Study of spray collapse phenomenon at flash boiling conditions using simultaneous front and side view imaging

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Abstract

Flash boiling has become a topic of interest to researchers due to its potential of achieving good fuel atomization and negative influence on GDI engine emissions when spray collapses and spray-wall impingement exists. Under flash boiling conditions, the accompanying spray collapse phenomenon and plume interaction are not clearly elucidated. Simultaneous side view diffused back illumination (DBI) and front view Mie-scattering were implemented in this work to capture transient plume to plume interaction of iso-octane fuel spray from a 10 hole gasoline direct injection (GDI) injector at flash boiling conditions. Fuel temperature and ambient gas pressure were varied in a wide range to cover collapse, transitional and non-flashing regimes. Two new criteria named ‘spray collapse percentage’, defined based on the front view Mie-scattering technique and ‘optical thickness’ based on the side view DBI

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technique, were developed for classification of different spray regimes. These two criteria distinguish the collapsing and transitional regimes well from the non-collapsing regime compared to other criteria used in the literature.

Keywords: Flash boiling; Spray collapse; Plume interaction; Gasoline direct injection (GDI) engine; Front, side view comparison

1 Graphical abstract

2 Highlights

- Simultaneous front view Mie-scattering and side view DBI images were captured to understand flash boiling.
- Collapse occurs in both radial and circumferential directions.

- 6 • Two criteria for determination of spray regimes were proposed.
- 7 • Plume interaction and spray collapse criteria change with fuel temper-
8 ature.
- 9 • Spray collapse depends on both ratio of ambient gas pressure to satu-
10 ration vapor pressure (R_p) and ambient pressure.

11 **1. Introduction**

12 In gasoline engines, flash boiling is a common phenomenon [1] that liquid
13 fuel boils suddenly when it goes through a fast depressurization process to a
14 pressure level lower than its saturated vapor pressure [2]. Flash boiling has
15 the advantage of achieving proper atomization at a lower cost compared with
16 increasing fuel injection pressure [3]. Droplet size has been reported [4, 5] to
17 decrease when flash boiling occurs. But heavy flash boiling, which should be
18 avoided, would cause spray collapse [3, 5], wall impingement [6] and reduces
19 internal nozzle fuel flow rate [7]. Wang et al. [8] studied the closely coupled
20 split injection strategy at flash boiling condition and concluded that it can
21 shorten the spray penetration length and reduce the potential of spray im-
22 pingement. Either to utilize or to prevent flash boiling, a better understand-
23 ing of this complex process is required. Flash boiling and its accompanying
24 spray collapse phenomenon have become an exciting topic among researchers
25 recently.

26 Three commonly used variables to control the flash boiling intensity are
27 the fuel temperature, ambient gas pressure, and saturation vapor pressure
28 of the fuel. To study the influence of these factors on flash boiling and

give general criteria, R_p (ratio of ambient gas pressure to saturation vapor pressure) and ΔT (superheat degree) are the two mainly used parameters [9, 10, 11, 12]:

$$R_p = P_a / P_s \quad (1)$$

$$\Delta T = T_f - T_s \quad (2)$$

where P_s is the saturation pressure at fuel temperature T_f , P_a is the ambient gas pressure, and T_s is the saturation temperature of the fuel at the ambient gas pressure P_a .

Different indicators have been used to distinguish three different regimes including flare flash regime, transitional regime, and non-flashing regime. Some researchers have studied flash boiling using an 8-hole GDI injector with 60° spray angle [3, 9, 13]. In their studies, penetration length, plume width, vapor quantity, droplet size and plume to plume distance (the two opposite plumes on the central cross section) were used as indicators to differentiate the regimes based on R_p . They classified the regimes as flare flashing regime ($R_p < 0.3$), the transitional regime ($0.3 < R_p < 1$) and the non-flashing regime ($R_p > 1$). Lacey et al. [10] studied propane flashing sprays using ECN spray G injector and proposed a new indicator D_n , with nozzle geometry taken into consideration, and generalized the flashing criteria to be $D_n \geq 1, d_t/d_{collapse} < D_n < 1, D_n \leq d_t/d_{collapse}$ from collapse regime to non-flash regime.

Spray collapse can happen both at non-flash boiling condition, and flash boiling condition for multi-hole GDI sprays. Guo et al. [14] explained them as jet induced collapse and condensation induced collapse, respectively. In both cases, plume to plume interaction is a vital precedent phenomenon.

Wang et al. [15] studied the near nozzle single hole spray pattern under flash boiling conditions and observed increased cone angle and spray area when flash boiling occurs. Wu et al. [16] studied 1-hole, 2-holes, and 6-holes sprays at near nozzle region from flare flash to sub-cooled conditions. It was revealed that the single plume swells and multi-plume interactions occur when flash boiling phenomenon takes place. Heldmann et al. [17] studied the separate single plume of the 5-hole injector and interaction between single plumes from two different 5-hole injectors. These above mentioned single plume and multi-plume interaction studies help to understand the spray pattern change in a multi-hole GDI injector under flash boiling conditions. Investigation of plume interaction is mandatory for better understanding of the complex collapse process.

Most reported experimental work on spray collapse phenomenon were through side view and volume illumination (backlight imaging) [11, 18, 19, 20, 21, 22, 23, 24], Mie-scattering [10, 25, 26] or schlieren [10, 12, 22, 25]), which has the advantage of capturing transient spray included cone angle or spray width and reporting directly whether spray collapse happens or not. But it inevitably has the drawback of overlapping of plumes and is not capable of illuminating inner structure of spray and demonstrating plume to plume interaction. It's challenging to explain that merge of plumes on the image is due to plume interactions or due to overlapping along the line of sight, especially when the number of holes is relatively high.

Few works [9, 13, 18, 27] have been reported with laser sheet illumination to show the cross-sectional view of the spray (either through central plane showing spray inner structure or perpendicular to injector axis show-

ing plumes cross section at a fixed distance from the nozzle). However, a very recent publication has reported laser sheet imaging for a 2-hole nozzle [28] showing plume to plume interaction. Again the setback of these laser sheet based imaging techniques is that it is very challenging to capture the interaction between adjacent plumes for a real multi-hole GDI injector.

For multi-hole injector sprays, Mie-scattering images taken from the front view (ahead of spray cone) can be an attractive choice to visualize the transition from segregated plumes to connected plumes or collapsed plumes, without the issue of overlapping between plumes. While minimal work has been done with this method on plume to plume interaction under spray collapsing conditions and particularly direct simultaneous comparison between side view and front view images, have not been done so far for flashing sprays. Sphicas et al. [21] have implemented front view Mie-scattering in the study of spray collapse at non-flashing conditions for ECN spray-G. Mojtabi [29] studied plume to plume interaction under flash boiling conditions on GDI injectors solely from front view. Gutierrez [30] studied ECN spray-G morphology in a single cylinder engine under flash boiling conditions using front view Mie-scattering.

Considering minimal work that has been done using front view imaging for plume interaction studies, this work bridges the gap by visualizing the spray from both the side view (DBI) and the front view (Mie-scattering) simultaneously with two high-speed cameras. It gives a clear image showing how the transient plume to plume interaction is related to the collapsing phenomenon usually observed from the side. Two new criteria based on front view Mie-scattering and side view DBI images were proposed to segregate

103 spray behavior into strong collapse regime, transitional regime, and non-
104 flashing regime. These criteria were compared with widely used conventional
105 indicators based on liquid penetration length and spray width.

106 **2. Experimental setup and diagnostics**

107 Experiments were carried out in KAUST Spray Lab. Figure 1 (a) shows
108 the setup alignment for simultaneous DBI and Mie-scattering imaging tech-
109 niques. The chamber used in this study is capable of handling gas pressure
110 from the sub-atmospheric condition to 10 bar absolute pressure. The large
111 chamber volume of 27 liters benefits the study of spray at low ambient gas
112 density conditions, like flash boiling, without encountering the problem of
113 wall interactions. A 10-hole GDI injector was mounted horizontally on one
114 side, and optical windows on the other three sides allow the possibility to
115 run diffused back illumination (DBI) and Mie-scattering at the same time.
116 Two high-speed cameras (Photron SA-X2) were mounted facing towards the
117 injector tip and from side for Mie-scattering and DBI imaging, respectively.
118 A high power LED was used in a high-speed repetitive pulse mode to ensure
119 sufficient Mie-scattering intensity. At the same time, optimized aperture and
120 neutral density (ND) filter were used for DBI imaging to avoid saturation of
121 the camera. Two cameras were synchronized at 40 kfps frame rate to capture
122 the same spray from different perspectives at a sufficiently high temporal res-
123 olution to obtain enough information of flashing sprays. Resolution of DBI
124 and Mie-scattering images are 0.22 mm/pixel (512×512) and 0.28 mm/pixel
125 (512×552), respectively.

126 An Aramco customized high-pressure multi-hole injector was studied in

127 this work. The injector was fixed in a custom-made fixture, which has an
 128 internal channel connected with a heat exchanger, shown in Figure 1(b). The
 129 internal volume of the fixture covers injector head thus that fuel temperature
 130 can be controlled. Figure 1(c) shows the orientation of 10 nozzle holes, each of
 131 diameter ϕ 165 μm . National Instruments Direct Injector Driver System (NI
 132 DIDS-2003) was used to drive the injector. The injector excitation duration
 133 was fixed at 1 ms throughout this study.

134 3. Experimental conditions

135 Table 1 shows the experimental conditions used for this study. In this
 136 work, a single component fuel iso-octane was studied as a surrogate of com-
 137 plex multi-component gasoline fuels. The injection pressure was fixed at 100
 138 bar and excitation duration of 1 ms. Ambient gas temperature was kept at
 139 room temperature. Fuel temperature and ambient gas pressure are the two
 140 variables examined in this study. Fuel temperature was varied from 60 $^{\circ}C$
 141 to 120 $^{\circ}C$. Since R_p is of more interest rather than the absolute ambient gas
 142 pressure, R_p was varied in 15 levels (0.05–1.4) for each fuel temperature. As
 143 saturation vapor pressure varies with fuel temperature, the absolute ambi-
 144 ent gas pressure was determined based on R_p and saturation vapor pressure
 145 accordingly as shown in Table 2. Iso-octane saturation vapor pressure was
 146 obtained using Antoine’s equation (Eq. 3) from the NIST website [31].

$$\log_{10}(P) = A - \frac{B}{T + C} \quad (3)$$

147 where, P is the vapor pressure in bar and T is the fuel temperature in K.

148 According to Xu et al. [3], R_p of 1 is the starting point of the transitional
 149 regime for their injector and fuel combination. Therefore in this study, R_p

150 data points are refined below 1 and further refined when $R_p \leq 0.3$ to capture
151 the change in plume interactions. Experimental conditions and iso-octane
152 vapor pressure curve are shown in Figure 2. Each case was repeated five
153 times.

154 4. Results and discussions

155 4.1. Comparison of instantaneous and averaged spray images

156 The average image from 5 repeats is compared against the five individual
157 runs in Figure 3. The selected case is for a fuel temperature of 120°C which
158 has a low $R_p(0.05)$ and spray shows an extreme collapse. DBI images show
159 that a central jet is formed and penetrates much longer than the surrounding
160 regions. The simultaneous Mie-scattering image confirms that this jet is
161 indeed along the center line by showing an entirely white area in the center.
162 In each instantaneous events, more detailed small scale features could be
163 seen from the images, while the averaged image would smooth these features.
164 However, the overall spray morphology and large scale features have remained
165 the same even after the averaging process. Since all Mie-scattering and DBI
166 videos are taken simultaneously for the same spray event, the averaged image
167 from five repeats for the two methods would still be comparable. Thus image
168 post-processing and criteria definition hereafter will be based on the averaged
169 images.

170 4.2. Plume interactions

171 Figure 4 shows the comparison of spray morphology at different R_p for a
172 fuel temperature of 120°C at a time after the start of injection (Time aSOI)

173 of 0.3 ms. The front view Mie-scattering images can reveal that plume in-
 174 teraction does not exist at conditions at $R_p \geq 0.6$. However, it is difficult
 175 to come to this conclusion from the DBI images due to the overlapping of
 176 plumes along the line of sight. Both methods qualitatively show that plumes
 177 become thicker when R_p decreases. When R_p decreased to 0.5, Mie-scattering
 178 image shows that plume to plume interaction starts between the two plumes
 179 at the horizontal plane (these two plumes have a smaller gap than that be-
 180 tween other plumes). This interaction becomes stronger when R_p is further
 181 decreased to 0.2, where plume interaction between other adjacent plumes also
 182 begins. Plumes shown in DBI images become connected. This condition can
 183 be regarded as the starting point of spray collapse due to flashing conditions.
 184 At $R_p = 0.15$, newly concentrated plumes are formed in the region between
 185 the original plumes and co-exist with them. At $R_p = 0.1, 0.05$, the plumes
 186 no more exist at its original positions. Instead, newly concentrated plumes
 187 caused by plume interaction are observed.

188 Figure 5a and b shows the comparison of two cases ($R_p = 0.05$ and 0.4)
 189 where plume directions are different. The intensity in the Mie-scattering
 190 images along the predefined circle (Figure 6) clearly shows the shift of plume
 191 orientation when R_p decreases from 0.4 to 0.15. The corresponding Mie-
 192 scattering images can refer to 4. With a R_p greater than 0.2, the original
 193 plumes are clear and intensity peaks fall on the original plume direction.
 194 However in the case of $R_p = 0.15$, main peaks are found between the original
 195 plumes and small intensity peaks coexist at the location of original plumes.
 196 This is the case where new concentrated plumes start to form. At $R_p = 0.1$,
 197 the original plumes start fading away and disappear at $R_p = 0.05$. Through

198 Figure 4 and Figure 6, how the plume interaction and spray collapse develop
199 when R_p decreases are clearly elucidated.

200 The collapsing phenomenon observed from the Mie-scattering images is
201 due to plume expansion and the adjacent two plumes interaction. The adja-
202 cent two plumes collapses in the circumferential direction and forms a new
203 concentrated jet in between. However, the 10 plumes also experience a radial
204 collapse, which should be highlighted. In the lowest R_p case, a central jet
205 was observed from DBI images. All the plumes expand due to flash boiling
206 and interact along injector axis. As a result of 10-plumes interaction and
207 collapse in the radial direction, a new concentrated jet was formed along the
208 injector center line. The location of this central jet was confirmed by the
209 Mie-scattering image since it is white within the center of the spray hiding
210 the nozzle behind. Similar phenomenon was observed previously by Schulz
211 and Beyrau [32] using a 6-hole GDI injector.

212 4.3. Effect of fuel temperature

213 Figure 7 shows the comparison of front view Mie-scattering images at
214 Time aSOI of 0.3 ms for all the cases. It shows very similar plume interaction
215 behavior for conditions with the same R_p . However, a slight difference still
216 can be found for each row in regards to plume width, length, and plume
217 interaction intensity. Under all the fuel temperatures from 60°C to 120°C,
218 all adjacent plumes start interacting at around $R_p = 0.2$, but the intensity
219 of interaction is different (At a lower fuel temperature, plume interaction
220 looks more complete than at a higher fuel temperature). Figure 8 shows
221 the corresponding side view DBI images. Similar spray patterns are found
222 at the same R_p but different fuel temperatures. Again, for the same R_p ,

plume merging looks more obvious at lower fuel temperatures. Qualitative comparison by looking at the Mie-scattering and DBI images is not very conclusive. Instead, a quantitative description is needed for the justification of the spray collapse phenomenon. Two new indicators, the spray collapse percentage based on the front view Mie-scattering image, and the optical thickness based on the side view DBI imaging are proposed and will be discussed in detail in the following sections.

4.4. Spray collapse criteria

4.4.1. Definition of spray collapse percentage (SCP) criterion

Figure 9 shows the spray morphology at (a) $R_p = 0.05$ and (b) $R_p = 1.4$ for fuel temperature of $T_{fuel} = 120^\circ\text{C}$ with detected spray boundary from the front view Mie-scattering images. The first criteria introduced in this study is based on the Mie-scattering front view images referred to as ‘spray collapse percentage (SCP)’. Spray collapse percentage (SCP) is defined as the ratio of the spray area inside a pre-defined circle to the area of the pre-defines circle, as shown in Eq. 4.

$$SCP = S_{spray}/S_{circle} \quad (4)$$

where, S_{spray} is the area of spray region calculated from the binary image within the pre-defined circle of radius r_0 and S_{circle} is the area of the pre-defined circle given by πr_0^2 . The r_0 is calculated as the radius of the circle which has an equal area as the whole spray region defined based on the lowest R_p case for a specific fuel temperature.

At non-flashing conditions, SCP will keep unchanged at a low level as expected. When flash boiling happens, the plume will expand, and SCP will

246 increase as a result. When R_p decreases to a low-value collapse of the spray
 247 increases, and the region in the center is fully occupied by spray and SCP
 248 approaches to 1. Therefore, the value of SCP would give information about
 249 spray collapse intensity. The change of SCP with R_p is shown in Figure
 250 9(c). The clear turning point can be found on the curve at around $R_p = 0.8$
 251 and $R_p = 0.2$, between which corresponds to the transitional regime. Thus
 252 SCP is a good candidate criterion for determination of collapsing regime,
 253 transitional regime and non-flashing regime.

254 Flare flash is an indicator on the intensity of phase change. However, the
 255 criteria defined in this work are based on spray morphology (spray collapsing
 256 phenomenon), which depends not only on flash boiling intensity but also
 257 on the nozzle geometry (the original gap between adjacent plumes). An
 258 injector with much-separated nozzle holes may experience flare flash under
 259 the extremely super-heated condition for all individual plumes, but spray
 260 collapse may not necessarily be there. Thus a spray shape based criterion
 261 would not be accurate to name a regime as flare flash regime. Therefore in
 262 this work, the three distinct regimes identified by the new criterion will be
 263 designated as collapsing regime, transitional regime, and non-flashing regime.

264 4.4.2. Definition of optical thickness (τ) criterion

265 For the side view DBI images, a new criterion based on optical thickness
 266 is used. The optical thickness (τ) is defined by Eq.5

$$I/I_0 = e^{-\tau} \quad (5)$$

267 where I is the attenuated light intensity and I_0 is the original light in-
 268 tensity. In this study, the average optical thickness is calculated from a DBI

269 image on the binarized spray region. Since flash boiling and spray collapse
 270 phenomena affect the atomization quality and droplet spatial distribution,
 271 the optical thickness distribution would also be changed with R_p .

272 Figure 10(a) and (b) shows the optical thickness distribution for $R_p =$
 273 0.05 and $R_p = 1.4$, respectively. For non-flashing spray with $R_p = 1.4$, the
 274 optically dense region is the plume liquid core region. When spray collapse
 275 happens, due to plume interaction, the original gap between adjacent plumes
 276 will be occupied with liquid as well. Thus the local optical thickness distri-
 277 bution can change dramatically. By averaging the optical thickness over the
 278 entire spray region defined by the green boundary line, its relationship with
 279 R_p can be plotted as Figure 10(c). The two clear turning points on this curve
 280 can be used to distinguish the three different spray regimes.

281 4.5. Sensitivity of spray collapse percentage (SCP) based criterion

282 4.5.1. Binarization threshold

283 The threshold used for image binarization can affect S_{spray} as well as
 284 the equivalent r_0 , thus affects SCP. Figure 11(a) shows the auto-calculated
 285 threshold value based on Otsu's method for all cases at $T_{fuel} = 120^\circ C$.
 286 The variance of the threshold value between cases is less than 20%, and
 287 the averaged threshold value is 0.3075. Fixed thresholds at the averaged
 288 threshold value and $\pm 10\%$, and $\pm 20\%$ are examined to study the influence
 289 of the threshold value on this criterion. Figure 11(b) shows the SCP trend
 290 obtained with the different threshold value. It is clear that threshold value
 291 can affect SCP value quantitatively, same like other indicators (penetration
 292 length, spray width). But the trend remains the same, and the turning
 293 points which distinguishes different regimes on the curve stay unchanged.

294 Thus hereafter, auto-calculated threshold value based on Otsu's method will
295 be used for each image.

296 4.5.2. Pre-defined circle radius

297 The circle radius should not exceed the spray region to avoid pure black
298 region on the images. A circle radius r_0 calculated based on the lowest R_p
299 case at a certain fuel temperature is a good selection as the upper limit and
300 as a reference. The sensitivity of SCP criterion on circle radius r is evaluated
301 based on the different values of r such as r_0 , $0.8r_0$, $0.6r_0$ and $0.4r_0$. Figure
302 12(a) shows that the SCP trend remains similar when r changes from $0.4r_0$
303 to r_0 , but the curves contrast changed a lot. When the r is selected to be
304 too small, the minimum SCP at non-flashing regime would still be high thus
305 reduced the contrast of the curve. This behavior is because of the high white
306 percentage in the near-nozzle region. To avoid the influence of this high
307 white percentage near the nozzle, the pre-defined circle radius should be
308 large enough. Therefore, the value of $r \geq 0.6r_0$ could be a good choice since
309 it clearly shows the starting point of the spray collapse regime. However,
310 throughout this study, the value of r_0 is used for analysis.

311 4.5.3. Time instant

312 Figure 12(b) shows that during the early injection period, penetration
313 length is short and the influence of near nozzle high white percentage will
314 affect the estimation of criterion. Spray morphology at late injection period
315 is a better choice for criterion determination since the spray is fully devel-
316 oped. The SCP at 0.3 ms to 0.9 ms indicate that it is a very consistent
317 criterion. Considering that starting from 0.5 ms the spray on DBI images

will be exceeded the optical limit of the window, therefore hereafter, 0.3 ms aSOI will be used for further comparison among different criteria.

4.6. Sensitivity of optical thickness (τ) based criterion

4.6.1. Binarization threshold

Firstly Otsu's method is used for image binarization($T_{fuel} = 120^{\circ}C$, Time aSOI =0.3ms). Figure 13(a) shows the threshold values for all cases with Otsu's method. And then the mean value of all these cases and $\pm 10\%$, and $\pm 20\%$ of this value are compared. Figure 13(b) shows that the turning point is consistent for these values of the binarization threshold. Thus the averaged optical thickness based criterion is not sensitive to the threshold as long as the same method of threshold selection is applied to all cases.

4.6.2. Time instant

Time instant selection is another factor that needs to be considered for the generalization of the optical thickness based criterion. For the calculation of averaged optical thickness based on the whole spray region, it would be better if the spray is entirely inside optical window access. Thus an earlier instant timing is a better choice. At 0.5 ms aSOI, the spray plumes already reached window edge. Therefore, time aSOI from 0.1 ms to 0.4 ms were considered for the sensitivity analysis (Otsu's threshold, $T_{fuel} = 120^{\circ}C$) as shown in figure 13(c). It can be seen that the turning point on the curves to distinguish different regimes is consistent with different time instant. Thus 0.3 ms aSOI was selected for this criterion, and also it was kept consistent with the time instant selected for SCP criteria based on Mie-scattering images.

341 4.7. Comparison between different criteria

342 Based on the sensitivity analysis of SCP based criterion, Otsu's threshold
343 method, r_0 for circle radius and 0.3 ms aSOI for Mie-scattering spray images
344 will be used. Figure 14(a) indicates that transitional regime starts at around
345 $R_p = 0.7 \sim 0.8$ and spray collapse regime starts at around $R_p = 0.15 \sim 0.2$.

346 The critical R_p value for the start of the transitional regime looks shifting
347 towards low R_p end when fuel temperature increases. To further confirm, the
348 derivative of SCP is calculated with respect to R_p and shown in Figure 14(b).
349 If for example a low absolute value of the derivative is regarded as the turning
350 point on the SCP curve, it shows that higher fuel temperature will reach this
351 turning point at lower R_p value. It means that increased fuel temperature
352 requires a lower R_p to achieve the same effect of plume expansion.

353 Since the plume interaction is due to the swelling of plumes at flash
354 boiling condition, the plume angle can be another good indicator for criterion
355 determination. Here the plume angle is defined inside the r_0 circle as well.
356 Each plume was separated by segmentation ($radius = r_0$, Figure 15) and
357 then binarized with Otsu's method. The area of the segmented plume and
358 the plume penetration length can then be used to calculate the plume angle
359 with the assumption that the segmented plume is sector-shaped. Average of
360 the 10 plume angles is shown in Figure 14(c) for different fuel temperatures
361 and R_p . It should be noted that when plume interaction starts, this definition
362 of plume angle will fail. Thus it is only used for the regime at $R_p \geq 0.4$. So
363 it can be used for the determination of the transitional regime and non-
364 flashing regime, but not suitable for spray collapse regime. It indicates that
365 transitional regime starts from R_p around 0.9. Meanwhile, it clearly shows

366 that at same R_p , higher fuel temperature has smaller plume cone angle, which
367 weakens the plume interaction.

368 In this study, the average optical thickness is calculated from a DBI image
369 based on the binarized spray region where the optical thickness is greater
370 than Otsu's threshold value. Using optical thickness as an indicator gives
371 the obvious trend shown in Figure 16(a). Both transitional regime and spray
372 collapse regime starting point are shifted slightly towards low R_p side when
373 T_{fuel} increases, from 0.9 to 0.6 and 0.2 to 0.15, respectively. This is consistent
374 with the Mie-scattering images shown in Figure 7. With same R_p , $T_{fuel} =$
375 $120^\circ C$ has a thinner spray plume and less plume interaction than $T_{fuel} =$
376 $60^\circ C$. This shifting could also be noted from Mie-scattering image based
377 criteria shown in Figure 14.

378 Penetration length and spray width from the side view DBI images are
379 commonly used criteria in the literature to describe the change in spray
380 morphology due to collapse [3, 9, 13]. They were defined as shown in Figure
381 17. Figure 16(b) and (c) shows the comparison of penetration length, and
382 spray width with corresponding R_p , respectively. The penetration length
383 and spray width are characterized at time instant of 0.3 ms aSOI to avoid
384 spray penetration exceeding the window limit. Liquid penetration length and
385 spray width both show a turning point at around $R_p = 0.1 \sim 0.2$, which is
386 due to spray collapse phenomenon. But between the transitional regime and
387 non-flashing regime, these two indicators are not capable of giving a distinct
388 criterion.

389 In general, both transitional and spray collapse criteria are based on spray
390 morphology, which is not only affected by flash boiling intensity (R_p) but also

391 by the ambient gas pressure. Thus higher fuel temperature, which simultane-
392 ously has higher ambient pressure for a specific R_p will make it more difficult
393 for plumes to expand, interact with each other and then collapse. Thus the
394 starting points of transitional regime and spray collapse regime are shifting
395 towards a low R_p end when fuel temperature increases.

396 Penetration length is defined as the farthest penetrated point on spray
397 boundary in the axial direction, and spray width is defined as the distance
398 between two farthest points on the spray boundary in the radial direction
399 (Figure 17). Both methods are defined on the extreme points on the spray
400 boundary. While these points are susceptible to the threshold or it may
401 tremendously change to another far away position when its original location
402 is diluted which means it exhibits high positional dependency and missed
403 by the boundary detection algorithm. Thus the trend based on these two
404 indicators will have considerable variation and make it challenging to define
405 the distinct regimes. The spray collapse percentage and averaged optical
406 thickness are based on the entire spray region. Therefore, these two indica-
407 tors are less sensitive to threshold selection and shot to shot variations as
408 already explained in previous sections. Thus these two indicators can show
409 a very consistent and clear trends with the change of R_p and helps in the
410 determination of distinct spray regimes.

411 5. Conclusions

412 In this study, the simultaneous side view DBI imaging and front view
413 Mie-scattering imaging were employed to study the spray collapse in flash
414 boiling conditions. The following conclusions can be drawn from this study.

- 415 • Simultaneous side view DBI and front view Mie-scattering enable corre-
416 lating plume interaction to spray collapse phenomenon and apparently
417 show when the plume to plume interaction starts. This method could
418 be a good way to study flash boiling and spray collapse phenomenon.
- 419 • At extremely low $R_p(0.05)$ conditions, a long central jet was observed
420 on DBI images, and this was confirmed by the entirely white area on
421 Mie-scattering images. This phenomenon is due to the 10-plumes in-
422 teraction and the radial collapse. The very different spray morphology
423 from other conditions was also reflected in the outwardly moving back-
424 ward spray periphery during the entire injection duration.
- 425 • Two new indicators, spray collapse percentage (SCP) based on Mie-
426 scattering imaging, and optical thickness based on DBI imaging were
427 proposed and used as the criteria for determination of spray collapse,
428 transitional, and non-flashing regime.
- 429 • SCP and optical thickness criteria were compared with criteria deter-
430 mined from other indicators like plume angle, spray penetration length
431 and spray width. Optical thickness from side view DBI images and SCP
432 from front view Mie-scattering images are two consistent and effective
433 indicators for the determination of spray regimes.

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Table 1: Experimental details

Item	Unit	Value
Injector	-	10-hole, 165 μm , 110°
Fuel	-	Iso-octane
Injection pressure	bar	100
Injection duration	ms	1
Ambient gas temperature	°C	23

Table 2: Fuel temperature and ambient gas pressure

$T_{fuel} (^{\circ}\text{C})$	P_{amb} (kPa)														
60	-	-	4	6	7	8	11	14	17	20	22	25	28	34	39
75	-	5	7	10	12	14	19	24	29	34	38	43	48	58	67
90	4	8	12	15	19	23	31	39	46	54	62	69	77	92	108
105	6	12	18	24	30	35	47	59	71	83	94	106	118	142	165
120	9	18	26	35	44	53	70	88	105	122	140	158	175	210	245
	$R_p = P_a/P_s$														
	0.05	0.1	0.15	0.2	0.25	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1	1.2	1.4

Figure 1: (a) Optical alignment for DBI and Mie-scattering; (b) Fuel temperature control; (c) Nozzle hole orientation

Figure 2: Iso-octane saturation vapor pressure and experiment conditions

Figure 3: Comparison of individual sprays and averaged spray, $T_{fuel} = 120^{\circ}C$, $R_p = 0.05$

Figure 4: Change of spray morphology with R_p , $T_{fuel} = 120^\circ C$, $Time aSOI = 0.3ms$

Figure 5: Shift of plume position $T_{fuel} = 120^{\circ}\text{C}$, $Time\ aSOI = 0.3\text{ms}$ (a) $R_p = 0.05$;
(b) $R_p = 0.4$

Figure 6: Shift of plume position $T_{fuel} = 120^{\circ}\text{C}$, $Time\ aSOI = 0.3ms$: Intensity along marked circle in Figure 5, R_p from 0.05 to 0.4.

Figure 7: Effect of fuel temperature on spray morphology using front view Mie-scattering technique, $Time aSOI = 0.3ms$

Figure 8: Effect of fuel temperature on spray morphology using side view DBI technique,
 $Time aSOI = 0.3ms$

Figure 9: SCP based criterion ($Time\ aSOI = 0.3ms$, global thresh based on Otsu's method[33], r_0 is equivalent radius defined at the most super-heated case at this fuel temperature. (a) $R_p = 0.05$; (b) $R_p = 1.4$; (c) SCP with regard to R_p

Figure 10: Optical thickness based criterion ($Time\ aSOI = 0.3ms$, global thresh based on Otsu's method. (a) $R_p = 0.05$; (b) $R_p = 1.4$; (c) Optical thickness with regard to R_p .

Figure 11: Sensitivity of SCP based criterion on threshold value

Figure 12: Sensitivity of SCP based criterion on: (a) pre-defined circle size; (b) instant time

Figure 13: Sensitivity of averaged optical thickness (τ) based criterion to threshold value in image post processing and instant timing $T_{fuel} = 120^\circ C$: (a) Time aSOI = 0.3 ms, different threshold values; (b) Sensitivity to threshold value, Time aSOI = 0.3 ms; (c) Sensitivity to instant timing, Otsu's threshold

Figure 14: Criteria based on indicators from Mie-scattering image (Time aSOI = 0.3 ms): (a) SCP based; (b) Derivative of SCP; (c) Plume angle based

Figure 15: Plume segmentation and plume angle determination at Time aSOI = 0.3 ms

Figure 16: Criteria based on indicators from DBI image (Time aSOI = 0.3 ms): (a) Optical thickness; (b) Spray penetration length; (c) Spray width

Figure 17: Definition of spray penetration length and spray width