Abstract

Spray nozzles with constant or diverging diameters are known to be subject to the phenomenon of hydraulic flip, where the fluid detaches from the nozzle wall prior to exiting the nozzle. This can have a significant impact on atomization; it is well established that hydraulic flip can substantially increase the breakup length of a jet. Geometric cavitation inside the nozzle often occurs under similar conditions to those that produce a flipped jet. The interactions between these phenomena are not fully understood. Hydraulic flip is challenging to study, particularly in round nozzles. Changes in refractive index between the nozzle wall material, ambient gas, and liquid make it very difficult to obtain good optical access at the nozzle exit plane. Strong geometric dependence and hysteresis in onset conditions makes it difficult to extend observations in rectangular nozzles to the axisymmetric case. It is also difficult to measure the difference between a void generated by cavitation inside the nozzle, and displacement of the liquid due to encroachment of the ambient gas. In this paper, we demonstrate a novel X-ray fluorescence experiment to study hydraulic flip in an X-ray transparent beryllium nozzle with diameter 330 μm and length 2 mm. The ambient gas was doped with 3% krypton and time-averaged measurements of krypton fluorescence allowed the volume fraction of ambient gas to be quantitatively measured both inside and outside the nozzle. A polycapillary X-ray optic was used to allow the detector to observe only a small portion of the focused 15 keV X-ray beam where it intersected the nozzle. We found that for a fluid with a vapor pressure much lower than the back pressure, the ambient gas can travel as far upstream as the nozzle inlet lip due to stabilized flow separation and displacement of cavitation voids.
1 Introduction

Hydraulic flip occurs when a liquid inside a nozzle issuing into a gaseous environment separates from the nozzle wall upstream of the exit plane [1, 2]. When conditions become favorable for flow separation, ambient gas can travel back upstream along the nozzle wall, causing the jet to contract. The jet becomes surrounded by a sheath of low-velocity gas, which stabilizes it and delays the onset of atomization [3].

The abrupt change in jet breakup length and discharge coefficient caused by the onset of hydraulic flip is particularly problematic for spray nozzles in rocket engines [4] and industrial manufacturing applications [5]. It is also of particular concern in high pressure direct fuel injection systems for gasoline and diesel engines. There is a significant body of work studying hydraulic flip in diesel injectors [6]. Using shadowgraphy and Mie scattering, Soteriou et al. [7] showed that there are strong interactions between upstream cavitation near the nozzle inlet, changes in jet morphology due to supercavitation (cavitation extending beyond the nozzle exit), backfilling of air into the nozzle, and eventual hydraulic flip of the exiting jet. Direct rate-of-momentum experiments in diesel injectors [8] have shown that the transition to hydraulic flip substantially changes the discharge coefficient, and phase Doppler (PDPA) measurements also show changes associated with the increase in breakup length [9]. Ultimately, this impacts combustion and emissions [10]. In diesel injectors, the hole is often tapered which prevents hydraulic flip. However, in gasoline direct injectors (GDIs) which have much smaller length to diameter ratios, hydraulic flip is difficult to avoid [11, 12].

Hydraulic flip has traditionally been studied in scaled-up, optically transparent nozzles at relatively modest pressures using shadowgraphy [3, 13]. Transparent models are also used to perform laser diagnostics such as Mie scattering [7], laser Doppler velocimetry [4, 14], and PDPA [9]. Recent developments in small, real-size optical nozzles allow these flows to be studied at pressures much closer to direct fuel injection conditions [11]. Numerical simulations are also used to provide insight into the flow physics [12].

Despite these recent advances, there remain two significant challenges associated with studying hydraulic flip in round nozzles. The first is an issue of optical access. Due to the curved nozzle wall and the refractive effects of the chaotic gas-liquid interfaces inside, it is difficult to quantify the volume of gas in the nozzle. For this purpose, two-dimensional rectangular nozzles are often used [14, 15]. These nozzles have different pressure recovery and flow behavior compared to an axisymmetric nozzle. The second challenge with hydraulic flip is the inability to discriminate cavitation vapor from ambient gas [16]. One of the open questions associated with the onset of hydraulic flip is what happens when the flow transitions from supercavitation to a true hydraulic flip. In the first case, the gas inside the nozzle near the exit is cavitation vapor, and in the second it is predominantly ambient gas [17]. Understanding the transition from one to the other is particularly important for atomizer design, since cavitation tends to enhance atomization and hydraulic flip suppresses it [18, 19]. Since the two gaseous phases are difficult to identify experimentally, the degree to which the ambient gas travels upstream is not fully understood.

X-ray diagnostics provide a useful tool to investigate these problems. X-rays have high penetrating power and refract very weakly from gas-liquid interfaces, and can be used to probe complex and dense multiphase flows [20–22]. X-ray radiography techniques developed to measure the density distribution of external fuel sprays [23] have also been extended to measuring cavitation vapor distribution inside plastic nozzles at low pressures [24]. Recently, measurements have been demonstrated using nozzles manufactured from beryllium alloy [25]. It can withstand much higher pressures than plastic nozzles, can be more precisely machined, and it is a weak absorber of X-rays.

While X-ray radiography provides a quantitative measurement of fluid density, it cannot easily discriminate between cavitation vapor and ambient gas. X-ray fluorescence spectroscopy (XFS) is ideally suited to this problem. An incident X-ray beam ionizes an atom by creating a core shell hole, and when the hole is filled, a characteristic fluorescence X-ray photon is emitted. By measuring the fluorescence line for a particular element using an energy-resolving detector, its mass concentration in the path of the X-ray beam can be quantified. Since most fluid flows in question consist of low-atomic number elements such as hydrogen, oxygen and carbon, whose X-ray fluorescence energies are too low to escape the sample environment, the flow is typically doped with a tracer element of higher atomic number. For example, XRF has been used to study gas jets using argon as a tracer [26], to study liquid sprays using bromine [27], and to measure dissolved gas concentration inside a plastic nozzle using krypton [28].

In this study, we present a proof of concept experiment in which we induce the flow in an axisym-
metric beryllium nozzle of 0.33 mm diameter and 2 mm length to undergo hydraulic flip. The ambient nitrogen environment was doped with 3% krypton, allowing X-ray fluorescence measurements of the ambient gas concentration to be performed inside the nozzle. Contraction of the liquid phase was quantified both internally and externally. In order to improve signal to noise ratio, a polycapillary X-ray optic was used to allow the fluorescence detector to observe only a small section of the focused X-ray beam, where it intersected the nozzle hole cross-section. Time-averaged raster-scan measurements are presented for a range of injection pressures up to 30 bar at 1 bar abs. ambient pressure. We show that when the nozzle is hydraulically flipped, the ambient gas encroaches as far upstream as the inlet of the nozzle hole, displacing the attached cavitation bubble due to the difference in pressure.

2 Methodology

The experiments were performed at the 7-BM beamline of the Advanced Photon Source at Argonne National Laboratory [29]. A gas-driven piston accumulator was used to provide a constant pressure fluid flow to the spray nozzle, as shown in the schematic diagram in Figure 1. The nozzle had a diameter of \( D = 0.33 \, \text{mm} \) and a length \( L = 2 \, \text{mm} \). The working fluid was a commercial gasoline surrogate (Viscor 16BR, Rock Valley Oil & Chemical Company) doped with a cerium X-ray contrast agent (Rhodia DPX9) at approximately 8:1 volume ratio, giving a concentration of 4% cerium by mass. The working fluid had a density of \( \rho_l = 817 \, \text{kg/m}^3 \) and a viscosity of 1.23 cSt at 25°C. All the experiments were conducted at this temperature. The vapor pressure of the fluid was 3.5 kPa.

In order to reduce the effect of dissolved gases on the flow [30] the fluid was de-gassed by storing it under a partial vacuum in a sealed fuel tank for several hours prior to commencing the experiments. A dome-loaded regulator was used to provide a continuous inlet pressure \( P_{in} \) to the nozzle, and a mini-turbine flowmeter was used to measure the volume flow rate of the fluid. In combination with a static pressure tap upstream of the nozzle inlet, the nozzle’s discharge coefficient was measured independently. The cavitation number \( K \), Reynolds number and discharge coefficient are defined respectively as

\[
K = \frac{P_{in} - P_v}{P_{in} - P_a}, \tag{1}
\]

\[
Re_D = \frac{4\dot{m}}{\pi D \rho_l v_l}, \tag{2}
\]

\[
C_D = \frac{4\dot{m}}{\pi D^2 \sqrt{2\rho_l (P_{in} - P_a)}}. \tag{3}
\]

where \( P_a \) is the ambient pressure, \( \dot{m} \) is the mass flow rate through the nozzle, \( P_v \) and \( v_l \) are the test fluid’s vapor pressure and kinematic viscosity.

The nozzle was mounted on a rotating clamp in a pressurized spray chamber with kapton film windows which allowed the X-ray beam to pass through while maintaining either a partial vacuum or elevated ambient pressure inside the chamber. A cross-section of the nozzle geometry and the spray chamber mounting geometry are shown in Figure 2. The spray from the nozzle impacted on a series of mesh screens far downstream of the X-ray windows, to reduce splashback. The krypton-doped ambient gas was continuously purged through the chamber at approximately 10 L/min to clear stray droplets. The gas-liquid mixture drained from the bottom of the chamber. The liquid flowed back to the evacuated drain vessel through a throttling valve and the purge gas was exhausted through a coalescing filter.

The experiment was set up as per the plan view shown in Figure 3. A monochromatic X-ray beam...
with a mean energy of 15 keV (1.0% full width at half maximum bandpass) was focused to a 5 × 6 μm spot using a pair of Rh-coated Kirkpatrick-Baez focusing mirrors. The incoming beam intensity (I₀) was monitored with a diamond transmission photodiode, to correct for any fluctuations in the incident beam flux. The beam then passed through the kapton windows of the spray chamber, and through the beryllium nozzle. Approximately 2/3 of the beam was absorbed by the ambient gas, kapton windows and beryllium nozzle. The transmitted beam was collected by a 200 μm thick PIN diode, which was used to record the total transmission of X-rays. As per Figure 3, fluorescence X-rays were collected by an energy-resolving silicon drift diode through a third kapton window. The polycapillary acts to slightly focus and collimate the X-rays (the effect is exaggerated in Fig. 3 for illustrative purposes). This has the practical effect of allowing the detector to view a small region of the X-ray beam and increase the effective solid angle of detection within this region, while reducing the sensitivity of the detector to X-rays emitted from outside this region. The end result is an effective probe volume of approximately 5 × 6 × 300 μm (x, y, z) where the X-ray beam intersects with the nozzle hole. The nozzle and spray chamber are translated vertically and horizontally while the X-ray beam and the detectors remain fixed, allowing the system to probe different locations in a raster scan pattern while the position along the z axis (incident beam direction) remains fixed.

A sample raw spectrum from the detector is shown in Fig. 4. Here, the nozzle hole is completely filled with ambient gas. The Fe and Ni lines are caused by fluorescence excited by scattered X-rays which hit the stainless steel support that holds the nozzle in place. The benefit of using the polycapillary optic is seen in the relative height of the Kr Kα peak (the energy that is useful for the measurement) as compared to the elastic and Compton scattering peaks at higher energy.

In order to perform this measurement, a high flux synchrotron source is required, as the X-ray flux recieved by the detector is orders of magnitude less than the incident flux. Approximately 1/3 of the incident beam is absorbed by the windows, ambient gas and nozzle walls before the beam arrives at the test section. With the orifice completely filled with gas, only 0.3% of the incident flux is absorbed by Kr. The total emission from the Kr inside the nozzle is therefore only 0.2% of the incident flux. Of this, the detector captures a small fraction of the solid angle. Within the solid angle of collection, approximately 85% of the emission is absorbed by the nozzle wall, ambient gas, and kapton window before reaching the detector. With an incident beam flux of 10¹¹ photons/s, the signal at the detector is on the order of

changes in the fluorescence inside the nozzle hole as the liquid is displaced by ambient gas. The change in the total path length of Kr in the X-ray beam is less than 1% when the nozzle is completely filled with liquid as compared to being filled with gas. Furthermore, elastic and Compton scattering add to the background level and reduce the detector's effective collection efficiency for the Kr Kα photons.

To overcome the problem of measuring a small signal against a large background, we used a polycapillary X-ray optic with a fixed 100 mm working distance, placed between the detector and the kapton window. The polycapillary acts to slightly focus and collimate the X-rays (the effect is exaggerated in Fig. 3 for illustrative purposes). This has the practical effect of allowing the detector to view a small region of the X-ray beam and increase the effective solid angle of detection within this region, while reducing the sensitivity of the detector to X-rays emitted from outside this region. The end result is an effective probe volume of approximately 5 × 6 × 300 μm (x, y, z) where the X-ray beam intersects with the nozzle hole. The nozzle and spray chamber are translated vertically and horizontally while the X-ray beam and the detectors remain fixed, allowing the system to probe different locations in a raster scan pattern while the position along the z axis (incident beam direction) remains fixed.

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Figure 3: Plan view of experiment setup (not to scale). The incident X-ray beam is shown in red, and the emitted fluorescence in blue.

Figure 4: Sample energy spectrum recorded by the fluorescence detector. The krypton K$_\alpha$ peak is integrated to measure the quantity of ambient gas inside the nozzle.
$10^4$ photons/s. This limits the measurement to being time-averaged, as a sampling time on the order of 1 second is required at each position.

The underlying theory for the fluorescence measurement is described in detail in previous publications [28]. Here, a brief overview is given. The intensity of fluorescence X-rays $dI_f$ emitted along a segment of the incident beam ($dz$) is described by

$$dI_f = \omega I_0 \mu_g \rho_g dz,$$

where $\omega$ is the fluorescence yield [33], $I_0$ is the incident flux, $\mu_g$ is the X-ray attenuation coefficient of the ambient gas, and $\rho_g$ is its density. For the purposes of this study, we wish to know the integral of the intensity $\int dI_f$ along a segment of the beam in the focus of the polycapillary optic, and from this we can determine the projected density of the gas phase in this region, defined as

$$M_g = \int \rho_g dz \text{ (mass/area)}.$$

If the density of the ambient gas is fixed, the quantity of gas in the path of the beam can also be expressed as a path length, which is easier to interpret:

$$l_g = \frac{M_g}{\rho_g}.$$

In order to convert the measured level of X-ray fluorescence from the Kr K$\alpha$ values at the detector (which are in arbitrary counts) to an absolute projected mass, several corrections are required. Known corrections for incident flux and the nonlinear response of the detector with count rate [34] were applied based on the measured values. Corrections for solid angle and the concentration, absorption coefficient & yield of the fluorescing species in the ambient gas were fixed properties of the experimental setup and were corrected using a lumped calibration constant. The nozzle hole was filled with gas, and the nozzle was traversed through the beam. The absolute path length of gas in the X-ray beam was determined by radiography measurements of the nozzle hole geometry. The intensity of transmitted X-rays at the PIN diode were converted to a path length equivalent to eqn. 6 using the Lambert-Beer law:

$$l_{g,cal} = -\frac{1}{\rho_g \mu_g} \ln \left( \frac{I_{PIN}}{I_0} \right).$$

The result of the calibration (with a least squares regression fit) is shown in Fig. 5.

Once the fluorescence measurement is calibrated, a final correction must be made to account for variable signal trapping; the absorption of fluorescence photons by the liquid inside the nozzle. While the signal loss due to the nozzle wall geometry and ambient gas are corrected for in the calibration, the signal trapping in the liquid must be corrected post-hoc as it depends on the position of the X-ray beam and the measured path length of fluid between the beam and the detector. The signal trapping correction was made by scanning the nozzle transversely through the beam at each axial position and measuring both the Kr fluorescence signal from the gas, and the path length of liquid in the beam using X-ray radiography. At each axial measurement position, an Abel inversion was used to estimate the cross-sectional density distribution of the liquid and gas from the calibrated projection

Figure 5: Calibration curve for the krypton fluorescence signal, measured by filling the nozzle hole with a known density of ambient gas at 3% Kr, 97% N$_2$. 

data. The transmission \((\tau)\) of fluorescence emission from the gas at each point in the measurement plane projected in the direction of the detector \((y')\) axis was made using the Lambert-Beer law, with the absorption coefficient calculated at the lower energy of the fluorescence photons \((\mu_{\text{fluor}})\):

\[
\tau_{\text{fluor}}(x, y, z) = \exp \left( - \sum_{j=l,g} \mu_{\text{fluor},j} \int_{y'=y}^{y_{\text{max}}} \rho_j dy' \right),
\]

In the above equation, \(j\) is a summation over the liquid and gas phases. The higher density of the Kr gas also has a measurable signal trapping effect which is accounted for, although secondary emission from this reabsorption is below the noise floor of the measurement and is disregarded. From an estimate of the two-dimensional signal trapping and distribution of the fluorescing species, a weighted reabsorption correction for the projection data is calculated, giving an estimate of the net signal trapping for a given line of sight projection:

\[
\tau_{\text{fluor}}(x, y) \approx \frac{\int \tau_{\text{fluor}}(x, y, z) \cdot \rho_j(x, y, z) dz}{\int \rho_j(x, y, z) dz}.
\]

Dividing the calibrated measurement (Fig. 5) with the signal trapping transmission (Eq. 9) gives the final calibrated measurement of the path length of ambient gas inside the nozzle. The largest signal trapping corrections for these experiments were approximately 5%, when the nozzle was filled with liquid. The average signal trapping correction was approximately 3%. The assumption of axisymmetry in the signal trapping correction introduces a small error into the correction. Since the correction is only several percent of the final measurement, the increase in error due to this assumption is within the uncertainty level of the measurement. The assumption of axisymmetry in the signal trapping does not require that the final data be axisymmetric.

Propagation of uncertainty through the calibration and corrections has been described in detail in prior work [28]. The two main contributors to measurement uncertainty are photon shot noise and calibration uncertainty. The signal trapping correction also amplifies the uncertainty. For this experiment, the integration time and photon count rates were relatively high, and the primary contributor to uncertainty was due to calibration (Fig. 5). The estimated uncertainty in the path length of gas \((l_g)\) was approximately 5%, or ±15 µm.

3 Results and Discussion

In the experiments, the ambient pressure was maintained at 1.05 bar abs. and the injection pressure was increased from 1.50 bar up to 23.10 bar abs. Measurements were made transversely across the nozzle at 32 positions, and repeated over 20 axial positions both inside and downstream of the nozzle. Ten injection pressures were tested, and each measurement condition was repeated twice.

The results for four of the injection pressure data sets are shown in Figure 6. The magnitude of the Kr path length (equation 6) is given in units of nozzle diameters on the vertical axes. The horizontal axis is the transverse position, with the nozzle centerline at \(y/D = 0\). The reference condition to which the measurements are compared is with the nozzle completely filled with liquid, and the outlet region completely filled with gas. The solid lines in Figure 6 are measurements made inside the nozzle \((x/L < 1)\) and the dashed lines are measurements made downstream of the nozzle \((x/L > 1)\). The axial position is also indicated by the color bar. The elliptical shape of the profiles in Fig. 6a shows that at very low injection pressure, the nozzle is almost uniformly filled with liquid (solid lines) and the exiting jet is relatively axisymmetric with a vena contracta of approximately 10% (dashed lines). The width of the exit jet is approximately the nozzle diameter (indicated by the black vertical lines). The small, positive Kr signal inside the nozzle in Fig. 6a is caused by background fluorescence from the gas surrounding the nozzle, and Kr which has become dissolved in the fluid due to the recirculation of the liquid in the hydraulic system.

As the injection pressure increases (Figs. 6b, 6c) we see the exiting jet contract slightly due to increased velocity, but the measurement inside the nozzle does not change substantially. In Fig. 6c, the cavitation number of the nozzle is \(K \approx 1.56\), just below the critical \(K\) value. We expect the nozzle to be cavitating at this condition. High-speed polychromatic phase-contrast imaging of the nozzle under these conditions has confirmed that cavitation is present under these conditions, before any hydraulic flip occurs. When the injection pressure is increased slightly to 3 bar (Fig. 6d) we see an abrupt increase in Kr concentration inside the nozzle, indicating that a hydraulic flip has occurred. Here, \(K \approx 1.49\), so the nozzle discharge coefficient due to cavitation effects alone should change by less than 3%. However, we record an abrupt decrease in flow rate; the discharge coefficient drops abruptly from approximately 0.75 to 0.65. This corresponds to similar measurements of the effect of hydraulic flip on discharge coefficient made by others [35]. As injection pressure continues to increase (Figs. 6e, 6f) the profiles remain similar, and the exit jet profile continues to contract.
Figure 6: Transverse plots of magnitude of net change in Kr path length at varying axial positions (x axis, indicated by color). Results are shown with increasing injection pressures, both (a) without and (b-d) with hydraulic flip. The solid lines indicate measurements made inside the nozzle, and the dashed lines indicate measurements made downstream outside the nozzle.
Figure 7: Contour plots of net change in Kr path length at four injection pressures, both (a,b) without hydraulic flip and (c,d) with hydraulic flip. The region from 0 < $X/L < 1$ on the left is measured inside the nozzle, and the region of $X/L > 1$ on the right is the free jet.
Figure 8: Transverse plots of net change in Kr path length at varying inlet pressures (indicated by line color), at (a) the nozzle inlet, (b) just upstream of the nozzle outlet, and (c) just downstream of the nozzle outlet.
The shape of the Kr distribution in Figures 6d-6f is approximately axisymmetric and matches the projection that one would expect if the liquid were surrounded by an annular sheath of gas. Interestingly, we see that elevated Kr levels are recorded not only at the nozzle exit plane (where we expect hydraulic flip to occur) but also as far upstream as the nozzle inlet plane. This can be visualized more clearly in Figure 7. Here, the measurements are shown as color contour plots with the axial position (normalized by diameter) on the horizontal axis and the transverse position (normalized by nozzle length) on the vertical axis. The liquid flow is left to right as indicated by the arrows. The beryllium nozzle wall is shown by the hatched region, and the vertical dashed lines indicate the nozzle inlet and outlet planes. In Figure 7, a two-tone color bar scale is used to show positive and negative net change in Kr level relative to the reference condition where the nozzle is filled with liquid and the outlet is filled with gas. The red color indicates additional Kr (displacement of liquid due to gas) and the blue color represents a deficit in Kr (displacement of the gas by the liquid). Figures 7a-7b show the results for cases without hydraulic flip. Figure 7b is a condition in which cavitation is expected, but no hydraulic flip. Figures 7c-7d show the distribution of Kr for cases with hydraulic flip. We see that once the flow transitions, excess Kr is measured along the nozzle walls all the way from the inlet to the outlet. This ‘total’ hydraulic flip is a known feature of perfectly straight nozzles. However, these measurements quantitatively demonstrate that the cavitation voids are completely displaced by the ambient gas, even at the nozzle inlet. The path length of Kr for $|Y/D| > 0.45$ is sufficiently large with respect to the path length through the geometry to indicate an annulus of 100% ambient gas by volume fully connecting the outlet plane to the nozzle inlet.

Further insight can be gained by visualizing the results as a function of injection pressure for a fixed axial position. Figure 8 shows the transverse measurement of Kr path length colored by the injection pressure, with low pressures in dark colors and high pressures in light colors. Figure 8a shows the change in gas distribution 100 μm (0.3 diameters) downstream of the nozzle inlet plane. Once the transition to hydraulic flip occurs, the gas level along the nozzle walls rises rapidly to nearly 100% of the path length for $|y/D| > 0.4$. The total volume of gas increases with increasing injection pressure, and the profile flattens out as the pressure rises. Figure 8b shows the gas distribution 200 μm upstream of the nozzle exit plane. Here, the onset of hydraulic flip causes a much larger increases in gas path length, indicating a greater contraction of the jet, and a sharper interface. Figure 8c shows the displacement of the gas by the exiting jet, 80 μm downstream of the nozzle exit plane. We see that the jet uniformly contracts and retains its elliptic profile as pressure continues to increase.

One of the distinct advantages of having quantitative measurements of the gas distribution in the nozzle is that the area contraction of the liquid can be measured by integrating the measurement of liquid path length across the nozzle plane and dividing by the nozzle area:

$$C_a(x) = 1 - \frac{4}{\pi D^2} \int l_g(x, y) dy. \quad (10)$$

Since the x-ray fluorescence measurements are made both inside and outside the nozzle, a contraction coefficient ($C_a$) can be calculated for both the internal flow, i.e. the vena contracta caused by the internal displacement of liquid due to the ingress of gas, and the external flow, the area contraction of the exiting jet. We find that these contraction coefficients are strongly correlated with the nozzle discharge coefficient. The results are shown in Figure 9, where the error bars indicate the uncertainty due to the propagation of experimental error through equation 10. At low injection pressures, the discharge coefficient is high, and as expected, the internal area contraction is close to 1, since there is very little gas inside the nozzle. The external area contraction of the jet is low, as the jet velocity is very low and the jet is being pulled downward under the influence of gravity. As $C_D$ drops and pressure in-
creases, we find that the internal contraction coefficient drops approximately linearly, and the external contraction increases approximately linearly. The discontinuity in contraction coefficient suggests that the back-filling of gas in the nozzle rapidly displaces pre-existing cavitation voids rather than generating a gradual displacement of the liquid as has been observed in rectangular nozzles and scaled-up flows.

4 Conclusions

In this paper we have presented a series of time-averaged, raster-scan x-ray fluorescence measurements of the quantitative distribution of ambient gas inside a beryllium nozzle. One novel advantage of this measurement is the ability to quantitatively measure the distribution of ambient gas independent of any cavitation voids inside the liquid. Cavitation and ambient gas in the nozzle would otherwise be indistinguishable using conventional optical techniques. Another advantage is the ability to make nearly simultaneous measurements both inside and outside the nozzle without any change to the experimental setup. This permitted correlations to be made between the changes in internal and external liquid and gas distribution.

The measurements clearly showed that the onset of hydraulic flip caused gas to abruptly backfill along the nozzle wall. An important observation was that a significant quantity of ambient gas was measured as far upstream as the nozzle inlet. The straight axisymmetric nozzle did not show any evidence of a stable partial hydraulic flip. The shape of the transverse profiles suggests that the gas distribution forms an annular ring around the liquid, similar to classical geometric cavitation.

As the injection pressure was increased, we observed a contraction of the liquid flow inside the nozzle, and an expansion of the jet outside the nozzle. The change in contraction followed an approximately linear trend with the nozzle discharge coefficient, which was measured independently.

The correlation between the discharge coefficient and area contraction coefficients both inside and outside the nozzle suggest that the discontinuity caused by the onset of hydraulic flip does not cause a significant deviation in the relationship between contraction coefficient and discharge coefficient. This suggests that the onset of hydraulic flip occurs when ambient gas displaces previously existing cavitation voids inside the nozzle. Since the ambient pressure is much higher than the fluid's vapor pressure, it makes sense that any continuous cavitation voids would be completely filled with ambient gas in a short time once the cavitation voids reached the exit plane of the nozzle. However, this hypothesis will require further investigation, as the data available in this preliminary study are limited. Future work could combine fluorescence and radiography measurements of the cavitation voids in order to build a more complete picture of the exchange between cavitation and ambient gas ingress. This exchange occurs rapidly (in milliseconds) and the flow is unstable around the transition pressure. The transition is difficult to capture using time-averaged measurements such as those shown here. High-speed x-ray phase contrast imaging [36] and time-resolved x-ray radiography techniques [37] could be used to better understand how ambient gas displaces pre-existing cavitation voids.

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References
