Measurement of Two-Phase Flow in a Fuel Assembly with a Dynamic Neutron Radiography

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1. Introduction

A test section simulating the HANARO fuel channel was constructed and the void fraction was measured with a high-speed neutron radiography technique. The test was conducted in the beam facility of HANARO called ENF (Ex-core Neutron-irradiation Facility). D_2O was used as the working liquid and air was used to simulate the vapor. The measurements were made at various combinations of the liquid flow and gas flow and the result were compared with the predictions of the existing correlations. The flow pattern was also detected with the ultrasonic technique and the results were compared with those from the neutron radiography images.

2. Methods and Results

2.1 Test section and Test loop

HANARO uses two types of fuel assemblies; 36-element assembly and 18-element assembly. A test section composed of the 4 FES's was built, which simulate a part of the 18-element assembly. Figure 1 shows the schematic diagram of the test loop with the NR setup. A spacer was installed at every quarter of the test section in vertical direction. The maximum path length of the neutron beam through the test section is 24.05 mm. The part of the test section facing the neutron beam was made of Al and the FES's were made of Al as well. A pump circulated D_2O and the air from the test section outlet was vent to the outside of the test section. A mass flow meter was used for the liquid flow rate measurement and rotor meters were used for the airflow rate measurement.

2.2 Imaging system and Ultrasonic setup

The list of optical devices used for the test is in Table 1. The HG-LE camera adopt CMOS sensor and the special resolution of 752x752 is available when the frame rate is less than 1500 fps. The test section was located at the position of 239 cm from the exit of the beam port and the distance between the test section and the converter was 71 mm. A neutron image covers the region of 26.8 cm to 117.8 cm from the top spacer. The camera frame rate was 1000 fps and the gate time of the image intensifier was 650 μsec. The gain of the image intensifier was maintained at its minimum value, which is 1.7E4 $lm/m^2/lx$.

An ultrasonic transmission technique was used for the flow pattern identification. The ultrasonic transducer is the model A133S of the Panametrics, Inc., and it has the frequency of 2.25 MHz and its diameter is 6.0 mm. The ultrasonic pulser/receiver is the model 5077PR of the Panametrics, Inc. The data acquisition system consists of the High speed A/D board (National Instruments™, NI5112) and its Interface program (LabVIEW™) [1].

The local void fraction was calculated by using the Σ-scaling method [2].

$$\alpha = 1 - \frac{\delta_{ML}}{\delta_L} = \frac{\ln\left[\dfrac{G_L - G_0}{G_M - G_0}\right]}{\ln\left[\dfrac{G_L - G_0}{G_G - G_0}\right]} \qquad (1)$$

where δ_L and δ_{ML} mean the object thickness of liquid and mixture, respectively. G_G, G_L and G_M are the image gray level of the test section filled with gas, liquid and two-phase mixture, respectively. The offset term G_0 includes the dark current of the imaging system and the gray level due to scattered neutrons. The void fraction obtained from the equation (1) is the line average void fraction and the area averaged void fraction should be obtained by integrating the line average void fraction weighted with the beam path length.

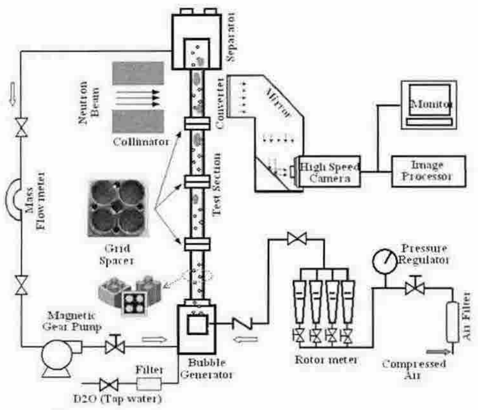


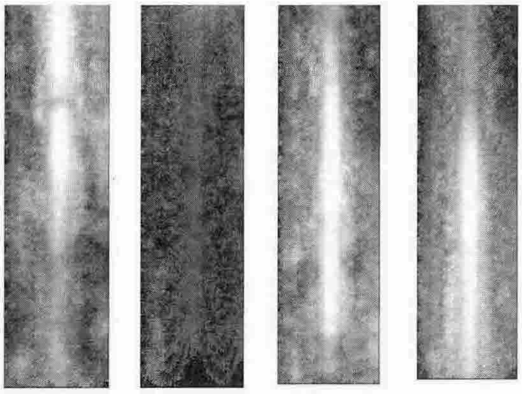
Figure 1. Schematics of the test loop with NR setup

Table 1. List of optical devices used for the test

Converter	NE426 type
Lens	NIKON 105 mm, Telegraphic lens
Image intensifier	HAMMATSU C6598 + booster
Relay lens	HAMMATSU A4539
Camera	REDLAKE HG-LE

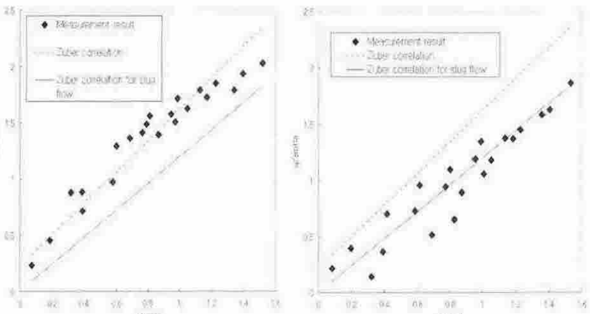
2.3 Test results

Figure 2 shows several instantaneous processed void fraction images for the test with three spacers. These images were taken for the test section having three spacers and the liquid velocity was 0.3 m/s and the air velocity was 0.82 m/s. The images were clear enough to discern flow patterns. The observed flow patterns from the test were the bubbly flow, the slug flow and the churn flow.



(a) 0 sec (b) 250 μsec (c) 500 μsec (d) 750 μsec

Figure 2. Instantaneous processed void fraction images (j_L = 0.3 m/s, j_G = 0.82 m/s, with three spacers)



(a)
(b)

Figure 3. Comparison of measure void fraction with the predicted values [(a)Tests with three spacers, (b)Tests without bottom and middle spacers]

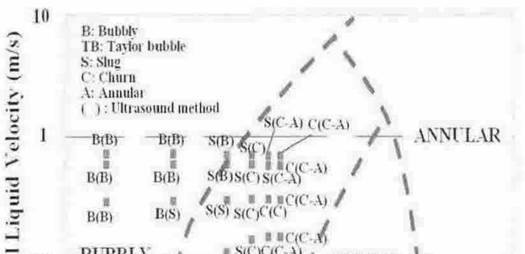


Figure 4. Observed flow patterns in the Taitel and Duckler map

In Figure 3, j_G/α are plotted against j for data from the tests with three spacers and without middle and top spacers. Here, j_G is the gas phase velocity and j is the summation of gas phase velocity and liquid phase velocity. The experimental results were compared with the prediction of the Zuber correlations [3]. In Figure 3 (a), it can be found that the Zuber correlation fits the experimental data very well. In Figure 3(b), it can be found that the Zuber correlation for slug flow fits the experimental data better. When the top and middle spacers do not exist, the bubbles coalesce easier and the bubble size becomes longer and larger. This is believed to be the reason why the Zuber correlation for slug flow gives better prediction.

Figure 4 shows the observed flow pattern with the NR and ultrasonic method with the flow pattern transition criteria proposed by Taitel and Duckler[4]. The flow patterns observed from the test without the top and middle spacer were close to those for the tests with the three spacers. When the top and middle spacers do not exist, the bubbles coalesce easier and the bubble size becomes longer and larger. However, the spacers had little effect on the flow patterns in this test. From Figure 4, the Taitel and Duckler correlation predicts the bubbly-to-slug flow transition in the test section very well when the liquid velocity is less than 0.3 m/s. The Taitel and Duckler correlation predicts the bubbly-to-slug flow transition which occurs at a higher gas velocity when the liquid velocity is greater than 0.3 m/s.

3. Conclusion

The void fraction and the flow pattern in a test section simulating the HANARO fuel channel were measured by using the high-speed dynamic neutron radiography technique and the ultrasonic technique. The high-speed NR images were taken at 1000 fps and the instantaneous processed void images were clear enough to identify the flow patterns.

The NR technique is more reliable than the ultrasonic technique in that the information is available for a larger area than the ultrasonic technique. The Zuber correlation gives the better prediction of void fraction when three spacers exist. The Zuber correlation for slug flow gives the better prediction of void fraction when the middle and top spacers do not exist. The Taitel and Duckler correlation predicts the bubbly-to-slug flow transition which occurs at a higher gas velocity when the liquid velocity is greater than 0.3 m/s.

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