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OPTICAL INVESTIGATION OF SPRAY CHARACTERISTICS FOR LIGHT FUEL OIL, KEROSENE, HEXANE, METHANOL, AND PROPANE

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9 ABSTRACT

10 The present study investigates fuel spray penetration and opening angles for EN 590 light fuel oil, kerosene, hexane, methanol, and propane. Furthermore, droplet sizes are studied for methanol and 11 light fuel oil sprays from a single location at the edge of the sprays. The fuels were injected from a 12 marine-size common rail diesel injector to a spray chamber filled with nitrogen, and the results 13 were based on the analysis of shadow images. The results indicated that propane sprays would 14 penetrate slower and less than the sprays of the other fuels, but that the differences are decreased 15 and finally almost disappeared when increasing chamber density. Apart from the lowest tested 16 17 chamber density of 1.2 kg/m³, propane formed significantly narrower sprays than the other fuels. With the exception of propane, the fuels had mostly similar responses to increased chamber 18 densities. Variations between repetitions were large in relation to the differences in average values 19 20 between the liquid fuels. Concerning droplet size measurements, the results suggested that methanol 21 sprays would be characterized by slightly smaller droplet sizes than LFO sprays in the tested conditions. This finding is in line with an earlier study, albeit the found differences were smaller. 22

Keywords: Alternative fuel, kerosene, hexane, methanol, propane, image analysis, spray geometry,
 spray penetration, spray angle, droplet size

25 **1 INTRODUCTION**

26 Over the past decades, the awareness of harmful emissions related to internal combustion engines has increased considerably. Together with other aspects, such as resulting emission regulations, this 27 has driven the research of alternative fuels that would be characterized by cleaner combustion and 28 29 thus lower emissions. Due to their chemical compositions, methanol and propane enable clean 30 combustion and low particulate emissions, which justifies their further research as motor fuels. Moreover, methanol can be seen as a potential biofuel (Dave 2008, Dolan 2010) that is capable of 31 32 increasing the efficiency of spark-ignited engines (Brusstar et al. 2002, Nguyen et al. 2018). As this study focuses on diesel-type direct injection, light fuel oil (LFO) used in diesel engines will 33 function as a primary reference fuel. Being used in aviation, kerosene is slightly lighter distillate 34 than LFO and is included to the experiments in order to investigate the possible effects of slight 35 36 changes in fuel properties. Hexane, on the other hand, has a known composition with five isomers 37 and is a lighter distillate than kerosene but heavier than gaseous propane. As presented in the subsequent chapter, all these fuels have different viscosities, densities, and surface tensions, which
suggests that their sprays might have different characteristics. In this study, the fuels are injected
from a high-pressure common rail diesel injector.

Macroscopic spray characteristics are typically described by tip penetration and opening 41 42 angle. Particularly in compression-ignited engines, these parameters are of high importance as they 43 have a significant effect on the mixing of fuel and air (Arai 2016, Heywood 1988, Hillamo 2011, 44 Lefebvre 1989). In plain-orifice pressure atomizers, such as diesel injector nozzles, cone angle is largely dependent on the viscosity and surface tension of the liquid as well as the amount of 45 turbulence in the jet (Lefebvre 1989). Several studies conducted with biodiesels indicate that fuels 46 47 with higher viscosities, surface tensions, and densities have longer spray penetration and narrower 48 opening angles (Deng et al. 2010, Desantes et al. 2009, Hwang et al. 2016, 2017, Li et al. 2006, Mohan et al. 2014), and the narrower sprays have also been found with biodiesel blends (Gupta and 49 50 Agarwal 2016). The same effects of viscosity are also supported by Dernotte et al. (2012), albeit this study did not find a significant effect of surface tension. Furthermore, their results suggested 51 52 that the effect of viscosity on opening angles would be decreased when increasing injection 53 pressure. Besides the decreased effects of fuel properties, increased injection pressure has also been connected to reduced nozzle orifice geometry effects as concluded by Hulkkonen et al. (2015) who 54 55 studied the effects of conical nozzle orifices on spray geometry.

56 Hulkkonen et al. (2011) have studied the differences between EN 590 diesel fuel and hydrotreated vegetable oil (HVO) in terms of spray geometry. Their results suggested that HVO, 57 having little lower viscosity and density than the reference fossil diesel, would be characterized by 58 slightly wider spray angles, whereas no significant difference was observed in penetration. 59 Nevertheless, HVO sprays were reported to have higher spray tip velocities at the early stage of 60 injection. With regard to the effects of increased ambient gas density/pressure, studies indicate both 61 increased cone angles (Choi et al.2015, Desantes et al. 2006, Jun et al. 2001, Mohan et al. 2014, 62 63 Sidu et al. 2001, Spiekermann et al. 2009) and slower penetration (Desantes et al. 2006, Naber and 64 Siebers 1996). The slower penetration with increased chamber density is also observed in the experiments and simulations by Kaario et al. (2013) who studied chamber densities of 39 and 115 65 66 kg/m³, the latter corresponding to peak cylinder pressures of approximately 300 bar.

67 In the analysis of sprays related to combustion or evaporation, Sauter mean diameter (SMD) is often used as a representative diameter (Arai 2016) as it describes the ratio of total liquid volume 68 and total droplet surface area in a spray (Sirignano 1999), and because the rate of evaporation in 69 70 droplets depends on surface area (Arai 2016). In the present study, droplet sizes are determined 71 from shadow images, and this technique has been shown to be capable of having a good agreement 72 with phase Doppler anemometry when studying moderately dense sprays with small diameters 73 (Kashdan et al. 2004). Feasible consistency between shadowgraphy and other techniques has also been found by Berg et al. (2006), albeit they studied slightly larger particles. While Berg et al. 74 75 (2006) conclude that all the tested methods are characterized by their own limitations and errors, 76 they also suggest that shadow imaging would be the most suitable method for particle and velocity 77 investigations in dense sprays. Besides these techniques, droplet sizes can also be analyzed by other techniques as presented by Coghe and Cossali (2012), Greenhalgh and Jermy (2002), Linne (2013), 78 79 and Zhao (2012).

80 To the knowledge of the authors, very few publications exist concerning the characteristics of high-pressure kerosene, hexane, methanol, and propane sprays, which indicates a research gap 81 82 and thus a need for new studies. In the present study, spray tip penetration and opening angles are determined for these fuels, and the results are compared with LFO sprays. Furthermore, due to the 83 potential of methanol as a future biofuel, droplet sizes are investigated for methanol, LFO being 84 again the reference fuel. In a study by Aigal et al. (1986), it was found that methanol sprays injected 85 from a diesel injector would be characterized by smaller droplets than those of LFO, and this was 86 87 taken, despite considerable differences in injection parameters, as a hypothesis for the performed 88 experiments. In table 1, injection parameters and reported mean droplet size ranges for LFO have been collected from literature, which enables the evaluation of the performed LFO droplet sizing 89

90 results. Finally, regarding the spray opening angles, it is noted that angle definitions vary between

91 publications (Dernotte et al. 2012, Desantes et al. 2009, Naber and Siebers 1996, Oguma et al.

92 2003, Shao et al. 2003, Wu et al. 2015, Yu et al. 2002), which should be considered when observing

93 the results on spray geometry.

JI	1		1	0			
	Aigal et al.	Cárdenas et	Dernotte et	Hwang et	Kawaharada	Komada et	Wu et al.
Parameter	(1986) ¹	al. (2010)	al. (2012) ²	al. (2017)	et al. (2015)	al. (2013)	(2015)
Nozzle orifice diameter [µm]	230	105 & 148	100	130	112	135	350
Injection pressure [MPa]	2030 (peak)	60 & 110	30150	40, 60, 80	65 & 135	80	2231
Ambient pressure [MPa]	0.05 & 0.4	5	1	0.1	0.1	0.1	n/a
Ambient temperature [K]	n/a	800	297	300	296	≈ 296	n/a
Axial distance from injector [mm]	929	30 & 35	50	6090	10 & 15	5, 7, 10, 15	80
Radial dist. from centerline [mm]	416	05	69 (edge)	03	01,5	02	n/a
Analysis method	Malvern	PDA	Malvern	PDI	L2F	L2F	Malvern
Mean size range, SMD [µm]	5.145.5	≈ 610	≈ 915	≈ 23,527	n/a	n/a	≈ <mark>9…15</mark>
Mean size range, D10 [µm]	n/a	≈ 47	n/a	n/a	≈ 525	≈ 1020	n/a

TABLE 1: Injection parameters and reported mean droplet size ranges for LFO/diesel in literature.

 1 For methanol, nozzle orifice diameter 320 μm and mean SMD size range 1.2...9.7 $\mu m.$

² The SMD range is for n-dodecane, density 749 kg/m³, surface tension 25.3 mN/m, kinematic viscosity ≈ 1.9 mm²/s.

94 2 METHODS

95 2.1 Experimented fuels

Table 2 presents densities, kinematic viscosities, and surface tensions for the tested fuels. Apart 96 from propane, they are liquids at room temperatures and atmospheric pressures. While the 97 properties found from literature may not be identical to the exact specifications of the tested fuels, 98 the presented values indicate a clear order between the fuels in terms of the presented 99 100 characteristics. The tested light fuel oil fulfilled European EN 590 requirements for automotive diesel fuels. While the standard allows variations in density and viscosity, the supplier of the LFO 101 offered typical values of 840 kg/m³ and 3.2 mm²/s (at 313 K), respectively. The studied hexane was 102 103 a mixture of hexane isomers, and the methanol was of laboratory grade with a minimum purity of 104 99.8%. Propane was stored in a commercial forklift LPG (liquid petroleum gas) bottle and had a 105 purity of over 95% according to the supplier.

Fuel	Density [kg/m³] ¹	Kinematic viscosity at 293 K [mm²/s]	Surface tension at 293 K [mN/m]				
LFO (EN 590)	820 – 845	2 – 4.5 (313 K) ¹	28 – 29.5 ^{4,5,6}				
Kerosene	770 – 830	2 ³	26 ⁷				
Hexane	660 ²	0.5 ³	18.4 ⁷				
Methanol	790	0.75 ¹	22.5 – 23 ^{8,9}				
Propane (liq.)	510	0.19 ³	6.4 (300 K) ⁷				

TABLE 2: Properties of experimented fuels from literature. The surface tensions of LFO not specifically for EN 590 fuels.

¹ Dietsche & Reif (2011), ² Producer datasheet: 672 kg/m³, ³ Based on dynamic viscosity from Lefebvre (1989), ⁴ Wang et al. (2006), ⁵ Das et al. (2018), ⁶ Esteban et al. (2012), ⁷ Lefebvre (1989), ⁸ Jasper (1972), ⁹ Vázquez et al. (1995)

106 **2.2 Test facilities**

107 The experiments were conducted in a spray chamber designed for fuel spray measurements. The 108 chamber, being filled with pressurized nitrogen, was equipped with two circular windows that 109 provided an optical access to the sprays from opposite sides and thus enabled the use of backlight 110 imaging method. The effective diameter of the borosilicate windows was 100 mm, and their

- 111 thickness was 55 mm to allow pressures up to 100 bar. The temperature of the chamber was not
- 112 controlled, and it remained at approximately 290...300 K during the measurements. Table 3 presents
- 113 the summary of test conditions, imaging parameters, and analysis techniques. Further explanations
- 114 on the analysis methods shall be given in the following chapter.

TADLE 5. Summary of lest conditions, imaging parameters, and analysis lectiniques	TABLE 3: Summary	v of test	conditions,	imaging	parameters.	and ana	lvsis t	techniques
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		Measurement type				
		Spray geometry	Droplet sizes			
	Test facility	Spray chamber, optical access from opposite sides				
Test	Chamber atmosphere	Pressurized nitrogen				
environment	Temperature	Room temperature, approx. 294 K				
	Chamber densities [kg/m ³]	1.2, 35 & 100	35 & 100			
	Injector body	Solenoid-driven, marine-size o	common rail diesel injector			
	Injector nozzle	8/9 orifices plugged, orifice diamet	er 0.3 mm, umbrella angle 153°			
Fuels &	Injection pressures [Mpa]	55 & 100				
injection	Injection signal duration	2 ms				
	Fuels	LFO ¹ , Kerosene, Hexane, MeOH ² , Propane	LFO ¹ & MeOH ²			
	MeOH lubrication additive	-	Ethomeen O/12, \approx 1 m-%			
	Imaging mode	High-speed (10 000 fps)	Single-shot			
Imaging	Optics	50 mm, F/1.4	Long-distance microscope			
	Image resolution	512x304 ³	2048x2048			
inaging	Image area [mm²]	79*47 or 81*48 ³	2.64*2.64			
	Backlight method	125 W DC halogen lamp	200 mJ Pulse laser			
	Exposure time	≈ 3.3 µs ³	≈ 20 ns			
Image	Analysis based on	Shadow images				
analysis	Analysis software	In-house Matlab scripts	Commercial (Davis X by LaVision)			
unary 515	Attributes to be analyzed	Penetration, opening angles	Mean droplet sizes & distributions			

¹ EN 590 light fuel oil, ² Methanol purity > 99.8 %, ³ For propane: resolution 512x256, image area 53*27 mm², and exposure time \approx 8.3 µs.

Figure 1 illustrates the schematics of fuel and nitrogen systems for the employed test setup. The 115 pressure inside the chamber was controlled by adjusting the pressure regulator, needle valve, and 116 117 pressure control valve manually. Chamber density was determined from the readings of pressure 118 and temperature sensors. With the lowest chamber density of 1.2 kg/m³, the pressure control valve 119 was fully open, and the pressure inside the chamber was equal to the atmospheric pressure plus 120 minor pressure losses in the exit pipe. During the acquisition of images for spray geometry analysis, a constant nitrogen flow was applied through the chamber. When taking images for droplet sizing, 121 122 the chamber was filled with new nitrogen after every 10 injections.

123 The fuel pressure in the common rail was manually controlled by regulating the air pressure 124 of the air-driven high-pressure (HP) fuel pump and adjusting the flow rate in the fuel return line. 125 The fuel cooler shown in figure 1 was in use only when acquiring methanol spray images for 126 geometry analysis. This prevented the exceedance of methanol's boiling point and thus its' abundant 127 vaporization into the laboratory room. Based on experiments with LFO, it was concluded that the 128 fuel cooler had no significant effect on spray geometry.



FIG. 1: Schematic flow chart for the fuel (excl. propane) and nitrogen systems of the experimental setup.

Due to its' low boiling point, propane required a special fuel system setup in order to keep the fuel in a liquid form. Instead of the fuel transfer pump and fuel filters shown in figure 1, a cooling system was built between the propane gas bottle and the HP fuel pump. This system comprised a freezer filled with ice as well as a fuel line coil inside the freezer to ensure efficient cooling. Moreover, a non-return valve was installed between the freezer and the HP fuel pump to prevent fuel backflow. Gaseous low-pressure propane from fuel return lines was directed away from the fuel system.

Figures 2 and 3 present schematic imaging system arrangements for the acquisition of spray geometry and droplet sizing images, respectively. Detailed information on imaging parameters has been listed in table 3. In order to achieve a flicker-free illumination, a direct current halogen lamp was used as a backlight in spray imaging. While the laser employed in droplet imaging had a typical pulse duration of 3...5 ns, the wavelength conversion into a non-coherent light prolonged the duration to approximately 20 ns. Furthermore, the droplet imaging system included an automatic background image subtraction.



FIG. 2: Schematic representation of the imaging system arrangement for spray geometry measurements.



FIG. 3: Schematic representation of the imaging system arrangement for droplet size measurements.

143 2.3 Analysis methods

The analysis of spray geometry was conducted with in-house Matlab scripts that recognized the 144 145 spray from the background on the basis of different intensity levels. The process of determining the spray area included intensity inversion, background subtraction, and intensity thresholding. Spray 146 147 penetration was defined from the pixel within the spray area that had the longest distance from the 148 nozzle orifice. The determination of an opening angle (θ in fig. 4) was based on finding the pixel that belongs to the spray area and has the longest perpendicular distance from the centerline of the 149 150 spray (y) calculated at a given distance from the nozzle orifice (x). In other words, the script 151 calculated the width of the half-spray at given distances from the injector nozzle. For the results 152 presented in this paper, these distances were 20 mm and 40 mm. This procedure was applied for both spray edges, and the average of these two angles was considered in further data processing. All 153 the results concerning spray penetration and opening angles were averaged over 50 (LFO and 154 155 methanol) or 60 (kerosene, hexane, propane) consecutive injections, and the error bars shown in the results are based on standard deviation. 156



FIG. 4: Schematic representation on the determination of penetration and opening angle as well as the field of view in droplet images. X = 20 mm and 40 mm, y depends on the local width of the spray.

157 The determination of characteristic opening angles depended on the shape of the opening angle time 158 histories. If a visible local minimum in the opening angle was observed before the end of injection (fig. 5, left), the characteristic opening angle was determined as the lowest value between initial and 159 160 post-injection transients. If no local minimum existed before the end of injection (fig. 5, right), or if the time history was monotonically increasing until the end of injection, the characteristic angle was 161 defined at the point of end of injection. The standard deviations for these angles were defined at the 162 163 same points in time as the angles themselves. The methods for defining the opening/cone angles 164 vary between publications (Dernotte et al. 2012, Desantes et al. 2009, Naber and Siebers 1996, Oguma et al. 2003, Shao et al. 2003, Wu et al. 2015, Yu et al. 2002), whereupon the results of this 165 166 study concerning opening angles may not be quantitatively comparable with other studies. Finally, 167 it was identified that the injection duration of 2 ms may have been too short for the spray to develop 168 a steady-state opening angle value at longer distances from the nozzle.



FIG. 5: Determination of characteristic opening angles from different time history shapes. Standard deviations also visible.

A proprietary analysis software (Davis 10 by LaVision GmbH) was employed for the detection of droplets from shadow images. The detected droplet areas with possibly arbitrary shapes were replaced by ellipses that fitted to the droplet shape (fig. 6). The centricity of a droplet was determined as the ratio between the short and long axes of the ellipse, and the droplet diameter was defined such that a circle with the specific diameter had the same area as the detected shadow area. The statistical weight of each detected droplet depended on diameter in order to consider the different detection probabilities between large and small droplets.

176 Table 4 presents the applied droplet analysis parameters, including minimum and maximum 177 filters. The parameters were chosen after experimenting with several combinations in order to find a 178 suitable compromise for the analyzed images. Minimum and maximum filters were included to further reduce the number of false detections. For instance, detected "droplets" with strong non-179 180 centricity were clearly false detections when observing detection results visually. An example on the effects of centricity parameter has been documented by Kashdan et al. (2004). The location of the 181 182 field of view in droplet imaging with respect to the injector is shown in figure 4, albeit minor 183 adjustments were necessary to capture the spray edge. As droplet velocities are generally lower far from the injector nozzle, the field of view was located rather far from the injector nozzle. The 184 scaling of the images was conducted by placing a piece of millimeter paper into the focal point of 185 186 the microscope and determining the pixel-to-micrometer ratio from the taken images.



FIG. 6: Example of detected droplets.

TABLE 4: Droplet detection	parameters
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Parameter	Unit	Value
Normalization radius	рх	4
Pixel noise reduction	-	Strong
Binarization threshold	%	35
Min. shadow area	px	7
Minimum slope	%	9
Minimum diameter	μm	5
Maximum diameter	μm	60
Minimum centricity	%	<mark>6</mark> 0

187 2.4 Uncertainties

188 The accuracy of image analysis is largely related to the calibration of pixel-to-length scale, motion blur, limited image resolution, and intensity thresholding. Furthermore, statistical error originates 189 190 from spray-to-spray variations. Scale error was estimated to be around 1%, whereas the error of 191 motion blur and resolution depended on measurement type. For spray geometry analysis, these were estimated to be around 0.7 mm (based on 3.3 µs exposure time and 200 m/s spray tip velocity) and 192 approximately 0.3 mm (2 px when analyzing opening angles), respectively. Nevertheless, the error 193 194 due to motion blur was lower for the determination of opening angles as the transversal velocities of sprays are much lower. It is also noted that while Kawaharada et al. (2015) and Komada et al. 195 (2013) have measured even higher velocities than the 200 m/s close to the nozzle, spray tip 196 velocities decrease rapidly when increasing the distance from the injector. Using a characteristic 197 length of 20 mm, the errors of 0.7 mm and 0.3 mm correspond to relative errors of 3.5% and 1.5%, 198 respectively. For propane image series, the motion blur error was larger due to the longer exposure 199 200 time (table 3).

201 Assuming a speed of 50 m/s at the spray edge (location in fig. 4) and an exposure time of 20 ns, the motion blur for droplet sizing images was calculated to be 1 µm. With a characteristic length 202 203 of 10 µm, the theoretical relative error due to motion blur becomes 10%. In practice, the error is 204 lower due to intensity thresholding that excludes a part of the blurred tail. Moreover, smaller 205 particles are known to have lower velocities, which further reduces the relative error. A theoretical resolution error of 2 pixels corresponds to approximately 2.6 um, which is considerable for the 206 smallest detected droplets. Despite the magnitudes of these error sources, it was thought that more 207 208 error originated from the limited image quality and hence the success of droplet detection. Optically challenging imaging environment was attributed to shallow depth of field, dense sprays, small 209 210 droplets with high velocities, and the chamber windows that unavoidably induced some light 211 reflections and refraction. The analysis parameters were determined to work moderately well for all 212 the image series, which inevitably resulted in varying detection success between individual images or droplets (fig. 6). The error arising from analysis has been identified by Kashdan et al. (2003, 213 214 2004) who found that the accuracy of image analysis is sensitive to thresholding, and that the sizes of small objects are underestimated, albeit post-processing was shown to facilitate the latter issue. 215 Finally, it is noted that droplet sizes may vary significantly within a spray, which should be kept in 216 217 mind when interpreting the results as this study investigated the droplet sizes in a single location at 218 the edge of the sprays.

During the experiments, small variations around the target value had to be accepted in fuel pressures and chamber densities. The fluctuations in the moving average of fuel rail pressure were typically in the range of \pm 2%, the worst cases being in the range of \pm 5%. At the lowest chamber density of 1.2 kg/m³, the chamber pressure could not be controlled because of the dependence on the atmospheric pressure. In practice, the measured values were slightly over 1.2 kg/m³. At the elevated chamber densities of 35 and 100 kg/m³, the accepted values typically deviated less than 2% or 1% from the target value, respectively.

226 3. RESULTS AND DISCUSSION

227 3.1. Visual observations

228 Figure 7 shows example spray images for all the fuels and chamber densities. The images have been 229 taken at the same time with respect to injection signal, which allows to see the effect of chamber 230 density and fuel on the shape and evolution of the spray. The differences between LFO, kerosene, 231 hexane, and methanol sprays are rather small, particularly when taking the existence of spray-to-232 spray variations into consideration. However, propane differs from the other fuels. At the lowest 233 chamber density of 1.2 kg/m³, propane seems to be characterized by a wider spray close to the 234 injector nozzle. At elevated chamber densities, and especially at the density of 100 kg/m³, the fast 235 evaporation of propane becomes obvious and results in shorter penetration and narrower spray 236 angles. It is noted though that had the methods been able to reliably detect fuel vapor, the observations concerning propane spray geometry would have been different. 237

Despite losing information on the structures of spray edges, the averaging of images enables to visualize the differences in overall spray geometry. Figure 8 compares the evolution and shape of methanol and LFO sprays and includes all the tested chamber densities. In the images, each frame is an average of 50 shots. At the two higher densities, the differences between the fuels are small yet visible when carefully observing the shapes of the sprays. At the chamber density of 1.2 kg/m³, the differences become more obvious as the spray tips have notably different shapes.



FIG. 7: Examples of fuel spray images taken at the same time with respect to injection signal. Injection pressure 1000 bar, image area 50*25 mm².



FIG. 8: Evolution and shape of average methanol and LFO sprays at different chamber densities. Start of injection approx. 0.1...0.15 ms before the upper image series. Images averaged over 50 shots. Injection pressure 1000 bar, image area 59*25 mm².

244 3.2 Penetration

Figures 9, 10, and 11 present spray tip penetrations for the chamber densities of 1.2, 35, and 100 245 kg/m³, respectively, and include both 550 and 1000 bar injection pressures. At the lowest chamber 246 density, the differences between the liquid fuels are rather small especially with the higher injection 247 pressure, whereas propane behaves differently. The error bars, showing the standard deviation of the 248 249 repetitions, also indicate that the penetration length of propane sprays varies significantly between 250 injections. This was thought to be the result of fast and varying vaporization rates. Due to the low 251 chamber density, the spray tips accelerate fast and reach the limits of the image area within a narrow 252 time window (fig. 9). When increasing chamber density, both standard deviations and the 253 differences between propane and the liquid fuels seem to decrease. Furthermore, the acceleration 254 and deceleration regions discussed by Hillamo (2011) can be identified from figures 10 and 11.

255 Overall, the differences between the liquid fuels are rather small also when increasing 256 chamber density. However, with the combination of 550 bar injection pressure and 35 kg/m³ 257 chamber density, fig. 10 indicates that LFO and methanol sprays would momentarily be 258 characterized by longer penetrations. As this observation is inconsistent with the other shown test 259 points, care should be taken not to give too much weight on these differences. Besides the aforementioned findings, figures 10 and 11 also suggest that the tip of LFO sprays would accelerate 260 261 slightly more than the other fuels in the beginning, but that it would also decelerate faster after 262 penetrating the first 30...35 mm. Finally, it is observed that an increased injection pressure decreases 263 injection delay, which is in line with the findings of Hwang et al. (2017). In the figures, time is 264 calculated from the start of injector energizing.



FIG. 9: Measured spray tip penetrations for the examined fuels. Chamber density 1.2 kg/m³, injection pressures 550 and 1000 bar. Error bars indicate standard deviation. ASOE: After start of energizing.



FIG. 10: Spray tip penetration, chamber density 35 kg/m³.



FIG. 11: Spray tip penetration, chamber density 100 kg/m³.

265 Regarding the effects of increased injection pressure, studies indicate faster penetration (Agarwal et 266 al. 2014, Du et al. 2017, Su and Farrell 1998). A study with a gaseous fuel, liquefied dimethyl ether (DME), indicates slower penetration when compared with diesel fuel (Jun et al. 2001), and the same 267 268 trend of slower penetration with respect to LFO was also found by Helin et al. (2006) who studied LPG sprays. Furthermore, Yu et al. (2002) conclude that the variations between DME and LFO 269 270 (diesel fuel) decrease at increased ambient pressures. In general, all these trends are in line with the 271 findings of this study as seen from figures 9 - 11. While DME certainly has different properties than 272 propane, they both are gaseous at room temperatures and seem to have, based on the referred 273 studies, some similarities with respect to LFO.

274 The shorter penetration of propane sprays can be explained by lower initial momentum due 275 to lower density as well as the loss of momentum during spray evolution as a result of droplet 276 breakup and evaporation. According to Yu et al. (2016), lower viscosity induces smaller droplets in 277 the spray, and this can, together with different densities, explain some of the differences between the fuels. This viewpoint is supported by Dernotte et al. (2012) who conclude that both viscosity 278 279 and fuel density affect spray penetration and opening angles. While the effect of density was 280 reported to be smaller than that of viscosity, surface tension was found to have no significant effect. However, the penetration curves of kerosene in figure 10 cannot be explained by these parameters 281 and leave room for other studies. 282

283 As chamber density is increased, drag forces increase as well, which explains why sprays 284 penetrate slower at increased chamber densities. Furthermore, faster penetration as a result of increased injection pressure can be explained by higher momentum due to increased liquid 285 velocities at the injector nozzle. The higher velocities, resulting from increased injection pressure, 286 can be explained by Bernoulli's well-known equation. Finally, it is noted that despite figure 11 287 288 shows almost no differences between propane and the other fuels, figure 7 indicates considerable evaporation at the tip area of the propane spray at the chamber density of 100 kg/m³. While this may 289 290 seem contradictory at first, the visible evaporation area at the tip region was, nevertheless, dark 291 enough for the analysis script to consider it as "spray area". It also needs to be noted that the role of 292 spray-to-spray variations cannot be evaluated from figure 7.

293 3.3 Opening angles

294 In order to get a better view on the differences in the shapes of the fuel sprays, characteristic 295 opening angles are determined at two different distances (x in fig. 4) from the injector nozzle. In 296 figure 12, the angles have been calculated from the width of sprays at the distance of 20 mm that is 297 approximately 67 times the nozzle orifice diameter. In figure 13, the distance is 40 mm, which 298 describes the width of the spray relatively far from the nozzle. At the closer distance, the response 299 of propane to the increased chamber density is opposite to the other fuels. The differences between 300 the liquid fuels are rather small, albeit kerosene sprays seem to have slightly larger opening angles in most of the test points. Moreover, with 1000 bar injection pressure and 100 kg/m³ chamber 301 302 density, LFO sprays seem to have little narrower sprays than kerosene, hexane, or methanol.



FIG. 12: Effect of chamber density on characteristic opening angles at the distance of 20 mm from the injector. Injection pressures 550 and 1000 bar.

303 When increasing the observation distance to 40 mm, the different behavior of propane is similarly visible. As chamber density was increased to 100 kg/m³ and injection pressure to 1000 bar, the 304 mean opening angle of propane sprays decreased to below 5 degrees (fig. 13, right), which 305 306 indicates, due to the system's inability to detect vapor phase, that the spray was strongly vaporized 307 at the distance of 40 mm from the injector nozzle. Furthermore, the error bar in this point suggests 308 large variations between repetitions and presumably complete vaporization in some repetitions. The 309 differences between the other fuels are again small, and kerosene would seem to be characterized by 310 slightly larger opening angles in most test conditions. Moreover, the angle of LFO sprays seems to 311 have slightly different response to the increase of chamber density. Overall, while it is clear that propane behaves differently due to fast vaporization, the differences between the other fuels in 312 313 terms of opening angles seem to be rather small. Apart from the cases of 1.2 kg/m³ chamber density, 314 the standard deviations are also much larger than the differences in mean values between the liquid 315 fuels.



FIG. 13: Effect of chamber density on characteristic opening angles at the distance of 40 mm from the injector. Injection pressures 550 and 1000 bar.

Concerning the effects of injection pressure on spray opening angles, Su and Farrell (1998) have found that an increased injection pressure would decrease opening angles, whereas Mohan et al.

318 (2014) and Wu et al. (2015) present opposite findings. On the other hand, Du et al. (2017) conclude

that injection pressure would not affect liquid phase cone angle, but that an increase in injection pressure would induce wider vapor phase cone angles. In the present study, the effect of increased injection pressure seemed to depend on chamber density, but a slight decreasing effect seems to be more common when combining the results from figures 12 and 13. Thus it can be concluded that the effect of injection pressure on opening angles is not as clear as its effect on tip penetration and injection delay.

325 The differences in opening angles between propane and the other fuels can be attributed to 326 propane's different properties. Being a light hydrocarbon with only three carbon atoms and having a low boiling point, it vaporizes quickly after being injected into the spray chamber. Combined with 327 328 an imaging system that can capture only liquid phase fuel, this explains the low measured opening 329 angles of propane sprays at elevated chamber densities. However, propane seems to have wider 330 sprays at the chamber density of 1.2 kg/m³ particularly close to the injector nozzle as seen from fig. 331 12. This suggests that the liquid propane spray is able to expand transversally, presumably due to stronger turbulence in the injector nozzle, which is a result of propane's low boiling point. As an 332 333 increased gas-to-liquid density ratio has been reported to increase spray angles (Heywood 1988, 334 Naber and Siebers 1996), it is concluded that the lower density of liquid propane (table 2) have contributed to the observations of wider liquid sprays at the lowest chamber density. Furthermore, 335 this relation between spray angles and gas-to-liquid density ratios also explains why the sprays 336 337 were, apart from propane, generally wider at increased gas densities.

A study by Helin et al. (2006) indicates that LPG sprays would be characterized by narrower 338 opening angles than diesel fuel sprays, which is in line with the present study except the lowest 339 tested chamber density. Nevertheless, the varying differences of a gaseous fuel with respect to a 340 reference diesel have also been observed by Suh and Lee (2008) who found that the differences 341 between DME and diesel fuel sprays depend on ambient temperature and pressure. Despite the 342 narrower propane spray angles found at elevated chamber densities, the results by Oguma et al. 343 344 (2003) support the viewpoint that gaseous fuel sprays have large vapor regions around the liquid 345 region.

Among the liquid fuels, kerosene is identified to have slightly larger opening angles in many test points (figures 12 and 13). With respect to LFO, the observation is in line with the results by Yu et al. (2016) who attribute the finding to increased turbulence in the injector nozzle. Increased turbulence, on the other hand, could be a result of decreased viscosity (Dernotte et al. 2012). However, based on kerosene's properties (table 2), it is closer to LFO than any other tested fuel, which suggests that kerosene should differ from LFO less than the other fuels. As this is not the case in the results, the observations could not be fully explained by fuel properties.

353 3.4 Droplet sizes

354 As the inner parts of diesel sprays are too dense for shadow imaging techniques, the image area was located at the edge of the spray (fig. 4). The imaging conditions were optically challenging, and 355 despite the selection of images for analysis, image quality left room for improvements. The number 356 357 of images and detected droplets as well as test variables and calculated mean diameters are 358 collected into table 5. According to Lefebvre (1989), a reasonable accuracy for a droplet size distribution should be achieved with a sample size of 5 000 droplets. While Paine (1993) states that 359 the adequate sample size for acceptable sampling error is not constant, the results of the same 360 361 reference indicate that a sample of approximately 5000 particles would clearly be on the safe side. 362 In the present study, the number of detected droplets per test point varied roughly between 4 000 and 13 000. 363

In figure 14, Sauter mean diameters (SMDs) have been plotted against injection pressure and chamber density, suggesting that methanol sprays would contain slightly smaller droplets than LFO sprays. Moreover, it seems that an increase in injection pressure would affect the SMDs of LFO sprays slightly more than those of methanol sprays, and that the differences between the fuels would decrease when increasing both injection pressure and chamber density. The droplet size 369 distributions (fig. 15) are in line with the calculated SMDs and indicate slight differences between

370 LFO and methanol. However, care should be taken not to highlight the absolute values due to the

371 limitations in image quality and consequently the success of droplet sizing. Instead, the relative

372 differences between LFO and methanol are addressed here.

Chamber density [kg/m^3]	Injection pressure [bar]	Fuel	Total number of images	Number of images in the analysis	Share of included images [%]	Number of detected droplets	D10 [µm]	D32 [µm]
35	550	MeOH	149	67	45,0	13388	16,2	23,5
35	1000	MeOH	110	57	51,8	11054	16,0	22,3
100	550	MeOH	270	54	20,0	3707	15,9	23,3
100	1000	MeOH	190	50	26,3	4115	14,5	23,0
35	550	LFO	170	51	30,0	5460	19,3	27,0
35	1000	LFO	180	54	30,0	6689	18,1	25,5
100	550	LFO	270	53	19,6	4364	18,4	26,7
100	1000	LFO	360	56	15.6	4753	15.8	23.8

TABLE 5: Summary of droplet size measurements. D10: arithmetic mean diameter, D32: Sauter mean diameter.



FIG. 14: Effects of injection pressure (left) and chamber density (right) on Sauter mean diameters.

373 Overall, despite the unavoidable uncertainties related to image quality and automated droplet 374 analysis, the results suggest that methanol sprays would be characterized by slightly smaller 375 droplets than LFO sprays in the measured injection conditions. The trend of smaller droplet sizes 376 with methanol has also been found by Aigal et al. (1986), albeit their results indicated much larger 377 differences. However, the results of the present study do not give support for their findings on 378 methanol's significantly narrower droplet size distributions. It shall also be noted that the results 379 may not be fully comparable due to different test parameters, equipment, and analysis methods.



FIG. 15: Droplet size distributions for methanol and LFO.

In spite of the differences in many test parameters (tables 1 and 5), the SMDs of LFO/diesel sprays reported by Hwang et al. (2017) are similar to the SMDs of the present study. Kawaharada et al. (2015) and Komada et al. (2013) have also studied droplet diameters in diesel sprays, and the large range in their reported arithmetic mean diameters covers the results of this study. On the other hand, Cárdenas et al. (2010) have found much smaller diameters, presumably due to substantially higher ambient temperatures.

In literature, an increase in injection pressure is attributed to smaller droplet sizes (Cárdenas 386 387 et al. 2010, Dernotte et al. 2012, Hwang et al. 2017, Su et al. 1995, Su and Farrell 1998, Wu et al. 388 2015), and the results of the present study support this viewpoint. On the other hand, the results by 389 Kawaharada et al. (2015) suggest that the effect of injection pressure on droplet sizes would depend on the location of measurements. Regarding the effects of increased fuel viscosity, Dernotte et al. 390 391 (2012), Goldsworthy et al. (2011), as well as Hiroyasu and Arai (1990) report increased SMDs, and 392 the same trend has been observed with biodiesel and biodiesel blends that are characterized by 393 higher viscosity, density, and surface tension than mineral diesel fuel (Gupta and Agarwal 2016, 394 Hwang et al. 2017). As methanol has lower viscosity, density, and surface tension than LFO, it can 395 be concluded that the findings of this study are in line with the aforementioned studies in terms of 396 the presented fuel properties.

While Dernotte et al. (2012) found that both viscosity and density have an effect on SMDs, they also concluded that viscosity would have a more significant role. Increased viscosity was thought to decrease the amount of turbulence and instabilities in the flow, which results in weaker atomization and hence larger droplet diameters. The small increase in SMDs caused by an increase in fuel density was suggested to result from the dependance of injection velocity on density when
keeping injection pressure constant. Finally, it is generally noted that an increased surface tension
should result in larger droplets as this parameter describes the magnitude of cohesive forces in a
droplet.

405 4. CONCLUSIONS

406 In this study, fuel spray penetration and opening angles were investigated for EN 590 light fuel oil, 407 kerosene, hexane, methanol, and propane. Furthermore, droplet sizes were studied for methanol and 408 light fuel oil sprays from a single location at the edge of the sprays. The fuels were injected from a 409 marine-size common rail diesel injector to a spray chamber filled with pressurized nitrogen, and the 410 results were based on the analysis of shadow images. The main findings of this study can be 411 summarized as follows.

412

413 1. Spray penetration: Propane sprays penetrate slower than the sprays of the other fuels, but the 414 differences are decreased and finally almost disappeared when increasing chamber density. From 415 the liquid fuels, apart from the lowest tested chamber density, the tip of LFO sprays seemed to 416 decelerate slightly more after the initial acceleration. Higher injection pressure decreased injection 417 delay, and increased chamber density reduced variations between repetitions.

418 2. Spray angles: Apart from the chamber density of 1.2 kg/m³, propane forms significantly narrower 419 sprays than the liquid fuels. This was attributed to propane's fast evaporation that resulted in a 420 narrow liquid spray. With the lowest chamber density, propane sprays were wider especially close to 421 the nozzle. Differences between the liquid fuels were mostly small, but kerosene seemed to form 422 slightly wider opening angles in many test points. With the exception of propane, the fuels had 423 mostly similar responses to increased chamber densities. Variations between repetitions were large 424 in relation to the differences in average values between the liquid fuels.

3. Droplet sizes: The results indicated that methanol sprays would be characterized by slightly smaller droplet sizes than LFO sprays, and that the differences would decrease when increasing both chamber density and injection pressure. The former finding is in line with an earlier study, albeit the found differences were much smaller. Measured mean droplet sizes were decreased with both fuels when increasing injection pressure, but the effect seemed to be slightly stronger with LFO.

Concerning overall spray geometry, subsequent studies could be conducted to reduce the amount of 431 uncertainty regarding the differences between the experimented liquid fuels. For instance, it could 432 433 not be explained by fuel properties why kerosene had slightly wider sprays in most test points. Furthermore, particularly the knowledge of propane sprays would be largely increased by using a 434 measurement system, such as Schlieren imaging, that is able to detect the vapor phase of sprays. 435 436 Nevertheless, the obtained results on propane are in line with the main findings of Helin et al. 437 (2006) on propane/butane mixtures. Regarding droplet size measurements, it is acknowledged that 438 high-pressure fuel sprays are a challenging environment for imaging techniques. Together with the 439 limitations in obtained image quality and the shortage of methanol spray droplet sizing studies, the 440 narrow range of applied test parameters, including injection parameters and only one analysis 441 location, leaves room for further studies with various and possibly more advanced measurement 442 techniques. Finally, further research is suggested to study the effects of different injector and nozzle types on droplet sizes while keeping the focus on alternative fuels, such as methanol. 443

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