Experimental study of leak flow rate through artificial slits

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1 INTRODUCTION

Many investigations have been done about the Leak-Before-Break (LBB) concept for LWR piping system. Though the fracture mechanics related to the LWR piping system has been studied very well, there are few studies about the leak flow rate from the through-wall crack in pipe. The evaluation of leak flow rate is necessary to judge the possibility of applying LBB concept to the design of piping system. The possibility is restricted by the sensitivity to detect the leakage of coolant in LWR plant.

The leak flow from the through-wall crack in pipe is a critical two-phase flow of initially saturated water. Henry (1970) and Henry & Fauske (1971) et al. studied the critical two-phase flow for the nozzle, short pipe and long pipe, in which the homogeneous flow model has been proposed. Recently, Amos & Schrock (1984) have pointed out the characteristics of leak flow rate from the narrow and short slit by their critical two-phase flow model for the initially subcooled water. However, there are few experimental studies about the leak flow rate from the narrow and short slit such as the through-wall crack in pipe. Therefore we have started to investigate the leak flow rate from the artificial slit experimentally and analytically, as shown by Yano et al. (1987).

This report describes the followings; (1) the experimental results of leak flow rate from the artificial slit simulating the through-wall crack for the initially saturated water, (2) the comparison between experimental results and analyses in which the effect of the nonequilibrium parameter on the leak flow rate is evaluated, (3) the analytical evaluation of the friction pressure drop which is obtained in the experiment.

2 EXPERIMENTAL APPARATUS AND CONDITIONS

Figure 1 is a schematic of the experimental apparatus which is composed of the pressure vessel and the test section. The pressure vessel has the internal heater, external heater wrapped around it and piping line of the nitrogen gas at the top. The nitrogen gas is used to keep the stagnation pressure constant during the leak test. The locations of pressure and temperature measurements are shown in Fig. 1.

Figure 2 shows the test section for the artificial slit. The rectangular narrow flow path can be obtained by sandwiching a slit gauge between the flanges of stainless steel. There is a space of 20 millimeter cubic as the stagnation at the center of the flanges. The heaters, which compensate the decrease of the water temperature, are wrapped around the test section and connecting pipe between the test section and pressure vessel.

Figure 3 shows the locations of pressure taps in the flow path of artificial slit. The inlet condition of fluid in slit is examined by the pressure and temperature of stagnation in the test section during the experiment. The pressure distribution along the flow path is given by measuring the pressure in slit. The leak flow rate from the slit is examined by the measurement of water level in the vessel, in which a differential pressure transducer is used.

In the experiment, the apparatus is heated to a uniform temperature of the initial test condition, after removing the dissolved gas in the water. After that, the nitrogen gas is charged just before starting the test to minimize the time for solution of nitrogen into the water.

The dimensions of the artificial slit is shown in Table 1. The crack length 2C equals 10 mm constantly. The ratio of the flow path length to the hydraulic diameter L/D is equal to the values between 4 and 362. The dimensions are determined by referring those of pipes used in the pipe lines of BWR. The influence of surface roughness K on the leak flow rate Gc is examined in the experiment, in which three kinds of machine finished surface roughness are used. The machined direction is perpendicular to the flow direction of the fluid in the slit. The stagnant conditions of the water in the experiment are about 6.8 MPa in pressure and the saturation temperature simulating the BWR fluid conditions.

3 ANALYSIS

In the present analysis, the critical two-phase flow model by Henry is used, in which the thermodynamic nonequilibrium processes are considered by using the parameter N, and the leak flow rate is evaluated by changing N. The correlation of N is expressed as $dX/dP=N(dX_E/dP)$, where X, P and X_E are the local quality, local pressure and local equilibrium quality, respectively.

Moreover in the analysis, the friction pressure drop ΔPf in slit is evaluated by using the following methods; (1) $(\Delta Pf)_1=f(Gc^2 Vm/2D)\Delta Z$ for the single-phase flow, (2) $(\Delta Pf)_2=\Delta P_{\ell o}\phi$ for the two-phase flow of water and steam mixture, where f, Gc, Vm, Z, $\Delta P_{\ell o}$ and $\phi\ell^2$ are the friction factor, leak flow rate, average specific volume of two-phase mixture, position in slit, assumed friction pressure drop when the only liquid flows through the path, and ratio of friction pressure drop which is determined experimentally by Martinelli & Nelson (M-N method), respectively. In the formulation of f, it is assumed that K equals two times of the center-line average roughness in material configuration Ra.

The analytical method related to the two-phase flow and pressure drop is fundamentally based on that by Mayfield et al. (1980) and Collier et al. (1984). However, the characteristics of present analysis is to evaluate the flow in slit as two-phase in whole region between the inlet and outlet of slit.

4 RESULT AND DISCUSSION

4.1 Leak flow rate from artificial slit

Figure 4 shows the comparison of Leak flow rate Gc between the experimental results and the analyses varying the nonequilibrium parameter N, for the normalized dimension of slit L/D. In the figure, Gc by the present experiment agree well with those by Amos & Schrock. In the analysis using the single-phase friction pressure drop (ΔPf) , when N proposed by Mayfield et al. ($N=1.2$, $X_E \geq 0.05$, $N=20X_E$, $X_E<0.05$) is used, Gc are much smaller than the experimental results. However, Gc in the analysis by using N equal to 0.1 or 0.3 agree well with that of experiment although there is the disagreement that Gc by the analysis is smaller than that of experiment when L/D is less than 12. This fact is caused by that the fluid flow is supersaturated through the slit. Hereafter N equal to 0.1 or 0.3 is used in analysis.

4.2 Pressure distribution

Figure 5 shows the experimental results of pressure distribution along the rectangular slit at the inside of flow path among different slit opening displacements δ, which are normalized by P/Po. and Z/L under the identical slit length and width conditions. In the figure, the pressure distribution along the large diameter pipe obtained by Yano et al. (1984) is also shown. The figure indicates that the gradient of pressure distribution becomes steeper with decrease of the hydraulic diameter D. The gradient of pressure distribution along the slit is 10 times steeper than that along the large diameter pipe, because the friction factor f of the slit is 10 times (10 times in terms of K/D) larger than that of the large diameter pipe. These tendencies of the pressure distribution by the narrow slit are also recognized in the experiment of the rectangular slit by Amos & Schrock.

Figure 6 shows the comparison of Pc/Po between the experimental results and the analyses using (ΔPf), in which Pc and Po are the exit pressure and stagnant pressure respectively. The present experimental data for Pc/Po agree well with those by Amos & Schrock, and are smaller than the analytical results by using N equal to 0.1 or 0.3. The exit pressure of the through-wall crack in LWR pipe is important to evaluate the influence of leak jet on the thermal insulator which disturbs the leak detection.

4.3 Influence of surface roughness on leak flow rate

Figure 7 shows the comparison between experimental results and analyses of Gc in the case of different surface roughnesses K in slit. The values of Gc by the experiment are smaller than those by the analysis in the case that K is equal to 31.24 and 70.0 μm. The experimental data of Gc at L/D equal to 4.2 obviously decrease with the increase of K although the analyses give about the same value of Gc for every K.

To improve the accuracy in analysis, the friction pressure drop is discussed in the followings by using the two-phase friction pressure drop $(\Delta Pf)_2$ of Martinelli & Nelson (M-N method). Figure 8 shows the comparison of Gc between the methods by using $(\Delta Pf)_1$ and by $(\Delta Pf)_2$. When L/D is smaller than 10, Gc analyzed by $(\Delta Pf)_2$ shows the identical value with that by $(\Delta Pf)_1$, and Gc by $(\Delta Pf)_2$ in L/D larger than 10 is

smaller than that by $(\Delta Pf)_1$. Concerning this, it is said that ϕ_ℓ^2 proposed by the Martinelli & Nelson becomes larger than the experimental values obtained by Isbin et al. (1959) with the increase of mass flow rate.

Figure 9 shows the comparison of Pc/Po for L/D between the experiment and analysis using the M-N method. In the analysis by $(\Delta Pf)_2$, Pc/Po abruptly decrease with the increase of L/D in small L/D, and the decreasing gradient of Pc/Po becomes smaller with the increase of L/D in large L/D. The tendencies are also shown in the present experiments and the data of Amos & Schrock. The value of Pc/Po analyzed by $(\Delta Pf)_2$ in very small L/D shows good agreement with that of the experiment, although the analysis overestimates Pc/Po against the experiment in large L/D.

Figure 10 shows the comparison of Gc between the experiments and the anayses using $(\Delta Pf)_2$. The analyzed Gc for every K is smaller than the experimental results. Moreover the experimental data of Gc at L/D equal to 4.2 decrease with the increase of K, although the analyses by $(\Delta Pf)_2$ also give about the identical value with Gc for every K.

5 CONCLUSION

The experimental and analytical results for the leak flow rate from narrow and short slit indicate the following conclusions.

(1) When the thermodynamic nonequilibrium parameter N is introduced in the analysis between 0.1 and 0.3, the leak flow rate Gc in the present experiment agrees well with the analysis.

(2) The tendency of exit pressure Pc for the normalized dimension of slit L/D, which is obtained by using the two-phase friction pressure drop $(\Delta Pf)_2$, is correspondence with that by the experimental results.

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Table 1. Experimental condition

δ = 0.05, 0.07, 0.1, 0.2, 0.5 mm

2C = 10 mm

L = 4, 15, 36 mm

Ra = 0.17 (▽▽▽), 15.7 (▽▽), 35.0 (▽) μm

⇩

$4 \leq L/D \leq 362$

$0.5 \leq A \leq 5$ mm²

K

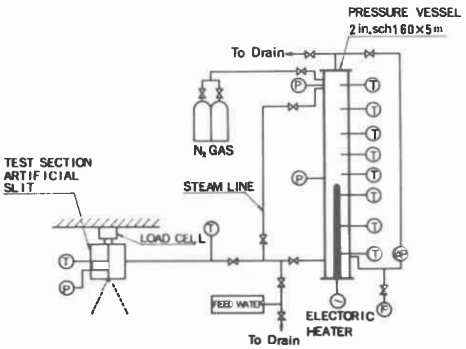

Figure 1. Schematic of experimental apparatus.

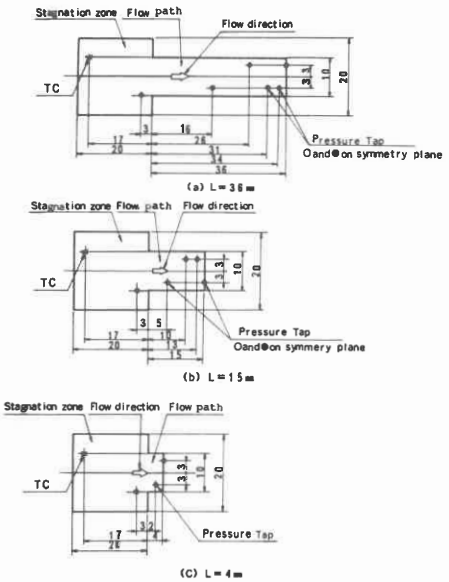

Figure 2. Locations of pressure tap and thermo-couple.

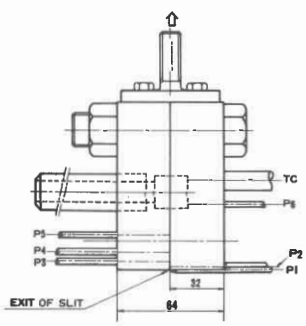

Figure 3. Test section.

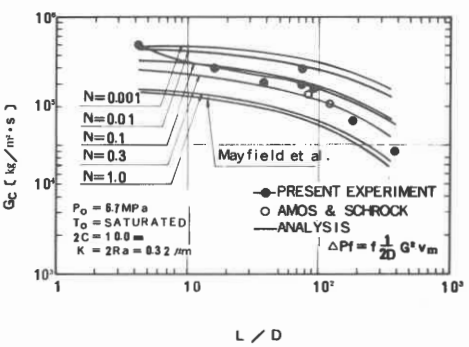

Figure 4. Leak flow rate.

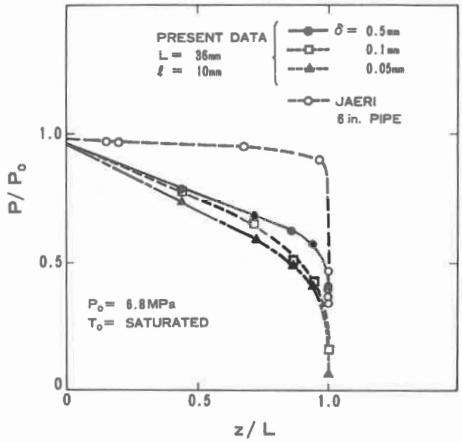

Figure 5. Pressure distribution in slit.

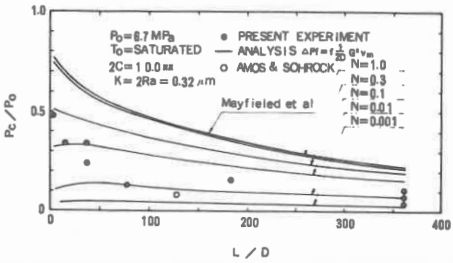

Figure 6. Critical pressure ratio.

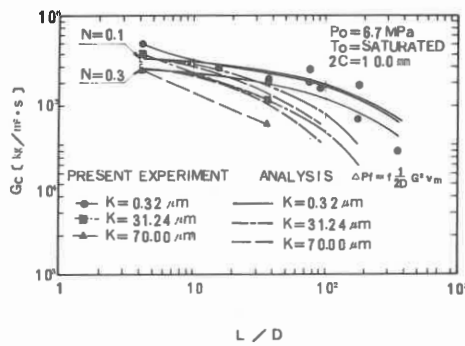

Figure 7. Leak flow rate from slits having different surface roughness.

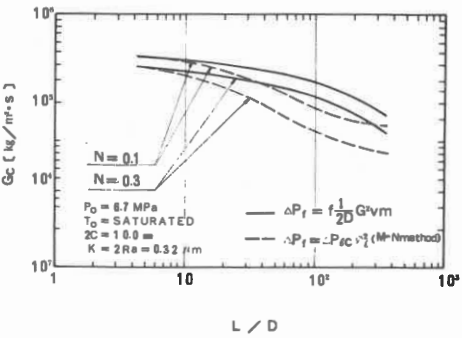

Figure 8. Analyzed leak flow rate by $(\Delta Pf)_2$ in friction pressure drop.

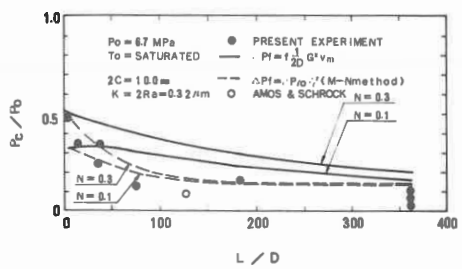

Figure 9. Analyzed critical pressure ratio by $(\Delta Pf)_2$ in friction pressure drop.

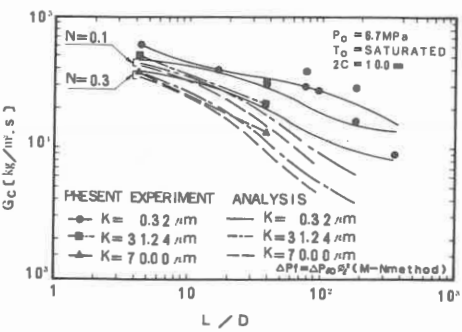

Figure 10. Leak flow rate from slits having different surface roughness, which is analyzed by $(\Delta Pf)_2$.