SMiRT-12 / K. Kussmaul (Editor)

G06/4

DEVELOPMENT OF SODIUM LEAK ESTIMATION METHOD IN FBR COMPONENTS

K. Tamura[1], T. Shimakawa[1*], M. Nakamura[1], K. Kashima[2], N. Miura[2] and T. Fujioka[2]

[1]Kawasaki Heavy Industries, Ltd., Tokyo, Japan
[2]Central Research Institute of Electric Power Industry, Tokyo, Japan

ABSTRACT

Estimation of sodium leak rate through a crack is essential in applying the safety design based on the LBB feature to FBR systems and components. Prediction of crack opening area is also of concern. This paper describes derivation of leak rate evaluation scheme based on the Bernoulli's formula and its validation by water leak tests. The GE/EPRI estimation scheme was extended to predict the crack opening area of a 3D crack under creep condition and its applicability was validated by FEM analyses.

1. INTRODUCTION

Estimation of sodium leak rate through a crack is essential in applying the safety design based on the LBB(Leak Before Break) feature to FBR systems and components. A study on leak rate has been performed for LWR$^{1)}$ and it was shown that Moody's critical flow model is available in two-phase critical flow characterized at LWR. On the other hand, coolant material is sodium at FBR, hence a leak rate model should be established for single-phase flow. As for the single-phase flow, the leak rate can be basically estimated by Bernoulli's formula. The leak rate estimation in actual plants, however, has not yet been fully established due to complex crack geometry defined by change of crack geometry through thickness, kinking, surface roughness etc. Major parameters are considered to investigate the effect of the complex crack geometry by using artificial slits and a fatigue crack in water testing. The present study has been carried out as the first step for developing the leak rate estimation method for the single-phase sodium leak at FBR components.

Estimation of crack opening area is also of concern in the safety design based on the LBB feature. The criterion of Dt/4 has been employed at the existing several FBR designs as reference piping break area$^{2)}$ with an ample margin, and hence rationalization of this criterion is expected in designing of safety related systems and equipments. Crack opening displacement(COD) can be evaluated by the GE/EPRI eatimation scheme$^{3)}$ for a 2D problem. Actual cracks, however, have complex 3D geometry, and it is needed to extend the GE/EPRI estimation scheme to a 3D problem. And most of sodium components are operated at creep temperature, then the GE/EPRI estimation scheme should be also extended to creep regime. Another problem is how to handle the crack opening geometry. This paper describes the extended estimation scheme for a 3D crack under the creep condition and the validation by FEM analyses.

2. LEAK RATE ESTIMATION

The flow diagram of this study is shown in Figure 1. We conducted a series of water tests prior to sodium tests to be expected in future, since water tests are more suitable than sodium tests for obtaining various kinds of data to examine major parametric effects on the leak rate. It is basically recognized that the flow behavior of water is similar to that of sodium, because both fluids are Newtonian fluid and the leak flow of our interest by characterized as single-phase incompressible flow. Hence flow phenomena are governed by the Navier-Stokes equation and the estimation scheme can be properly derived on the basis of the similarity law that employs the Reynolds number as a non-dimensional parameter. The friction factor f and the form loss coefficient ζ obtained by water tests are applicable to sodium in spite of the difference in physical properties, since they are also non-dimensional quantities correlated with the Reynolds number.

2.1 Simplified Estimation Scheme

The leak rate is calculated from the fluid velocity at the outlet of the crack by the following Bernoulli's formula. The flow model is shown in Figure 2.

$$p_{\mathrm{in}} = \Delta p + \frac{\gamma}{2g} V_{\mathrm{out}}^2 , \tag{1}$$

where p_{in} is the upstream stagnation pressure, Δp the pressure loss through the crack, g the acceleration of gravity, γ the specific weight of the fluid and V_{out} the average cross section velocity at the crack outlet. The pressure loss Δp is given by

$$\Delta p = \Delta p_{\mathrm{c}} + \Delta p_{\mathrm{fric}} , \tag{2}$$

where Δp_{c} is the form loss caused by the flow contraction at the crack inlet and Δp_{fric} the frictional pressure loss through the total flow pass length.

The inlet form loss Δp_{c} is presented by

$$\Delta p_{\mathrm{c}} = \zeta \frac{\gamma}{2g} V_{\mathrm{in}}^2 \ ; \ \zeta = 0.5 , \tag{3}$$

where V_{in} is the average cross section velocity of the fluid at the crack inlet.

The frictional pressure loss Δp_{fric} is determined by using the following experimental correlation4)5) of the friction factor f for single-phase flow between parallel plates

$$\Delta p_{\mathrm{fric}} = f \frac{\gamma}{2g} \frac{L}{D_{\mathrm{h}}} V^2 , \tag{4}$$

$$f = \frac{96}{\mathrm{Re}} \quad : \ \mathrm{Re} < 2000 \text{ (laminar flow)}, \tag{5}$$

$$f = 0.508\,\mathrm{Re}^{-0.3} \quad : \ \mathrm{Re} \geq 2000 \text{ (turbulent flow)}, \tag{6}$$

where V is the average cross section velocity through the crack, L the flow pass length in the crack and D_{h} the hydraulic diameter. Taking into consideration geometrical change of the crack through thickness, the flow pass is divided into several sections and the frictional pressure loss of each section is calculated based on local averaged flow area and hydraulic diameter. The frictional pressure loss through the crack is simply obtained as the sum of that in each section.

2.2 Validation of Estimation Scheme

The water leak tests were performed using seven different artificial slits and one fatigue crack slit. Test parameters are listed in Table 1. The geometry of an artificial slit was adjusted with spacers, and that of the fatigue crack was controled by loading level in a fatigue test. A test equipment shown in Figure 3 was used.

Comparisons between predicted leak rate and test result are shown in Figures 4 to 7. Figure 4 shows the results for the several crack opening displacements where crack length is 80mm. The estimated results coincide with the experiment results for a wide range of crack opening displacement. Figures 5 and 6 show the validation for an application to the crack where geometry changes. The water leak tests were performed for the cracks which have 80mm inlet crack length and 0.15 mm COD but have different outlet crack length. The results are shown in Figure 5 and the leak rates are estimatd well by this proposed simplified scheme. The water leak tests were also performed for the cracks which have different inlet CODs. The results are shown in Figure 6 and it is noted that proposed estimation scheme can represent the leak rates where the crack geometry changes through thikness. Figure 7 shows an application of the estimation scheme to the fatigue crack where both crack length and COD are varied through thikness. It is confirmed that this proposed scheme can be applied for leak estimation through 3D crack where both crack length and COD are varied, and it is also noted in Figure 7 that the effects of surface roughness and kinking considered in actual crack may be negligible.

3. CRACK OPENING AREA ESTIMATION

3.1 Simplified Estimation Scheme

Crack opening displacement δ^{ep} is evaluated by the following equation in the GE/EPRI estimation scheme

$$\delta^{ep} = \delta^{e} + \delta^{p} , \tag{7}$$

where δ^{e} is the elastic component of COD represented by

$$\delta^{e} = \frac{4a\sigma}{E'} \cdot V_1 , \tag{8}$$

and δ^{p} is the plastic component represented by

$$\delta^{p} = \alpha\varepsilon_0 a h_2 \left(\frac{\sigma}{\sigma_0} \right)^n , \tag{9}$$

when a stress-strain curve is given by using the following Ramberg -Osgood equation,

$$\left(\frac{\varepsilon^{p}}{\varepsilon_0} \right) = \alpha \left(\frac{\sigma}{\sigma_0} \right)^n . \tag{10}$$

Deformation rate δ^{c} under the creep condition is represented by

$$\delta^{c} = a h_2 B(\sigma_{net})^n , \tag{11}$$

when a creep curve is given by using the following Norton type creep equation,

$$\dot{\varepsilon}_c = B(\sigma_{net})^n . \tag{12}$$

The following approximation is introduced in the extension to a 3D problem. A 3D crack is devided into some layers of 2D plates along the thickness direction. Crack opening displacement of each layer is calculated using the averaged crack length and the applied stress of each layer under the plane stress condition. Crack opening geometry is assumed as an ellipse defined by crack length and COD.

3.2 Validation of Estimation Scheme

The crack opening area estimated by the simplified scheme was compared with that of FEM result. Finite element anlyses were performed using the ABAQUS code. Parameters of analyses are crack length and loading condition as shown in Table 2.

Figure 8 shows a comparison between crack opening area evaluated by this estimation scheme and that by the 3D FEM analysis under pure tension loading. Thickness of the plate is 20mm and crack lengths on front and back surface are identical of 80mm. Crack opening area of mid-plate is the same as that of surfaces, and both areas are calculated by the estimation scheme under the plane stress condition. Figure 9 shows a comparison when crack lengths of both surfaces are not identical: crack length of front surface is 40mm and that of back surface is 80mm. The estimated area on the longer crack side is slightly larger than that of the 3D FEM result, while estimated area at shorter crack side is smaller. However, total flow pass as the integral of crack opening area of each layer is considered to be equal, and difference of each surface is not so significant for engineering use. Figure 10 shows a comparison under a bending load condition. Crack opening area on the tension side can be well evaluated by this estimation scheme using a 2D plate model. Surface of the plate under bending is approximated by a 2D plate under pure tension where stress is equal to the surface bending stress of a 3D plate. Crack opening area on the compression side is approximately zero as expected. Figure 11 shows a comparison under a creep condition. Difference in the creep calculation is the same as that arise in elastic-plastic calculation which is observed at time 0.0hr.

4. CONCLUSIONS

(1) The leak rate estimation scheme was derived from Bernoulli's formula with the friction factor correlation for flow between parallel plates. The scheme was validated by the results of water leak tests using artificial slits with various geometry and a fatigue crack.

(2) The GE/EPRI estimation scheme for a 2D problem was extended to the simplified estimation scheme of crack opening displacement for creep, 3D and bending problems. The scheme was validated by FEM analyses.

5. ACKNOWLEDGMENTS

This study was carried out as part of the project of the Ministory of International Trade and Industry titled "Verification Tests of Fast Breeder Reactor Technology", which has been conducted since 1987.

REFERENCES

1. T.Narabayashi, et al., 1991, Experimental study on leak flow model through fatigue crack, Nuclear Engineering and Design, Vol. 128, pp.17-27
2. U.S.Standard Review Plan: 3.6.2 Determination of rupture locations and dynamic effects associated with the postulated rupture of piping, NUREG-0800
3. V.Kumar, et al., 1981, An engineering approach for elastic-plastic fracture analysis, EPRI NP-1931.
4. Rohsenow and Hartnett, 1973, Handbook of Heat Transfer, McGraw-Hill.
5. M.Nakajima and K.Fukui,1980, Buoyancy effect on turbulent transport in combined free and forced convection between vertical parallel plates, International Journal of Heat and Mass Transfer, Vol. 23, pp.1325-36.

Table 1 Test specimens

Type of crack	Thickness [mm]	COD [mm]		Crack length [mm]	
		Inlet	Outlet	Inlet	Outlet
Artificial slit	20	0.37	0.37	80	80
Artificial slit	20	0.13	0.13	80	80
Artificial slit	20	0.04	0.04	80	80
Artificial slit	20	0.15	0.15	80	40
Artificial slit	20	0.15	0.15	80	30
Artificial slit	20	0.15	0.15	80	20
Artificial slit	20	0.35	0.15	80	80
Fatigue crack	20	0.14	0.08	76	46

Table 2 Analysis Conditions

Method	Material model	Loading condition	Crack length [mm]
3D FEM	Elastic-plastic	Tensile	80
3D FEM	Elastic-plastic	Tensile	40/80
3D FEM	Elastic-plastic	Bending	80
2D FEM	Creep	Tensile	80

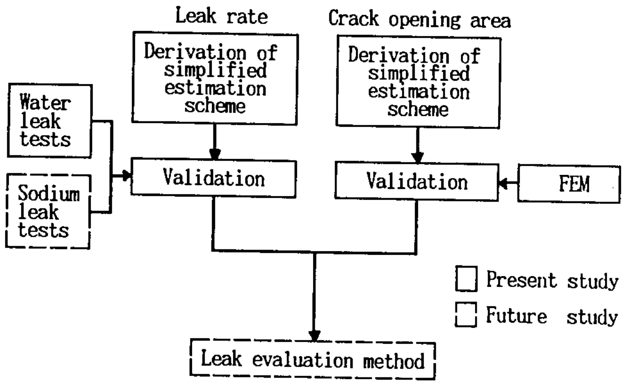


Fig. 1 Flow diagram of the whole study

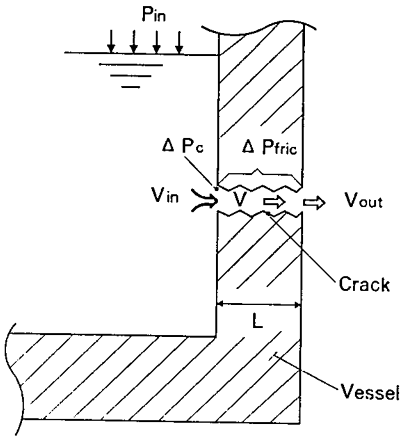


Fig.2 Flow model for crack

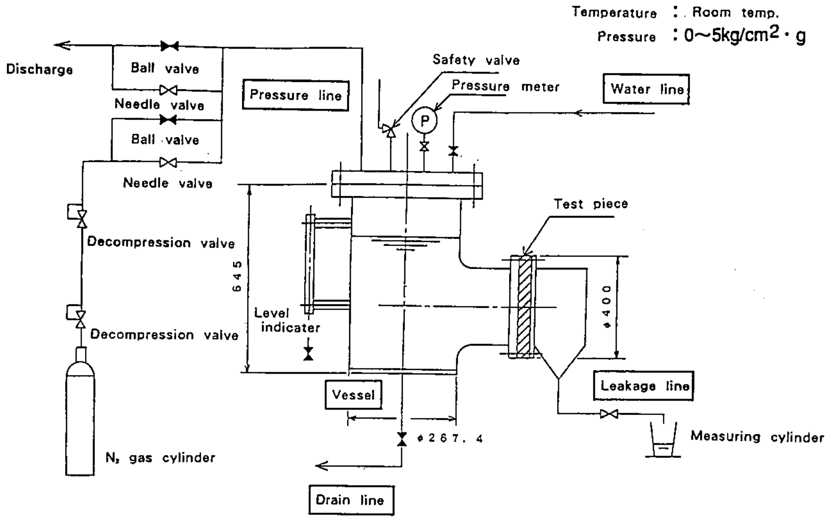
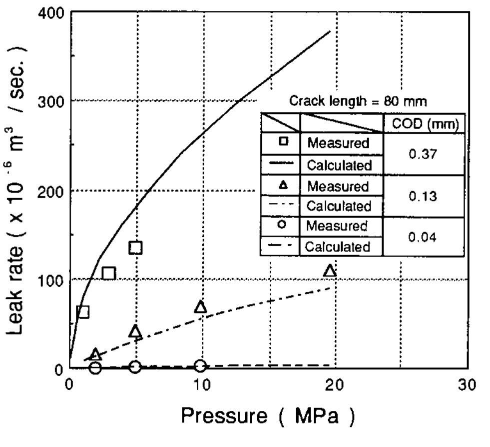


Fig. 3 Water leak test equipment



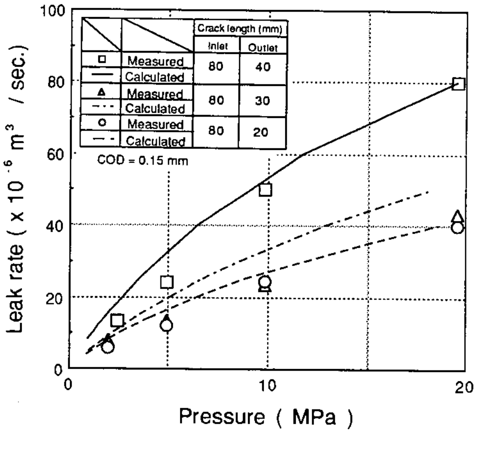


Fig.4 Comparison of calculated and measured leak rates (Effect of crack opening displacement)

Fig.5 Comparison of calculated and measured leak rates (Effect of crack length ratio)

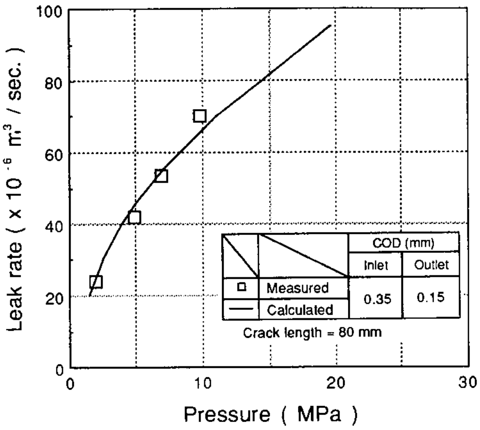


Fig.6 Comparison of calculated and mesured leak rates (Effect of crack opening ratio)

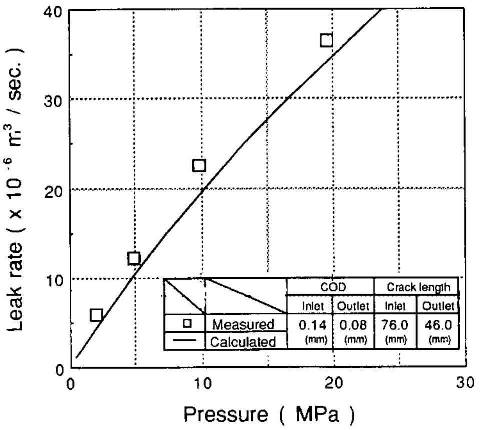


Fig.7 Comparison of calculated and measured leak rates (Fatigue crack slit)

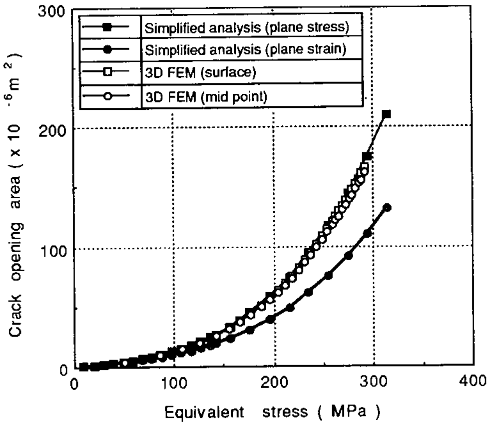


Fig.8 Comparison of Crack opening area between simplified and 3D FEM analyses

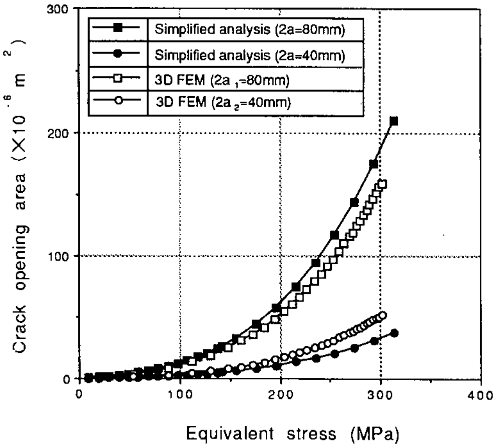


Fig.9 Effect of crack geometry on crack opening area

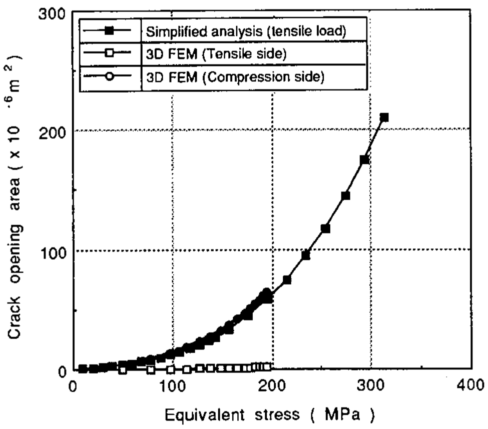


Fig.10 Crack opening behavior under bending load

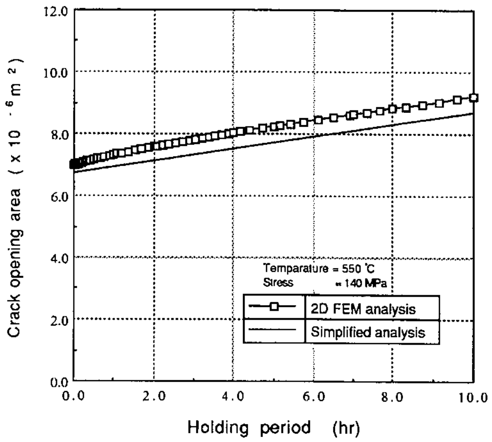


Fig.11 Variation of crack opening area during creep holding