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Time-averaged Spray Analysis in the Near-field Using X-ray Measurements

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Abstract

The characterization of a spray in the near-field region is challenging because of its high optical density in this region. X-ray based techniques, with weak scatter and strong penetration properties, can provide better characterization than optical assessment techniques in this region. In this work, the effects of various operating parameters on the evaluation of the optical depth (defined as the accumulated liquid thickness in the beam path times the X-ray attenuation coefficient) and spray profile of an atomizing spray in the near-field region are evaluated based on time-averaged X-ray analysis techniques. Controlling parameters in the spray structure include swirl ratio, liquid phase Reynolds number, and gas phase Reynolds number. Data from the broadband X-ray radiographs obtained using a tube source at Iowa State University and from focused beam measurements at the Advanced Photon Source at Argonne National Laboratory are compared. The X-ray tube source at ISU was operated at two different energy levels, which reveals that the X-ray tube source energy influenced the magnitude of the optical depth but did not change the shape of the distribution. For the no swirl condition, gas flow rate and liquid flow rate had opposite effects on the spray profile, where the spray widens as the gas flow rate increases and narrows as the liquid flow rate increases. As the swirl ratio increases from 0 to 1, the spray widens and then narrows, which indicates that the effect of swirl being more dramatic

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28 and then weaker. The critical swirl ratio at which the spray reaches its widest spread differs at
29 different flow conditions.

30 **Key Words:**

31 Coaxial atomizer, Spray near-field, Synchrotron X-rays, Tube source X-rays, X-ray radiography

32 **1. Introduction**

33 Sprays are an important part of many industrial processes, including energy conversion,
34 propulsion, spray drying, pharmaceutical production, agriculture applications, and additive
35 manufacturing. Precise control of the spray can effectively improve process efficiency. However,
36 before a spray can be controlled, it must be properly characterized. A spray can be roughly
37 divided into three regions: the near-field, the mid-field, and the far-field. The near-field region
38 covers the dense spray near the nozzle exit, where primary breakup happens and influences spray
39 formation (Som and Aggarwal, 2010). The near-field region is generally optically dense,
40 increasing the difficulty of characterizing the spray in this region using optical or laser-based
41 techniques (MacPhee et al., 2002). X-ray based techniques, with weak scatter and strong
42 penetration, can provide alternative measurements for effective spray characterization (Heindel,
43 2018).

44 X-ray radiography is a common X-ray imaging method which produces a shadow-like
45 image of an object where the intensity of the “shadow” is a function of X-ray power and the
46 object’s X-ray attenuation (Heindel, 2011). X-rays can be classified according to how the X-rays
47 are produced, and are generally divided into tube source X-rays and synchrotron source X-rays.
48 Tube source X-rays contains two electrodes: the cathode for emitting electrons and the anode as
49 the metal target for the electrons. Broadband tube source X-rays are produced by bombarding the

50 target with high-speed electrons. Synchrotron X-rays are emitted when charged particles, moving
51 at close to the speed of light, interact with bending magnets or undulators.

52 Synchrotron X-rays, with much higher energy levels and photon flux, can provide more
53 detailed data than tube sources, especially for small-scale objects with low contrast like sprays,
54 because they can provide much higher intensity (flux) levels than tube sources (up to 6 orders of
55 magnitude higher (Matusik et al., 2018)). The highly collimated synchrotron X-rays also
56 decrease image distortion caused by cone beams, which are common in tube sources. Because of
57 the higher X-ray flux from synchrotron X-rays, a monochromatic filter can be used in the beam
58 path to produce narrowband X-rays that eliminate beam hardening effects commonly found
59 when using broadband X-rays (Hsieh, 2003). However, the large footprint and high construction
60 and maintenance costs of a synchrotron X-ray facility limit the accessibility of synchrotron
61 X-rays as a regular tool to acquire data. Synchrotron X-rays can only be produced at specialized
62 facilities, such as the Advanced Photon Source (APS) at Argonne National Laboratory. Several
63 investigations using synchrotron X-rays for radiography of sprays have been completed at APS
64 (Powell et al., 2000; MacPhee et al., 2002; Kastengren et al., 2009; Kastengren et al., 2014a),
65 where the high flux X-ray beam provides high spatial and temporal resolution images of the
66 spray. The APS also enables focused beam X-ray measurements by placing a monochromator
67 and focusing mirrors in the beam path while using a PIN photodiode to record the X-ray
68 attenuation in the spray liquid as a function of time along the beam path (Heindel, 2018).

69 Tube source X-rays typically operate at lower flux levels, limiting penetration and
70 temporal resolution, and results in lower contrast and quality of the X-ray images. Additionally,
71 monochromatic filters are typically not feasible for tube source X-rays because of the low
72 operating flux. However, the low operating and maintenance costs of tube source X-rays reduce

73 the data acquisition costs, and make them easier and more flexible to operate. Tube source X-ray
74 can easily be found in hospitals and universities. Another advantage of tube source X-rays is that
75 they usually provide a larger field of view of the object of interest. X-ray imaging using a tube
76 source X-ray has been used to study multiphase flow with a dense distribution of the disperse
77 phase (Kingston et al., 2014; Heindel et al., 2008), as well as the near-field region of a spray
78 (Halls et al., 2014a). A comparison of the spray equivalent path length of liquid determined using
79 tube source X-rays and synchrotron X-rays was completed by Halls et al. (2012; 2014b) using an
80 impinging jet spray.

81 The goal of this paper is to reveal the effects of various parameters on the near-field
82 region of a spray from a canonical coaxial two-fluid atomizer. The data obtained from tube
83 source broadband X-ray radiographs are compared to those obtained using focused beam
84 synchrotron radiography. Two spray characteristics that will be reported include optical depth
85 and spray profile. Operating parameters that control the spray structure and are varied in this
86 study include liquid Reynolds number, gas Reynolds number, and swirl ratio. The effect of X-ray
87 tube source energy level in the measurement quality is also studied.

88 **2. Experimental setup**

89 In the current research, the broadband X-ray radiographs of the near-field in a canonical
90 coaxial two-fluid spray were taken using a tube source at Iowa State University. The broadband
91 X-ray radiographs were taken using a LORAD LPX-200 Industrial X-ray source (Heindel et al.,
92 2008). The LPX-200 can generate an X-ray tube potential up to 200 keV, a tube current up to 10
93 mA, and a maximum allowable power of 900 W. The radiographs were taken at 10 frames per
94 second for 2 minutes (1200 frames) at each condition, with a field of view of approximately 117
95 mm x 86 mm (1388 x 1024 pixels). The exposure time was 20 ms. More details of the X-ray

96 imaging facility at Iowa State University (ISU) can be found elsewhere (Heindel et al., 2008).
 97 The focused beam X-ray data were acquired using the 7-BM beamline at the Advanced Photon
 98 Source of the Argonne National Laboratory. The monochromatic synchrotron X-rays were
 99 focused to $5 \mu\text{m} \times 6 \mu\text{m}$ FWHM and recorded by a silicon PIN diode at an effective frequency of
 100 270 kHz. Similar techniques were performed by Kastengren et al. (2009; 2012; 2014a; 2014b).

101 X-ray radiograph quantification is based on Beer-Lambert's law (Pedrotti et al., 2007): if
 102 a monochromatic X-ray beam with an intensity of I_0 traverses through a medium, the X-ray
 103 energy will be attenuated to I because of absorption, which is a function of the material
 104 attenuation coefficient (μ) and the path length (l) through the object, and can be described by:

$$105 \quad I = I_0 \exp(-\mu \cdot l) \quad (1)$$

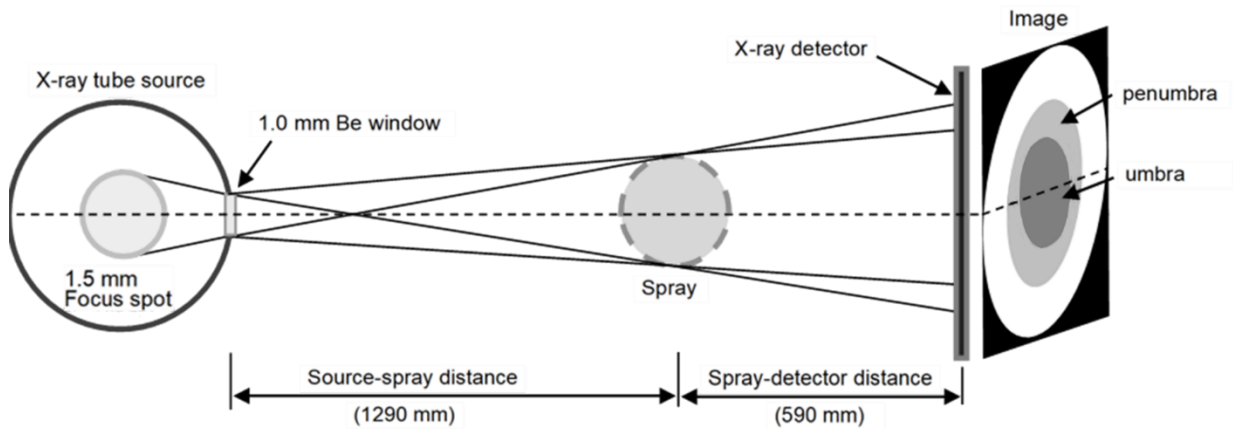
106 For a spray consisting of a distribution of droplets, the path length cannot be determined
 107 for individual droplets, instead the equivalent path length (EPL) is defined as the accumulated
 108 length for the liquid phase along the path of the beam, and is used to describe the spray structure.
 109 Hence, using Beer-Lambert's law, the equivalent path length can be determined by:

$$110 \quad I = I_0 \exp(-\mu \cdot \text{EPL}) = I_0 \exp(-\text{OD}) \quad (2)$$

111 where I_0 is the intensity without the spray, I is the intensity after passing through the spray, EPL
 112 is the equivalent path length for the liquid in the spray, and μ is the attenuation coefficient of the
 113 liquid medium through which the beam passes. Note that μ is a function of the material and
 114 X-ray energy (wavelength) and is tabulated for monochromatic X-ray sources, like the focused
 115 beam radiographic measurements available at APS. The product of the attenuation coefficient
 116 and the equivalent path length is called the optical depth (OD). For the same spray, the averaged
 117 EPL from the APS focused beam data and ISU broadband radiographs should be identical:

$$118 \quad \text{EPL}_{\text{radiograph}} = \frac{\text{OD}_{\text{radiograph}}}{\mu_{\text{radiograph}}} = \frac{\text{OD}_{\text{focused}}}{\mu_{\text{focused}}} = \text{EPL}_{\text{focused}} \quad (3)$$

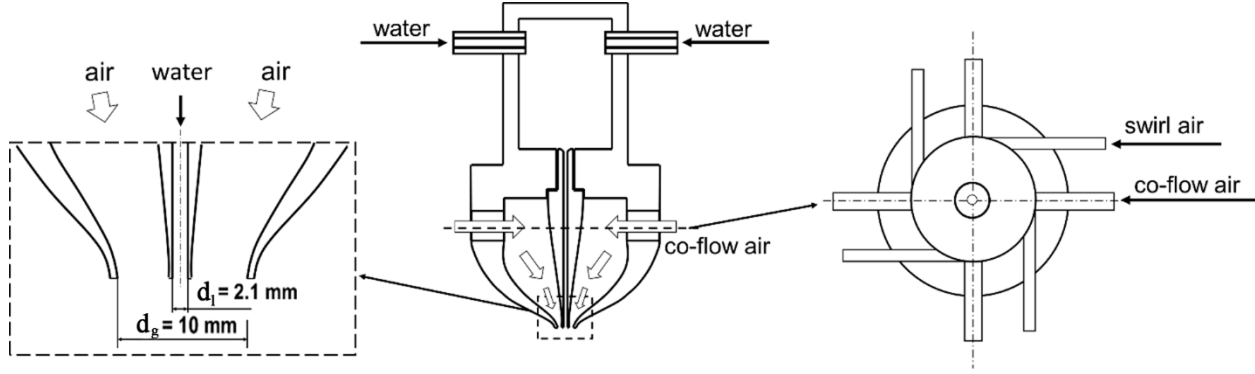
119 For narrowband focused beam X-ray data, the attenuation coefficient (μ_{focused}) is a
 120 constant, and it is easy to calculate $\text{EPL}_{\text{focused}}$. However, for broadband X-ray radiographs,
 121 $\mu_{\text{radiograph}}$ is a complicated function of X-ray wavelength and path length due to beam hardening
 122 effects and is difficult to determine directly. Additionally, due to the non-negligible size of the
 123 X-ray tube source at ISU, the penumbra, as shown in Figure 1, complicates the tube source
 124 measurements. The penumbra effect happens when the X-ray source cannot be regarded as a
 125 point source and is enhanced as the distance between the object and the detector increases.
 126 Previous work attempted to account for the effect of beam hardening and penumbra (Li et al.,
 127 2018), but the correction lost efficacy when the EPL was small. In the current work, however, a
 128 normalized OD was used instead of the EPL to avoid the need for beam hardening and penumbra
 129 corrections when describing spray characteristics. Additionally, the results and discussions
 130 presented here are based on time-averaged data.



131
 132 Figure 1: The penumbra effect in the ISU X-ray facility (not to scale).

133 The two-fluid coaxial atomizer* used in this research has been designed to be an open
134 source canonical atomizer that can be reproduced in any laboratory experiment or numerical
135 simulation that aims to compare or validate data against that obtain in this study or others
136 published with this system (Machicoane et al., 2019; Huck et al., 2018). As Figure 2 suggests,
137 liquid and gas enter the atomizer separately and flow parallel to each other at the nozzle exit.
138 Water enters into the top chamber from both sides, and then flows out through the centrally
139 located liquid needle with an inner diameter $d_l = 2.1$ mm and an outer diameter at the atomizer
140 exit of $D_l = 2.7$ mm. Air is used as the atomizing gas in this study. To investigate the effects of
141 swirl (angular momentum) on the spray, air was divided into two streams, co-flow air and swirl
142 air. Co-flow air enters the gas plenum from four symmetrical inlets that are perpendicular to the
143 water needle centerline. The curved inner wall of the gas plenum turns the air downward to
144 create a coaxial air flow at the nozzle exit, where the inner diameter at the gas exit is $d_g = 10$
145 mm. When swirl is imparted, a portion of the air stream enters the plenum through four
146 centrosymmetric inlets that are off-axis, creating swirl flow. The concentric liquid and air
147 streams meet and interact at the atomizer exit to create a spray. In this research, the central axis
148 of the atomizer defines the x-axis (vertical axis) and points downward with the origin
149 corresponding to the atomizer exit plane. The y-axis (horizontal axis) is the spray spanwise
150 coordinate. It has an origin corresponding to the liquid needle centerline and is perpendicular to
151 the X-ray beam path direction, which defines the z-axis. A description of the complete
152 experimental flow loop can be found elsewhere (Li et al., 2018); the identical flow loop was used
153 at ISU and at APS.

* Open-source two-fluid coaxial atomizer: <http://depts.washington.edu/fluidlab/nozzle.shtml>



154

155 Figure 2: Schematic representation of the aluminum two-fluid coaxial atomizer.

156 The ratio of swirl air flow rate to co-flow air flow rate is defined as the swirl ratio (SR) to
 157 reflect the amount of angular momentum in the gas phase.

$$158 \quad SR = \frac{\text{swirl air flow rate}}{\text{co-flow air flow rate}} \quad (4)$$

159 In this study, $0 \leq SR \leq 1$ while the total gas flow rate remained constant when the swirl ratio
 160 was varied.

161 The gas Reynolds number (Re_g) is defined as:

$$162 \quad Re_g = \frac{U_g d_{\text{eff}}}{\nu_g} = \frac{U_g \sqrt{d_g^2 - D_1^2}}{\nu_g} \quad (5)$$

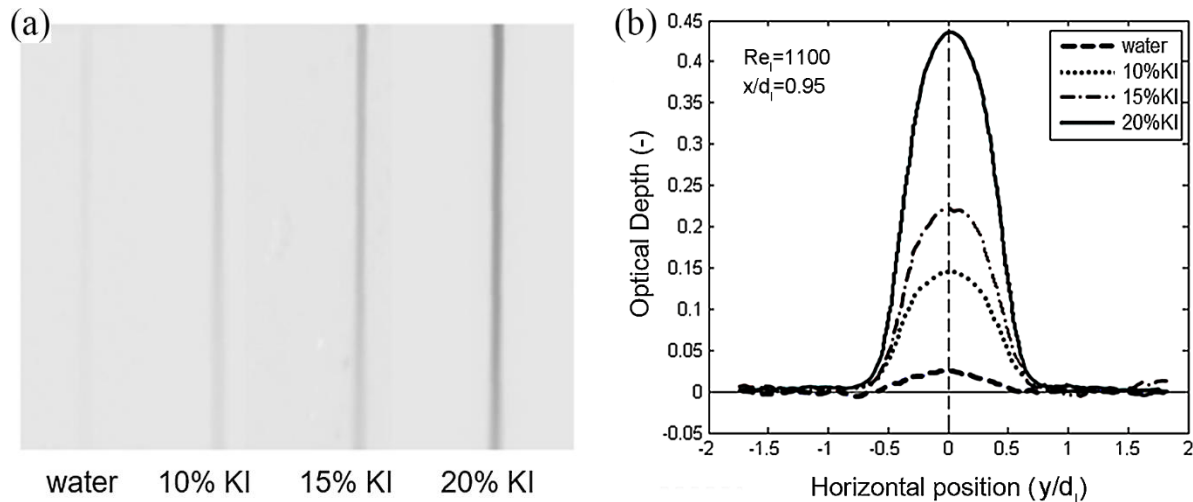
163 where U_g is the mean gas velocity at the nozzle exit; ν_g is the kinematic viscosity of air at 25°C;
 164 and d_{eff} is the gas effective exit diameter of the air stream at the nozzle exit, defined as the
 165 diameter of a circle with the same area as the gas exit area. Two gas Reynolds numbers were
 166 investigated: $Re_g = 21,200$ and $Re_g = 46,500$.

167 The liquid phase for the focused beam X-ray data from APS was distilled water. For the
 168 ISU broadband X-ray radiographs, 20% by mass potassium iodide (KI) was added to the water as
 169 a contrast enhancement agent. The liquid Reynolds number (Re_l) is defined as:

170
$$Re_1 = \frac{U_1 d_1}{\nu_1} \quad (6)$$

171 where U_1 is the mean liquid velocity at the nozzle exit; d_1 is the inner diameter of the liquid
 172 needle (2.1 mm), which is also used as the characteristic length for nondimensionalization; and
 173 ν_1 is the kinematic viscosity of water at 25°C. Three liquid Reynolds numbers were considered
 174 in this study: $Re_1 = 1100, 1600,$ and 2200 .

175 Figure 3a shows imaging with various KI concentrations (by mass) in the broadband
 176 X-ray radiographs for a liquid stream (no gas flow). In these flows, $Re_1 = 1100$ and $Re_g = 0$. The
 177 pure water stream is difficult to distinguish from the background. The image contrast improves
 178 as the KI concentration increases. Figure 3b plots the OD distributions of the liquid streams at
 179 $x/d_1 = 0.95$ (at 2 mm below the atomizer exit). The maximum optical depth (OD_{stream}) for pure
 180 water, 10% KI, 15% KI, and 20% KI is 0.03, 0.15, 0.22, and 0.44, respectively. The increased
 181 OD with increasing KI concentration is the result of increased X-ray attenuation (μ), which
 182 improves the image contrast.



183
 184 Figure 3: Liquid streams with changing KI concentration by mass: (a) broadband X-ray
 185 radiographs (same colorbar), and (b) optical depth distributions.

186 Peak signal-to-noise ratio (PSNR) for OD is used to evaluate the influence of KI
 187 concentration:

$$188 \quad \text{PSNR} = 10 \cdot \log_{10} \left(\frac{\text{OD}_{\text{stream}}^2}{\text{MSE}_{\text{noise}}} \right) \quad (7)$$

189 where $\text{OD}_{\text{stream}}$ is the maximum OD of the different KI concentrations as mentioned above, and
 190 $\text{MSE}_{\text{noise}}$ is the mean square error of OD measured where there is no liquid, representing the
 191 noise calculated from a selected region of the background. Note that the $\text{MSE}_{\text{noise}}$ is a position-
 192 dependent error that is related to the number and position of pixels used in its calculation. Time-
 193 dependent noise is minimized by averaging 1200 radiographic frames. The form of $\text{MSE}_{\text{noise}}$
 194 should be the same as OD^2 for comparison:

$$195 \quad \text{MSE}_{\text{noise}} = \frac{1}{n} \sum_{i=1}^n \left[-\log \left(\frac{I_{\text{noise}}}{I_0} \right) \right]^2 \quad (8)$$

196 where n is the number of pixels used to calculate $\text{MSE}_{\text{noise}}$ ($n = 2500$), I_0 is the time-averaged
 197 background intensity and I_{noise} is the root mean squared intensity of each pixel used to calculate
 198 $\text{MSE}_{\text{noise}}$. According to Eq. (7) and (8), the PSNR for pure water, 10% KI, 15% KI and 20% KI
 199 are 65.4 dB, 97.6 dB, 105.2 dB, and 119.1 dB, respectively. The KI PSNR shows an
 200 approximately linear relationship to the KI concentration. Hence, to achieve better contrast, 20%
 201 by mass KI was added to the liquid phase for the broadband X-ray radiographs. The additional
 202 KI could increase the surface tension but only by a 2% (Ali and Bilal, 2009), which should not
 203 make a significant influence on the spray structure. Also, the work of Halls et al. (2014b) has
 204 shown that KI concentration has a linear relationship with the X-ray attenuation coefficient with
 205 KI concentrations as high as 20%. Therefore, the 20% KI does not significantly enhance beam
 206 hardening. Others have also used KI as a contrast enhancement agent and have shown negligible

207 effects on water density and viscosity, and observed no change in the flow behavior (Radke et
208 al., 2014; Halls et al., 2014b).

209 **3. Results and discussion**

210 The following results describe the optical depth maps and profiles of the atomized spray
211 over a range of Re_l , Re_g , and SR. The influence of X-ray tube source energy levels is evaluated.
212 The spray profile determined from broadband X-ray radiographs with 20% KI added for contrast
213 enhancement are also compared to profiles determined from focused beam measurements of the
214 same atomizing spray using distilled water.

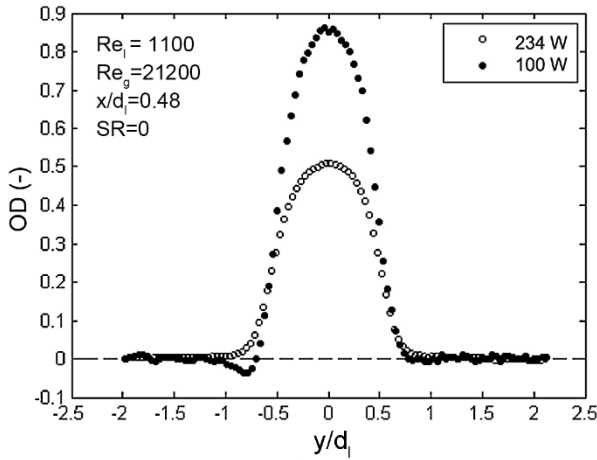
215 **3.1 Optical Depth**

216 The X-ray source operating potential can influence the radiograph intensity, which may
217 affect the data obtained from the image because of beam hardening and the attenuation
218 coefficient, which is a function of wavelength for a polychromatic X-ray beam. In this work,
219 radiographs were taken at two power levels of 100 W and 234 W with corresponding potentials
220 summarized in Table 1. Figure 4 shows a comparison of the OD, determined using Eq. (2), with
221 234 W and 100 W power levels at identical spray conditions and axial position. In general, the
222 two plots are both bell-shaped curves, but the magnitudes of the two plots vary greatly because
223 of the different attenuation coefficients caused by the change in X-ray energy. To eliminate the
224 effect of power level, the OD is normalized by the local maximum OD. Note that the local
225 maximum OD is the maximum value at the given axial location and not the maximum for the
226 entire spray.

227 Table 1: Related parameters for different operating potentials.

Operating potential	Tube current	Tube potential	Exposure	Frame rate	Frame count
234 W	3.0 mA	78 kV	20 ms	10 FPS	1200
100 W	2.0 mA	50 kV	20 ms	10 FPS	1200

228

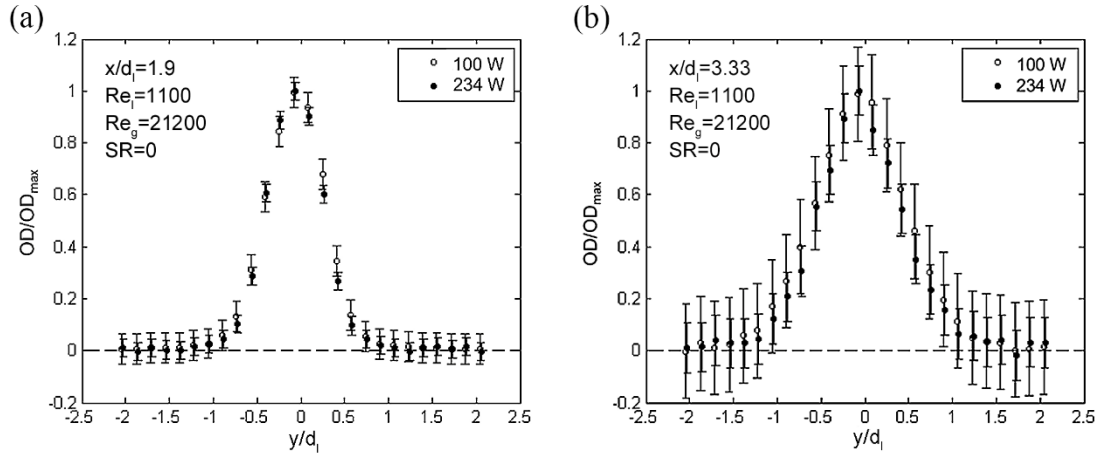


229

230 Figure 4: OD distributions near the nozzle exit with different X-ray source power levels.

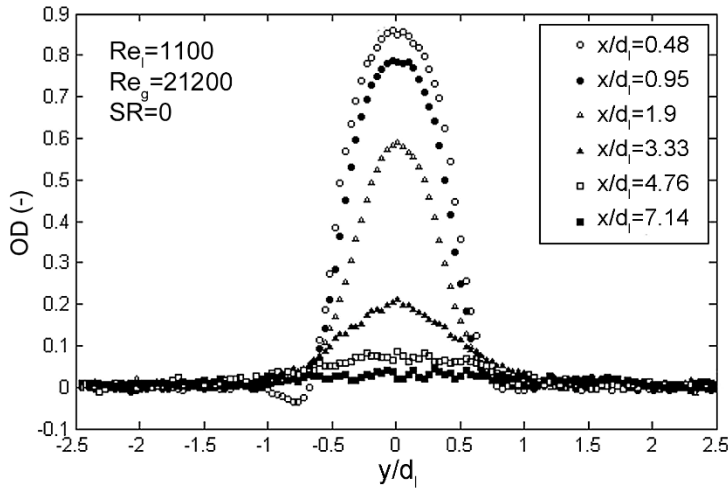
231 Figure 5 shows the normalized OD distributions for the two power levels, where the error
 232 bars represent the relative error calculated from the spatial-dependent background noise by the
 233 $3\text{-}\sigma$ rule (Pukelsheim, 1994). The absolute error in OD is 0.02 for all conditions, and this is
 234 normalized by the local maximum OD at the given x -location. At both positions in Figure 5, the
 235 normalized OD distributions are similar regardless of power level. This indicates that the change
 236 of X-ray tube source power level does not significantly influence the shape of the OD
 237 distribution. Comparing the profiles for the two axial locations of $x/d_1 = 1.9$ and 3.33, it is
 238 evident that the relative OD error in Figure 5b is larger than in Figure 5a. The absolute OD error
 239 generally remains unchanged with position, but the maximum OD decreases with increasing x/d_1
 240 as the spray spreads out. This leads to an increase in relative error as x/d_1 increases. For the same
 241 reason, the span of the normalized OD distribution increases from approximately $y/d_1 = \pm 0.75$

242 to $y/d_1 = \pm 1.25$ when x/d_1 increases from 1.9 to 3.33. Hence, as the atomized spray disperses,
 243 the profile spreads out, and the broadband X-ray measured OD becomes less accurate due to the
 244 increasing relative error.



245 Figure 5: Normalized OD distributions with different X-ray source power levels at: (a)
 246 $x/d_1 = 1.9$ ($x = 4$ mm), and (b) $x/d_1 = 3.33$ ($x = 7$ mm).
 247

248 Figure 6 shows the magnitude and shape changes of the OD distribution for different
 249 axial positions ranging from $x/d_1 = 0.48$ to 7.14 when no gas swirl is added ($SR = 0$). Every
 250 distribution shows an approximate Gaussian distribution (Powell et al., 2000; Yue et al., 2001)
 251 with a maximum at $y/d_1 = 0$ (the central axis). The distributions in the near nozzle region
 252 ($x/d_1 = 0.48$ to 1.9) are influenced by a liquid core which show a flatter top compared to a typical
 253 Gaussian distribution. The OD maximum then decreases with increasing axial distance from the
 254 atomizer exit. At $x/d_1 = 0.48$ ($x = 1$ mm), the maximum OD is 0.87. When x/d_1 increases to 4.76
 255 ($x = 15$ mm), the maximum OD decreases to less than 0.1, where the OD distribution flattens out
 256 to nearly a straight line. For this no swirl condition, the span of the OD distribution increases
 257 slightly with increasing x/d_1 , forming a slender spray.



258

259 Figure 6: OD distributions at different axial positions for $Re_l = 1100$, $Re_g = 21,200$, and $SR = 0$,

260

with tube power level of 100 W.

261

When the swirl ratio increases but Re_g and Re_l remain constant ($Re_g = 21,200$,

262

 $Re_l = 1100$), the OD distribution shows a similar approximate Gaussian feature but the span and

263

magnitude change. At $SR = 0.5$, the OD decreases over a smaller axial distance, and the span

264

increases along the axial direction. This indicates that the spray is more spread out in the radial

265

direction (Hopfinger and Lasheras, 1996). When $SR = 1$, the OD profile is similar to that of

266

 $SR = 0$. Compared with $SR = 0.5$, when $SR = 1$ the span of the OD distribution decreases. For

267

example, at $x/d_1 = 3.33$, the maximum OD for $SR = 0, 0.5$, and 1 are $0.20, 0.09$, and 0.43 ,

268

respectively. This reveals that as SR increases, the spray changes from slender to broad to

269

slender again.

270

For example, at $x/d_1 = 0.48$ (Figure 7a), the normalized OD distributions overlap. This

271

position is close to the atomizer exit, where the spray is not completely developed, and the intact

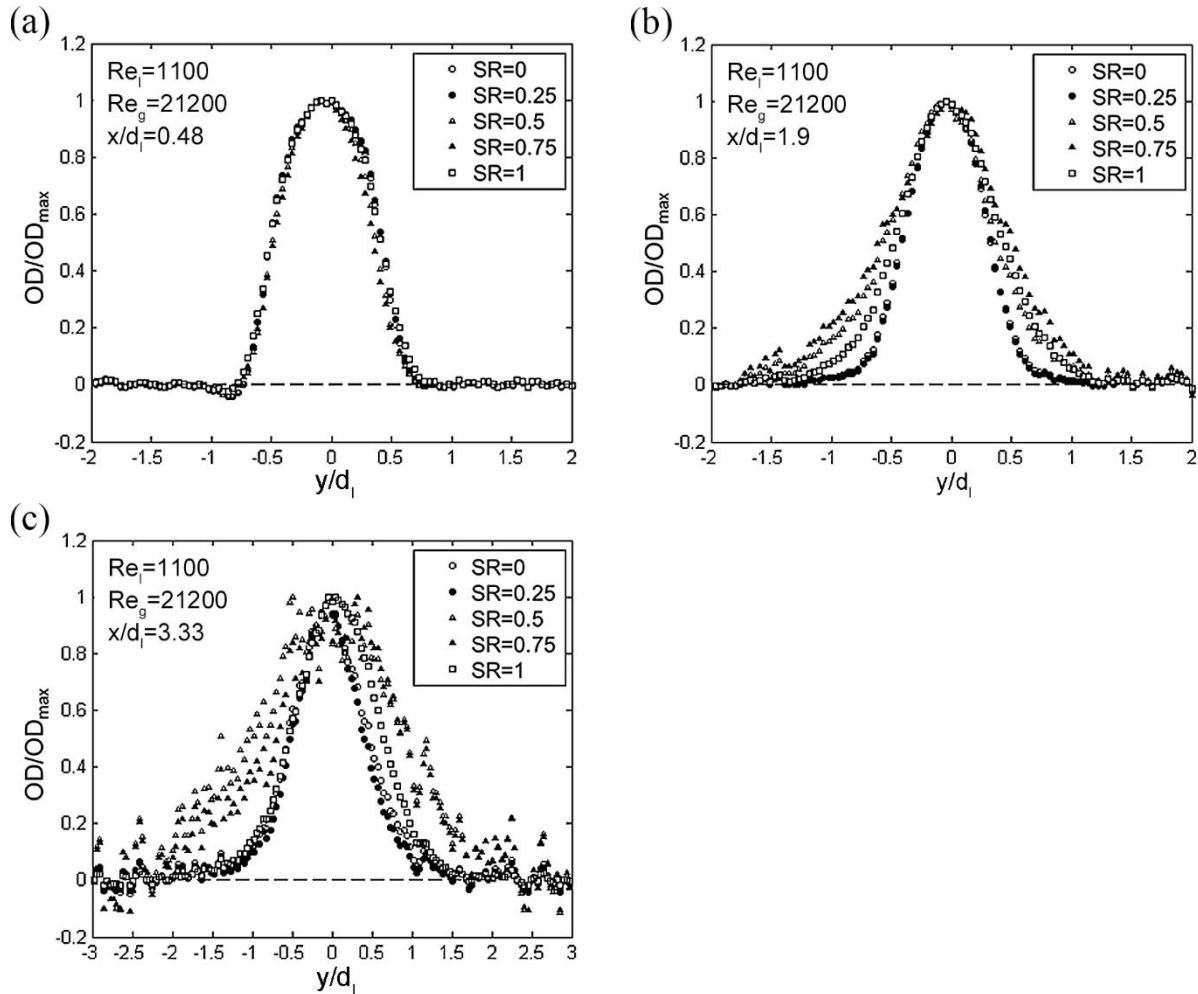
272

liquid core still has a significant diameter (Bothell et al., 2018). The magnitude of the intact

273

liquid core, common for all swirl ratios, provides the similarity in the OD distributions. At

274 $x/d_1 = 1.9$ (Figure 7b), the normalized OD distributions begin to show a trend as a function of
 275 swirl ratio. The normalized OD with $SR = 0$ and 0.25 still overlap. However, the normalized OD
 276 distributions with $SR = 0.5, 0.75,$ and 1 become wider and spread from each other. The
 277 distribution with $SR = 0.75$ is the widest, then $SR = 0.5$ and $SR = 1$. At $x/d_1 = 3.33$ (Figure 7c),
 278 the normalized OD distributions with $SR = 0$ and 0.25 still overlap. The distribution with $SR = 1$
 279 approaches the distributions of $SR = 0$ and 0.25 . The distributions with $SR = 0.5$ and 0.75 are
 280 much wider. Note there is also more scatter in the data at $x/d_1 = 3.33$ because the relative error at
 281 this location is larger (see Figure 5b) due to the smaller absolute OD measures (see Figure 6).



282

283

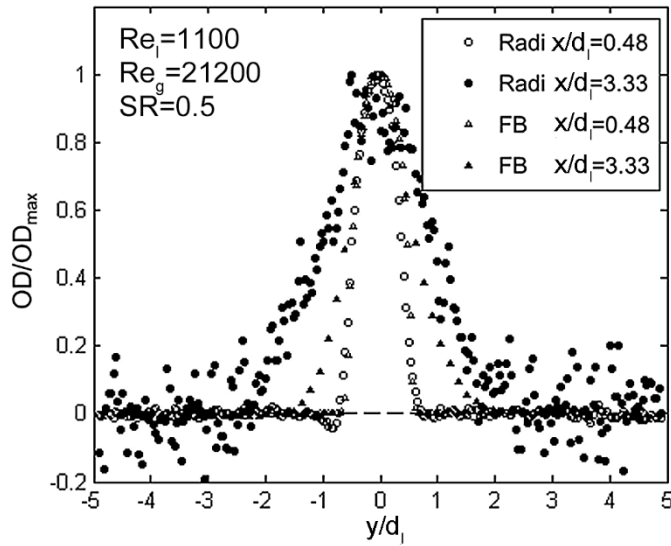
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Figure 7: Normalized OD distributions with various SR: (a) $x/d_1 = 0.48$, (b) $x/d_1 = 1.9$, and (c)

285

$x/d_1 = 3.33$.

286 Figure 8 shows a comparison of the normalized OD distributions between broadband and
287 focused beam radiographs. The circles in the plot represent broadband radiograph data (marked
288 as ‘Radi’), and the triangles represent focused beam data (marked as ‘FB’). The unfilled symbols
289 represent data at the position $x/d_1 = 0.48$, while the filled symbols represent $x/d_1 = 3.33$. The
290 unfilled circles and triangles overlap, which means that at $x/d_1 = 0.48$ where the OD is large,
291 broadband and focused beam measurements are well matched. At this position, the penumbra,
292 beam hardening, and the 20% KI do not show a significant impact on the normalized OD
293 distribution. The filled symbols reveal some differences at $x/d_1 = 3.33$. The focused beam OD
294 distribution is narrower than that of the broadband OD. At this axial position, the OD is very
295 small, which enhances the penumbra and beam hardening effects as well as the relative error
296 from the broadband measurements. Hence, the broadband measurements are noisier at this axial
297 position. Furthermore, although the flow loop used in the broadband and focused beam
298 measurements was identical, the exhaust system downstream from the spray was not because of
299 space restrictions at APS. Both exhaust systems provided a slight suction to prevent
300 recirculation. The APS system, however, had a more powerful suction system that could have
301 hindered the spray spreading, making the focused beam profile narrower than the broadband
302 profile, and this was exacerbated further downstream.



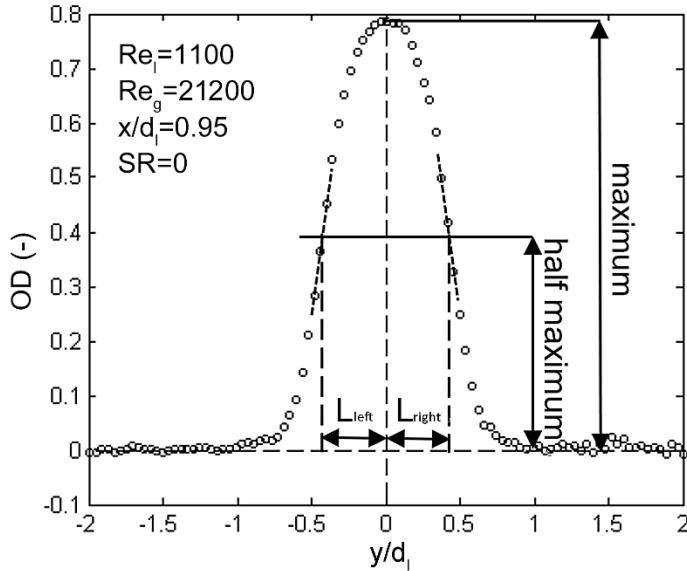
303
 304 Figure 8: Comparison of normalized OD distributions between broadband and focused beam
 305 radiographs with $SR = 0.5$.

306 3.2 Spray profile

307 The edge of the spray at any given axial location is defined as the location where the OD
 308 is equal to 1/2 of the maximum OD at that axial location (as shown in Figure 9), and is used to
 309 characterize the spray spatial extent. Because of the limitations in radiography contrast, it is
 310 easier and more accurate to identify the spray edge using 50% of the local maximum OD,
 311 particularly when the OD is small. Figure 9 shows an OD distribution at $x/d_1 = 0.95$. For focused
 312 beam data, the edge of the spray was defined by interpolating between 2 data points of which the
 313 OD values were closest to the half maximum OD. For broadband radiograph data, of which the
 314 interval between data points is very small, the edge of the spray was directly defined by the data
 315 point closest to the half maximum OD. The corresponding distances from the spray edges on both
 316 sides to the central axis are defined as L_{left} and L_{right} ; these two measures are averaged to get a
 317 more accurate evaluation of the spray profile, defined as delta:

318
$$\delta = \frac{1}{2}(L_{\text{left}} + L_{\text{right}}) \quad (9)$$

319 The error in δ that resulted from the discreteness of the broadband radiograph data points is
 320 ± 0.08 mm, and is assumed to be small when compared to the characteristic length (2.1 mm).

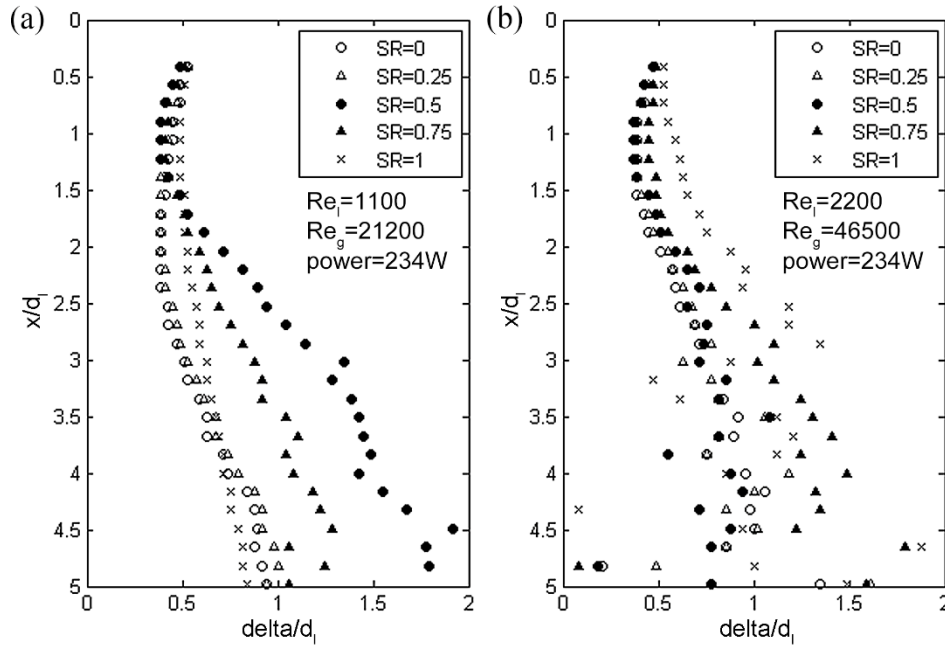


321
 322 Figure 9: Defining the edge of the spray at the half maximum OD.

323 The spray profile is determined by plotting the measured δ value at various axial
 324 locations. Figure 10 shows the spray profile for two different Re_i and Re_g values for a range of
 325 swirl ratios. The atomizer exit plane corresponds to $x/d_1 = 0$, but data are available starting at
 326 $x/d_1 = 0.3$ ($x = 0.63$ mm) because the image at the nozzle exit is distorted due to the image
 327 resolution and processing. Note that δ is normalized by d_1 . In general, the spray profiles focus
 328 near the nozzle exit and then spread out. The focused region correlates with the position where
 329 the liquid core (Faeth, 1991) begins to disappear, and the primary atomization has fully occurred
 330 (Li et al., 2018).

331 The broadband radiographs have an axial resolution of 0.08 mm, but the data in Figure 10
 332 shows every fourth data point for better visualization. Figure 10a shows the spray profile for

333 $Re_l = 1100$ and $Re_g = 21,200$. When SR increases from 0 to 0.25, the spray profile remains
 334 unchanged. The point of minimum spray width is around $x/d_1 = 1.3$. At $x/d_1 = 4$, $\delta/d_1 = 0.6$
 335 and the spray continues to spread as x/d_1 increases. When SR = 0.5, the point of minimum spray
 336 width is around $x/d_1 = 1.1$, and the spray gets much wider as x/d_1 increases. Further increasing SR
 337 to 0.75 and then to 1 provides a narrower spray compared to SR = 0.5, and the point of minimum
 338 spray width moves downstream to $x/d_1 = 1.6$.

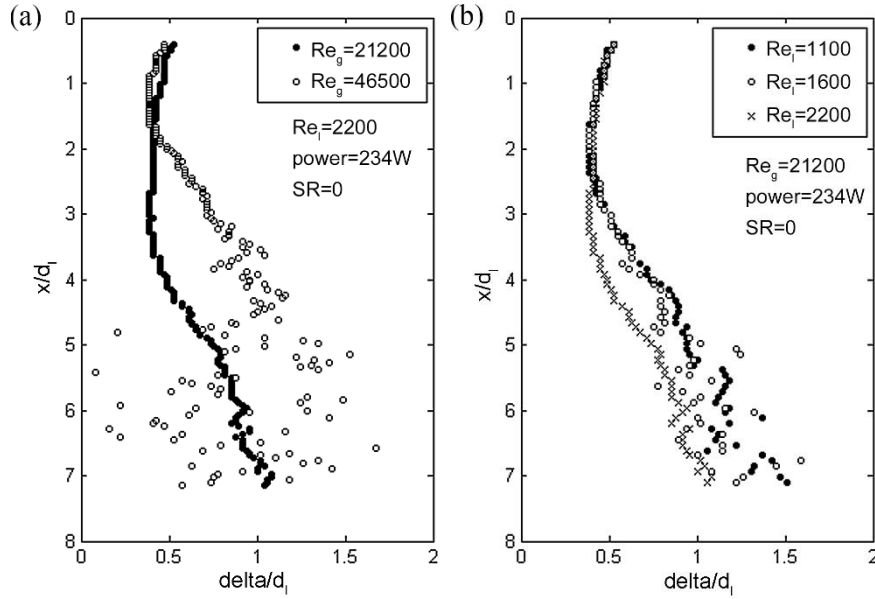


339
 340 Figure 10: Spray profiles with various SR at: (a) $Re_l = 1100$, $Re_g = 21,200$, and (b) $Re_l = 2200$,
 341 $Re_g = 46,500$.

342 Figure 10b shows the spray profile for $Re_l = 2200$ and $Re_g = 46,500$. As Re_g increases,
 343 spray atomization improves and the spray becomes too dilute to be captured by the broadband
 344 radiographs, creating large fluctuations in the data when $x/d_1 > 3$. At this condition, the profiles
 345 for SR = 0, 0.25, 0.5 and 0.75 are similar, the point of minimum spray width corresponds to
 346 $x/d_1 \approx 1.3$, and $\delta/d_1 = 0.7$ at $x/d_1 = 3$. When SR increases beyond 0.75, the spray widens with
 347 the widest profile at SR = 1. At SR = 1, the point of minimum spray width seems to move closer

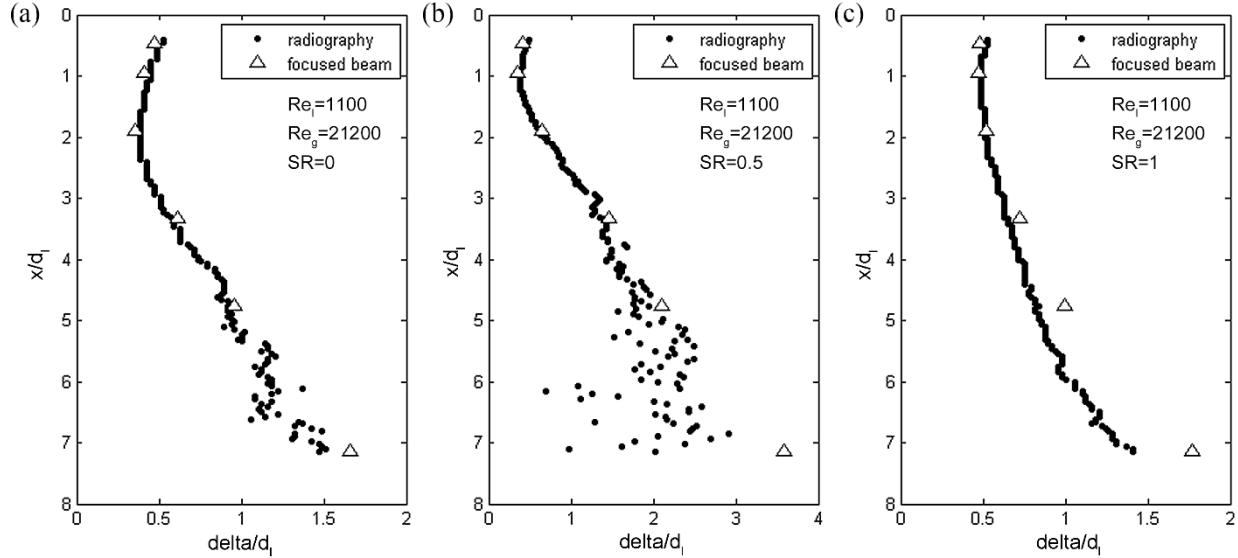
348 to the exit, showing a shape that gradually widens from top to bottom. In both conditions shown
349 in Figure 10, a large change in the spray profile happens at certain SRs. For the low gas
350 Reynolds number (Figure 10a), δ sharply increases when SR increases from 0.25 to 0.5. For
351 the high gas Reynolds number, this happens at the maximum SR = 1 (Figure 10b).

352 When there is no gas swirl (SR = 0), the effect of Re_g and Re_l on the position of the point
353 of minimum spray width show opposite trends. As shown in Figure 11a for a fixed $Re_l = 2200$,
354 increasing Re_g from 21,200 to 46,500 causes the point of minimum spray width to move closer to
355 the nozzle exit. The spray also spreads out more as Re_g increases. This is caused by the
356 additional gas momentum enhancing the liquid atomization and mixing, promoting the spreading
357 of the spray. When Re_g is fixed at 21,200 and Re_l increases from 1100 to 1600 (Figure 11b), the
358 effects are negligible. However, when Re_l is further increased to 2200, the point of minimum
359 spray width moves downstream, and the spray elongates. This is caused by the additional mass
360 loading of the liquid, delaying the atomization process and therefore the spreading of the spray.
361 Limited by the image resolution, the spray profiles in the far-field region are hard to analyze and,
362 therefore, not included here. From the near-field results shown here, it appears that Re_g and Re_l
363 also have opposite trends on the spread of the spray in the radial direction. Data from the mid-
364 field region of the spray are needed to confirm this.



365
366 Figure 11: Spray profiles changing with (a) Re_g and (b) Re_l , while all other conditions are fixed.

367 Delta from the broadband radiographs is normalized by d_l . As mentioned above, the error
368 in delta from the broadband radiographs determined by the resolution of the image is fixed at
369 ± 0.08 mm (± 0.04 normalized by d_l). Compared to the characteristic length scale, this error is
370 small, therefore interpolation was not applied to the broadband radiograph data to determine the
371 edge of the spray. The focused beam data, however, are taken at different sampling intervals, so
372 the normalized error ranges from ± 0.04 to ± 0.23 , which requires interpolation to minimize the
373 position error. The broadband radiographs also have a disadvantage because, as the spray
374 disperses (large x/d_l), image contrast decreases and the scatter in the spray profile increases as
375 shown in Figure 12a and 12b. The spray profiles from broadband radiographs match well with
376 that from the focused beam data at $SR = 0$ and 0.5 as Figure 12a and 12b show. At $SR = 1$
377 (Figure 12c), the profile from broadband radiographs is narrower. This is possibly due to the
378 atomization enhancement along the radial direction caused by swirl air. Compared with the no
379 swirl condition (Figure 12a), strong swirl air significantly improved spray dispersion along the
380 radial direction and lowered the contrast of the image, causing a narrower spray profile.



381
 382 Figure 12: Comparison of the spray profile between broadband radiographs and focused beam
 383 data with (a) $SR = 0$, (b) $SR = 0.5$, and (c) $SR = 1$.

384 4. Conclusions

385 The current work evaluated the effect of operating parameters on spray formation from a
 386 two-fluid coaxial atomizer in the near-field region. The two metrics of the spray discussed in this
 387 work were optical depth (OD) and spray profile. Controlling parameters were the Re_g , Re_i , and
 388 swirl ratio. The data obtained from broadband X-ray radiographs using a tube source were
 389 compared to synchrotron X-ray focused beam data. Two tube X-ray source energy levels for
 390 broadband X-ray radiography were analyzed and their differences were found to be negligible
 391 when the data were normalized properly.

392 The OD provided an approximate Gaussian distribution across the spray width. The
 393 magnitude of the OD decreased uniformly across the spray diameter, as the spray developed
 394 downstream from the atomizer nozzle. The X-ray tube source energy influenced the magnitude
 395 of the OD but did not change the shape of the distribution. Compared to focused beam data, the

396 normalized OD distributions obtained from the broadband radiographs matched well at small x/d_1
397 but deviated at large x/d_1 because of the penumbra effect and beam hardening.

398 The spray profile was defined by the location of the half maximum OD. The swirl ratio
399 influenced the spray profile with trends related to Re_g . At $Re_g = 21,200$, the spray widened and
400 then narrowed as SR increased from 0 to 0.5 to 1; the width increased significantly when SR
401 increased from 0.25 to 0.5. At $Re_g = 46,500$, the widest spray occurred at the maximum SR
402 studied, $SR = 1$, and the spray width increased significantly when SR increased from 0.75 to 1.
403 This implied a critical value for SR, related to Reynolds numbers, above which the spray width
404 increased significantly. For the no swirl condition, Re_g and Re_l showed opposite effects on the
405 spray profile, where increasing Re_g broadened the spray but increasing Re_l narrowed the spray.
406 Compared to focused beam data, the spray profile from the broadband radiographs matched well
407 at $SR = 0$ and 0.5, but were narrower downstream at $SR = 1$.

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497 **Figure captions**

- 498 Figure 1: The penumbra effect in the ISU X-ray facility (not to scale).
- 499 Figure 2: Schematic representation of the aluminum two-fluid coaxial atomizer.
- 500 Figure 3: Liquid streams with changing KI concentration by mass: (a) broadband X-ray
501 radiographs (same colorbar), and (b) optical depth distributions.
- 502 Figure 4: OD distributions with different X-ray source power levels.
- 503 Figure 5: Normalized OD distributions with different X-ray source power levels at: (a) $y/D_i =$
504 1.9 ($y = 4$ mm), and (b) $y/D_i = 3.33$ ($y = 7$ mm).
- 505 Figure 6: OD distributions at different axial positions for $Re_1 = 1100$, $Re_g = 21,200$, and $SR = 0$,
506 with tube power level of 100 W.
- 507 Figure 7: Normalized OD distributions with various SR: (a) $x/d_1 = 0.48$, (b) $x/d_1 = 1.9$, and (c)
508 $x/d_1 = 3.33$.
- 509 Figure 8: Comparison of normalized OD distributions between broadband and focused beam
510 radiographs with $SR = 0.5$.
- 511 Figure 9: Defining the edge of the spray at the half maximum OD.
- 512 Figure 10: Spray profiles with various SR at: (a) $Re_1 = 1100$, $Re_g = 21,200$, and (b) $Re_1 = 2200$,
513 $Re_g = 46,500$.
- 514 Figure 11: Spray profiles changing with (a) Re_g , and (b) Re_1 while all other conditions are fixed.
- 515 Figure 12: Comparison of the spray profile between broadband radiographs and focused beam
516 data with (a) $SR = 0$, (b) $SR = 0.5$, and (c) $SR = 1$.