Measurement of Void Distribution in Transient Flows*

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By means of X-ray Beam Scanning Method, void distributions in horizontal pipes during blowdown were measured for various conditions. Two types of X-ray void fraction meters were used; One was scanning upward and downward across the pipes, and the other was highspeed scanning type using a rotating disc. Highspeed scanning type had a void distribution color display system that made it easy to recognize even a slug flow. The data were plotted on the flow regime map and compared with available data. For high mass flux, the flow pattern became annular and was weakly dependent on pressure. For low mass flux, the flow pattern became stratified due to gravity.

Key Words: Flow Measurement, Void Distribution, Unsteady Blow, X-ray Beam Scanning, Flow Pattern Map

1. Introduction

In the safety study of nuclear reactors dealing with the blowdown phenomenon in which a two-phase flow passes from a high-pressure vessel through piping at high speeds, it is important to precisely measure void fraction under transient condition and to know flow patterns. Recently, with development of large capacity computers, a more precise flow pattern map of a two phase flow required for safety analysis of nuclear reactors has become necessary. Also in each blowdown experiment performed for verifying the calculation codes, it became necessary to clarify the behavior of such components as piping, valves, and pumps in order to measure the void fraction and flow behavior of the two-phase flow.

The conventional measuring method of the void fraction in piping employs an electrode probe and a γ -ray and X-ray void fraction meter. However, for measuring the void fraction of the two-phase flow in a high-temperature and high-pressure pipe under transient state, they are not always satisfactory with respect to the accuracy and response speed.

Conventional flow pattern maps including comparatively high pressure regions are made from a few visual observations, using the electrode probe method, and X-ray photograph etc., and each flow pattern map is different with differences in discrimination standards and measuring methods.⁽¹⁾

In this study, therefore, measurements were made during blowdown by using a newly developed X-ray beam scanning void fraction meter.⁽²⁾⁽³⁾ Experimental results

were compared with flow pattern map including the comparatively high pressure regions for which few data were available⁽⁴⁾. As for the slug flow which was difficult to measure owing to a large amplitude of fluctuation and a high frequency, its average sectional void fraction could be measured in an on-line state. This permitted display on a CRT by improving the scanning method and the data processing method. A summary thereof will be given hereunder.

Incidentally, it is possible to apply this X-ray void fraction meter not only to safety study of nuclear reactors but also to the measurement of a two-phase flow in a general two-phase flow study and in a chemical plant. Applicable two-phase fluid may be either a two-phase mixture of solid/liquid or one of solid/gas as well as one of gas/liquid.

2. Experimental apparatus

The apparatus for experiment is shown in Fig. 1. The pressure vessel was a cylinder having an inner diameter of 36 cm and a height of 7 m. It was heated and pressurized up to the maximum pressure of 7.0 MPa by a 100 kW electric heater provided at the vessel bottom. An X-ray void fraction meter incorporating the void fraction measuring section was installed in the piping connected to the bottom of the pressure vessel. The blowdown was effected by suddenly opening the air actuator valve attached downstream from the void fraction measuring section. The mass flow rate of outflow from the pressure vessel was measured by means of the differential pressure gauge (DP cell) attached to the pressure vessel. Further, an orifice plate or a nozzle was flange-connected upstream or downstream from the void fraction measuring section, as required, to generate a critical flow for regulating the mass-flux or the void fraction.

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3. X-ray void fraction meter

3.1 Measurement principle

As generally known, the intensity of the X-ray I for initial intensity I_0 is expressed by the following equation.

$$I = I_0 \exp(-\rho \mu l) \quad (1)$$

where ρ is density of fluid through which X-ray beam passes, μ is mass absorption factor of X-ray, and l is path length.

When the pipe is filled with air as shown in Fig. 2(a), the X-ray at a height of x is attenuated by the pipe wall and air between the X-ray source and the X-ray detector excluding the inside of the test section pipe. In this study, a metallic beryllium pipe having a small X-ray attenuation factor is used for the test section. Accordingly, the normalized intensity $I_A(x)$ of X-ray at a height of x is expressed, with the subscripts B and A corresponding to beryllium and air respectively, as follows:

$$I_A(x) = \frac{I}{I_0} = \exp\{-\rho_B \mu_B l_B(x) - \rho_A \mu_A l_T(x) - \rho_A \mu_A l_A(x)\} \quad (2)$$

When the pipe is filled with water of normal temperature as shown in Fig. 2(b), the intensity is expressed, with the subscript w corresponding to water, as follows:

Fig. 1 Schematic diagram of the experimental apparatus

$$I_w(x) = \frac{I}{I_0} = \exp\{-\rho_B \mu_B l_B(x) - \rho_w \mu_w l_T(x) - \rho_A \mu_A l_A(x)\} \quad (3)$$

When the pipe is filled with a two-phase flow of high temperature and high pressure, the intensity thereof is expressed, with a void fraction of a X-ray path, as $\alpha(x)$, as follows:

$$I_x(x) = \frac{I}{I_0} = \exp\{-\rho_B \mu_B l_B(x) - \rho_A \mu_A l_A(x) - \mu_w l_T(x)[\rho'_w(1-\alpha(x)) - \rho'_v \alpha(x)]\} \quad (4)$$

where ρ'_w and ρ'_v are saturation densities of water and vapour under high temperature and high pressure, respectively.

Putting Equations (2) - (4) in order with respect to X-ray void fraction $\alpha(x)$ at a beam height of x , the following equation can be obtained:

$$\alpha(x) = F(p) \frac{\ln\{I_x(x)/I_w(x)\}}{\ln\{I_A(x)/I_w(x)\}} - G(p) \quad (5)$$

where $F(p)$ and $G(p)$ are functions of pressure and can be calculated easily by using the steam tables as indicated by the following equations:

$$F(p) = \frac{\rho_w - \left(\frac{\mu_A}{\mu_w}\right) \rho_A}{\rho'_w - \rho'_v} \quad (6)$$

$$G(p) = \frac{\rho_w - \rho'_w}{\rho'_w - \rho'_v} \quad (7)$$

where, in Equation (6), $(\rho_A/\rho_w)\rho_A$ is negligible since it is very small as compared with ρ_w . In Fig. 3, the functional forms of $F(p)$, $G(p)$ calculated by Equations (6), (7) are shown. Both the functions present

(a) For air (b) For water (c) For two phase flow

Fig. 2 Principle of measuring X-ray void fraction meter

approximately straight lines for a pressure of 2 MPa or more, thus providing practical convenience. In Eq. 5, $I_A(x)$, $I_W(x)$ are determined by the shape of the beryllium pipe so only one measurement is enough, and the distribution form of void fraction $\alpha(x)$ can be obtained immediately by only measuring $I_{\alpha}(x)$. The average sectional void fraction $\bar{\alpha}$ can be calculated from $\alpha(x)$ using the following equation, wherein $\bar{\alpha}$ is an important factor for comparison with analysis results of calculation codes.

$$\bar{\alpha} = \int_{-r_0}^{+r_0} 2\sqrt{r_0^2 - x^2} \alpha(x) dx / \pi r_0^2 \dots \dots \dots (8)$$

where r_0 is the inner radius of a beryllium pipe.

Fig. 3 Functional forms of F(P) and G(P)

Fig. 4 Upward and downward scanning mechanism of X-ray beam

3.2 Upward and downward scanning type X-ray void fraction meter

In order to scan the X-ray beam in a plane perpendicular to the axis of the measured pipe section, the X-ray tube and the X-ray detector were synchronously moved up and down by a motor as shown in Fig. 4. The X-ray was narrowed to a slender beam through a small hole 2 mm in diameter.

A device incorporating an NaI scintillator and a photo-multiplier tube was used for the X-ray detector. The time required for one scan was 0.3-0.7s. An external view of the upward and downward scanning type X-ray void fraction meter used for this study is shown in Fig. 5.

For calibration of the void fraction meter, it is convenient to use an acrylic test piece which has an X-ray absorption factor approximately the same as that of water. An example of calibration results is shown in Fig. 6. This acrylic test

Fig. 5 External view of upward & downward scanning type X-ray void fraction meter

Fig. 6 Example of calibration results by acrylic test piece

piece is a hollow cylindrical tube having an inner dia. of 15 mm and an outer dia. of 30 mm. At the beam height $x = 0$ mm, the measured value is 48 % against the geometrical void fraction of 50 %, the measuring error being as small as 2 %.

However, the calculated average sectional void fraction $\bar{\alpha}$ is 25 % is contrast to the measuring average sectional void fraction of 24.2 %, the measuring error being about 1 %.

3.3 Rotary disc scanning type X-ray void fraction meter

In the scanning system in which the X-ray beam was moved vertically, the time limit of the scanning cycle was as low as 0.5 s due to its mechanism. Therefore, in order to further increase the scanning speed, the rotary disc scanning type X-ray void fraction meter as shown in Fig. 7 had been developed.

The X-ray was provided in the form of segments with the X-ray tube and the X-ray detector being fixed, and the X-ray beam was scanned by moving a slitted rotary disc. The rotary disc was rotated at a constant speed by a pulse-motor synchronously with a sampling signal from the digital data recording system. The maximum rpm was 1500. Eight slits were provided on an identical circumference on the outer peripheral of the rotary disc to allow the piping section to be scanned in turns, so the maximum scanning speed was 200 Hz. One void fraction distribution curve was obtainable every 5.0 ms. Measured X-ray signals were immediately converted by Equation (5) to the void fraction $\alpha(x)$ by using a high-speed analogue operation circuit. In this instance, necessary functions $F(p)$, $G(p)$ were converted from measured pressure signals to be put into the operation circuit by using the function generator. Measured values of the void fraction $\alpha(x)$ were put into the pulse height integrating circuit to calculate the average sectional void fraction $\bar{\alpha}$ of Equation (8), and at the same time sent to the A/D convertor for making a color display as shown in Fig. 8 according to the color classification of Table 1 with use

Fig. 7 Illustration of rotary disc scanning type X-ray void fraction meter

of a micro-computer. In this display, one line was composed of 64 picture elements in one scan, and one picture was composed of 40 lines. When the scanning speed was 200 Hz for example, the time required for one scan was 5 ms, so that a 40-line picture displayed a transient change of the void fraction distribution during 0.2 s. Since a vapour slug having a length of 1 m and a flow speed of 10 m/s passes the measuring section during 0.1 s, it could be displayed on the picture a length of 20 lines.

4. Experimental results

4.1 Results of experiment using a vertical scanning type void fraction meter

A stainless steel piping of 74 mm (inner diameter) and a metallic beryllium pipe of the same diameter were flange connected downstream from the nozzle (30 mm inner diameter). The section of the beryllium pipe was measured for the void fraction. Orifices of various diameters were inserted into the pipe downstream thereof, and various void fraction data were collected in relation to the identical mass-flux by changing the pressure at the void fraction measuring section.

Figure 9 is a typical example of loci during blowdown on a plane with the abscissa representing the average sectional void fraction $\bar{\alpha}$ and the ordinate representing the mass-flux. In the experiment, 19 blowdowns from A to S were performed with the initial pressure and the orifice diameter used as parameters. The void fraction distribution data were put in order by occa-

Fig. 8 Color display of void fraction distribution

Table 1. Color classification for void fraction display

VOID FRACTION (%)	COLOR
0 - 5	BLACK
5 - 25	BLUE
25 - 45	GREEN
45 - 65	CYAN
65 - 85	RED
85 - 100	MAGENTA

sionally changing the pressure, mass-flux, and average sectional void fraction. Some examples of the measured results are shown in Fig. 10 to Fig. 12.

Figure 10 shows data summarized in one graph, wherein only the pressure is changed with the average sectional void fraction and the mass-flux being fixed to 80% and about 3000 kg/(m²·s) respectively. It can be seen from this graph that the shape of the void fraction distribution curve shows approximately similar annular mist flows within a pressure range from 2.0 MPa to 4.5 MPa. The void fraction distribution will present identical distribution forms regardless of the pressure if the average sectional void fraction and the mass-flux remain constant. Figure 11 shows a similar case with the average sectional void fraction changed to 50%.

Also in Fig. 11, the void fraction distribution curves are approximately identical regardless of the pressure and they present a flow in which a constituent of stratified flow having a high void fraction at the upper part of pipe is added to the annular flow. When the pressure is

Fig. 9 Typical example of loci during blowdown

Fig. 10 Influence of pressure $\bar{G} \approx 3000 \text{ kg}/(\text{m}^2 \cdot \text{s})$

2.6 MPa, however, the ripple of void fraction distribution curve becomes larger; this is due to a constituent of slug flow included in the flow, suggesting that the measurement is to be done by further increasing the scanning speed.

Figure 12 shows data obtained by examining the influence of the mass-flux with the average sectional void fraction of about 80% and the pressure of about 4 MPa respectively. The distribution form is approximately identical excluding the case of low mass-flux of $\bar{G} = 100 \text{ kg}/(\text{m}^2 \cdot \text{s})$. In the case of $\bar{G} = 100 \text{ kg}/(\text{m}^2 \cdot \text{s})$, the flow presents the stratified flow of a low void fraction at the lower section of the pipe and 100% void fraction at the upper section of the pipe, thus showing a rather rippled wave surface.

4.2 Measured results using a rotary disc scanning type void fraction meter

Because the scanning speed is low in the vertical scanning type, this type of meter is not suitable for measurement of such flows as a slug flow including a large time fluctuation of void fraction.

Fig. 11 Influence of pressure $\bar{\alpha} = 50\%$, $\bar{G} \approx 3000 \text{ kg}/(\text{m}^2 \cdot \text{s})$

Fig. 12 Influence of mass-flux $\bar{\alpha} = 80\%$, $P \approx 4 \text{ MPa}$

Therefore, the measurement was done in the slug flow region using a rotary disc scanning type X-ray void fraction meter. A nozzle of 12 mm inner diameter was connected downstream of the void fraction measuring section (36 mm inner diameter) for the purpose of lowering the average sectional void fraction. Thus the critical flow was generated at the downstream side of the void fraction measuring section. An example of time change of the average sectional void fraction $\bar{\alpha}$ is shown in Fig. 13. The average sectional void fraction $\bar{\alpha}$ will be negative immediately after discharge of subcooled water, and a flow of subcooled water will continue for about 40 s. The flow will be a two-phase flow having a void fraction as low as 0–20 % from 40 s to 110 s thereafter. During the 110 s to 150 s thereafter, the flow changes from a two-phase flow of low void fraction and to that of high void fraction, so that the average sectional void fraction $\bar{\alpha}$ fluctuates violently owing to the slug flow. Then, the void fraction approaches gradually vapour 100 %. Figure 14 shows photos of the color display of the void fraction distribution

Fig. 13 Time change of average sectional void fraction $\bar{\alpha}$ during blowdown

for each time. From those photos, flow patterns under a transient condition from the bubbly flow through the wavy flow and the slug flow to the annular mist flow can be identified.

4.3 Flow pattern map

It has been seen that the pressure has a little influence on the void fraction distribution. Thus a flow pattern map as shown in Fig. 15 is drawn by using the blowdown data obtained from 20 experiments from A to T.

It can be seen from this figure that the area of annular mist flow stretches to the area of low void fraction in a high mass-flux region, and that a stratified flow prevails in a low mass-flux region from the influence of gravity. Solid lines and broken lines in the figure are boundaries given by photos and X-ray photos of Bennet et al. for $p = 6.9$ MPa and 3.4 MPa respectively⁽¹⁾. The boundaries on the whole roughly coincide with each other except that there exists no area of a stratified flow due to a vertical heating pipe. In order to determine precise boundaries, additional measuring data is required.

5. Conclusions

The void fraction distribution was measured during blowdown by an X-ray beam scanning method and the usefulness of the method was proved. Especially, the effective color display of the void fraction distribution helped to discriminate the flow pattern of a violently fluctuating flow such as a slug flow. Further, it was found that the void fraction distribution became identical regardless of the pressure and could be put in order as a flow pattern map if the average sectional void fraction and the mass-flux remained constant. Consequently, it was found that the

Fig. 14 Example of color display of flow pattern (scanning speed: 80 Hz, corresponding to phenomena of one picture during 0.5 s)

Fig. 15 Flow pattern map

area of annular mist flow stretched to the area of low void fraction in the high mass-flux region, and that a stratified flow prevailed in the low mass-flux region from the influence of gravity.

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