquid is observed in the experiment. The images present equivalence ratio at two different planes and timings after start of injection (aSOI) timings. The Lagrangian parcel simulation does not provide total (liquid and vapor) fuel-air ratio by default, so it was calculated using cell mass, mass fraction, volume fraction of parcel in a cell, cell volume, and fuel density, as shown by equation (3) to equation (5) below.
where $m_{f_v}$ is vapor mass of iso-octane in a cell, $m_{N_2}$ is mass of nitrogen in a cell, $m_{cell}$ is a total mass in a cell, $x_{N_2}$ is a mass fraction of nitrogen in a cell, $m_{f_l}$ is a liquid mass of iso-octane in a cell, $V_{cell}$ is a volume of a cell, $\alpha_p$ is a volume fraction of parcel in a cell, and $\rho_f$ is a liquid fuel density. Even though the simulations and experiments are for mixing of fuel with nitrogen, we convert to equivalence ratio as if the mixture were pure air to provide a more intuitive sense of the mixture using equation (5) where $\varphi$ is an equivalence ratio, $F$ is a fuel mass in a cell, $A$ is a nitrogen mass in a cell and $(F/A)_s$ is stoichiometric fuel/air ratio by mass for iso-octane and pure air (value of 0.0661 was used). In fact, the equilibrium calculations shown in Fig. 8 are also for nitrogen-fuel mixtures, but are presented as equivalence ratio also using equation (5).

Fig. 9 shows very local equivalence ratios that exceed a value of 8 even after the spray becomes dilute after the end of injection. According to the thermodynamic analysis given in Fig. 8, these mixtures must have liquid even at equilibrium. Therefore, it is expected that liquid persists. However, the simulation may belie this conclusion if the degree of stratification is unnatural and sensitive to modeled spray parameters. To gain a better understanding of the mean mixture prediction, a quantitative comparison of the liquid volume fraction and equivalence ratio is presented in Fig. 10, where the average of these data cutting through the center of all 8 plumes is plotted versus radial position. The measured liquid volume fraction after tomographic reconstruction (and also the average of 8 plumes) is presented as a solid line. The averaged liquid volume fraction curve derived from simulation was a bit noisy because of uneven parcel distribution in the spray so binned-pixel average (10 by 10) value was used for presentation. Fig. 10(a) shows that the liquid volume fraction from the simulation is higher and has a wider distribution compared to the experimental data. While the assumed droplet size creates some uncertainties in the experimental LVF data, the overall trend is that the simulation predicts less evaporation compared to the experiment. It is also obvious that the spray is rich enough to have liquid and vapor mixture during injection.

Simulation results at 1.2ms aSOI (Fig. 10(b)) show a mismatch in the plume liquid center and width compared to the experiment, with the experiment showing more of a plume collapse towards the injector axis compared to the
simulation. This plume movement throughout injection will be discussed in more detail later. The mean (and spatial average of all plumes) equivalence ratio is predicted to be less than two. If the system were truly mixed and at equilibrium, there should be no liquid. Since liquid is measured and predicted in the simulation, there is high confidence that mixture stratifications exist and that vaporization is not dictated by mixing in the mean sense.

3.2. Effects of ambient condition on plume direction

The availability of three-dimensional LVF data, created by tomographic reconstruction of line-of-sight PLV data, enables detailed analysis of the radial and axial movement of individual plumes. Figure 10 showed a snapshot of the LVF data for the G2 condition at only two timings, but the overall motion of the plumes for other axial positions and timings is available for analysis. Outlines of the liquid spray with a LVF threshold of 0.5 ·10⁻³ are presented along the Y-Z cut plane in Fig. 11 for iso-octane at G2, G3, and G3HT conditions. The contours are given at several timings aSOI, but full movies of the same data are available to view at [36]. The nozzle drill angle is indicated as a grey dotted line that forms a 37° from the injector axis (refer Fig. 1 for injector Z-axis). The macroscopic spray characteristics discussed using PLV results in the last section are consistent with the planar data cutting directly through plume centers (Y-Z plane cuts through centers of Plumes 3 & 7). For example, the faster evaporation for G3HT and longer axial liquid penetration for G2 conditions is easily shown along the plane. What is more clearly manifest in cut plane data, however, is the G2 condition plumes deflect more to axis centerline. Plumes at all conditions contract towards the centerline with increasing time aSOI, departing from the hole drill angle, but the deflection is higher for G2 conditions. One effect of the plume direction contracting in time, even prior to the end of injection, is that plumes show a curved or bent shape, retaining a ‘memory’ of the earlier plume direction but also contracting towards the injector axis.

A quantitative measurement of the plume direction angle is provided by defining the plume center as that with near-maximum LVF. The maximum is a justified choice because it removes artifacts created by plumes that are not orthogonal to an axial plane, as is the case for Spray G [32]. For example, rotated ideal-distribution (Gaussian) plumes defined with center at full-width at half maximum have a bias towards a larger plume direction, and one that does not correspond to the actual center. We therefore define plume center as the mean of 99% peak LVF positions to eliminate this bias, and compute a plume direction back to the hole origin from this center. Results are shown in Fig. 12 for data analyzed at Z = 30mm from the nozzle tip. As the plume arrives at 30 mm, the plume direction angle
is already approximately 3° smaller as compared to the drill angle regardless of ambient conditions. The plume direction angle of G3 and G3HT are more or less the same, while it is contracts by several degrees for the G2 condition during injection, and more so after the end of injection—results that are consistent with data rendered on a plane in Fig. 11. These results show a greater degree of plume movement towards the centerline, but not complete spray collapse at G2 (flash-boiling) conditions. The Mie-scattering images presented at the top of the figure show greater plume growth and more plume-to-plume interaction with smaller area between plumes at G2 conditions. The quantitative measurement of plume cone angle will be discussed in Section 4.

Adding understanding of the plume dynamics between conditions, we show LVF values on the z=30mm X-Y plane and the average through the center of all eight spray plumes as a function of radial position in Fig. 13. A more narrow spacing between plumes is shown in the X-Y plane at G2 conditions. G3 and G3HT conditions also show some LVF between plumes, but at lower intensity. The averaged LVF radial profiles given in Fig 13 (b) show that peak LVF during injection (solid lines) is only slightly less for G2 conditions compared to G3 conditions but there are greater differences after the end of injection (dashed lines), once more confirming a faster final vaporization for G2 conditions. The LVF radial shift towards the centerline for the G2 condition is pronounced during and after injection. As part of the general collapse of the spray, plumes clearly merge together more rapidly for the G2 condition with individual plume structure between plumes nearly absent by 1.07 ms aSOI. The LVF peak at G2 conditions also translates approximately 4mm from that at 0.54 ms aSOI, compared to only 1-2 mm shift for G3 or G3HT conditions. While lacking a complete collapse and mixing to the injector axis, all indications are that plume collapse is more severe for the G2 condition than other cases.

3.3. Effect of fuel on macroscopic spray characteristics

Experiments were performed for the entire Table 3 test matrix, but for brevity, we show the effect of fuel type on macroscopic spray properties only at the G2 condition. At this experimental condition, the pressure ratios ($P_a/P_p$) are 0.17, 0.29, 0.67, and 0.71 for e30, olefinic, di-isobutylene, and iso-octane, respectively. Using the same definitions for liquid and vapor penetration used above (see Fig. 7), a comparison between fuels is provided in Fig. 14. Generally, the overall spray morphology of iso-octane and the di-isobutylene blend is similar to each other. The statistical data in Figs 14 (c) and (d) showed slightly longer liquid and vapor penetration lengths for di-isobutylene but the difference is still minor. However, distinct differences in fuel spray characteristics are found for olefinic and
e30 blends. The e30 blend shows a shorter penetration length and a narrower liquid width at the beginning of injection, accompanied by wider radial dispersion at 15 to 25 mm axial positions. But e30 eventually overtakes the other fuels in axial liquid and vapor penetration after 1.5ms aSOI. The olefinic fuel is somewhat intermediate to e30 and the lighter fuels in terms of maximum axial liquid penetration, and in the contour of PLV plot that shows a clustering of liquid towards the center. The olefinic and e30 blends have significant times for persistence of liquid, to 4.9ms and over 5ms, respectively, despite heated fuel (90°C) as an injection boundary condition.

The vapor envelope measurements indicate the same general shape but the olefinic and e30 fuels tended to have a more narrow tail in vapor distribution after the end of injection. Using the three-dimensional LVF data, we will show below that these changes in vapor distribution are the result of significant spray collapse for olefinic and e30 fuels.

3.4. Effect of fuel on plume direction

As shown above, the availability of three-dimensional LVF data provides a much better understanding of spray dynamics. A comparison of all fuels at the G2 condition is shown in the Y-Z plane Fig. 15 (a), using the same threshold used for iso-octane (0.5 ·10^{-3}) at all experimental conditions (in Fig. 11). While plumes move towards the centerline for iso-octane and di-isobutylene fuels, liquid moves all of the way to center for e30, and to a large degree for the olefinic fuel. For e30, individual plume identification is almost immediately lost after start of injection, while there is clearly evidence of plumes connected at the centerline at z = 20mm for the olefinic fuel by 0.5 ms aSOI as shown in Fig. 15 (b). The strong collapse to a single jet structure (for e30), produces a repeatable head vortex structure in the leading edge of the spray, such that it appears even in the ensemble-average. While some plume bend is observed for other fuels, including the olefinic fuel, the head-vortex structure is not as prominent.

The LVF boundary at 1.26 ms aSOI highlights the strong differences in liquid distribution for each fuel. While iso-octane and di-isobutylene have evaporated to lower LVF concentrations by the timing, the olefinic and e30 blends show significant liquid remaining near the centerline. One reason for the persistence of liquid is the high boiling point constituents, and high heat of vaporization (e30), but a second contributing factor is that fuel plumes are clustered together at the center and experiencing poor mixing. A complete merging of plumes (spray collapse for e30) creates a merged jet with cumulative momentum higher than that of individual plumes, and this can also explain the greater axial penetration for e30, along with greater potential for liquid impingement on engine wall
surfaces. The significant departure of liquid from the original drill angle projection (dashed line) is an indication of how different the fuel delivery becomes under spray collapsing scenarios. We emphasize that the 3D diagnostic for local LVF provides this level of detail and new understanding.

Using the 3D LVF data, a quantitative comparison of plume direction angle for all fuels is also provided in Fig. 16, using the same definitions as that used in Fig. 12 for the z=30 mm position. The trend for a decrease in plume direction angle with time is exactly consistent with the pressure ratio \( P_a/P_v \) for each fuel. While appearing nearly identical, the measured plume direction angle of di-isobutylene is approximately 1° smaller than that of iso-octane, a result that is within the resolution of the optical setup and statistically significant because of the well-converged average data. This result shows that the di-isobutylene had slightly more plume collapse than iso-octane, potentially facilitated by the fast evaporation of the light component (4% 1-hexene) in the blend, even though at low concentration. On the other hand, the olefinic and e30 blends have massive differences in plume direction, consistently smaller than the drill angle even from the time of first arrival at z=30 mm. The smaller initial plume direction angle indicates the spray contraction by plume collapse is well underway even at early stages of injection, consistent with Fig. 15. The plume direction angle for these fuels abruptly decreases and is not measurable once plumes combine and collapse.

The fuel effect on plume collapse is illustrated with even more detail by considering results along the X-Y plane in Fig. 17, with analogy in presentation to Fig. 13. Fig. 17(a) shows significant plume-to-plume interaction for the olefinic and e30 blends during injection at 0.54 ms aSOI, illustrating a symptom of spray collapse. A close look also shows higher LVF between plumes for di-isobutylene compared to iso-octane, potentially indicating slightly more plume-to-plume interaction leading to the subtle decrease in plume direction for di-isobutylene compared to iso-octane. The LVF distributions across plumes presented in Fig. 17(b) shows wider plumes for the olefinic and e30 blends compared to the lighter fuels at 0.54 ms, indicating distortion and stretch towards the center. Plume direction (at maximum LVF) is discernable at this time for the olefinic and e30 blends, but at 1.07 ms the peak LVF is at the centerline, indicative of full spray collapse and undefined plume direction for these fuels (see Fig. 16). Interestingly, the peak LVF is actually nearly the same or higher, despite the fact that 1.07 ms is after the end of injection and there is an expectation for further dilution with time. This rising LVF in time can only be accomplished if mixing with air is impaired, as is the case for central collapse for all plumes. By contrast, at 1.07 ms LVF decreases quickly
and significantly for iso-octane and di-isobutylene, assisted by ambient gas surrounding each of the eight separated plumes.

A comparison of the overall spray processes between iso-octane and e30 blends is exhibited in Fig. 18. Mie-scattering images are shown at the top and the 3D LVF maps rendered in transparency are given at the bottom. The Mie-scattering images from the iso-octane indicate light plume-to-plume interaction, not severe enough to induce complete collapse. On the other hand, the e30 blend suffers from strong plume collapse from the beginning, so that each plume could not be identified. At 0.1ms aSOI, e30 shows specific patterns in Mie-scattering images, but these patterns are not created by individual plumes. Rather, the strongest signature is at the position bisecting the plume position, as if the injector were rotated. This observation is another indication of strong plume-to-plume interaction. The Mie-scatter images and 3D LVF images show significant liquid at the jet centerline by 0.5ms aSOI, consistent with Fig. 15. The complete spray collapse to the center and rollup of the head vortex for e30 are illustrated dynamically in the 3D LVF images (and movie available at [36]).

4. Plume vapor cone angle

A potential hypothesis to explain the fuel effects demonstrated in this paper is that fuel sprays with low \(\left(\frac{P_d}{P_e}\right)\) have significant vapor formation from flash boiling that tends to enlarge individual plume cone angle. With larger plume cone angle, interaction between plumes is accelerated, air entrainment is shut off, and spray collapse occurs. To substantiate this hypothesis, it is necessary to have a direct assessment of plume cone angle. While radial LVF distributions may be used to understand liquid plume growth, the width of the liquid region may not be representative of plume growth because of confounding factors such as vaporization dependencies upon distillation properties as well as ambient conditions. These confounding factors are overcome if able to measure the plume vapor cone angle corresponding to the lowest fuel mixture fraction.

To accomplish this goal, we use the vapor boundary from line-of-sight schlieren imaging, in concert with the plume center measured from 3D tomographic reconstruction, to obtain the plume vapor cone angle. The process is illustrated schematically in Fig. 19. While schlieren imaging only measures the outer vapor envelope of two plumes (Plumes 3 and 7 in the primary 0° rotation view), the average plume center and average vapor envelope can be combined to approximate vapor plume cone angle. The plume vapor cone angle was measured near the nozzle at \(z=8.5\) mm to avoid distortion from the head vortex zone shown in the figure. Fig. 19 shows a schematic diagram in
which the vapor boundary with 0.5 intermittency is presented as red solid line. Averaged plume centers (from 3D LVF analysis) are also indicated as triangles on the line of plume direction (dotted blue lines). A line orthogonal to the plume direction angle intersects the vapor boundary and is shown with a circle. At this moment, the angle formed by two lines, circle to orifice outlet and averaged plume center to orifice outlet, can be considered as half of the plume vapor cone angle. Combining the measurement of plume center (via 3D tomographic reconstruction) and vapor envelope offers a new technique to measure plume vapor cone angle in realistic multi-plume GDI sprays. A technique to measure plume cone angle, rather than total spray angle or width, is critical because interaction and merging between plumes also affects total spray angle or width.

The measured plume vapor cone angle presented in Fig. 20 (a) is an average value from top and bottom plumes during 200µs to 680µs aSOI for all conditions and fuels. As can be seen, the pressure ratio has a significant effect on plume cone angle, which has been observed in past single-hole studies [37]. A strong inflection occurs near a pressure ratio of 0.5. Fuels with a high portion of light species have high Pe and lower pressure ratio (Pa/Pv), and are more susceptible to higher plume growth. As shown in earlier sections, conditions with higher plume growth also show more tendency for spray collapse, as confirmed by 3D LVF measurements, generating the hypothesis that initial plume growth is a key factor for spray collapse. With measurement of both plume direction and plume cone angle, facilitated by the 3D measurements of this study, we can investigate this hypothesis through a correlation between these two quantities. Fig. 20 (b) shows plume direction angle measured at z=30mm and 0.37ms aSOI according to averaged plume vapor cone angle presented in Fig. 20 (a). This result clearly shows that smaller plume direction angle, as a sign of more plume-to-plume interaction, is induced by a larger plume vapor cone angle over a broad range of conditions and fuels. For example, under G3 conditions the e30 blend (purple triangle) has a slightly smaller plume vapor cone angle and a corresponding larger plume direction angle than the olefinic fuel under G2 conditions (orange circle). Subtle effects such as the greater plume interaction and smaller plume direction for di-isobutylene compared to iso-octane are also consistent with lower pressure ratio and greater plume cone angle for di-isobutylene. While the conclusion and relation of greater spray growth with lower pressure ratio is consistent with past literature observations for single-hole injectors [37], or in some cases multi-hole nozzles [38], we emphasize that this study is the first to provide measurement of individual plume growth, rather than total spray angle, for realistic multi-plume GDI sprays.
5. Conclusion

In this study, a series of high-speed Mie-scattering, extinction, and schlieren imaging was carried out in a constant-flow spray vessel under G2, G3 and G3HT conditions, consistent with realistic intake-injection conditions in an engine. Four different fuels: iso-octane, di-isobutylene surrogate, olefinic, and a 30% ethanol blend were injected using an ECN Spray G 8-hole injector. CFD Lagrangian parcel simulations were also performed to understand mixing and liquid residual time. We applied computed tomographic reconstruction using extinction imaging to measure the 3D liquid volume fraction of all plumes, and schlieren imaging to identify the vapor boundary for some of the plumes. Measurements of individual plume dynamics were resolved in time and space, and include statistics such as plume direction angle, plume cone angle, liquid penetration, vapor penetration, and so forth. The dataset offers unique information on plume growth and movement in the midst of a realistic multi-hole spray, and are available to view/download [36]. The major findings from this study as follows.

1) Liquid persists under a flash-boiling G2 condition for more than 3ms even with iso-octane fuel, showing a longer liquid penetration than the non-flashing G3 condition and enough time and penetration distance to cause liquid impingement in engine. Equilibrium mixture calculations can explain the long persistence at G2 conditions as liquid is expected if mixtures have an equivalence ratio greater than a value of four. At 30 mm downstream of the injector, CFD simulations predict mixtures with $\varphi > 4$ during injection, but $\varphi < 4$ at 0.4 ms after the end of injection, even though liquid is measured and predicted at this same time. These data support the notion that the system is not mixing-limited or at equilibrium. Fuels containing heavy species such as olefinic and e30 showed even longer liquid residual time, up to the end of the experimental acquisition at 5ms, which is likely to cause piston/cylinder wetting.

2) Using tomographically reconstructed liquid volume fraction data centered upon a plume, a noticeable plume movement towards the injector axis (decrease in plume direction angle) occurs under G2 conditions. The iso-octane spray under G2 conditions shows an approximately 6° smaller plume direction angle at the end of injection ($z=30\text{mm}$) as compared to the drill angle (37°). For all conditions and fuels, an analysis of measured plume cone angle versus plume direction angle shows excellent correlation for a smaller plume direction angle when there is a larger plume cone angle. The logical conclusion is that a larger plume cone angle enhances aerodynamic interaction between plumes, pulling plumes closer to one another and
reducing plume direction angle relative to the injector axis. For larger plume cone angles, the plumes may combine to undergo complete spray collapse.

3) Plume vapor cone angle measurements were made possible in a multi-plume spray by a combination of 3D liquid distribution measurements to fine the plume center, combined with schlieren imaging to find the vapor boundary for two of the plumes. The plume cone angle with various fuels and conditions shows a strong inflection at a pressure ratio of 0.5 \((P_a/P_v)\), or where the ambient pressure is half of the vapor pressure. The plume vapor cone angle increases sharply at a pressure ratio less than 0.5.

4) Strong plume interaction and collapse may leave high liquid fuel concentrations in the spray core region. For a volatile 30% ethanol fuel (e30) at flash-boiling conditions, peak fuel concentration actually increases after the end of injection, as the result of plume combination and collapse during injection.

Acknowledgements

The authors would like to thank Tim Gilbertson, Alberto Garcia, Brian Patterson, Keith Penny, Nathan Harry, Aaron Cyzenski, Chris Ingwerson, Laurie Bell, Paul Abers, and Peter Cable for their dedicated support for the research facility. The work was performed at the Combustion Research Facility (CRF), Sandia National Laboratories, Livermore, CA. This research was conducted as part of the Co-Optimization of Fuels & Engines (Co-Optima) project sponsored by the U.S. Department of Energy (DOE) Office of Energy Efficiency and Renewable Energy (EERE), Bioenergy Technologies and Vehicle Technologies Offices. Sandia National Laboratories is a multi-mission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC., a wholly owned subsidiary of Honeywell International, Inc., for the U.S. Department of Energy’s National Nuclear Security Administration under con-tract DE-NA0003525.

References


Figure 1. Cut plane image of ECN spray G injector with dimensions (upper right shows 3-D rendering of the injector with primary orientation) [26].
Figure 2. (a) Distillation curve and (b) vapor pressure of iso-octane, olefinic, di-isobutylene, and e30 blend fuels [27].

Fig. 3. Sandia constant-flow spray vessel with simultaneous high-speed extinction and Mie-scattering imaging setup.
Fig. 4. Image processing for tomographic reconstruction from the top: raw extinction images at three different viewing angle, calculated projected liquid volume based on the Beer-Lambert law and Mie-theory, and scaled full range line data at a target plane (pink, green, and yellow lines are from the measurement, filled region between measurement is from linearly-weighted interpolation and extrapolation).
Fig 5. Image processing routine for schlieren image (a) isolation of spray from background by subtracting $I$ from $I_0$ , (b) get gradient magnitude of (a) by using ‘imgradient’ function, (c) binarize gradient magnitude map with a threshold, (d) fill inside region of spray envelope, (e) visual check of derived spray boundary with original spray image, (f) overlap 100 shots of binarized image (for example (d)) to get schlieren probability.
Fig. 6. CONVERGE simulation domain (fix embedding with scale of 3 was applied in upstream region of spray).
Fig. 7. Macroscopic spray characteristics of iso-octane showing (a) liquid spray boundary determined by a projected liquid volume threshold of $0.2 \cdot 10^{-3} \text{mm}^3/\text{mm}^2$ under G2, G3, and G3HT conditions (vertical lines in the spray boundary image present liquid penetration length), (b) Vapor boundary (dotted line, 20% intermittency) with liquid boundary (solid) from under G2, G3, and G3HT conditions at different aSOI timings, (c) Liquid and vapor penetration length defined a distance from nozzle tip and axial farthest point, (d) Liquid width at 15mm and 25mm from the nozzle tip. Simulation results are presented as grey lines in both (c) and (d).
Fig. 8. Thermodynamic calculation result for equilibrium mixture temperature according to initial equivalence ratio.
Fig. 9. CFD simulation results at G2 conditions showing the equivalence ratio at $x=0$ and $z=30\text{mm}$ plane at two different aSOI timing.
Fig. 10. Liquid volume fraction from experiment (blue solid line), simulation (blue dotted line), and equivalence ratio (black dotted line) at z=30mm plane.
Fig. 11. Boundary of liquid spray at Y-Z plane enabled by three-dimensional tomographic reconstruction. The boundary was determined with a liquid volume fraction threshold of $0.5 \times 10^{-3}$. iso-octane fuel.
Fig. 12. Mie-scattering images (top) from the front view under G2 and G3 condition at 0.5ms aSOI and plume direction angle (bottom) defined by an angle between nozzle orifice and center of plume width at 99% of the peak liquid volume fraction.
Fig. 13. (a) Liquid volume fraction and (b) Averaged liquid volume fraction across centerline (white dotted lines in (a)) at $z=30\text{mm}$ (X-Y plane) under G2, G3, and G3HT conditions. Solid lines present data at 0.54ms aSOI and dotted lines are at 1.07ms aSOI timing.
Fig. 14. Macroscopic spray characteristics of tested fuels under G2 condition showing (a) liquid spray boundary determined by a projected liquid volume threshold of $0.2 \cdot 10^{-3} \text{mm}^3/\text{liquid/mm}^2$ (vertical lines in the spray boundary image present liquid penetration length), (b) Vapor boundary (dotted line, 20% intermittency) with liquid boundary (solid) from under G2 conditions at different aSOI timings, (c) Liquid and vapor penetration length defined a distance from nozzle tip and axial farthest point, (d) Liquid width at 15mm and 25mm from the nozzle tip.
Fig. 15. (a) Liquid spray boundary of tested fuels under G2 condition at Y-Z plane enabled by three-dimensional tomographic reconstruction (The boundary is defined as a liquid volume fraction threshold of $0.5 \cdot 10^{-3}$) and (b) Mie-scattering image at 0.5ms aSOI.
Fig. 16. Plume direction angle of tested fuels under G2 condition defined by an angle between nozzle orifice and center of plume width at 99% of the peak liquid volume fraction at z=30mm plane.
Fig. 17. (a) Liquid volume fraction and (b) Averaged liquid volume fraction across centerline (white dotted lines in (a)) at z=30mm (XY plane) under G2 condition. Solid lines present data at 0.54 ms aSOI and dotted lines are from 1.07 ms aSOI timing.
Fig. 18. Comparison of entire spray evolution between iso-octane and e30 blend under G2 condition. Top shows Mie-scattering images at the front view and the bottom presents three-dimensional rendering of liquid volume fraction.
Fig. 19. Schematic diagram for plume vapor cone angle derivation.
Fig. 20. (a) Averaged plume vapor cone angle (200µs to 680µs) with 0.5 intermittency of vapor boundary and (b) correlation of plume direction angle measured at 0.37ms aSOI, $z=30$mm and averaged plume vapor cone angle (Circle, triangle, and square mean spray cone angles under G2, G3, and G3HT conditions).
<table>
<thead>
<tr>
<th>Parameters</th>
<th>iso-octane</th>
<th>di-isobutylene</th>
<th>olefinic</th>
<th>e30</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density @15°C [kg/m^3]</td>
<td>698.7</td>
<td>736.2</td>
<td>722.9</td>
<td>752.7</td>
</tr>
<tr>
<td>Viscosity (ν) @40°C [mm^2/s]</td>
<td>0.574</td>
<td>0.541</td>
<td>0.477</td>
<td>0.695</td>
</tr>
<tr>
<td>Viscosity (μ) @40°C [10^-3 Pa·s]</td>
<td>0.401</td>
<td>0.398</td>
<td>0.345</td>
<td>0.523</td>
</tr>
<tr>
<td>Research octane number (RON)</td>
<td>100</td>
<td>98.3</td>
<td>98.3</td>
<td>97.9</td>
</tr>
<tr>
<td>Motor octane number (MON)</td>
<td>100</td>
<td>88.5</td>
<td>87.9</td>
<td>87.1</td>
</tr>
<tr>
<td>Vapor pressure @90°C [kPa]</td>
<td>70.9</td>
<td>74.2</td>
<td>170.6</td>
<td>286.8</td>
</tr>
<tr>
<td>Aromatics (vol.%)</td>
<td>0</td>
<td>20.1</td>
<td>13.4</td>
<td>8.1</td>
</tr>
<tr>
<td>Olefins (vol.%)</td>
<td>0</td>
<td>4.0</td>
<td>26.5</td>
<td>5.0</td>
</tr>
<tr>
<td>Paraffins (vol. %)</td>
<td>100</td>
<td>56.3</td>
<td>56.4</td>
<td>57.1</td>
</tr>
<tr>
<td>Cycloalkanes (vol. %)</td>
<td>0.0</td>
<td>0.0</td>
<td>2.9</td>
<td>7.0</td>
</tr>
<tr>
<td>Ethanol (vol.%)</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>30.0</td>
</tr>
<tr>
<td>Lower heating value [MJ/kg]</td>
<td>44.8</td>
<td>43.5</td>
<td>44.1</td>
<td>38.2</td>
</tr>
<tr>
<td>Stoichiometric A/F ratio [-]</td>
<td>15.1</td>
<td>14.7</td>
<td>14.8</td>
<td>12.8</td>
</tr>
<tr>
<td>Heat of vaporization [kJ/kg]</td>
<td>20.8</td>
<td>21.5</td>
<td>21.1</td>
<td>38.4</td>
</tr>
</tbody>
</table>
Table 2. Optical setups for Mie-scattering, extinction, and schlieren imaging.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Mie-scattering</th>
<th>extinction</th>
<th>schlieren</th>
</tr>
</thead>
<tbody>
<tr>
<td>LED color</td>
<td>Red</td>
<td>Green</td>
<td>Red</td>
</tr>
<tr>
<td>Actual LED on time</td>
<td>1 μs</td>
<td>220 ns</td>
<td>500 ns</td>
</tr>
<tr>
<td>High-speed camera</td>
<td>Phantom, v311</td>
<td>Photron, SA-Z</td>
<td>Photron, SA-Z</td>
</tr>
<tr>
<td>Optical lens</td>
<td>Nikkor, 50mm</td>
<td>Nikkor, 50mm</td>
<td>Nikkor, 85mm</td>
</tr>
<tr>
<td>f-stop</td>
<td>f/4</td>
<td>f/2.8</td>
<td>f/1.4</td>
</tr>
<tr>
<td>Filter</td>
<td>N/A</td>
<td>band pass filter (center wavelength: 527nm, bandwidth: 20nm, full width-half max: 22nm)</td>
<td></td>
</tr>
<tr>
<td>Frame rate [fps]</td>
<td>25,000</td>
<td>67,200</td>
<td>67,200</td>
</tr>
<tr>
<td>Exposure time [μs]</td>
<td>39.4μs</td>
<td>13.27μs</td>
<td>13.27μs</td>
</tr>
<tr>
<td>Image size</td>
<td>304×304</td>
<td>512×512</td>
<td>512×512</td>
</tr>
<tr>
<td>Image resolution [mm/pixel]</td>
<td>0.661</td>
<td>0.191</td>
<td>0.213</td>
</tr>
</tbody>
</table>
### Table 3. CONVERGE simulation setup

<table>
<thead>
<tr>
<th>Item</th>
<th>Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plume cone angle</td>
<td>25</td>
</tr>
<tr>
<td>Plume direction angle</td>
<td>34</td>
</tr>
<tr>
<td>Fuel</td>
<td>iso-octane</td>
</tr>
<tr>
<td>Discharge coefficient ($C_v$)</td>
<td>0.5</td>
</tr>
<tr>
<td>Total number of cell</td>
<td>~520,000</td>
</tr>
<tr>
<td>Cell size [µm]</td>
<td>20-160</td>
</tr>
<tr>
<td>Turbulence model</td>
<td>Reynolds averaged Navier-Stokes (RANS), Standard k-ε</td>
</tr>
<tr>
<td>RANS constants</td>
<td>$C_{μ}=0.09$, $C_{ε1}=1.44$, $C_{ε2}=1.96$, $C_{ε3}=-1.0$</td>
</tr>
<tr>
<td>Initial turbulent kinetic energy</td>
<td>$k = 1 \text{ m}^2/\text{s}^2$</td>
</tr>
<tr>
<td>Initial TKE dissipation rate in the region</td>
<td>$\varepsilon = 100 \text{ m}^2/\text{s}^3$</td>
</tr>
<tr>
<td>Number of parcels per plume</td>
<td>70,000 (total 560,000)</td>
</tr>
<tr>
<td>Simulation time</td>
<td>5ms aSOI</td>
</tr>
</tbody>
</table>
Table 4. Experimental conditions

<table>
<thead>
<tr>
<th>Item</th>
<th>G2</th>
<th>G3</th>
<th>G3HT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Injector viewing angle</td>
<td>3 views (0°, 11.25°, 22.5°)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Repetition number</td>
<td></td>
<td>300</td>
<td></td>
</tr>
<tr>
<td>Fuel</td>
<td>iso-octane, olefinic, di-isobutylene, e30 blend</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Injection pressure [bar]</td>
<td></td>
<td>200</td>
<td></td>
</tr>
<tr>
<td>Fuel temperature [°C]</td>
<td></td>
<td>90</td>
<td></td>
</tr>
<tr>
<td>Injection duration (hydraulic duration) [µs]</td>
<td></td>
<td>680 (780)</td>
<td></td>
</tr>
<tr>
<td>Ambient pressure [bar]</td>
<td>0.5</td>
<td>1.0</td>
<td>1.18</td>
</tr>
<tr>
<td>Ambient temperature [°C]</td>
<td>60</td>
<td>60</td>
<td>120</td>
</tr>
<tr>
<td>Ambient density [kg/m³]</td>
<td>0.5</td>
<td>1.01</td>
<td>1.01</td>
</tr>
</tbody>
</table>