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S. S. Glickstein, W. H. Vance & H. Joo

Westinghouse Electric Corporation
Bettis Atomic Power Laboratory
P. O. Box 79
West Mifflin, PA 15122
(412) 476-5185

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VOID FRACTION MEASUREMENTS USING NEUTRON RADIOGRAPHY

S. S. Glickstein, W. H. Vance & H. Joo
Bettis Atomic Power Laboratory

ABSTRACT

Real-time neutron radiography is being evaluated for studying the dynamic behavior of two phase flow and for measuring void fraction in vertical and inclined water ducts. This technique provides a unique means of visualizing the behavior of fluid flow inside thick metal enclosures. To simulate vapor conditions encountered in a fluid flow duct, an air-water flow system was constructed. Air was injected into the bottom of the duct at flow rates up to 0.47 l/s (1 cfm). The water flow rate was varied between 0-3.78 l/m (0-1 gpm). The experiments were performed at the Pennsylvania State University nuclear reactor facility using a real-time neutron radiography camera. With a thermal neutron flux on the order of 10^8 n/cm²/s directed through the thin duct dimension, the dynamic behavior of the air bubbles was clearly visible through 5 cm (2 in.) thick aluminum support plates placed on both sides of the duct wall. Image analysis techniques were employed to extract void fractions from the data which was recorded on videotape. This consisted of time averaging 256 video frames and measuring the gray level distribution throughout the region. The distribution of the measured void fraction across the duct was determined for various air/water mixtures. Details of the results of experiments for a variety of air and water flow conditions are presented.

I. INTRODUCTION

Neutron radiography techniques are being evaluated as a means of measuring void fractions in two-phase flow under various conditions and to determine the dynamic behavior of fluids within an opaque container. It has been shown that thermal neutrons, because of their relatively high reaction rate with hydrogen, are sensitive to small changes in water thickness and that neutron radiography techniques potentially can be used to measure void fractions and to study the dynamic behavior of flowing fluids inside opaque containers (References 1,2).

To better understand this experimental technique, initial neutron radiography testing was undertaken using a step gage of varying water thickness. The tests, reported in Reference 3, indicate that small differences in water thickness in a narrow test duct, sandwiched between 5 cm (2 in.) thick aluminum plates could be detected with reasonable precision. Analytical methods using the Monte Carlo program RCP01 (Reference 4) were developed and extensive studies were performed which explained much of the optical density distributions that were measured from the radiographs. The RCP01 results revealed the importance of edge effects, shielding the test device to eliminate extraneous neutrons, and collimating the incident neutron beam. The good agreement of the Monte Carlo simulation with experiment demonstrated that Monte Carlo code predictions could be effectively used to guide future experimental work.

II. EXPERIMENTAL AIR-WATER TEST LOOP

A. Initial Experiments With Plexiglas Flow Channel

The air-water flow system shown in Figures 1 and 2 was constructed. The narrow Plexiglas duct shown in these figures was 5 cm (2 in.) wide by 61 cm (24 in.) high. Air was injected at the bottom of the duct through a tube that contained a large number of small holes. The air bubbles rose through the test section into a large overflow reservoir at the top of the channel where the air separated and escaped out of the top. The water circulated back through the loop with the help of a small pump. The inlet air flow rate and water flow rate were monitored. In addition, a differential pressure cell monitored the pressure drop across a 55 cm (22 in.) region of the channel. The water was colored using blue dye to provide good visual contrast between the air bubbles and the water. The dynamics of the fluid flow with the channel in an upright and an inclined position was recorded using a Panasonic WV-BL600 high performance black and white video camera as shown in Figure 2.

Tests were performed at various combinations of air and water flow rates. Video recordings were taken at the normal camera shutter speed of 1/30 second and then with the variable strobe effect shutter speed set at 1/250, 1/500 and 1/1000 second. Typical results shown in Figures 3 through 5 reveal the smearing effect of the slower speed shutter (which is used in performing real-time neutron radiography studies). Air flow rates varied between 0 and 0.47 l/s (0-1 cfm) and water flow rates between 0 and 3.78 l/m (0-1 gpm).

These results provided a good visual baseline of the bubble shapes and flow regimes that one could expect to observe when neutron radiography is employed with an opaque test section.

B. Experiments With Flattened Oval Metal Channel

After the initial tests with the Plexiglas test section, the Plexiglas was replaced with a metal duct. The stainless steel test section was made by flattening a standard 3.175 cm (1¼ in.) stainless steel tube of 0.045 cm (0.018 in.) wall thickness into a wide oval shape approximately 5 cm (2 in.) wide. The entire rig was transported to the Pennsylvania State University (PSU) nuclear reactor facility, where neutron radiography tests were performed. The apparatus was positioned so that the center of the test section was approximately in the center of the 25 cm (10 in.) diameter, thermal neutron beam whose flux was on the order of 10^6 n/cm²/s. A schematic diagram of the facility is shown in Figure 6. Video pictures were taken with the PSU neutron radiography Precise Image camera described in Reference 5. The experiments performed were designed to evaluate the methodology and the image analysis data reduction system. Most neutron radiography studies are done for non-destructive testing purposes and the majority of the analyses entail visual inspection of the radiograph. Little work has been done on extracting numerical data from the radiographs. In contrast to such practices, these studies were directed toward extracting precise numerical data. Thus, much concern was directed toward maintaining neutron beam stability, measuring the thermal neutron beam spatial distribution, determining the detector response efficiency at each point on its surface, and most important, evaluating the effect of scattering as the removal mechanism of neutrons from the incident beam.

III. DATA REDUCTION

A. Image Analysis Procedure

For each test run, the neutron radiographic camera recorded on 1.9 cm (3/4 in.) video tape the air-water flow pattern in a 23 cm (9 in.) field of view for several minutes. Each video frame records data for 1/30 second. The first and last run in each set consisted of a background run with zero airflow. A typical background picture is shown in Figure 7. A single frame with airflow is shown in Figure 8. To obtain time average void fractions in the channel, it is necessary to accumulate data over a given time interval. The Recognition Technology Imaging system used for analyzing the data is capable of automatically averaging 2^8 frames (8.5 seconds at 30 frames per second) into a single image. Figure 9 shows the results of time averaging a background test run and a test with the air flow rate of 0.094 l/s (0.2 cfm).

A "lane" across the center of the channel, as indicated in Figure 9, was selected as the region for void fraction evaluation. The gray scale pixel distribution in the y-direction (approximately 0.635 cm (1/4 in.) high) was averaged and a plot of the gray scale distribution in the x-direction for several different air input rates is shown in Figure 10. The tilt in the data across the duct was attributed to spatial variation in neutron beam distribution and/or the detector response function. The data were normalized by dividing each measurement by the no-air test data (Figure 11). To first order, the void fraction was assumed to be linearly proportional to the normalized gray scale. This was substantiated by evaluating the images of a step gage (Reference 3) which contained known thicknesses of water. A normalization factor was determined for each set of data by comparing the gray scale reading in regions outside the channel (no water, no stainless steel) to that in the region of the channel completely filled with water. Additional experiments were performed to account for the stainless steel channel walls (see Figure 12). Typical void fraction distributions from the above analysis are shown in Figure 13.

The entire set of experiments was repeated several times, but with different initial fluid flow conditions. The results for each set of data are similar to that shown in Figures 10, 11, and 13. Void fraction as a function of airflow for these runs is shown in Figure 14. The increase in void fraction with increased airflow is evident. However, there appear to be some unexpected trends, which remain unexplained.

B. Uncertainties

There are several experimental uncertainties that limit the use of the data. For example, the inlet air distribution across the channel is unknown. It appeared that the air bubbles did not exit uniformly from the series of air holes in the inlet manifold. There is also experimental evidence that the camera position was not firmly fixed, causing some concern when comparing one run to another. Finally, the normalization procedure needs to be examined with great care. Neutron attenuation by the water is predominantly due to scattering and not absorption. Thus, neutrons arriving at a pixel point in the imaging system contain contributions from neighboring points. This has been previously discussed in detail in Reference 3. These effects can perturb the

normalization procedure and are the reasons for the negative void fraction noted in Figure 13. Monte Carlo simulations are currently being performed to examine this concern. The data reduction needs to properly account for the fact that neutrons are removed from the direct beam by scattering and can be detected in a neighboring region. Procedures are currently being developed to properly account for this effect.

IV. SUMMARY & CONCLUSIONS

An atmospheric-pressure, unheated, air-water loop was built to explore the capabilities of real-time neutron radiographic methods for measuring void fractions and observing two-phase flow dynamics. Initially, a Plexiglas duct was inserted in the loop for visual studies. Video pictures were taken of air-water flow with the air injected by a manifold in the inlet plenum just below the test section. Image analysis of the video tapes confirmed that the flow loop and the image analyzer functioned well.

The Plexiglas duct was then replaced with a metal, flattened-oval duct. The entire experimental apparatus was transported to the Pennsylvania State University Neutron Radiography Facility. Using one of the thermal-neutron ports on their nuclear reactor, the air-water tests carried out with the Plexiglas duct were repeated with the flattened-oval duct. Data were obtained with and without 5 cm (2 in.) thick aluminum blocks placed in front and in back of the test section, the anticipated geometry for future testing with a pressurized heated duct.

The Penn State real-time neutron radiography camera was used to acquire flow-visualization data on video tape. Image analysis of the tapes produced single-frame, "snap-shot" images of the flow field and time-averaged images, from which time-average void fraction distributions were derived.

These experiments have demonstrated the viability of neutron radiography techniques for measuring vapor fractions. They have also highlighted areas needing further developments, including more accurate evaluation of edge effects and development of more rapid, systematic methods of data reduction.

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Figure 1 Schematic of Air-Water Test Assembly

Figure 2 Air-Water Test Assembly

(a)

(b)

Figure 3 Full View, Air Flow = 0.1 CFM
a) Shutter Speed 1/1000 Second
b) Shutter Speed 1/30 Second

Figure 4. Single Frame, Run 72 Shutter Speed
1/30 Second, Air Flow = 0.1 CFM

Figure 5 Single Frame, Run 72 Shutter Speed
1/1000 Second, Air Flow = 0.1 CFM

Figure 6 Pennsylvania State University Reactor Pool and Beam Hole Laboratory With the Reactor Core in Position for Neutron Radiography
a) Top View
b) Side View

Figure 7 Typical Background Run;
Single Frame Run #173

Figure 8 Single Frame Run 174

Figure 9
Time average of 256 Frames (a) Run 173 Background, No Air, (b) Run 175 Air Flow Rate at 0.1 CFM
(Note Increased White in Water Region.)

PSU GRAY SCALE RAW DATA

JULY 1991

1 ___ PSU173, AIR=0.0 CFM, WAT 2 ___ PSU174, AIR=0.1 CFM, WAT 3 ___ PSU175, AIR=0.2 CFM, WAT
4 ___ PSU176, AIR=0.3 CFM, WAT 5 ___ PSU177, AIR=0.5 CFM, WA 6 ___ PSU178, AIR=0.8 CFM, WAT

Figure 10
Raw Data Gray Scale Distribution for Runs 173-178. Net Water Flow = 0.0 gpm.

PSU GRAY SCALE NORMALIZED DATA

JULY 1991

- 1 - PSU173, AIR=0.0 CFM, WAT - 2 - PSU174, AIR=0.1 CFM, WAT - 3 - PSU175, AIR=0.2 CFM, WAT
 - 4 - PSU176, AIR=0.3 CFM, WAT - 5 - PSU177, AIR=0.5 CFM, WAT - 6 - PSU178, AIR=1.0 CFM, WAT
- Water flow = 0.0 GPM for all runs
psu002 psu001.wk3

Figure 11
Raw Data Gray Scale Normalized with No Air Run 173 To Account for
Asymmetric Flux and Possible Detector Efficiency Variation.

COMPARISON OF NO WATER TO WATER IN CHANNEL

Note effect of stainless channel wall

Figure 12
Effects of Water and Stainless Steel Channel Can Be Observed

VOID FRACTIONS FOR VARIOUS AIR/WATER MIXTURES

Normalize to Run 179

- 1 - psu179,air=0.0cfm,water=0.20 - 2 - psu180,air=0.1cfm,water=0.35 - 3 - psu181,air=0.2cfm,water=0.50
 - 4 - psu182,air=0.3cfm,water=0.55 - 5 - psu183,air=0.5cfm,water=0.50 - 6 - psu184,air=0.8cfm,water=0.65
 PSU006 PSU180-.WK3

Figure 13 Void Fractions Across the Channel for Various Air Flow Rates

Figure 14 Void Fraction versus Air Flow Rate

END

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