Neutron Imaging for the Two-Phase Flows inside an Aluminum Aerated-Liquid Injector

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Abstract
Aerated-liquid (or effervescent, or barbotage) injection has been shown to be a capable liquid atomization scheme. The objective of the present study is to characterize the two-phase flow structures in aerated liquid within an aluminum nozzle, using the neutron imaging technique available at the Oak Ridge National Laboratory. Long-exposure neutron images of two-phase flows at different injection conditions, including variations in liquid flow rate, aeration level, and aerating tube configuration, were obtained. Water and nitrogen were used as the working fluid and aerating gas, respectively. For the purposes of direct comparison, high-speed x-ray images with aluminum and beryllium nozzles were obtained at the Argonne National Laboratory, using the same injector assembly and injection conditions. It was found that time-averaged two-phase flow structures inside an aluminum nozzle can be successfully visualized by the present neutron imaging setup, without the use of any dopant in the injection fluid. Effects of liquid flow rate, aeration level, and aerating tube configuration on internal two-phase flow structures were subsequently explored, based on the neutron images. Comparisons between neutron imaging and the companion x-ray imaging clearly demonstrate the advantages and challenges in applying each in-situ imaging technique for the present imaging setup configurations. Neutron imaging at Oak Ridge National Laboratory provides time-averaged qualitative line-of-sight liquid distribution patterns inside a more practical metal nozzle. X-ray imaging at Argonne National Laboratory provides time-resolved qualitative line-of-sight distributions or evolution (in compiled movie clips) of the doped two-phase flow with a satisfactory quality for the beryllium nozzle and with somewhat degraded quality for the aluminum nozzle. Comparison between neutron imaging and quantitative x-ray radiography and fluorescence measurements highlights the need to improve the spatial resolution and to extract quantitative liquid mass distributions from neutron images in the future.

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INTRODUCTION
Aerated-liquid (or effervescent, or barbotage) injection is a promising method for rapid liquid atomization. This method mixes gas and liquid upstream of the spray nozzle, resulting in the discharge of a complex two-phase mixture. Depending on the injection conditions, enhanced liquid atomization can be achieved from the breakup processes of the discharged two-phase mixture. The structures of the discharged aerated-liquid jets, however, are dictated by the two-phase flow structures within the aerated-liquid injector, so it is of great interest to explore the time-averaged and time-resolved internal two-phase flow structures in a given injector configuration, using in-situ advanced diagnostics.

Recently, two-phase flow structures within an aerated-liquid injector have been extensively explored at the Advanced Photon Source (APS) at Argonne National Laboratory (ANL), using various x-ray diagnostic techniques, including x-ray radiography, x-ray fluorescence, and x-ray imaging. For instance, time-averaged x-ray radiography and fluorescence techniques were successfully used to measure quantitative mass distributions within beryllium nozzles. Time-resolved x-ray imaging with beryllium nozzles was found to be very successful for qualitative visualization of internal two-phase flow dynamics. To facilitate these x-ray measurements, however, specially selected dopants at a sufficient concentration were typically added to the injection fluid to either increase the x-ray absorption coefficients for enhanced imaging contrast or facilitate the generation of emitting photons in proportional to the spatial fluid density. In addition, a special nozzle made out of metal with a low atomic number for high x-ray transmittance, such as beryllium, was used to enhance the data quality. Beryllium nozzles, while they offer high x-ray transmittance and are very useful for laboratory programs in specialized facilities, are not appropriate to real-world applications. Successful application of x-ray diagnostics in aluminum or other relatively heavy metal nozzles requires the selection of other dopants, such as xenon, and the application of elevated x-ray energy. More practical in-situ diagnostic techniques capable of exploring flow structures within injectors made out of aluminum, stainless steel, or Inconel are therefore desired for testing with direct application to practical uses.

Neutron radiography has been developed at the Oak Ridge National Laboratory (ORNL). Neutrons have a zero net charge, and constitute a complementary probe for imaging, interacting with the nucleus of the atom, rather than the electron cloud. Unlike x-rays for which object penetration decreases with the atomic number, the strong interaction forces between neutrons and nuclei do not follow a systematic correlation. Neutrons typically exhibit relatively good penetrating power for metals (Fe, Al) used in practical applications. A major advantage of the use of neutron imaging is the high neutron absorption of hydrogen atoms (or hydrogen-bearing substances); water (or hydrocarbon fuel) in a metal injector is expected to exhibit favorable contrast and offer enhanced flow visualization, as illustrated in the study of Smith et al. No specially selected dopant is required. The working principles and demonstrations of the neutron imaging technique can be found in the study of Santodonato et al.

The objective of the present study is to demonstrate the effectiveness of using neutron imaging on two-phase flow structures in an aerated-liquid injector with the nozzle section fabricated from aluminum. Comparison with results from companion and previous x-ray diagnostic programs is used to assess the results. Advantages and limitations in applying both in-situ imaging techniques will also be briefly discussed.

EXPERIMENTAL METHODS
Neutron Imaging at ORNL
The experiment was carried out at the CG-1D beamline of the High Flux Isotope Reactor (HFIR) at ORNL. The details of this beamline can be found in Ref. [9]. Figure 2 shows the HFIR CG-1D beamline layout. Neutrons generated from the HFIR reactor core were guided through an aperture (D) of 4.1 mm with a beam divergence of 2.7 degrees followed by a helium-filled flight tube with silicon windows and motorized boron-nitride exit slits to reach the sample of interest. The neutron flux is around $1 \times 10^8$ n/cm²-s at the sample position. A thin aluminum plate (1.0 mm thick) followed by an LiF/ZnS scintillator (50 µm thick) was placed behind the injector to convert neutron transmission to a visible-light image. The distance between aperture and the aluminum plate, $l$, is around 6.6 m, resulting in an ID of 1,610. A mirror was placed at 45 degrees relative to the beam axis, in order to direct the visible light to an off-axis camera assembly. An ANDOR Zyla 5.5 sCMOS camera with 2,560 (H) x 2,160 (V) pixels was operated with a 10-s exposure time for each image frame. The camera was located within a light-tight box to avoid ambient light interference. The resulting image has a field of view of 51.5 mm (H) x 48.1 mm (V) and a spatial resolution of 20.1 (W) x 22.3 (V) µm/pixel.

Injection Setup
Figure 3 shows the experimental setup. The injector was placed in front of the aluminum plate. Due to the need for a cylindrical aluminum sheet to prevent splash from reaching the scintillator assembly, the distance between the injector axis and the aluminum plate was around 70 mm, resulting in a slight decrease in spatial resolution. The spatial resolution of the present setup is acceptable for qualitative characterization of time-averaged flow structures.
Figure 4 shows the aerated-liquid injector assembly, which consists of a stainless steel injector body, an aluminum aerating tube, and an aluminum nozzle. It features the inside-out aerating configuration with the aerating gas flowing in an aerating tube and then entering the annulus liquid flow passage through specially-placed aerating orifices. The aluminum nozzle has a plenum diameter ($d_{p}$) of 4.8 mm (0.188”) and a plain orifice nozzle of diameter ($d_{n}$) = 1.02 mm (0.04”) and passage length ($L$) = 10.2 mm (0.4”). Critical dimensions and regions of interest within the aluminum nozzle are shown in Fig. 5. For the present study, gas plume formation and two-phase flow evolution within both aerating and mixing regions are of special interest. As will be discussed later, the two-phase mixtures in the nozzle and spray regions could not be clearly explored by the present imaging setup and should be investigated in the future.

Two aerating tubes were tested, as shown in Fig. 6. Both tubes have been previously used with x-ray diagnostics at APS in the study of Peltier et al. Critical dimensions of each aerating tube are listed in Table 1. One of the main features of both aerating tube designs is that the total aerating cross-sectional area ($A_{t}$) is comparable to the internal cross-sectional area of the tube ($A_{i}$), or $A_{t}/A_{i} \approx 1$. Each aerating tube has an outside diameter ($d_{r,o}$) of 3.18 mm (0.125”) and an inside diameter ($d_{r,i}$) of 2.16 mm (0.085”). There is a constant distance of 1.27 mm (0.05”) between the rows of aerating orifices. The distance between last row of aerating orifices and the tip of aerating tube is 4.45 mm (0.175”). The tip of the aerating tube is 3.18 mm (0.125”) from the entrance of the nozzle passage.

For the present study, water and nitrogen were used as the liquid and aerating gas, respectively. Unlike previous studies with x-ray fluorescence and imaging at APS, no doping species were added into the fluid to enhance neutron absorption coefficient. The test matrix consists of variations in liquid flow rate, aerating level (in terms of gas-to-liquid mass ratio, GLR), and aerating tube configuration.

**Imaging Processing**

Three types of images were obtained with the present neutron imaging settings: clean, with nothing within field of view, nozzle-only (no spray), and intended injection conditions. The images were then further processed with the ImageJ software package, using the following two approaches: flat-field image normalization with clean image, and flat-field image normalization with nozzle-only image. Further adjustments in contrast and brightness were subsequently made for each image, in order to enhance the presentation.

Figure 7 shows the flat-field images of both nozzle assemblies with no injection. Both images were taken after several injection trials (during setup), so residual water was present inside both nozzle assemblies even after repeated nitrogen purges. Efforts to totally remove the residual water were not carried out, due to constraints in available beam time. Nonetheless, the processed images show a fairly high neutron beam transmittance through both nozzle and aerating tube. Due to the presence of residual water in the nozzle-only images, the clean flat-field images are used for discussion and comparison.

An unexpected network outage during the experiment curtailed the original test plan. Nonetheless, meaningful results and useful insights were obtained and are presented here.

**RESULTS AND DISCUSSION**

**Effects of Liquid Flow Rate**

Figure 8 shows the time-averaged two-phase flow structures inside the aluminum nozzle coupled with the Configuration #1 aerating tube at various liquid flow rates and a fixed aeration level ($GLR = 4\%$). Several key features of the time-averaged two-phase flow structures can be identified in the figure. It should be noted that the aerating tube was not symmetrically positioned inside the aluminum nozzle, resulting in an uneven annular water flow passage, and uneven mixing between water and aerating gas.

Water accumulation in the wake region downstream of the aerating tube can be observed for the injection condition with a liquid flow rate ($m_{l}$) of 4.5 g/s (0.01 lb/s). As the liquid flow rate is increased to 18.2 g/s (0.04 lb/s), the amount of liquid in the wake region is reduced, and liquid can be clearly observed in the shear layer created by the tip of the aerating tube. Water accumulation can also be observed at the end of the plenum section within the aluminum nozzle, with a variety of liquid distribution patterns. The accumulated liquid appears to be distributed in three lobes for the injection condition with $m_{l}$ = 18.2 g/s.

Figure 8 also shows that the width or spreading rate of the gas plume from the upstream aerating orifices decreases as the liquid flow rate increases, mainly due to an increase in the required injection pressure. The penetration of the gas plume, however, increases as the liquid flow rate (or the absolute gas flow rate) increases, leading to impingement of the gas plume onto the nozzle interior wall and the formation of a liquid film flowing along the aerating tube. The combination of a narrow plume width and more liquid flowing on the aerating tube leads to more liquid in the shear layer for the injection condition with high liquid flow rate.

Under the present imaging setup, no distinct phase boundary is distinguishable in the two-phase flow inside the nozzle region (see Fig. 5) for any of the injection conditions. With a 22:1 reduction in flow passage cross-sectional area across the nozzle entrance, the two-phase mixtures with a small length scale flow at a high speed
in the nozzle region. The two-phase flow structures identifiable using the present imaging setup are, therefore, relatively featureless.

The discharged plume exhibits fairly low contrast, indicating low density within the highly dispersed plume for the $m_L = 18.2$ g/s injection condition.

Similar features can be observed in Fig. 9 for the time-averaged two-phase flow structures using the Configuration #2 aerating tube. Water accumulation can be clearly observed near the end of gas flow passage. With more aerating orifices distributed over a longer distance along the aerating tube, the two-phase mixture can be generated further upstream, but the aerating gas flow appears to be unable to efficiently purge accumulated water from the nozzle. (It is worth noting that this observation of water accumulation highlights the capability of neutron imaging in exploring the two-phase flow structures inside the aluminum aerated-liquid injector assembly.) For the injection condition with $m_L = 18.2$ g/s and GLR = 4%, the gas plumes from upstream aerating orifices exhibit a fairly narrow width and therefore limited mixing with water.

The two-phase flow structures are qualitatively similar within the mixing region at the same injection condition for the two aerating tube configurations shown here.

### Effects of Aeration Level

The effects of liquid aeration level on two-phase structures are shown in Figs. 10 and 11 for the Configuration #1 and #2 aerating tubes, respectively. At a fixed liquid flow rate of 18.3 g/s, an increase in aeration level, which also requires an increase in the absolute gas flow rate, leads to 1) wider gas plumes, 2) changes in liquid distribution patterns in the shear layer off the aerating tube and at the end of the nozzle plenum section, and 3) significantly reduced contrast within the highly-dispersed discharged plume.

The present observations demonstrate the capability of neutron imaging technique to qualitatively characterize time-averaged line-of-sight two-phase flow structures within an axisymmetric aerated-liquid nozzle assembly made out of aluminum.

### Comparison with X-Ray Diagnostics

Various x-ray diagnostics have been applied to explore two-phase flow structures within an aerated-liquid injector.\textsuperscript{7,8} In this section, the results of neutron imaging and selected x-ray diagnostics, including high-speed x-ray imaging, x-ray fluorescence, and x-ray radiography, are compared, using the same injector configuration and the same injection condition, $m_L = 18.2$ g/s and GLR = 4%.

#### Comparison with X-Ray Imaging

Details of the x-ray imaging technique can be found in the study of Lin et al.\textsuperscript{8} The x-ray imaging at ANL can be operated at a fairly high frame rate of 271,554 frames per second, to provide time-resolved flow visualization, but the field of view is limited by the x-ray beam size and the choice of field of view (here, 5.0 mm (H) × 2.8 mm (V) in Table 2). In order to increase the absorption coefficient of the liquid phase under the x-ray, potassium iodide (KI) was added to water at a concentration of 10% by mass. X-ray images with both aerating tube configurations were obtained with aluminum and beryllium nozzles, in order to compare the differences between the nozzles and also to directly compare the x-ray images with the neutron images with the aluminum nozzle. Table 2 lists the setup conditions for the neutron imaging and x-ray imaging. The obtained x-ray images can be compiled as a movie clip for playback at a reduced framing rate; in this paper, however, only representative images are shown to demonstrate the capability of high-speed x-ray imaging.

Figure 12 shows composite x-ray images with aluminum and beryllium nozzles, using the same Configuration #1 aluminum aerating tube. The as-built cross-sectional contour of the Configuration #1 aerating tube, which clearly exhibits several machining imperfections, is overlaid with instantaneous x-ray images for flow boundary identification. Each composite instantaneous x-ray image consists of uncorrelated flat-field sub-images with a reduced field of view from various regions of the flow field. Also shown in the figure are average and standard deviation images from 7,500 collected images for each field of view (equivalent of 27.6 ms exposure time). With a relatively high x-ray transmittance through the beryllium nozzle, the two-phase mixture exhibits a relatively large contrast ratio. Identification of two-phase interfaces and qualitative line-of-sight liquid mass distribution in instantaneous and average x-ray images, respectively, can be made with confidence. The line-of-sight projection through the aluminum aerating tube, however, exhibits a reduced contrast ratio, due to elevated photon absorption by aluminum. The reduction in contrast ratio can be further observed when the beryllium nozzle is replaced by an aluminum nozzle. The average x-ray image obtained with the aluminum nozzle exhibits a low signal-to-noise ratio and, therefore, is not shown here.

Figures 13 and 14 shows comparisons of high-speed x-ray imaging and neutron imaging inside the same nozzle geometries with the Configurations #1 and #2 aerating tube, respectively. The as-built cross-sectional contour of each aerating tube is also overlaid with the corresponding neutron images, for improved flow visualization. One major advantage in using the neutron imaging technique to characterize the time-averaged two-phase flow structures inside an aluminum nozzle is the ability...
to depict the gas plumes within the line-of-sight projection of the aerating tube. The high-speed x-ray imaging, however, gives a degraded flow visualization within this “masked” region. Some improvement in x-ray images can be achieved with the beryllium nozzle, as demonstrated in Fig. 12. Please note that both neutron and x-ray images have a similar per-pixel resolution of around 20 μm, as listed in Table 2. As noted above, the combination of neutron beam divergence and necessary spacing between the injector and the aluminum plate may somewhat limit spatial resolution in the present neutron images, and in fact the spatial resolution of the neutron images is considerably poorer than that of the x-ray images.

Each of the present imaging techniques has its own strengths and limitations with regard to interrogating the two-phase flow structures and dynamics inside an aerated liquid injector. The neutron images were obtained with a 10-s per image exposure time, to give a more representative depiction of the time-averaged flow structures in the present setup. The temporal resolution of the neutron imaging setup may be limited by the ORNL reactor configuration. The averaged high-speed x-ray images come from 7,500 individual images, accounting for a very short time span of 27.6 ms, and may not depict the actual time-averaged two-phase flow structures, though this could be remedied by adjusting the frame rate of the high-speed camera used for these images. Nonetheless, the combination of the two imaging techniques with appropriate choice of metal materials for injector bodies can greatly enhance the current understanding of both time-resolved and time-averaged two-phase flow structures inside an injector of interest.

Comparison with X-Ray Radiography and Fluorescence

Figure 15 shows a comparison between the present neutron imaging and the quantitative line-of-sight liquid density contours obtained from x-ray radiography and fluorescence measurements in the study of Lin et al.,7 for both aerating tube configurations. Details of both x-ray radiography and fluorescence measurements can be found in Ref. [7]. Both x-ray measurements were obtained with a beryllium nozzle, because beryllium offers reduced attenuation for both transmitting and emitting photons. The x-ray detection duration was set at one second at each measurement location, in order to obtain time-averaged line-of-sight liquid density contours. The neutron images appear similar to the quantitative time-averaged line-of-sight liquid mass distributions obtained using both x-ray measurements. Again, the combination of time-averaged x-ray measurements and neutron imaging provides considerable information on the two-phase flow structures within an aerated-liquid injector. Derivation of quantitative mass distributions from neutron images should be explored in the future.

SUMMARY

Two-phase flow structures in aerated liquid within an aluminum nozzle were explored using the neutron imaging technique at the Oak Ridge National Laboratory. Long-exposure neutron images of two-phase flows under different injection conditions, including various liquid flow rates, aeration levels, and aerating tube configurations, were obtained. Water and nitrogen were used as the working fluid and aerating gas, respectively. For direct comparison purposes, companion high-speed x-ray images with aluminum and beryllium were also obtained at the Argonne National Laboratory, using the same injection conditions and injector assemblies. Major conclusions of the present study are as follows:

1. Time-averaged in-situ two-phase flow structures inside an aluminum nozzle were successfully visualized with the neutron imaging technique, without the use of any dopant in the injection fluid.

2. Effects of liquid flow rate, aeration level, and aerating tube configuration on internal two-phase flow structures were subsequently explored from the neutron images.

3. Comparisons between neutron imaging and companion x-ray imaging clearly demonstrate the advantages and challenges in applying each imaging technique for the present setup configurations

- Neutron imaging at Oak Ridge National Laboratory provides time-average qualitative line-of-sight liquid distribution patterns inside an aluminum metal nozzle. For the present setup, a full-field flow measurement can be achieved but with a relatively long exposure for each image and poorer spatial resolution than with x-rays.

- X-ray imaging at Argonne National Laboratory provides time-resolved qualitative line-of-sight distributions or evolution (in compiled movie clips) of the doped two-phase flow with a satisfactory quality for the beryllium nozzle and a lower quality for the aluminum nozzle. The field of view is limited by the size of the x-ray beam.

Comparison between neutron imaging and quantitative x-ray radiography and fluorescence measurements highlights the need to improve the spatial resolution and to extract quantitative liquid mass distributions from neutron images, in order to expand the capability of the neutron imaging technique in the future.
ACKNOWLEDGEMENTS
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REFERENCES
### Table 1. Aerating tube configurations

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<th>Configuration</th>
<th>$d_r$ (mm)</th>
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<th>Offset (degree)</th>
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<td>2</td>
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<tr>
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<td>10</td>
<td>2</td>
<td>90</td>
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### Table 2. Comparison between neutron and x-ray imaging setups

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<tr>
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<th>ORNL Neutron Imaging</th>
<th>ANL X-Ray Imaging</th>
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<td>Image Field of View</td>
<td>51.5 mm (H) × 48.1 mm (V)</td>
<td>5.0 mm (H) × 2.8 mm (V)</td>
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<tr>
<td>Camera Pixel</td>
<td>2,560 (H) × 2,160 (V) pixels</td>
<td>256 (H) × 144 (V) pixels</td>
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<tr>
<td>Spatial Resolution</td>
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<td>Framing Rate</td>
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<td>Beryllium, Aluminum</td>
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<td>Use of Dopant</td>
<td>Not needed</td>
<td>Potassium iodide (KI) 10% by mass</td>
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### Figure 1. Comparison of cross sections of x-ray and neutron. Neutron is very sensitive to hydrogen and almost transparent to metals, while x-ray is the opposite.

### Figure 2. High Flux Isotope Reactor (HFIR) CG-ID beamline layout at the Oak Ridge National Laboratory
Figure 3. Experimental setup at the HFIR CG-1D beamline

Figure 4. Injector assembly

Figure 5. Schematic of regions and dimensions of interest around the aluminum nozzle
Figure 6. Aerating tubes

Figure 7. Flat-field neutron images of injector assemblies with no water injection (residual water present)

Figure 8. Flat-field corrected neutron images of time-averaged two-phase flow structures at various liquid flow rates, Configuration #1 aerating tube, $GLR = 4\%$
Figure 9. Flat-field corrected neutron images of time-averaged two-phase flow structures at various liquid flow rates, Configuration #2 aerating tube, $GLR = 4\%$

Figure 10. Flat-field corrected neutron images of time-averaged two-phase flow structures at various aeration levels, Configuration #1 aerating tube, $m_L = 18.2 \text{ g/s}$
Figure 11. Flat-field corrected neutron images of time-averaged two-phase flow structures at various aeration levels, Configuration #2 aerating tube, $m_L = 18.2 \text{ g/s}$

Figure 12. Comparison of beryllium (left) and aluminum (right) nozzles under high-speed x-ray imaging. Configuration #1 aerating tube, $m_L = 18.2 \text{ g/s}, \text{GLR} = 4\%$
Figure 13. Comparison between x-ray imaging (left) and neutron imaging (right), aluminum nozzle, Configuration #1 aerating tube, $m_L = 18.2$ g/s, $GLR = 4\%$

Figure 14. Comparison between x-ray imaging (left, beryllium nozzle) and neutron imaging (right, aluminum nozzle), Configuration #2 aerating tube, $m_L = 18.2$ g/s, $GLR = 4\%$
Figure 15. Flat-field corrected neutron images (left) and line-of-sight liquid density measurements from x-ray radiography and x-ray fluorescence techniques (right), $m_L = 18.2 \text{ g/s}$, $GLR = 4\%$, x-ray measurements with a beryllium nozzle, from Ref [7]