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VAPOR FRACTION MEASUREMENTS IN A STEAM-WATER TUBE AT UP TO 15 BAR USING NEUTRON RADIOGRAPHY TECHNIQUES

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ABSTRACT

Real-time neutron radiography has been used to study the dynamic behavior of two-phase flow and measure the time averaged vapor fraction in a heated metal tube containing boiling steam-water operating at up to 15 bar pressure. The neutron radiographic technique is non-intrusive and requires no special transparent window region. This is the first time this technique has been used in an electrically heated pressurized flow loop. This unique experimental method offers the opportunity to observe and record on videotape, flow patterns and transient behavior of two-phase flow inside opaque containers without disturbing the environment. In this study the test sections consisted of stainless steel tubes with a 1.27 cm outer diameter and wall thicknesses of 0.084 cm and 0.124 cm. The experiments were carried out at the Pennsylvania State University 1 megawatt TRIGA reactor facility utilizing a Precise Optics neutron radiography camera. The inlet water temperature to the test section was varied between 120°C-170°C and the flow rate set to 2.3 l/min. T_{sat} is 200°C at these conditions. The tube was resistively heated by passing high currents (~1000 A) through the stainless steel wall. Scattering due to water in the 1 cm tube is significant and Monte Carlo calculations simulating the experiment were made to correct for this effect on the vapor fraction measurement. Details of the experimental technique, methods for analyzing the data and the results of the experiments are discussed.

INTRODUCTION

Real-time neutron radiography has been used to study the dynamic behavior of two-phase flow and measure the time averaged vapor fraction in a heated metal tube containing boiling steam-water flow operating at up to 15 bar pressure. The atmospheric-pressure neutron radiographic flow loop used at the Pennsylvania State University (PSU) neutron radiography facility (Reference 1) was upgraded for 250 psi operations. The loop is portable and can be moved in and out of the beam port area. Most of the control system for the loop has been made remotely operable. This includes lowering and raising the entire system in order to view the full length of the 74 cm test section. Heat is provided to the loop by an 80 kW diesel generator driving a Miller Model CP/CC1500 arc welding DC power source.

EXPERIMENTAL PROCEDURE

A typical test run consists of establishing stable operating conditions for a fixed flow rate, inlet temperature, and heat input. Real-time neutron radiographic video pictures of the fluid flow in a 23 cm high region of the test section are recorded for approximately four minutes. The neutron radiography data are recorded on videotape as a series of discrete frames at a rate of 30 frames per

second. Each frame shows a gray scale representation of a portion of the test section, with the gray level at any point being an indication of the relative proportion of liquid versus vapor. Using an image processor, a segment of the videotape is time-averaged (Figure 1; typically, 4096 frames corresponding to 2.27 minutes of data acquisition) and digitized for storage as an image file containing a matrix of gray scale values. The full matrix represents 480 pixels in the vertical direction and 512 pixels in the horizontal direction. The gray scale values range from 0 to 255.

Two camera were evaluated as part of this testing. Both were manufactured by Precise Optics Corp. and are the same model. This testing was initiated as a result of observations made while using the Penn State camera which revealed a significant non-uniform spatial response and a hot spot (increased response in one region as compared to other areas). The manufacturer was asked to check the system but could not address this problem adequately. It is believed that the thin layer of gadolinium dioxysulfide absorber on the converter screen may have eroded. The second neutron radiography camera was borrowed from Sandia National Laboratories and is almost identical to the Penn State camera. The comparative response functions for the cameras are shown in Figure 2. The results reveal a more uniform response but not completely flat with the Sandia camera. It was used for the tests discussed in this paper. While non-uniformity is undesirable, this effect is accounted for during the data reduction process.

RESULTS OF VAPOR FRACTION TESTS

1. Measurements

Vapor fraction results are determined by digitizing the time-averaged radiographic measurements to determine grayscale pixel value $E(x,y)$ when the tube is empty, $W(x,y)$ when the tube filled with water and $V(x,y)$ when the tube is under operating conditions. Under these conditions, the vapor fraction $VF(x,y)$ is determined from the following equations:

$$E(x,y) = E_o \quad (1)$$

$$W(x,y) = E_o \exp(-\mu t_f) \quad (2)$$

$$V(x,y) = E_o \exp(-\mu t_w) \exp(-\mu(t_f - t_w)) \quad (3)$$

$$VF(x,y) = \frac{\mu_w(x,y,T) \ln W(x,y) - \mu_{wf}(x,y,T_{ref}) \ln V(x,y) + [\mu_{wf}(x,y,T_{ref}) - \mu_w(x,y,T)] \ln E(x,y)}{[\mu_w(x,y,T) - \mu_v(x,y,T_{sat})] \ln (W/E)} \quad (4)$$

where:

- (x,y) = pixel position
- $E(x,y)$ = gray scale reading of digitized radiograph with the test section empty
- $W(x,y)$ = gray scale reading of digitized radiograph with the test section full of water
- $V(x,y)$ = gray scale reading of digitized radiograph at test conditions
- $\mu_v(x,y,T_{sat})$ = attenuation coefficient of vapor at saturation conditions
- $\mu_w(x,y,T_{sat})$ = attenuation coefficient of water at saturation conditions
- $\mu_{wf}(x,y,T_{ref})$ = attenuation coefficient of water under conditions when the test section is full of water
- T = temperature
- T_{ref} = reference temperature at background conditions when test section was full of water

It should be noted that the measured vapor fraction represents a line average value through the tubular test section. The measured vapor fraction needs to be corrected for scattering effects as has been discussed in prior reports (References 2 and 3). Neutron scattering in this tubular test section (OD=1.27 cm, ID= 1.10 cm), with a water region whose diameter is 1.10 cm is significant. The methodology for correcting for neutron scattering discussed in Reference 3 was developed on

the basis of a single scattering event. This is appropriate for thin water channels when the water thickness is on the order of the mean free-path of thermal neutrons. It was not designed for use with this relatively large diameter tube, where there are numerous multiple neutron scattering collisions. A series of Monte Carlo computer runs were therefore made using a Monte Carlo program to estimate the correction factors for this set of tests.

2. Monte Carlo Analysis of Transverse/Radial Vapor Fraction Profiles

From the initial measured vapor fractions which assumed simple exponential attenuation through the tube, vapor fraction estimates were made for input to the Monte Carlo model that simulated the experiment. The vapor fraction was assumed to vary linearly with a value of 0.45 at the edge of the tube to 0.85 at the center. The tube was divided into 11 annuli as shown in Figure 3. The resultant absorption as would be measured by the neutron radiography camera was determined for the tube filled with water, the tube empty and for the tube with an assumed vapor fraction. The results are shown in Figure 4. Assuming simple exponential attenuation through the tube, the vapor fraction $VF(x,y)$ determined from equation (4) is shown in Figure 5. Correction factors determined from Figure 5 were then applied to the measured vapor fraction determined by neutron radiography and are shown in Figure 6. As discussed before, these results represent line averaged vapor fractions. By assuming that the vapor fraction $VF(x,y)$ is symmetrical about the center of the tube, a radial form of the vapor fraction $VF(r)$ can be determined. These results are also shown in Figure 6. The final average vapor fraction corrected for scattering along a 20 cm length of viewing area is shown in Figure 7 along with computational results using a Westinghouse-developed computer program with four-field calculations.

3. Axial Variation of Vapor Fraction

Testing along the full length of the test section was done by lowering and raising the entire loop that rested on a lift table. These tests used a second 1.27 cm OD tubular test section but with a wall thickness of 0.124 cm. A second series of Monte Carlo computer runs were made to estimate the correction factors for this set of tests, since in this series of measurements the vapor fraction varied over a very wide range of values in the vertical direction. A constant (in radial direction) vapor fraction was input throughout the tube and the resultant response as calculated at the camera is shown in Figure 8. Assuming simple exponential attenuation through the tube the measured vapor fraction can be determined from equation (4). Results for a series of runs with the vapor fraction varying between 0.05 and 0.95 are shown in Figure 9. From these Monte Carlo calculations estimates were made of the scattering correction factors to be applied across and up the channel. Figure 10 shows the results for the centerline correction as a function of vapor fraction. Additional 3-D Monte Carlo calculations were made that studied the effect of an increasing vapor fraction in the vertical direction varying from 0 to 1.0 along the length of the test section. The results had less than a 2% perturbation from the values shown in Figure 10. A typical 3-D representation of the measured vapor fraction across the tube and along most of its length is shown in Figures 11. Anomalous data points that show up along the outer edge of the test section are attributable to small differences in repositioning of the test section from run to run. Resolution limitations also made the exact position of the edge of the water region difficult to determine. Line averaged vapor fractions along the center of the test section are shown in Figure 12. With measured uncertainties in the absolute values of the vapor fraction on the order of ± 0.1 , the agreement with the calculations is considered good. The results furnish useful guidance for both the fluid dynamics code developers and the experimentalists for future work.

SUMMARY AND CONCLUSIONS

This report presents for information the results of experimental studies performed to support the methodology for measuring vapor fractions using neutron radiographic techniques. It documents experimental results of a series of tests designed to measure vapor fraction in a heated pressurized

tubular test section taken under different operating conditions. A series of Monte Carlo computer calculations were needed to determine the scattering corrections which are significant for a tubular test section whose diameter is 1 cm. The scattering correction methodology (Reference 3) developed for the thin water was developed on the basis of a single scattering event which is appropriate for thin water channels and was not designed for use with this relatively large diameter tube, where there are multiple neutron scattering collisions.

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Figure 1 Typical time-averaged neutron radiograph of tubular test section

Neutron Radiography – Gray Scale Run 262

■	236. – 242.
■	229. – 236.
■	223. – 229.
■	216. – 223.
■	210. – 216.
■	203. – 210.
■	197. – 203.
■	190. – 197.

Figure 2a Response of Penn State neutron radiography camera

Neutron Radiography – Gray Scale Run 279

■	184. – 190.
■	178. – 184.
■	171. – 178.
■	165. – 171.
■	159. – 165.
■	153. – 159.
■	146. – 153.
■	140. – 146.

Figure 2b Response of Sandia neutron radiography cameras

Figure 3 Geometric layout of simulated neutron radiography experiments using Monte Carlo analysis for determining scattering effects.

Figure 4 Integrated absorption rate as seen by neutron detector in Monte Carlo analysis.

Figure 5 Void fraction results across tube as determined by Monte Carlo simulation.

Figure 6 Measured radial and line averaged vapor fraction.
 Input Power = 16.9 kW, Flow = 2.27 l/min, $T_{in} = 127^{\circ}\text{C}$, Pressure = 13.4 bar

Figure 7 Average vapor fraction of tubular test section from the bottom to the top of the viewing area as compared to calculational results along entire length. Flow = 2.27 l/min, Pressure = 13.8 bar, $T_{in} = 332\text{ }^{\circ}\text{C}$, Run 319

Figure 8 Results of simulated neutron radiography experiments using Monte Carlo analysis for determining scattering effects.

Figure 9 Vapor fraction results determined from simulated Monte Carlo calculations in a tubular test section.

Figure 10 Vapor fraction scattering correction factors from Monte Carlo simulation problems for tubular test section. Water temperature = 194 °C, Pressure= 200 psia

—■— tube ID = 1.10 cm —◆— tube ID = 1.02 cm

Figure 11 Typical 3D representation of vapor fraction data, liquid flow rate = 2.27 l/min.

Figure 12 Comparison of experimental and calculational results for vapor fraction through center of tubular test section for a flow rate of 2.27 l/min.

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