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# Development of a gas layer to mitigate cavitation damage in liquid mercury spallation targets

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ABSTRACT

Establishment of a gas layer between the flowing liquid and container wall is proposed for mitigating the effects of cavitation in mercury spallation targets. Previous work has shown an order of magnitude decrease in damage for a gas layer developed in a stagnant mercury target for an in-beam experiment. This work is aimed at extending these results to the more complex conditions introduced by a flowing mercury target system. A water-loop has been fabricated to provide initial insights on potential gas injection methods into a flowing liquid. An existing full-scale flow loop designed to simulate the Spallation Neutron Source target system will be used to extend these studies to mercury. A parallel analytical effort is being conducted using computational fluid dynamics (CFD) modeling to provide direction to the experimental effort. Some preliminary simulations of gas injection through a single hole have been completed and show behavior of the models that is qualitatively meaningful.

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## 1. Introduction

The Spallation Neutron Source (SNS) is a high-power accelerator-based user facility located at the Oak Ridge National Laboratory (ORNL) which will achieve high fluxes of neutrons for scientific experiments. Neutrons are produced when a pulsed (<1-μs, 60-Hz) proton beam impacts liquid mercury flowing in a stainless steel target vessel. Erosion of the target vessel due to cavitation bubble collapse has the potential for limiting the lifetime of the target and is the motivation for this work.

Introduction of a gas layer between the container wall and the liquid mercury is proposed as a method for mitigating damage from cavitation bubble collapse. Previous tests at the Los Alamos Neutron Science Center Weapons Neutron Research (LANSCE/WNR) facility by Haines et al. [1] have shown promising results for this method. These in-beam tests using nonprototypic targets with stagnant mercury showed a reduction of material erosion by an order of magnitude. These tests are described in more detail in Wendel et al. [2].

The long-term objective of the current work is to develop methods for maintaining a gas layer at the wall of critical surfaces in the SNS mercury target. This must include development of diagnostics for evaluating the gas layer, including gas surface coverage area, gas layer thickness, and temporal stability of the layer. Additionally, the effectiveness of the gas layer in mitigating cavitation damage under more prototypic hydraulic conditions must be confirmed.

A literature search has not revealed any specific information dealing with maintaining a gas layer on a wall in flowing liquid. A good source on related work is from the steel industry where gas injection is used in casting operations. Bai and Thomas [3] have studied bubble formation during horizontal gas injection in downward flowing liquid for application to Tundish nozzles. This work included measurements in air-water systems and models developed and applied to argon-molten steel systems. Their summary predictions indicate that compared to the air-water system, bubbles in liquid steel should tend to spread more over the ceramic nozzle wall, argon bubbles in liquid steel should be larger than air bubbles in water for the same flow conditions, and that it is possible to use high liquid velocity, high gas flow rate conditions to prevent liquid contact with the wall; however, gas injection rates are prohibitively high, and other flow-related problems are likely. Indeed, for the liquid mercury system of interest for this application, gas flow rates will be limited by the ability to remove the gas and by potential instabilities caused in the bulk mercury flow – along with loss of neutron production if too much mercury is displaced from the beam region.

A combined experimental and analytical approach is being initiated. This paper describes the facilities that are being developed and some preliminary results from both experimental testing and numerical simulation work. Initial testing is being performed in water. These tests are providing insight into various injection methods and bubble dynamics within a flowing liquid. A range of

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injection methods will be tested, including porous plate material and discrete holes – in arrays and with screens and other methods for affecting gas dynamics. Test section designs and sealing techniques for replaceable inserts are being proven in water before being used in mercury. Tests in water will be followed by similar tests in a full-scale mercury loop. Significant differences in wetting, density, and surface tension in mercury are expected to yield different results than those seen in water testing. The results of gas injection through simple geometries into water are being used to develop and benchmark numerical simulations. The numerical simulation work will be used to provide both guidance and analysis of results for the tests in mercury. Results from the target nose region geometry will provide information on suitability of the current target design to accommodate a gas layer. It may be necessary to modify the existing target design to more easily incorporate the gas dynamic behavior by using the liquid flow to help transport the gas along the wall in critical areas.

## 2. Test facilities

A water-loop has been fabricated to provide initial insights on potential gas injection methods into a flowing liquid. A transparent acrylic tube with a removable wall section allows various injection methods and materials (e.g., a porous plate) to be studied for effectiveness in covering the wall with a gas layer. The pipe-section geometry of the water test section is also being used to evaluate gas flow control requirements as well as diagnostics for evaluating gas layer thickness and time-dependent surface coverage. A high-speed camera is used as a primary diagnostic in these studies.

The water-loop is designed to provide water flow at bulk velocities typical of the SNS mercury target. A photograph of the loop is shown in Fig. 1. A Bell & Gossett Model 4BG centrifugal pump with a design capacity of 44 L/s and 25 m of head is driven by a 11-kW (15-hp) motor using a Robicon variable-speed drive. A 1.1-$m^3$ tank open to atmosphere provides water to the pump suction and acts as a passive gas separator for the return flow. An EMCO Model 3100 flow meter with a range of 0–15 L/s is used to measure water flow in the test section leg. The loop is constructed primarily using schedule 80 PVC piping and 150-lb flanges. A number of additional connection points are provided on the loop for future use.

A gas injection panel is shown on the right side of Fig. 1. This panel contains a range of rotameters for gas flow indication and control along with pressure gage and a relief valve (not shown). Mass flow controllers of various ranges are also used for more accurate gas flow measurement and control. A gas cylinder with regulator is used as the gas source.

The loop configuration shown includes a clear acrylic tube ~1.5-m long, containing a test section assembly with replaceable inserts. These inserts may be readily changed to accommodate various gas injection methods. A drawing view of the assembly is shown in Fig. 2. O-rings are used to seal the replaceable inserts on the pipe wall. A second acrylic window may be used to create a gas manifold region to supply gas to inserts with multiple injection holes. The inside surface of the inserts cover 90° of the inside wall circumference (diameter of 76 mm) and are 200 mm long. The inside radius of the tube was chosen to be similar to that of the nose region in the SNS target. The viewable included angle (from the insert side) is reduced to 70° by the insert seal plate and to 50° if the second window is used to create the gas manifold region. Rotating flanges on the 1.5-m long acrylic tube allows the insert region to be located in any vertical/horizontal orientation.

An existing full-scale flow loop at ORNL designed to simulate the SNS target system will be used to extend these studies to mercury. The Target Test Facility (TTF) has been described in [4,5]. Two different test sections have been designed and are in the process of being fabricated, a pipe-section geometry similar to that used in the water-loop and a target nose test section simulating the region where the proton beam is incident in the real target. These will allow various gas injection concepts to be tested in flowing mercury. The designs will include transparent acrylic windows (for discrete injection methods) that will allow visual evaluation of gas coverage at the wall using high-speed video images. For discrete injection methods, holes will be drilled in the acrylic windows to provide injection sites. A view of the target end of the TTF is shown in Fig. 3. A drawing view of the nose test section assembly is shown in Fig. 4. The same sealing technique and window design is used

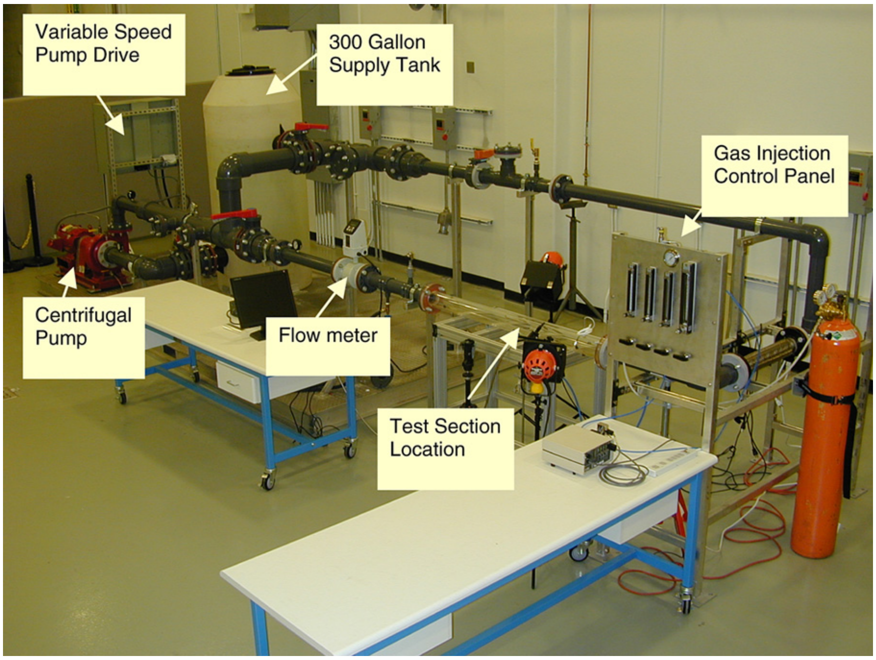

**Fig. 1.** Water test loop.

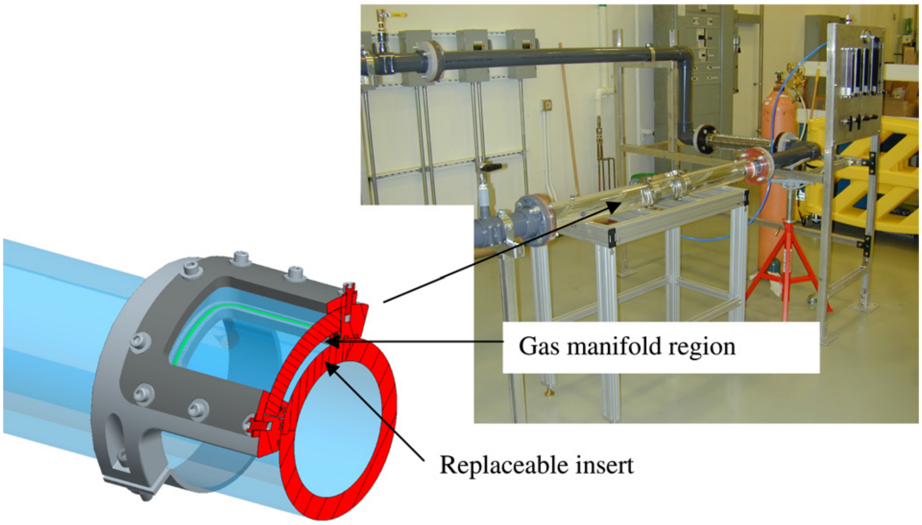

**Fig. 2.** Drawing view of clear acrylic test section assembly.

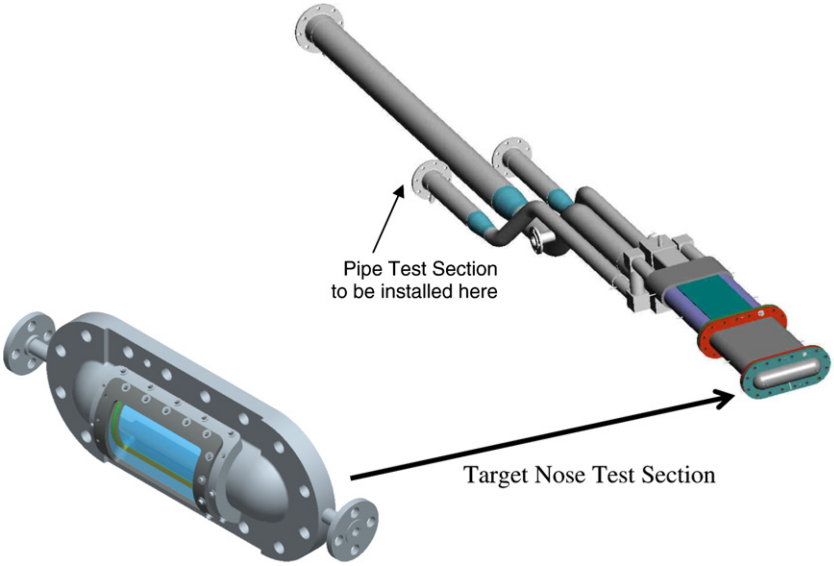

**Fig. 3.** View of TTF and test section locations.

on the nose region as was used in the water-loop. The included angle of the window is larger on the nose assembly than in the pipe section, with 100° for the inner window and 80° with the outer window installed. The pipe test section is the same design as the water-loop test section, except that the assembly is mounted on 76-mm ID stainless steel tube rather than acrylic tube.

Development of diagnostic instruments to measure and evaluate bubble and gas layer properties is a critical part of this effort. Gas layers on the wall lend themselves to visual observation through transparent walls. A high-speed video camera, an Olympus i-Speed 2, is used to obtain images of bubble and gas layer formation. The camera has capability of up to 33000 frames per second (fps), with full 800 × 600 pixel resolution at 1000 fps.

A Frequency Modulated Coherent Laser Radar (FM CLR) system is available and shows promise for measuring the mercury surface location through an acrylic window. The instrument measures distance from a reflective surface with submillimeter accuracy and can be used to scan an area, in this case the acrylic window region in the TTF. It is hoped to measure the location of the mercury free surface relative to the acrylic window and quantitatively determine the gas gap and gas layer coverage area. The instrument measurement time is on the order of 1 ms at a given location, so the temporal nature of the gas layer will most likely impact the interpretation of the results. It may be necessary to obtain time-averaged gas gap information at a given location and build a composite of the total surface response based on these individual measurements.

In areas away from the surface and where transparent walls are not feasible (e.g., for a porous wall), other diagnostic methods are needed. An ultrasonic probe is being developed for use in the target nose region of the TTF. The probe will be located inside the nose in the bulk flow just in front of the 'Optional Support Bar' shown in Fig. 4. Refraction of the sound waves at stainless steel and mercury interfaces precludes obtaining signals from probes mounted on the outside walls for most of the regions of interest, so the probe is located on the center line of the inside wall radius. The intent is to measure the distance from the probe to the gas/liquid interface and thereby deduce the gas layer distance from the wall. The probe can rotate and slide from side to side to allow measurements over most of the inside nose region of interest. It does provide an

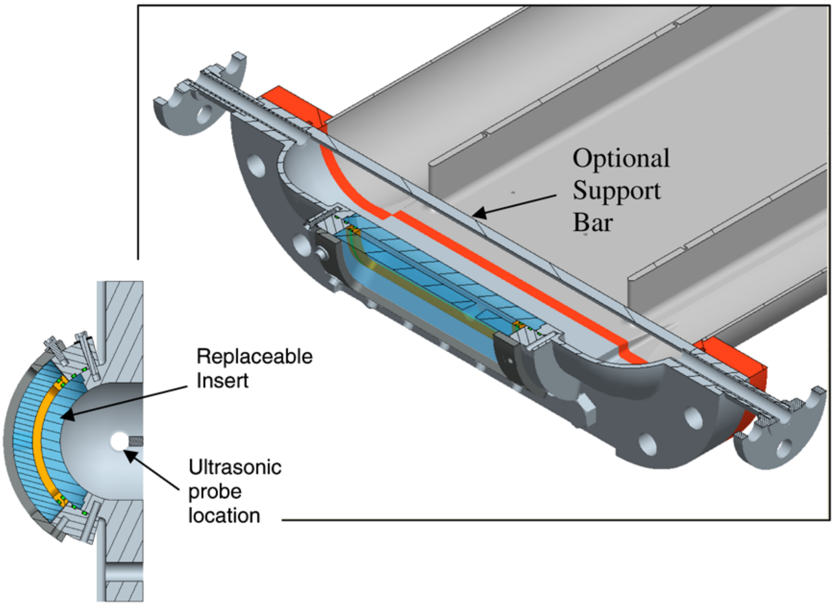

**Fig. 4.** Cross-section of TTF nose region test section assembly.

intrusion to the bulk flow field, but measurement of local effects at the wall are deemed more important.

## 3. Scoping tests in water

Several different types of injection methods are being tested. Discrete holes of various sizes and with different upstream gas supply conditions are being evaluated. The upstream compressibility of the gas supply to the injection site has an expected large effect on the uniformity and periodicity of the bubbles entering at the wall. Tests have been performed with single and multiple holes being fed from the gas manifold region formed between the clear acrylic test insert and the outer acrylic cover plate. Especially at low gas flow rates, bubble formation is not very regular, and there are periods of time where no bubbles are being injected. For the multiple-hole case, the bubble formation is more or less synchronized (i.e., bubbles are generated from all holes or none). An example of a multiple-hole injection is shown in Fig. 5. This shows a frame from a movie clip taken at 1000 fps. The three injection holes at the wall that are being used are 1 mm in diameter. The holes are machined at a 45° angle through the 12.7-mm-thick wall. Bubbles are carried downstream by the 1-m/s bulk water velocity in this case.

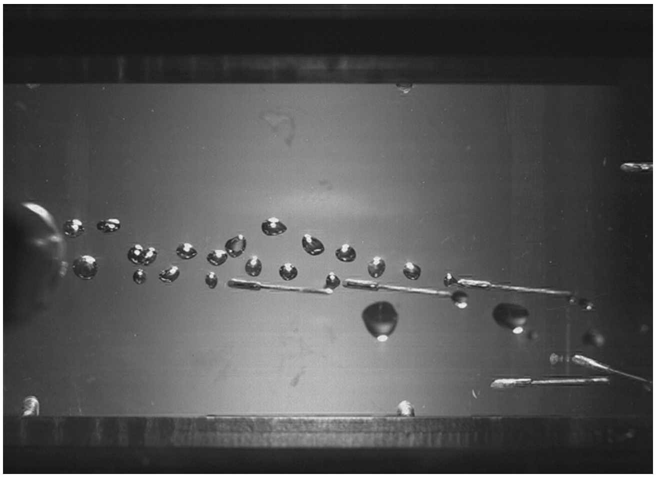

**Fig. 5.** Multiple-hole injection, 45° entrance angle, 1 mm diameter at wall, 1-m/s water velocity, 0.28 standard liters per minute (slpm) nitrogen total gas flow rate from gas plenum (file 6616179m).

More uniform bubble generation is obtained using individual feed lines with higher pressure drops in the line. It was difficult to machine orifices in the acrylic that are small enough to impose a significant pressure drop near the wall, especially for low gas flow rates, but small-diameter feed lines (tenths of millimeter inside diameter) of nominally 250 mm in length worked reasonably well.

Porous metal walls are also being tested. A drawing view and photograph of a porous plate insert is shown in Fig. 6. The porous plate shown has 0.5-μm pore size, is 1.2-mm-thick, and is fabricated by the Mott Corporation. It is welded into a stainless steel frame creating an integral gas manifold region.

Especially at low gas flow, bubble formation is not particularly uniform over the surface of the porous media. As gas flow increases, more injection sites come into play. An example at a reasonably high gas flow rate is shown in Fig. 7. The test section

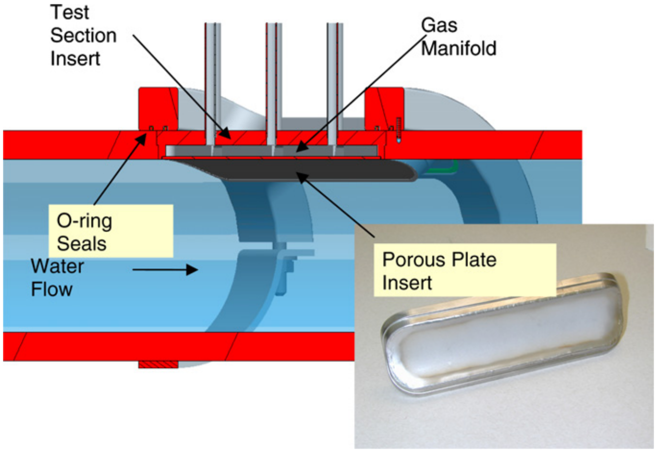

**Fig. 6.** Porous plate test section assembly.

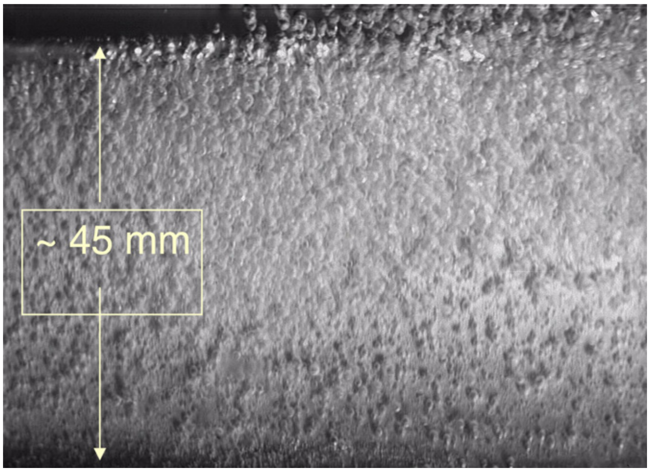

**Fig. 7.** Porous plate, 0.5-μm pore size, 1.2-mm-thick, 1-m/s water flow, 7.4-slpm nitrogen gas flow over ~90-cm$^2$ porous area (file 6803399m).

insert is mounted vertically in the tube (e.g., the horizontal midplane of the pipe is in the center of the photograph, so the buoyancy force is in the upward direction on the page). Water flow is from left to right in the photo at 1-m/s bulk flow velocity. Coverage is better in the top and right section of the photo because buoyancy and water flow act to carry bubbles in that direction.

Perforated plates and screens were tested as a means of modifying the bubble shape and affecting the local liquid velocity at the wall. A photograph of a stainless steel perforated plate installed on the wall is shown in Fig. 8. The perforated plate is spaced ~1.2–1.5 mm from the wall and is open at the edges. The perforated plate has circular holes of 0.5 mm with a 30% open area. As shown in Fig. 9, the area coverage for a given gas flow rate – and bubble – is increased significantly. The gas bubble shown in the center of the photograph is located between the wall and the perforated plate. Movie clips show the bubbles moving predominantly upward due to the buoyancy force and are significantly less affected by the liquid bulk flow. The bubbles in this case still show the periodic formation and release from the opening at the wall. The gas generally flows between the perforated plate and the wall, with little pass-through observed until gas flow rates are relatively high.

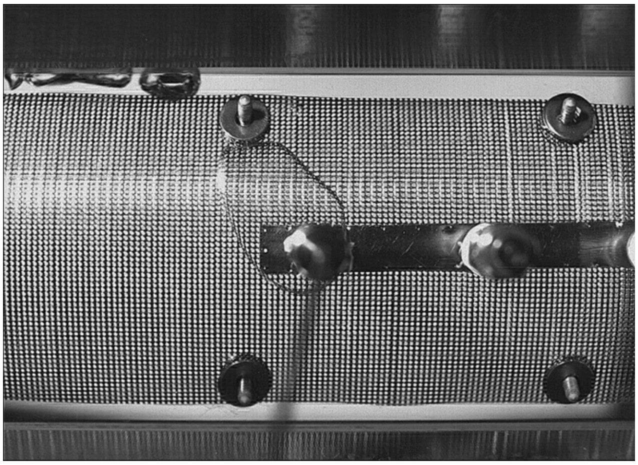

**Fig. 9.** Nitrogen gas flow 1.2 slpm, water velocity 1 m/s, perforated plate with 0.51-mm-dia holes and 30% free area (file 6706288m).

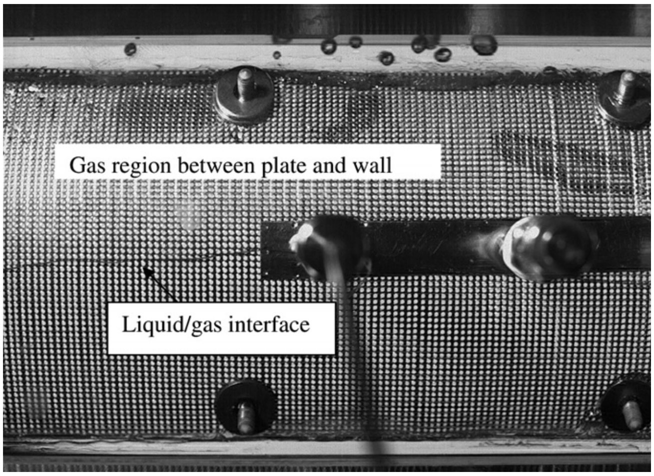

**Fig. 10.** Nitrogen gas flow 1.2 slpm, water velocity 1 m/s, perforated plate with 0.51-mm-dia holes and 30% free area, sealed at edges with RTV silicon sealant (file 6720347m).

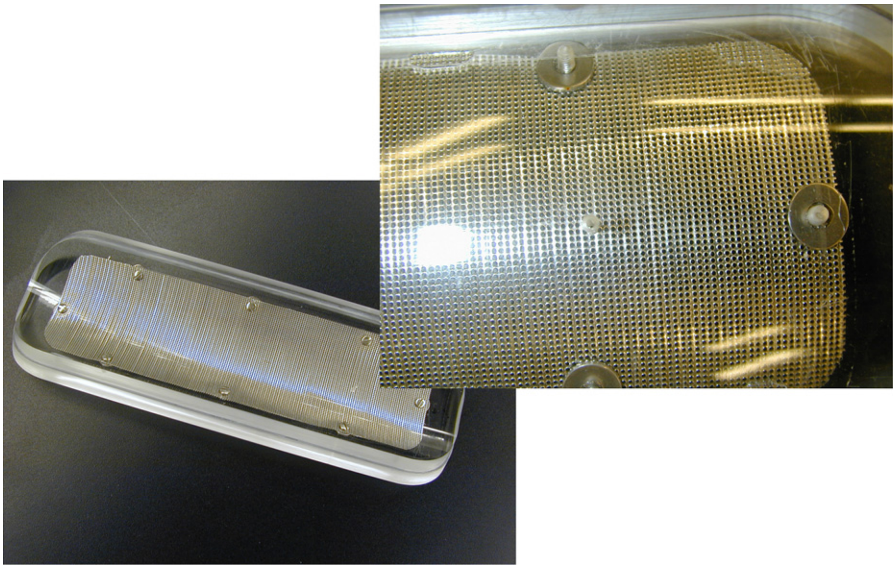

**Fig. 8.** Acrylic insert with stainless steel perforated plate attached to wall, ~1.3-mm spacing, 0.5-mm-dia holes with 30% open area.

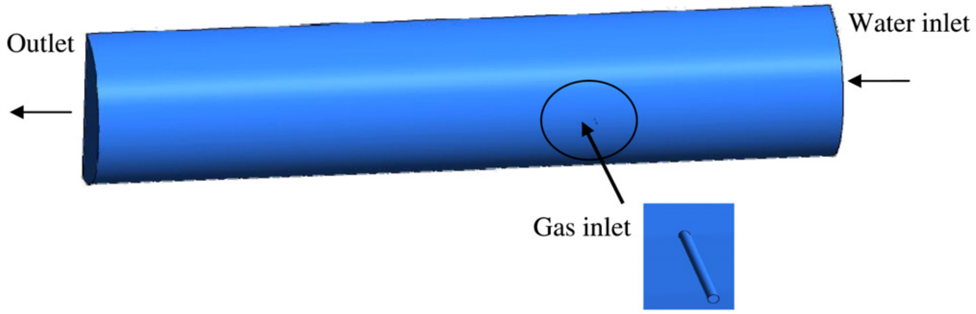

**Fig. 11.** Schematic of the computational domain.

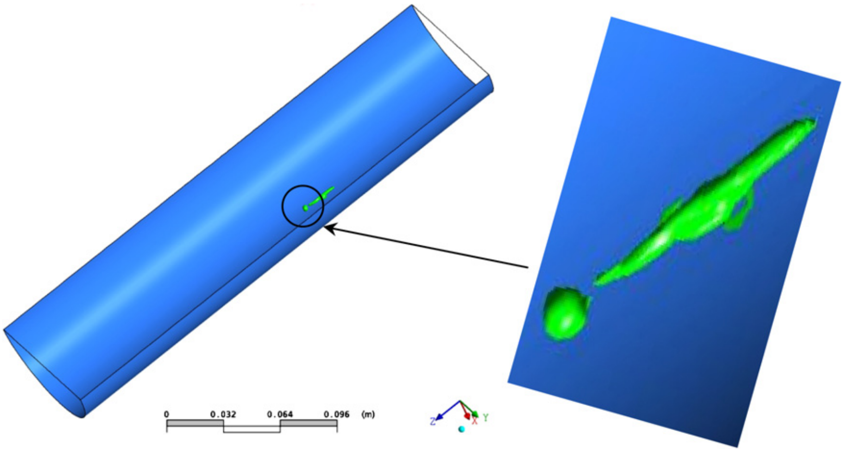

**Fig. 12.** Iso-surface with gas volume fraction of 0.5.

The stainless steel strip seen in the photo is present to prevent this pass-through at the higher gas flow rates. It should be emphasized that these results are for water, and the different wetting and surface tension properties of mercury may lead to significantly different behavior.

It is the wetting of the stainless steel perforated plate and the surface tension of the water that apparently provides a barrier to the gas. A check of this was made by using an RTV silicon sealant around the edges of the perforated plate. This method was not a very reliable method of sealing the plate, but was sufficient to show the general characteristics. Fig. 10 shows a case at similar gas flow conditions as the open (unsealed) perforated plate of Fig. 9. The gas forms a layer between the wall and the plate over the top half of the perforated plate at this flow rate. Gas was not observed to pass through the perforations in the plate, but rather was leaking through the RTV seal at the edges (some bubbles can be observed as shadows behind the screen that are generated by an upstream leak at a location on the seal out of the camera view). As a simple comparison, the capillary pressure for this diameter of hole is ∼25 mm of water, and this observed behavior is consistent with that value (the viewable window dimension in the vertical direction is ∼50 mm along the circumference of the wall).

Mercury will act differently because it does not wet stainless steel as well as water, and its surface tension is significantly higher. It remains to be seen how well a perforated plate or screen will perform with mercury. In addition, use of a perforated plate or screen does not necessarily provide a viable solution in that the screen may now be vulnerable to cavitation damage and may not survive long in the beam. The interaction of the pressure wave with a screen or perforated plate, and particularly whether it acts as a free surface, solid surface, or some combination depending on length scales in the screen, will also be an important factor affecting the lifetime.

## 4. Numerical simulation

Computational fluid dynamics (CFD) modeling of two-phase (gas–liquid) flow is also underway to enhance the development of an effective gas layer. The gas-liquid flow is simulated using the homogeneous two-phase model in ANSYS-CFX[2] version 10. The volume of fluid (VOF) method is used to capture the gas–liquid interface. Fig. 11 shows the physical model and the boundary conditions. The gas is injected at constant flow rate of 188-standard $cm^3$/min (sccm) through a single orifice on the side of the water-loop pipe into axially moving water (1.0 m/s). Fig. 12 presents the gas/liquid interface defined in the model as the iso-surface with a gas volume fraction of 0.5. The bubble detachment time is 13 ms. The predicted bubble diameter is about 3 mm, and the measured bubble size is about 3.3 mm. The comparison between the computed and measured bubble diameter shows good agreement.

## 5. Summary

Initial scoping tests in water have been performed and provide insights into gas injection dynamics and gas mass flow control

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[2] ANSYS-CFX is a commercially available CFD solver developed by ANSYS, Inc., Southpointe, 275 Technology Drive, Canonsburg, PA 15317.

requirements. Several different injection methods including discrete holes, discrete holes with perforated plates and screens, and porous media have been tested in flowing water. Test sections have been designed to perform similar tests in flowing mercury in the existing TTF. Testing in this facility will start in the near future. Diagnostics are being developed to provide quantitative measurement capability for evaluating gas layers, both spatially and temporally. Numerical simulations are being developed in parallel to provide direction for the experiments and diagnostic information about regions difficult to measure.

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