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1 **Spatio-temporal identification of plume dynamics by 3D computed tomography using**
2 **Engine Combustion Network Spray G injector and various fuels**

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8 **Abstract**

9 Understanding of plume direction and mixture quality in a combustion chamber is crucial to improve engine
10 performance. While a variety of diagnostics using laser and x-ray facilities have been applied to identify plume
11 direction, most applications require sophisticated experimental setup as well as troubleshooting for light attenuation
12 or scattering issues. In this study, we acquire temporally and spatially resolved liquid volume fraction by three-
13 dimensional tomographic reconstruction of ensemble-averaged extinction images to produce unique information on
14 plume movement and growth in the midst of a multi-plume spray. Measurements were carried out in a constant-flow
15 spray vessel coupled with high-speed Mie-scattering, diffused back-illumination extinction, and schlieren imaging.
16 Four different fuels, a single component iso-octane, a multi-component surrogate with di-isobutylene, a multi-
17 component fuel with olefinic molecular structure, and a [70% standardized gasoline](#) 30% ethanol (e30) blend were
18 injected using Engine Combustion Network (ECN) Spray G injector under ECN G2 (50 kPa absolute), G3 (100 kPa
19 absolute), and G3HT (G3 with 393K ambient temperature) conditions. Planar slices, available from the
20 tomographically reconstructed extinction data, confirmed greater plume-to-plume interaction for the flash-boiling G2
21 iso-octane condition with an approximately 6° smaller plume direction angle relative to the injector axis, compared to
22 the nozzle drill angle. The olefinic and e30 fuels, which have broader distillation curves, exhibited stronger plume
23 growth and eventual complete spray plume collapse and longer time for evaporation. Using the 3D dataset, we show
24 that factors that increase plume growth also create more interaction between plumes to ultimately reduce the plume
25 direction angle.

26 **Keywords:** Flash boiling; Tomographic reconstruction; Plume direction; Plume-to-plume interaction; Projected liquid
27 volume; Spray cone angle

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34 **Abbreviations**

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

35 **Nomenclature**

α_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]	φ	Equivalence ratio [a.u.]
F/A	Fuel to air ratio [a.u.]	Re	Reynolds number [a.u.]
I	Image frame with spray [a.u.]	ρ_f	Fuel density [kg/m ³]

I_o	Averaged background image [a.u.]	τ	Optical thickness [a.u.]
m_{cell}	Total mass in a cell [kg]	V_{cell}	Volume of a cell [m ³]
m_{f_l}	Liquid fuel mass in a cell [kg]	We	Weber number [a.u.]
m_{f_v}	Vapor fuel mass in a cell [kg]	x_{N_2}	Nitrogen mass fraction in a cell [a.u.]
m_{N_2}	Nitrogen mass in a cell [kg]	y	Projection direction [a.u.]

36 1. Introduction

37 Gasoline direct injection (GDI) engines have been adopted by the automotive industry over the past few years.
38 Different from conventional port fuel injection (PFI) engines, fuel is injected directly into the combustion chamber,
39 creating charge cooling and higher turbulence. These improvements mitigate knocking tendency and improve engine
40 efficiency. A combination of direct fuel injection with additional engine-operation technological enhancements such
41 as high-pressure injection, multiple injection strategies, exhaust gas recirculation (EGR) and enhanced air utilization
42 by swirl or tumble motion enable GDI engines to be operated under fuel-lean conditions with even higher efficiency
43 [1-4]. Furthermore, advanced combustion concepts such as low-temperature gasoline combustion (LTGC) and spark-
44 controlled compression ignition (SPCCI) have been considered as next-generation GDI engine technologies [5-6].
45 These concepts utilize early fuel injection during the intake stroke to form a homogeneous air-fuel mixture, followed
46 by injection during compression to create a stratified charge near the spark plug and stable flame kernel. For such
47 technologies to succeed, spray control during all stages of the operating cycle is of utmost importance. Inappropriate
48 injection parameters and fuel properties cause fuel impingement on the cylinder wall and result in unacceptable
49 particulate matter (PM) emissions [7]. Thus, understanding the direction and ultimate penetration of each liquid plume
50 of the injector under various ambient conditions and fuels is crucial to improve combustion and emission
51 characteristics.

52 Gasoline sprays exhibit a distinct topology evolution under flash-boiling conditions. Flash boiling occurs at throttled
53 or early-injection conditions when ambient pressure is lower than the saturation pressure. Rapid changes in
54 temperature and the velocity field are accompanied by a bulk conversion of fuel from liquid to vapor during injection.
55 Common observations under flash-boiling conditions are shorter liquid penetration length, enhanced atomization,
56 lower mixture temperature, and large recirculating vortex closer to the injector tip [8-10]. The ratio of ambient pressure
57 to vapor pressure (P_a/P_v) has a dominant impact on spray process under flash-boiling conditions, unlike non-flashing

58 sprays where relationship such as Reynolds number (Re) and Weber number (We) are typically used to summarize
59 spray characteristics [11-13]. A key feature of flash-boiling operation is that vapor formation commences when
60 pressure decreases as fuel flows through the nozzle, even without any fuel-air mixing or heat transfer, thereby creating
61 a wider radial dispersion of individual injector plumes. Plume dispersion increases with higher fuel temperature or
62 lower ambient pressure (i.e. lower P_a/P_v). The larger plume dispersion enhances plume-to-plume interaction and alters
63 velocity and pressure field, which may lead to deflection of the plume direction or complete combinations of plumes
64 and collapse at certain conditions of injection timings. In the previous study of Zeng et al., it was found that sprays
65 from an eight-hole injector with a nominal total spray angle of 60° had a linear increase in liquid spray width as the
66 pressure ratio decreased from 1.0 to 0.3, and finally spray collapse occurred at pressure ratios under 0.3, showing one
67 integrated large plume [14]. Flow analysis using particle image velocimetry (PIV) showed the vortex around spray
68 plumes strengthening under lower pressure cases due to enhanced momentum transfer by interaction between thicker
69 spray plumes and ambient air [15]. Plumes also move towards each other during time, accelerated by a larger pressure
70 difference between the center of the spray and the ambient air [8], and complete collapse occurs under flare flash-
71 boiling conditions.

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

85 Numerous non-intrusive optical diagnostics have been applied to investigate the internal motion of plumes and the
86 mixing process, rather than being limited to line-of-sight information. Among the techniques, laser diagnostics were
87 widely employed. In one example, the peak velocity magnitude in a spray plane measured by phase-doppler
88 interferometry (PDI) was analyzed to represent plume direction movement throughout injection [21]. Planar laser
89 imaging with corrections for multiple-scattering has been performed, however, light attenuation issues still inhibit
90 quantification [22]. On the other hand, x-ray radiography with tomographic reconstruction has been applied to identify
91 individual plume direction [23-24]. X-rays have high penetrating power and negligible scattering to enable data
92 acquisition even in the near-nozzle region, but measurements have been performed only under low-temperature
93 atmospheric ambient conditions at a few planes. A commercial optical patternator (En'Urga Inc, SETscan AP400)
94 using line-of-sight measurements along a plane has been applied to windowed spray chambers at engine-relevant
95 pressures and temperatures including intake-injection as well as late-injection conditions [25]. By rotating the injector
96 in 22.5° increments for a total of eight views over 180° rotation, sufficient data was collected to enable computed
97 tomography along the plane. The technique showed success in identifying major changes in plume position and growth
98 with variation in chamber conditions, including flash-boiling conditions. However, the technique was limited to only
99 1 kHz temporal resolution, which is essentially an average over the entire injection event [25]. Further work is needed
100 to identify the plume direction and growth under engine-like conditions with improved temporal and spatial resolution.
101 The techniques described above have drawbacks in terms of complexity in measurement, high-cost in measuring
102 equipment, laborious measurement procedures, or lower spatial and temporal resolution.

103 In this study a new three-dimensional tomographic reconstruction method using ensemble averaged extinction images
104 was developed to overcome technical issues that conventional diagnostic approaches have. This new method can be
105 applied in the entire spray domain and injection period with a much simpler setup compared to conventional laser or
106 x-ray facilities. High-speed Mie-scattering, diffused back illumination extinction, and schlieren imaging were
107 performed in a constant flow vessel using the Engine Combustion Network (ECN) Spray G injector. The primary
108 objective of this work is to understand plume direction and spatial mixing quality based on tomographically
109 reconstructed spray in three-dimensional space. Four different fuels including single component fuel iso-octane, the
110 multi-component fuel di-isobutylene, olefinic, and e30 blend were applied under flash-boiling and early injection
111 ambient conditions. The tested fuels are considered as promising alternative fuels for conventional gasoline because
112 of high research octane number (RON, 98) and production from renewable sources. Furthermore, large differences in

113 vapor pressure and distillation characteristic between fuels also provide opportunity to investigate their effects on
114 plume direction and collapse process. Augmenting interpretation of the new experimental data, in this study
115 computational fluid dynamics (CFD) simulations using CONVERGE code were also performed to estimate mixture
116 equivalence ratio effects on vaporization, as these data have not yet been acquired in the experiment.

117 **2. Test method and condition**

118 **2.1. Injector and fuels**

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

126 Four different test fuels, single component iso-octane, multi-component surrogate di-isobutylene, multi-component
127 fuel with olefin molecular structure, and e30 blend fuel were tested and their properties are shown in Table 1. Among
128 the fuels, e30 blend has the highest density, viscosity, and heat of vaporization amongst test fuels. The e30 blend has
129 the lowest energy content due to oxygenated species (30% ethanol). The vapor pressures of olefinic and e30 blends at
130 90°C are approximately 2.5 and 4 times larger than iso-octane, respectively. The effect of compositional difference
131 between fuels is illustrated in distillation and vapor pressure curves presented in Fig. 2 [27]. Ambient pressure of test
132 conditions are also presented in Fig. 2. The distillation curve of iso-octane is shown as a straight line at the boiling
133 point. A pseudo distillation curve for the di-isobutylene blend is provided, based on the boiling point temperatures of
134 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-
135 isobutylene (19.6% v/v). The curve remains relatively flat because these species have a relatively narrow range of
136 boiling point temperatures. It is noted that even though the di-isobutylene blend contains species heavier than iso-
137 octane, the vapor pressure is higher because of the existence of light species (1-hexene). On the other hand, olefinic
138 and e30 blends have light and heavy components contributing to a wide range of distillation temperature from 50°C

139 to 200°C. The large amount of light species in olefinic and e30 blends creates higher vapor pressure, and this trend is
140 maintained throughout the temperature range.

141 **2.2. Vessel system and optical setup**

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

155 A schematic of the constant-flow spray vessel is presented in Fig. 3. The vessel has an injector port and three optical
156 windows. Quartz windows which have a diameter of 130mm are installed in the three ports for optical access. Internal
157 heaters and an internal optical section are designed to be thermally isolated (with insulation) from the outer pressure
158 vessel. The designed maximum operating pressure and temperature are 150 bar and 1100 K, respectively. Water
159 cooling jackets in the wall, exhaust pipe, and the outer window ports are utilized to cool the pressure vessel, especially
160 under high ambient temperature conditions. Sprays are injected into a continuous nitrogen flow (~0.1m/s) controlled
161 by an electro-pneumatic flow controller. The rate of nitrogen flow is measured by flow meters at the upstream of the
162 vessel and at the exhaust pipe. A customized vacuum pump is used to reach sub-atmospheric conditions in the vessel.
163 The vessel pressure is measured by three different pressure transducers at the vessel inlet line, used for control and
164 appropriate pressure range. The nitrogen flow enters a heating coil surrounded by an insulator piece at the bottom part
165 of the vessel and then moves through a diffuser to enhance uniformity in the velocity and temperature field. To monitor

166 temperature distribution prior to spray events, 24 thermocouples were installed above the diffuser, under the spray,
167 and above the spray region. The vessel region corresponding to gases that mix with the spray was controlled to a given
168 target temperature. The mixture of injected fuel and nitrogen gas scavenges through the exhaust pipe at the top of the
169 vessel, replaced by a fresh charge of ambient gas before the next injection. Relevant temperature, oxygen
170 concentration, and vessel pressure are digitally recorded.

171 Two different optical setups were employed in this study. The first setup is for liquid fuel visualization by Mie-scatter
172 extinction and scattering imaging at the side and front views, respectively. The liquid-phase fuel was identified by the
173 diffused back illumination extinction imaging technique shown in Fig. 3. A high-speed green light-emitting diode
174 (LED), Fresnel lens (150mm, $f=150\text{mm}$), engineered diffuser (20°), and band pass filter (center wavelength: 527nm,
175 bandwidth: 20nm, full width-half max: 22nm) were utilized. The engineered diffuser (and collection optics) supplied
176 a homogeneous light field and suppressed beam steering by evaporation or temperature field in the vessel [29]. This
177 imaging technique is designed to collect extinction only by liquid phase fuel, but not from fuel vapor. The recording
178 was extended up to 5ms after the start of injection (SOI) to capture the entire spray development and evaporation
179 process. Normalized by incident light intensity (and other optical parameters), the side-view extinction imaging is
180 quantitative for projected liquid volume (PLV) as explained below. Mie-scatter imaging from the front view was used
181 primarily for visualization of plume-to-plume interaction effects. Here in the first optical setup, extinction and Mie-
182 scattering imaging were carried out simultaneously using two different cameras. The second optical setup is Z-type
183 schlieren imaging to capture the extent of fuel vapor penetration along a line of sight [30]. An effective point source
184 was created using light from a red LED (500ns duration) collected by lens (Nikkor, 50mm $f/1.8$) and then focused
185 through an aperture (0.6mm diameter). The expanding light collimated by a concave mirror (GSO, 152mm $f/6.0$) and
186 the parallel rays of light passed through spray region. The parallel light after the spray was then collected by an
187 identical concave mirror, with knife-edge ($\sim 50\%$ cut-off) was located at the focal point to enhance sensitivity. Table
188 2 lists detailed values for optical imaging setup.

189 **2.3. Image processing method**

190 **2.3.1. Extinction image and tomographic reconstruction**

191 [Liquid characterization using projected liquid volume \(PLV\) through](#) extinction imaging is highly recommended by
192 the ECN community. [Thresholding with a certain PLV provides a great potential to resolve experimental issues.](#) In

193 the past, liquid penetration was usually measured by Mie-scattering imaging and arbitrary thresholding, associated
194 with high uncertainty [31]. At the same time, an arbitrary threshold value based on pixel intensity was utilized so
195 liquid length can be varied according to optical setup and research institute even if the spray test was performed under
196 identical target condition. Therefore, extinction imaging with diffused backlit was suggested to measure optical
197 thickness, not scattered light intensity as in Mie-scattering imaging. Using optical thickness rather than Mie image is
198 much more universal and it enables direct comparison with CFD simulation result. At first to acquire PLV, the optical
199 thickness in a spray region can be calculated based on Beer-Lambert law as equation (eq-1).

$$200 \quad \tau = -\ln(I/I_o) \quad (\text{eq-1})$$

201 Where I is transmitted light intensity with extinction (from droplets) and I_o is incident light intensity without
202 extinction. This level of transmission is reasonable for detection of spray “edge” above the noise floor of the camera,
203 but considerations such as vapor-phase beam steering need consideration [29].

204 The measured optical thickness τ may be related to the PLV, which is the integral of liquid volume fraction (LVF)
205 along the cross-stream direction y , as

$$206 \quad \text{PLV} = \tau \frac{\pi d^3/6}{C_{ext}} = \int_{-y_\infty}^{y_\infty} (\text{LVF}) \cdot dy \quad (\text{eq-2}).$$

207 Mie scattering and extinction theory is applied in eq-2, along with the simplifying assumption that droplet diameter
208 d and extinction coefficient C_{ext} (which depends upon d) do not vary along the line of sight. The PLV has units of
209 liquid volume per projected area, or $\text{mm}^3(\text{liquid})/\text{mm}^2$, and may be easily calculated from CFD simulations for
210 comparison to experiment. However, the experimentalists must have access to information about d and C_{ext} to
211 estimate PLV. In particular, C_{ext} depends upon droplet size, wavelength of light, and collection angle of the receiving
212 optics (e.g. some forward-scattered light is collected). Fortunately, droplet diameter measurements have been
213 performed for Spray G by ECN participants at General Motors and Shanghai Jiao Tong University using phase-doppler
214 interferometry (PDI) [26]. The measurements show an SMD near $7\mu\text{m}$ with fair uniformity across the plume during
215 injection, which justifies the assumption to use single values for d ($7\mu\text{m}$) and C_{ext} ($72.70 \cdot 6 \text{ mm}^2$, from Mie-theory
216 relations using experimental collection angle of 69.3mrad , light wavelength of 527nm , refractive index of 1.391 and
217 $7\mu\text{m}$ droplet diameter, MiePlot available at [32] was used). Note that droplet size measurements were performed only
218 upstream at one axial position (at $z = 15 \text{ mm}$). We make use of these droplet size measurements only during injection

219 because droplets produced upstream during injection constitute the majority of droplets in the domain—they are
220 transported downstream and reside after injection has ended. [We will discuss uncertainties associated with the droplet](#)
221 [size assumptions in the Appendix section.](#)

222 For the macroscopic spray characterization, a threshold for PLV may be chosen to indicate the extent of liquid
223 penetration and width. The ECN recommends thresholds of $0.2 \cdot 10^{-3}$ or $2 \cdot 10^{-3} \text{ mm}^3(\text{liquid})/\text{mm}^2$ [33]. [This is correlated](#)
224 [to past definitions of liquid length \(3% of maximum intensity in Mie-scattering image, optical thickness of 0.374 by](#)
225 [laser-derived measurement \(Please refer to \[34-35\]\)](#) In this study, the lower threshold value of $0.2 \cdot 10^{-3}$
226 $\text{mm}^3(\text{liquid})/\text{mm}^2$ was applied to process and binarize PLV images according to this threshold value. In the binarized
227 image, liquid penetration length was defined as the farthest axial distance from the nozzle at the primary view point
228 (0° rotation angle) and the spray liquid width was measured at axial distances of 15mm and 25mm away from the
229 nozzle tip.

230 Ensemble-averaged PLV data from 300 injections at [three different viewing angles](#) were utilized for tomographic
231 reconstruction. Fig. 4 indicates extinction images at three different views and corresponding PLV images in the
232 middle. The built-in ‘iradon’ function in Matlab was used for tomographic reconstruction, using a Hamming filter
233 value of 0.7. It is noted that reconstruction routine creates artifacts in optically thick region so each individual plumes
234 could not be identified for near nozzle spray ($\sim z=5\text{mm}$), however, comparison with x-ray data revealed that it predicts
235 plume center correctly at $z=12\text{mm}$. For the first step, PLV data at a certain location (presented as line in the PLV
236 images) need to be extracted and placed in a map shown at the bottom of the figure. Because of the limited injector
237 turns, the data within the viewing angle was interpolated and then the data out of viewing angle was extrapolated by
238 using the map from 0° to 22.5° . The interpolation and extrapolation were performed by linearly-weighted averaging.
239 Through this method, a projection map from 0° to 180° is generated for each axial position. After tomographic
240 reconstruction, a three-dimensional liquid volume fraction distribution is generated at each time after the start of
241 injection. The detailed description and validation of reconstruction method can be found in [36], including
242 confirmation of the process using synthetic model data for liquid volume fraction.

243 **2.3.2. Schlieren image**

244 Schlieren images under high-pressure and high-temperature conditions are sensitive to fuel vapor (with a different
245 refractive index than the ambient), however, non-uniformities in refractive index created by window thermal boundary

246 layers must also be considered [37]. The problem is especially severe if the window thermal boundary layer moves
247 during injection, making image normalization at the beginning of injection unsuitable for processing. However, in the
248 present study an image correction before the start of injection was sufficient to identify the jet vapor boundary. The
249 image processing routine for schlieren results is shown in Fig. 5(x). First (a), the spray was isolated from the initial
250 background I_o by subtracting spray image I from I_o . (b) The vapor envelope was identified by using the Matlab
251 ‘imgradient’ function, returns the spatial gradient magnitude. (c) The gradient magnitude was binarized with a certain
252 threshold value and (d) the area inside the vapor boundary (where gradient magnitude is low because of liquid spray)
253 was filled to create a single, connected vapor boundary (e), produced using the ‘bwperim’ Matlab function and
254 presented as red line in Fig. 5(e) as a visual check of the process. Vapor penetration length is defined at each time and
255 injection as the distance between the nozzle tip and the farthest axial length on the boundary. (f) A vapor probability
256 map was also derived using results from multiple injections. For 100 injections, the binarized image (d) from each
257 injection and time step was summed to represent the probability percent. The region between 0 to 100 represents a
258 zone of intermittency for low fuel mixture fraction, which can be evaluated with some rigor when compared to CFD.

259 **2.4. Computational setup**

260 Lagrangian parcel spray simulations using CONVERGE (v2.4) were performed to estimate mixing effects
261 (equivalence ratio) on evaporation and overall spray development. The simulation work in this study mainly used
262 default CONVERGE settings for an example Spray G case, so only a brief review of the setup is provided here. The
263 injector specifications for the 8-hole nozzle are given in Fig. 1. The modified settings from the example case were
264 plume cone angle (25°), plume direction angle (34°), domain size (to enlarge without wall impingement), and
265 turbulence model. [Initial values for the plume cone angle and plume direction angle eventually used for the simulations](#)
266 [were determined by comparing the liquid-penetration predicted values with the experimentally derived PLV values.](#)
267 Simulations were performed for Spray G conditions using iso-octane as fuel at ambient conditions matching the
268 experiment. Following the Spray G work of Saha et al. [38], Reynolds averaged Navier-Stokes (RANS) standard k- ϵ
269 model was used instead of the large-eddy simulations (LES) example case. Beginning with blob injection at the size
270 of the nozzle, O’Rourke dispersion, Kelvin-Helmholtz (KH) and Rayleigh-Taylor (RT) models were used to capture
271 turbulent dispersion, primary and secondary breakup, respectively, while the Frossling model is used for evaporation.
272 An injection rate profile provided by ECN was used for the simulation [26]. The simulation time was extended up to

273 5ms after start of injection (SOI) to match with experimental data. The computational domain and detailed setting for
274 simulation are presented in Fig. 6 and Table 3, respectively.

275 **2.5. Operating conditions**

276 The spray experiments were carried out under ECN Spray G2 (flash-boiling), G3 (early injection), and G3HT (G3
277 with elevated temperature conditions). As per ECN Spray G standard, an electronic injection command with a duration
278 of 680 μ s (780 μ s actual hydraulic duration) was delivered to inject 10mg of fuel with injection pressure of 200 bar.
279 The temperature of injector tip was maintained by a water circulator at 90°C during entire experiments. The ambient
280 temperature was set to 60°C for G2 and G3 condition, but increased to 120°C under G3HT condition. The ambient
281 pressures were 0.5 bar, 1 bar, and 1.18 bar for G2, G3, and G3 HT, respectively. Corresponding ambient densities
282 were 0.5 kg/m³ for G2, and 1.01 kg/m³ for G3 and G3HT conditions. Three different injector viewing angles were
283 applied and the spray was repeated 300 times per case for extinction imaging. The schlieren imaging was repeated for
284 100 injections at the primary viewing angle. The experimental conditions are summarized in Table 4.

285 **3. Results and discussion**

286 **3.1. Effects of ambient condition on macroscopic spray characteristics**

287 Providing a general overview of the baseline iso-octane sprays, the liquid and vapor envelopes under G2, G3, and
288 G3HT conditions are presented in Fig. 7 ([Data available at \[39\]](#)). Recall that the liquid and vapor results here are
289 derived from ensemble averaging many different injection events. The liquid boundaries determined with PLV
290 threshold of 0.2·10⁻³ mm³(liquid)/mm² are compared according to ambient conditions with vertical lines indicating
291 liquid penetration length in Fig 7(a). Fig. 7(b) shows vapor boundary (dotted) with 20% intermittency and liquid
292 boundary (solid) as defined above. The quantitative comparison of liquid penetration length and liquid width is given
293 in Figs 7(c) and 7(d). [In the plots, standard error \(-2 \$\sigma\$ / \$\sqrt{n}\$ to +2 \$\sigma\$ / \$\sqrt{n}\$ \) of the data is shown as a shade area. Error](#)
294 [analysis showed that shot-to-shot variations in spray penetration and width converged after 100 injections.](#) Results
295 from the CFD simulation were also analyzed by applying the identical PLV criteria as the experiment, and results for
296 the G2 condition are shown for simplicity.

297 Analysis of macroscopic spray characteristics shows that the spray under G3HT condition evaporates much faster than
298 G2 and G3 conditions, which is expected because of the higher ambient temperature. Higher ambient density also

299 tends to slow vapor penetration, and results are indistinguishable for G3 versus G3HT. Higher ambient temperature
300 confines liquid to a smaller radial width, which also eventually applies to axial penetration. However, the more
301 remarkable effect is that after liquid penetrates to approximately the same maximum axial position, [the time of](#)
302 [complete evaporation](#) to the PLV criteria is much earlier for G3HT (about 2 ms aSOI) compared to that of G3 (about
303 3.5 ms aSOI). The vapor envelope is similar for either G3 or G3HT conditions. The G2-condition spray shows the
304 longest vapor penetration length, which is expected because of the lower ambient density. Liquid penetration is also
305 the longest, despite the enhancement in vaporization expected for the G2 flash-boiling condition. The spray boundary
306 images and liquid width measurements indicate a transition in spray mixing at some point. While the near nozzle spray
307 outline (refer Fig. 7(a)) under G2 and G3 conditions is similar at 0.5 and 0.8ms, contraction of the spray in radial
308 direction begins under flash-boiling G2 conditions, leading to smaller liquid width than the G3 condition. Factors such
309 as potential for a larger individual plume growth for G2 condition and overall 3D liquid plume movement deserve
310 consideration, and we will discuss these issues after 3D data are presented.

311 [One of the most interesting](#) results from the macroscopic liquid spray parameters is the extended persistence of liquid
312 in both space and time, particularly for the flash-boiling G2 condition with liquid persistence exceeding 3 ms. The
313 long persistence of liquid time under G2 and G3 conditions, even with heated fuel and somewhat elevated gas
314 temperature, is considered significant time scale in an engine system. There is clearly enough penetration distance and
315 time for liquid to impinge upon in-cylinder surfaces during intake injection in an engine. To gain some physical insight
316 into factors affecting vaporization, we perform a thermodynamic analysis for different mixtures (equivalence ratio),
317 guided by CFD simulations for prediction of these mixtures.

318 Equilibrium-state calculations are performed with liquid and vapor fraction predictions for different mixtures, using
319 standard energy and fugacity balances for liquid fuel and gas initially at the conditions of the experiment. [This](#)
320 [calculation predicts the mixture composition \(solution\) and temperature according to equivalence ratio. For example,](#)
321 [a small amount \(low equivalence ratio\) of liquid fuel at fuel temperature of 90°C under G2 condition \(0.5bar, 60°C\)](#)
322 [will be evaporated. In this process, heat is absorbed due to phase change, thus mixture temperature decreases.](#)
323 [However, achieving complete evaporation under high equivalence ratio is not possible, thus, a certain amount of liquid](#)
324 [will persist. In other words, the term ‘solution’ refers to vapor only or liquid/vapor mixture under complete and](#)
325 [incomplete evaporation conditions, respectively.](#) The calculation result shown in Fig. 8 present the equilibrium

326 mixture temperature according to a given equivalence ratio for G2, G3, and G3HT conditions. If the solution is for
 327 entirely vapor, a dashed line is indicated. If the solution shows a mixture with both liquid/vapor present, a solid line
 328 is used. The transition point is a saturated vapor-liquid equilibrium mixture. If vaporization is driven entirely by
 329 mixing, and perfect equilibrium mixtures are formed, no liquid will exist at equivalence ratios less than this transition.
 330 While this assumed state is unlikely in a dynamic spray, this very assumption has been applied with encouraging
 331 results at diesel conditions at higher temperature and pressure [40]. Fig. 8 shows that the rank ordering for saturated
 332 equivalence ratio is in agreement with the experiment in terms of vaporization time. But it also shows that substantial
 333 vaporization cooling occurs under all conditions. Fuel initially at 363 K and ambient initially at 333 K cools below
 334 300 K at saturated conditions, and the cooling is more substantial for the flash-boiling condition. Moreover, an
 335 equilibrium condition with liquid exists even for flash-boiling conditions. Therefore, it is not surprising to observe
 336 liquid for an extended period of time as even equilibrium calculations show a liquid state provided that the mixture
 337 equivalence ratio is rich enough.

338 CFD simulations are utilized to estimate the actual equivalence ratio, in comparison to equilibrium expectations. Fig.
 339 9 shows mixture total equivalence ratio (considering both liquid and vapor) predictions both during and after injection
 340 at positions where liquid is observed in the experiment. The images present equivalence ratio at two different planes
 341 and timings after start of injection (aSOI) timings. The Lagrangian parcel simulation does not provide total (liquid and
 342 vapor) fuel-air ratio by default, so it was calculated using cell mass, mass fraction, volume fraction of parcel in a cell,
 343 cell volume, and fuel density, as shown by equation (3) to equation (5) below

$$344 \quad m_{f_v} = m_{cell} - m_{N_2} = m_{cell} - m_{cell} \cdot x_{N_2} \quad (\text{eq-3})$$

$$345 \quad m_{f_l} = V_{cell} \cdot \alpha_p \cdot \rho_f \quad (\text{eq-4})$$

$$346 \quad \varphi = \frac{(F/A)_{actual}}{(F/A)_s} = \frac{(m_{f_v} + m_{f_l})/m_{N_2}}{(F/A)_s} \quad (\text{eq-5})$$

347 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}
 348 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, α_p is a
 349 volume fraction of parcel in a cell, and ρ_f is a liquid fuel density. Even though the simulations and experiments are
 350 for mixing of fuel with nitrogen, we convert to equivalence ratio as if the mixture were pure air to provide a more
 351 intuitive sense of the mixture using equation (5) where φ is an equivalence ratio, F is a fuel mass in a cell, A is a

352 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
353 was used). In fact, the equilibrium calculations shown in Fig. 8 are also for nitrogen-fuel mixtures, but are presented
354 as equivalence ratio also using equation (5).

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

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

374 **3.2. Effects of ambient condition on plume direction**

375 The availability of three-dimensional LVF data, created by tomographic reconstruction of line-of-sight PLV data,
376 enables detailed analysis of the radial and axial movement of individual plumes. Figure 10 showed a snapshot of the
377 LVF data for the G2 condition at only two timings, but the overall motion of the plumes for other axial positions and
378 timings is available for analysis. Outlines of the liquid spray with a LVF threshold of $0.5 \cdot 10^{-3}$ are presented along the

379 Y-Z cut plane in Fig. 11 for iso-octane at G2, G3, and G3HT conditions. It is emphasized that the threshold of $0.5 \cdot 10^{-3}$
380 corresponds to LVF and should not be confused with the threshold of $0.2 \cdot 10^{-3} \text{ mm}^3(\text{liquid})/\text{mm}^2$ set for PLV in
381 Fig. 7. Error analysis showed that more than 100 injections were sufficient to acquire converged data (no variation in
382 plume direction angle and LVF according to number of injection) with low noise. The contours are given at several
383 timings aSOI, but full movies of the same data are available to view at [41]. The nozzle drill angle is indicated as a
384 grey dotted line that forms a 37° from the injector axis (refer Fig. 1 for injector Z-axis). The macroscopic spray
385 characteristics discussed using PLV results in the last section are consistent with the planar data cutting directly
386 through plume centers (Y-Z plane cuts through centers of Plumes 3 & 7). For example, the faster evaporation for
387 G3HT and longer axial liquid penetration for G2 conditions is easily shown along the plane. What is more clearly
388 manifested in cut plane data, however, is the G2 condition plumes deflect more to axis centerline. Plumes at all
389 conditions contract towards the centerline with increasing time aSOI, departing from the hole drill angle, but the
390 deflection is higher for G2 conditions. One effect of the plume direction contracting in time, even prior to the end of
391 injection, is that plumes show a curved or bent shape, retaining a ‘memory’ of the earlier plume direction but also
392 contracting towards the injector axis.

393 A quantitative measurement of the plume direction angle is provided by defining the plume center as that with near-
394 maximum LVF. The maximum is a justified choice because it removes artifacts created by plumes that are not
395 orthogonal to an axial plane, as is the case for Spray G [36]. For example, rotated ideal-distribution (Gaussian) plumes
396 defined with center at full-width at half maximum have a bias towards a larger plume direction, and one that does not
397 correspond to the actual center. We therefore define plume center as the mean of 99% peak LVF positions to eliminate
398 this bias, and compute a plume direction back to the hole origin from this center. Results are shown in Fig. 12 for data
399 analyzed at $Z = 30\text{mm}$ from the nozzle tip. As the plume arrives at 30 mm, the plume direction angle is already
400 approximately 3° smaller as compared to the drill angle regardless of ambient conditions. The plume direction angle
401 of G3 and G3HT are more or less the same, while it contracts by several degrees for the G2 condition during injection,
402 and more so after the end of injection—results that are consistent with data rendered on a plane in Fig. 11. These
403 results show a greater degree of plume movement towards the centerline, but not complete spray collapse at G2 (flash-
404 boiling) conditions. The Mie-scattering images presented at the top of the figure show greater plume growth and more
405 plume-to-plume interaction with smaller area between plumes at G2 conditions. The quantitative measurement of
406 plume cone angle will be discussed in Section 4.

407 Adding understanding of the plume dynamics between conditions, we show LVF values on the $z=30\text{mm}$ X-Y plane
408 and the average through the center of all eight spray plumes as a function of radial position in Fig. 13. A more narrow
409 spacing between plumes is shown in the X-Y plane at G2 conditions. G3 and G3HT conditions also show some LVF
410 between plumes, but at lower intensity. The averaged LVF radial profiles given in Fig 13 (b) show that peak LVF
411 during injection (solid lines) is only slightly less for G2 conditions compared to G3 conditions but there are greater
412 differences after the end of injection (dashed lines), once more confirming a faster final vaporization for G2 conditions.
413 The LVF radial shift towards the centerline for the G2 condition is pronounced during and after injection. As part of
414 the general collapse of the spray, plumes clearly merge together more rapidly for the G2 condition with individual
415 plume structure between plumes nearly absent by 1.07 ms aSOI. The LVF peak at G2 conditions also translates
416 approximately 4mm from that at 0.54 ms aSOI, compared to only 1-2 mm shift for G3 or G3HT conditions. While
417 lacking a complete collapse and mixing to the injector axis, all indications are that plume collapse is more severe for
418 the G2 condition than other cases. Recall that G2 and G3HT condition did not show noticeable difference in spray
419 liquid width in Fig. 7(d), movement in plume center under G2 condition is considered as substantial change. This
420 result suggests that plume contraction had a dominant role for smaller spray liquid width for G2 condition, on the
421 other hand, similar result was derived by faster evaporation under G3HT condition as it shows much lower peak of
422 LVF than G2 condition.

423 3.3. Effect of fuel on macroscopic spray characteristics

424 Experiments were performed for the entire Table 4 test matrix, but for brevity, we show the effect of fuel type on
425 macroscopic spray properties only at the G2 condition. At this experimental condition, the pressure ratios (P_a/P_v) are
426 0.17, 0.29, 0.67, and 0.71 for e30, olefinic, di-isobutylene, and iso-octane, respectively. Using the same definitions
427 for liquid and vapor penetration used above (see Fig. 7), a comparison between fuels is provided in Fig. 14. Generally,
428 the overall spray morphology of iso-octane and the di-isobutylene blend is similar to each other since they showed
429 minor differences in fuel properties. The statistical data in Figs 14 (c) and (d) showed slightly longer liquid and vapor
430 penetration lengths for di-isobutylene but the difference is still minor. However, distinct differences in fuel spray
431 characteristics are found for olefinic and e30 blends. The e30 blend shows a shorter penetration length and a narrower
432 liquid width at the beginning of injection, accompanied by wider radial dispersion at 15 to 25 mm axial positions. But
433 e30 eventually overtakes the other fuels in axial liquid and vapor penetration after 1.5ms aSOI. The olefinic fuel is

434 somewhat intermediate to e30 and the lighter fuels in terms of maximum axial liquid penetration, and in the contour
435 of PLV plot that shows a clustering of liquid towards the center. The olefinic and e30 blends have significant times
436 for persistence of liquid, to 4.9ms and over 5ms, respectively, despite heated fuel (90°C) as an injection boundary
437 condition. The slower evaporation of e30 is entirely expected because of the extensive vaporization cooling associated
438 with its heat of vaporization compared to other fuels, as well as the presence of heavy species in the multi-component
439 blend compared to single-component surrogates with lower distillation temperature. However, we will show below
440 that e30 vaporization is also affected by impaired mixing because of plume collapse.

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

444 **3.4. Effect of fuel on plume direction**

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

454 The LVF boundary at 1.26 ms aSOI highlights the strong differences in liquid distribution for each fuel. While iso-
455 octane and di-isobutylene have evaporated to lower LVF concentrations by the timing, the olefinic and e30 blends
456 show significant liquid remaining near the centerline. One reason for the persistence of liquid is the high boiling point
457 constituents, and high heat of vaporization (e30), but a second contributing factor is that fuel plumes are clustered
458 together at the center and experiencing poor mixing. A complete merging of plumes (spray collapse for e30) creates
459 a merged jet with cumulative momentum higher than that of individual plumes, and this can also explain the greater
460 axial penetration for e30, along with greater potential for liquid impingement on engine wall surfaces. The significant

461 departure of liquid from the original drill angle projection (dashed line) is an indication of how different the fuel
462 delivery becomes under spray collapsing scenarios. We emphasize that the 3D diagnostic for local LVF provides this
463 level of detail and new understanding.

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

475 The fuel effect on plume collapse is illustrated with even more detail by considering results along the X-Y plane in
476 Fig. 17, with analogy in presentation to Fig. 13. Fig. 17(a) shows significant plume-to-plume interaction for the
477 olefinic and e30 blends during injection at 0.54 ms aSOI, illustrating a symptom of spray collapse. A close look also
478 shows higher LVF between plumes for di-isobutylene compared to iso-octane, potentially indicating slightly more
479 plume-to-plume interaction leading to the subtle decrease in plume direction for di-isobutylene compared to iso-
480 octane. The LVF distributions across plumes presented in Fig. 17(b) shows wider plumes for the olefinic and e30
481 blends compared to the lighter fuels at 0.54 ms, indicating distortion and stretch towards the center. Plume direction
482 (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
483 centerline, indicative of full spray collapse and undefined plume direction for these fuels (see Fig. 16). Interestingly,
484 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
485 is an expectation for further dilution with time. This rising LVF in time can only be accomplished if mixing with air
486 is impaired, as is the case for central collapse for all plumes. By contrast, at 1.07 ms LVF decreases quickly and
487 significantly for iso-octane and di-isobutylene, assisted by ambient gas surrounding each of the eight separated plumes.

488 A comparison of the overall spray processes between iso-octane and e30 blends is exhibited in Fig. 18. Mie-scattering
489 images are shown at the top and the 3D LVF maps rendered in transparency are given at the bottom. The Mie-scattering
490 images from the iso-octane indicate light plume-to-plume interaction, not severe enough to induce complete collapse.
491 On the other hand, the e30 blend suffers from strong plume collapse from the beginning, so that each plume could not
492 be identified. At 0.1ms aSOI, e30 shows specific patterns in Mie-scattering images, but these patterns are not created
493 by individual plumes. Rather, the strongest signature is at the position bisecting the plume position, as if the injector
494 were rotated. This observation is another indication of strong plume-to-plume interaction. The Mie-scatter images and
495 3D LVF images show significant liquid at the jet centerline by 0.5ms aSOI, consistent with Fig. 15. The complete
496 spray collapse to the center and rollup of the head vortex for e30 are illustrated dynamically in the 3D LVF images
497 (and movie available at [41]).

498 **4. Plume vapor cone angle**

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

507 To accomplish this goal, we use the vapor boundary from line-of-sight schlieren imaging, in concert with the plume
508 center measured from 3D tomographic reconstruction, to obtain the plume vapor cone angle. The process is illustrated
509 schematically in Fig. 19. While schlieren imaging only measures the outer vapor envelope of two plumes (Plumes 3
510 and 7 in the primary 0° rotation view), the average plume center and average vapor envelope can be combined to
511 approximate vapor plume cone angle. The plume vapor cone angle was measured near the nozzle at $z=8.5$ mm to
512 avoid distortion from the head vortex zone shown in the figure. Fig. 19 shows a schematic diagram in which the vapor
513 boundary with 0.5 intermittency is presented as red solid line. Averaged plume centers (from 3D LVF analysis) are
514 also indicated as triangles on the line of plume direction (dotted blue lines). A line orthogonal to the plume direction

515 angle intersects the vapor boundary and is shown with a circle. At this moment, the angle formed by two lines, circle
516 to orifice outlet and averaged plume center to orifice outlet, can be considered as half of the plume vapor cone angle.
517 Combining the measurement of plume center (via 3D tomographic reconstruction) and vapor envelope offers a new
518 technique to measure plume vapor cone angle in realistic multi-plume GDI sprays. A technique to measure plume
519 cone angle, rather than total spray angle or width, is critical because interaction and merging between plumes also
520 affects total spray angle or width.

521 The measured plume vapor cone angle presented in Fig. 20 (a) is an average value from top and bottom plumes during
522 200 μ s to 680 μ s aSOI for all conditions and fuels. As can be seen, the pressure ratio has a significant effect on plume
523 cone angle, which has been observed in past single-hole studies [42]. A strong inflection occurs near a pressure ratio
524 of 0.5. Fuels with a high portion of light species have high P_v and lower pressure ratio (P_a/P_v), and are more susceptible
525 to higher plume growth. As shown in earlier sections, conditions with higher plume growth also show more tendency
526 for spray collapse, as confirmed by 3D LVF measurements, generating the hypothesis that initial plume growth is a
527 key factor for spray collapse. With measurement of both plume direction and plume cone angle, facilitated by the 3D
528 measurements of this study, we can investigate this hypothesis through a correlation between these two quantities.
529 Fig. 20 (b) shows plume direction angle measured at $z=30$ mm and 0.37ms aSOI according to averaged plume vapor
530 cone angle presented in Fig. 20 (a). This result clearly shows that smaller plume direction angle, as a sign of more
531 plume-to-plume interaction, is induced by a larger plume vapor cone angle over a broad range of conditions and fuels.
532 For example, under G3 conditions the e30 blend (purple triangle) has a slightly smaller plume vapor cone angle and
533 a corresponding larger plume direction angle than the olefinic fuel under G2 conditions (orange circle). Subtle effects
534 such as the greater plume interaction and smaller plume direction for di-isobutylene compared to iso-octane are also
535 consistent with lower pressure ratio and greater plume cone angle for di-isobutylene. While the conclusion and relation
536 of greater spray growth with lower pressure ratio is consistent with past literature observations for single-hole injectors
537 [42], or in some cases multi-hole nozzles [43], we emphasize that this study is the first to provide measurement of
538 individual plume growth, rather than total spray angle, for realistic multi-plume GDI sprays.

539 **5. Conclusion**

540 In this study, a series of high-speed Mie-scattering, extinction, and schlieren imaging was carried out in a constant-
541 flow spray vessel under G2, G3 and G3HT conditions, consistent with realistic intake-injection conditions in an

542 engine. Four different fuels: iso-octane, di-isobutylene surrogate, olefinic, and a 30% ethanol blend were injected
543 using an ECN Spray G 8-hole injector. CFD Lagrangian parcel simulations were also performed to understand mixing
544 and liquid residual time. We applied computed tomographic reconstruction using extinction imaging to measure the
545 3D liquid volume fraction of all plumes, and schlieren imaging to identify the vapor boundary for some of the plumes.
546 Measurements of individual plume dynamics were resolved in time and space, and include statistics such as plume
547 direction angle, plume cone angle, liquid penetration, vapor penetration, and so forth. The dataset offers unique
548 information on plume growth and movement in the midst of a realistic multi-hole spray, and are available to
549 view/download [41]. The major findings from this study as follows.

550 1) Liquid persists under a flash-boiling G2 condition for more than 3ms even with iso-octane fuel, showing a
551 longer liquid penetration than the non-flashing G3 condition and enough time and penetration distance to
552 cause liquid impingement in engine. Equilibrium mixture calculations can explain the long persistence at G2
553 conditions as liquid is expected if mixtures have an equivalence ratio greater than a value of four. At 30 mm
554 downstream of the injector, CFD simulations predict mixtures with $\varphi > 4$ during injection, but $\varphi < 4$ at
555 0.4 ms after the end of injection, even though liquid is measured and predicted at this same time. These data
556 support the notion that the system is not mixing-limited or at equilibrium. Fuels containing heavy species
557 such as olefinic and e30 showed even longer liquid residual time, up to the end of the experimental acquisition
558 at 5ms, which is likely to cause piston/cylinder wetting.

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

- 568 3) Plume vapor cone angle measurements were made possible in a multi-plume spray by a combination of 3D
569 liquid distribution measurements to find the plume center, combined with schlieren imaging to find the vapor
570 boundary for two of the plumes. The plume cone angle with various fuels and conditions shows a strong
571 inflection at a pressure ratio of 0.5 (P_a/P_v), or where the ambient pressure is half of the vapor pressure. The
572 plume vapor cone angle increases sharply at a pressure ratio less than 0.5.
- 573 4) Strong plume interaction and collapse may leave high liquid fuel concentrations in the spray core region. For
574 a volatile 30% ethanol fuel (e30) at flash-boiling conditions, peak fuel concentration actually increases after
575 the end of injection, as the result of plume combination and collapse during injection.

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677 **Appendix**

678 In this section, effects of droplet-size distribution on projected liquid volume, liquid volume fraction, and plume
679 direction will be discussed. First, PLV was calculated according to different droplet diameters as shown in Fig. 21.
680 An optical thickness of 0.081, which corresponds to PLV of $0.2 \cdot 10^{-3} \text{ mm}^3(\text{liquid})/\text{mm}^2$ for $7\mu\text{m}$ droplet diameter was
681 held constant in the calculation. According to eq-2, and demonstrated in Fig. 21, the calculated PLV for the same
682 optical thickness decreases nearly linearly with droplet diameter. Thus, the actual liquid envelope, defined with PLV
683 of $0.2 \cdot 10^{-3} \text{ mm}^3(\text{liquid})/\text{mm}^2$ would shrink if droplet diameter is smaller than $7\mu\text{m}$, or it would grow if droplet diameter
684 is larger than $7\mu\text{m}$. We note that droplet sizing measurements for ECN Spray G show a rather flat distribution when
685 spanning the radial position within the plume [36]. Droplet size decreases from $10\mu\text{m}$ to about $7\mu\text{m}$ at the edge of the
686 plume, so our assumption of $7\mu\text{m}$ droplet size had the best application for positions at the jet periphery. However, as
687 droplet size is not measured for all conditions and fuels, we can consider the likely scenario of decreasing droplet size
688 (from vaporization) at the spray periphery. For example, using the standard criteria of PLV of $0.2 \cdot 10^{-3}$
689 $\text{mm}^3(\text{liquid})/\text{mm}^2$, liquid penetration and width decrease by about 5% if droplet diameter decreases from $7\mu\text{m}$ to $2\mu\text{m}$,
690 at $Z=15\text{mm}$ and 0.78ms aSOI under G2 condition.

691 We also note the significant uncertainty associated with droplet size for prediction of LVF through tomographic
692 reconstruction. Even though we used a value of $7\mu\text{m}$ from direct measurements, there is some measured variation in
693 droplet size towards larger droplet sizes (about $10\mu\text{m}$) at the plume centerline. Should $10\mu\text{m}$ be a more appropriate
694 assumption, the LVF at the plume center would increase by 30%. However, experimental measurements to date are
695 limited, leading to significant uncertainty were the droplet sizes to vary from our assumptions. Fig 22 indicates the
696 effect of droplet diameter on LVF predictions with droplets as large as $20\mu\text{m}$ or as small as $1\mu\text{m}$ [36]. While the peak
697 liquid volume fraction value changes depending upon the droplet size, the experimental measurements of droplet size
698 to date do not show a significant change in droplet size with radial position that would cause an incorrect determination
699 of the plume center, and plume direction. However, we recommend that droplet size distribution measurements be
700 performed for as many locations as possible during the entire spray process, while working to overcome challenging
701 limitations with respect to optically thick or optically thin (overly dilute) regions of the fuel spray in the complex
702 vaporizing environment.