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Original Article

ESTIMATION OF LEAK RATE THROUGH CIRCUMFERENTIAL CRACKS IN PIPES IN NUCLEAR POWER PLANTS

JAI HAK PARK [a,*], *YOUNG KI CHO* [a], *SUN HYE KIM* [b], *and JIN HO LEE* [b]

[a] *Department of Safety Engineering, Chungbuk National University, Cheongju, Chungbuk 362-763, South Korea*
[b] *Mechanical and Material Assessment Department, Korea Institute of Nuclear Safety, Daejeon 305-338, South Korea*

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ABSTRACT

The leak before break (LBB) concept is widely used in designing pipe lines in nuclear power plants. According to the concept, the amount of leaking liquid from a pipe should be more than the minimum detectable leak rate of a leak detection system before catastrophic failure occurs. Therefore, accurate estimation of the leak rate is important to evaluate the validity of the LBB concept in pipe line design. In this paper, a program was developed to estimate the leak rate through circumferential cracks in pipes in nuclear power plants using the Henry–Fauske flow model and modified Henry–Fauske flow model. By using the developed program, the leak rate was calculated for a circumferential crack in a sample pipe, and the effect of the flow model on the leak rate was examined. Treating the crack morphology parameters as random variables, the statistical behavior of the leak rate was also examined. As a result, it was found that the crack morphology parameters have a strong effect on the leak rate and the statistical behavior of the leak rate can be simulated using normally distributed crack morphology parameters.

1. Introduction

The leak before break (LBB) concept is widely used in designing pipe lines in nuclear power plants. According to the concept, the amount of leaking liquid from a pipe should be more than the minimum detectable leak rate of a leak detection system before catastrophic failure occurs [1,2]. Therefore accurate estimation of leak rate is important to evaluate the validity of the LBB concept in pipe line design.

Several programs have been developed to evaluate leak rates through a crack in a pipe. In 1984, the PICEP program [3,4] was developed by Electric Power Research Institute (EPRI) based on Henry's homogeneous nonequilibrium critical flow model modifying the previous EPRI LEAK-01 Code [5]. In 1994, the first version of the SQUIRT program [6] was developed, in which the Henry–Fauske model [7–9] of thermal-hydraulic behavior was used. The Henry–Fauske model allows for nonequilibrium vapor generation rates as the fluid flows through the crack. The model also considers the pressure losses due to friction, bends, and protrusions in the crack flow path. The leak rate results obtained using the SQUIRT program were compared with the experimental data on two-phase flow through long tubes, slits, and actual cracked pipes [6]. The Henry–Fauske model was also used in the

* *Corresponding author.*
E-mail address: jhpark@chungbuk.ac.kr (J.H. Park).

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PRAISE program [10,11], which was developed in order to evaluate the leak and loss-of-coolant accident (LOCA) probabilities of pipes in nuclear power plants.

Collier et al. [12] compared the calculated leak rates from the Henry–Fauske model with the measured leak rates over five orders of magnitude in flow rate using simulated cracks and intergranular stress corrosion cracks in stainless steel pipes. They found that the analytical model agrees relatively well with the mean value of the measured leak rate. They also observed significant scatter in the experimental leak rate data. They mentioned that this scatter is because of partial plugging of the flow area by particulates.

Rahman et al. [2] introduced a modified Henry–Fauske flow model. In the previous model, the surface roughness is assumed to be constant. In the new model, however, the surface roughness is assumed to be a function of crack opening displacement (COD). Depending on whether COD is large or small, the surface roughness is assumed to be large or small also. The number of turns and actual length of the flow path are also assumed to be a function of COD. The modified Henry–Fauske model was implemented in the PRO-LOCA program (Battelle, Columbus, USA) [13], which is a probabilistic fracture mechanics program used to estimate the frequencies of LOCA.

A program was made to evaluate the leak rate through circumferential cracks in pipes using the Henry–Fauske flow model and the modified Henry–Fauske flow model. The calculated leak rate and pressure loss results from the two flow models were compared and discussed. Considering crack morphology parameters, such as surface roughness and the number of turns along the flow path, as random variables, the distribution characteristics of the leak rate were examined.

2. Flow and COA models

2.1. *Henry–Fauske flow model*

Mass flux through a crack in a pipe can be calculated using the Henry–Fauske flow model given as the following Eqs. (1) and (2) [6-9]:

$$\psi(G_c, p_c) = G_c^2 - \frac{1}{\left[\frac{X_c v_{gc}}{\gamma_o p_c} - (v_{gc} - v_{Lc}) N \frac{dX_E}{dp}\right]_c} = 0 \tag{1}$$

$$\Omega(G_c, p_c) = p_c + p_e + p_a + p_f + p_k + p_{aa} - p_o = 0. \tag{2}$$

Here the subscripts o and c mean the values at the crack entrance plane and at the crack exit plane respectively. G is mass flux, p is pressure, v_{gc} and v_{Lc} are specific volumes of saturated vapor and saturated liquid at exit pressure, and γ_o is the isentropic expansion coefficient. In Eqs. (1) and (2), mass flux at crack exit plane, G_c, and pressure at crack exit plane, p_c, are unknowns. After solving the equations, the leak rate through a crack can be obtained by multiplying G_c by the crack opening area at crack exit plane, A_c.

In Eq. (1), X_c is the nonequilibrium vapor generation rate given by:

$$X_c = NX_E\{1 - \exp[-B(L/D_H - 12)]\}, \tag{3}$$

where:

$$X_E = \left[\frac{S_o - S_{Lc}}{S_{gc} - S_{Lc}}\right]. \tag{4}$$

Here S_o is the entropy at the crack entrance plane, S_{Lc} is the entropy of liquid at the crack exit plane, S_{gc} is the entropy of saturated vapor at the crack exit plane, and N is defined by:

$$\begin{aligned} N &= 20X_E \text{ for } X_E < 0.05 \\ N &= 1.0 \text{ for } X_E \geq 0.05. \end{aligned} \tag{5}$$

The constant B in Eq. (3) is given by 0.523 [7] and L is the length of the flow path. D_H is the hydraulic diameter defined by:

$$D_H = \frac{4 \times area}{wetted\ perimeter}, \tag{6}$$

Here, *area* is the cross-sectional area of the flow path. If the cross-section of the flow path is a circle with diameter D, D_H becomes equal to D. If the cross-section of the flow path is a crack with length $2b$, D_H=*area*/b.

In Eq. (2) p_e, p_f, p_k, p_a, and p_{aa} are the pressure losses due to entrance effects, friction, bends and protrusions in the flow path, phase change acceleration, and area change acceleration respectively. Each of these terms is expressed by the following equations.

The pressure loss due to entrance effects, p_e, is given by:

$$p_e = \frac{G_o^2 v_{Lo}}{2C_D^2}, \tag{7}$$

where C_D is the coefficient of discharge. A value of $C_D = 0.95$ is recommended for tight cracks with CODs < 0.15 mm. For cracks with larger CODs, a coefficient of discharge between 0.62 and 0.95 should be used. $C_D = 0.95$ was used in this study.

The pressure loss due to friction, p_f, is given by:

$$p_f = \left(f\frac{L}{D_H}\right)\frac{\overline{G}^2}{2}\left[(1-\overline{X})\overline{v}_L + \overline{X}\overline{v}_g\right], \tag{8}$$

where f is the friction factor, X is the fluid quality, and a bar on the variable means the average value in the region. The flow path can be divided into two ranges of $L/D_H > 12$ and $0 < L/D_H < 12$. The range $L/D_H > 12$ corresponds to the two-phase flow region with liquid and gas and the range $0 < L/D_H < 12$ corresponds to the one-phase flow region with only liquid. Thus Eq. (8) can be expressed as follows:

$$p_f = f\left(\frac{L}{D_H} - 12\right)\frac{G_c^2}{2}\left[(1-\overline{X})\overline{v}_L + \overline{X}\overline{v}_g\right] + 12f\frac{G_o^2}{2}v_{Lo}. \tag{9}$$

Considering the relationA_oG_o=A_cG_c, Eq. (9) becomes:

$$p_f = f\left(\frac{L}{D_H} - 12\right)\frac{G_c^2}{2}\left[(1-\overline{X})\overline{v}_L + \overline{X}\overline{v}_g\right] + 6f\left(\frac{A_c}{A_o}\right)^2 G_c^2 v_{Lo}. \tag{10}$$

Based on the PRAISE program [10] the friction factor f is given by:

$$f = \left[C_1 \log\left(\frac{D_H}{2\mu}\right) + C_2\right]^{-2}, \tag{11}$$

where μ is the surface roughness and has a value of 6.20 μm (0.0002441 inch) in SCC growth and 40.0 μm (0.0015748 inch) in fatigue crack growth. The coefficients C_1 and C_2 are given by [10]:

$$C_1 = 3.39,\ C_2 = 0.86 \ \text{for}\ \frac{D_H}{2\mu} \le 27.74$$
$$C_1 = 2.0,\ C_2 = 1.74 \ \text{for}\ \frac{D_H}{2\mu} > 27.74 \tag{12}$$

The pressure loss due to bends and protrusions in the crack path, p_k, is given by:

$$p_k = (e_v)\frac{\overline{G}^2}{2}\left[(1-\overline{X})\overline{v}_L + \overline{X}\overline{v}_g\right] \tag{13}$$

where e_v is the total loss coefficient over the crack flow path length. The variable e_v can be determined experimentally by defining:

$$e_v = e[L], \tag{14}$$

where e is the number of velocity heads lost per unit flow path length for a given type of crack. The experimental data from a fatigue crack in a girth weld suggests a value of $e = 6$ velocity heads per mm of crack flow path. For SCC crack growth, a value of $e = 3$ velocity heads per mm of flow path is appropriate. $\overline{G}$ is the mean value of mass flux given by:

$$\overline{G} = \frac{A_o G_o + A_c G_c}{A_o + A_c}. \tag{15}$$

The pressure loss due to phase change acceleration, p_a, is given by:

$$p_a = \overline{G}_T^2\left[(1-X_c)v_{Lc} + X_c v_{gc} - v_{Lc}\right] \tag{16}$$

where $\overline{G}_T$ is the mean value of mass flux in the two-phase region of the flow path.

The pressure loss due to area change acceleration, p_{aa}, is given as follows [6]:

$$p_{aa} = \frac{G_c^2 v_{Lo}}{2}\left[\left(\frac{A_c}{A_i}\right)^2 - \left(\frac{A_c}{A_o}\right)^2\right] + \frac{G_c^2}{2}\left[(1-X)v_{Lc} + X v_{gc}\right] \times \left[1 - \left(\frac{A_c}{A_i}\right)^2\right], \tag{17}$$

where A_i is the cross-sectional area at the plane where the two-phase flow starts, i.e., where L/D_H=12.

In the program it is assumed that the cross-sectional area is constant along the flow path. Then G_o=G_c and p_{aa} becomes 0. Considering Eqs. (7), (10), (13), and (16), it can be noticed that the pressure losses, p_e, p_f, p_k, and p_a, can be expressed as a function of G_c. Then from Eq. (2), p_c can be expressed as a function of G_c. Substituting the relation into Eq. (1), we can get an equation with only one unknown variable, G_c.

2.2. *Modified Henry–Fauske flow model*

Rahman et al. [2] introduced a model modifying the Henry–Fauske flow model. In their model the surface roughness is assumed to be a function of COD at the crack center. The number of turns and actual length of the flow path are also assumed to be a function of COD.

The surface roughness is assumed to be a function of COD as follows [2]:

$$\mu = \mu_L \quad \text{for}\ 0 < \frac{\delta}{\mu_G} \le 0.1$$
$$\mu = \mu_L + \frac{\mu_G - \mu_L}{9.9}\left(\frac{\delta}{\mu_G} - 0.1\right) \ \text{for}\ 0.1 < \frac{\delta}{\mu_G} \le 10. \tag{18}$$
$$\mu = \mu_G \quad \text{for}\ 10 < \frac{\delta}{\mu_G},$$

where μ_L and μ_G are the local and global surface roughness, respectively, and δ is COD at the crack center.

The number of 90° turns in the flow path is also assumed to be a function of δas follows [2]:

$$n_t = n_{tL} \quad \text{for}\ 0 < \frac{\delta}{\mu_G} \le 0.1$$
$$n_t = n_{tL} - \frac{n_{tL}}{11}\left[\frac{\delta}{\mu_G} - 0.1\right] \ \text{for}\ 0.1 < \frac{\delta}{\mu_G} \le 10 \tag{19}$$
$$n_t = 0.1 n_{tL} \quad \text{for}\ 10 < \frac{\delta}{\mu_G},$$

where n_{tL} is the local number of turns in the flow path. Because one 90° turn corresponds to one velocity head loss, n_t has the same meaning as e in Eq. (14).

As the flow path is not perpendicular to the pipe surface and not straight, the real flow path length is longer than the wall thickness. The real path length, L_a, can be obtained by multiplying the wall thickness, t, by a correction factor K as follows:

$$L_a = Kt. \tag{20}$$

The correction factor K is also given as a function of δ as follows:

$$K = K_{GL} \quad \text{for}\ 0 < \frac{\delta}{\mu_G} \le 0.1$$
$$K = K_{GL} - \frac{K_{GL} - K_G}{9.9}\left[\frac{\delta}{\mu_G} - 0.1\right] \ \text{for}\ 0.1 < \frac{\delta}{\mu_G} \le 10 \tag{21}$$
$$K = K_G \quad \text{for}\ 10 < \frac{\delta}{\mu_G}.$$

If the pipe wall thickness to hydraulic-diameter ratio, L/D_H, is larger than 30, the Henry–Fauske two-phase flow model can be used. Here the surface roughness, number of turns, and actual length of the flow path are assumed to be functions of COD. When (L/D_H)<30, the model needs to be modified. The PRO-LOCA program uses the following modified Henry–Fauske flow model [13]. If $(L/D_H) \ge 30$, the Henry–Fauske two-phase model is used to calculate the mass flux G_c, calculate p_c/p_o and the mass flux for L/D_H=30, and let the values be $(p_c/p_o)_1$ and $(G_c)_1$ respectively. When $4.6 \le (L/D_H) < 30$, p_c/p_o is assumed to be $(p_c/p_o)_1$ in the region $(L/D_H) < 4.6$, p_c/p_o is assumed to increase linearly with L/D_H from 0 to $(p_c/p_o)_1$, when $12 \le (L/D_H) < 30$, the mass flux is assumed to be $(G_c)_1$. When $(L/D_H) \le 4.6$, the leak rate is obtained using an orifice-type flow equation where the fluid properties are evaluated at the average pressure, $(p_o+p_c)/2$. In the region $4.6 \le (L/D_H) < 12$, the mass flux is assumed to increase linearly with L/D_H from the mass flux at $L/D_H = 4.6$ to the mass flux at $L/D_H = 12$.

2.3. COA and COD equations

To obtain the leak rate through cracks, a solution for the crack opening area (COA) is necessary. In the PRAISE program the following COA solution was used [10]:

$$A = \frac{4}{\sigma}\int_0^b J(x)dx, \tag{22}$$

where $J(x)$ is the applied J integral expressed as a function of the half crack length x, σ is applied stress, and b is the half crack length at which COA is obtained.

COA can be obtained using the elastic plastic crack opening displacement (COD) solutions. For a circumferential through-wall crack under axial tension load, COD is expressed by the following Eq. (23) [14]:

$$\delta = f_2\left(\frac{P}{tE}\right) + \alpha\epsilon_0\pi R\cdot H_2\cdot\left(\frac{P}{P_0}\right)^n, \tag{23}$$

where:

$$f_2 = 2\left(\frac{\theta_e}{\pi}\right)\cdot\left[1 + A\left\{4.55\left(\frac{\theta_e}{\pi}\right)^{1.5} + 47.0\left(\frac{\theta_e}{\pi}\right)^3\right\}\right]$$

$$\theta_e = \theta\left[1 + \frac{\left(\frac{F_t^2}{\beta}\right)\cdot\left(\frac{n-1}{n+1}\right)\cdot\left(\frac{\sigma_t}{\sigma_0}\right)^2}{1 + \left(\frac{P}{P_0}\right)^2}\right]$$

$$F_t = 1 + A\left[5.3303\left(\frac{\theta}{\pi}\right)^{1.5} + 18.773\left(\frac{\theta}{\pi}\right)^{4.24}\right] \tag{24}$$

$$A = \left[0.125\left(\frac{R}{t}\right) - 0.25\right]^{0.25} \quad \text{for } 5 \le \frac{R}{t} \le 10$$

$$A = \left[0.4\left(\frac{R}{t}\right) - 3.0\right]^{0.25} \quad \text{for } 10 \le \frac{R}{t} \le 20$$

$$\sigma_t = \frac{P}{2\pi Rt}$$

$$P_0 = 2\sigma_0 Rt[\pi - \theta - 2\arcsin(0.5\sin\theta)].$$

Here P is the applied axial load. H_2 is a constant depending on θ/π, n, and R/t. R, t, and θ are the pipe mean radius, wall thickness, and crack half-angle, respectively. α, σ_0, ϵ_0, and n are constants in the Ramberg–Osgood stress–strain relationship. $\beta = 2$ for plane stress and $\beta = 6$ for plane strain crack tip condition. The value of $\beta = 2$ was used in this analysis. The Ramberg–Osgood stress–strain relationship is given by the following equation:

$$\frac{\epsilon}{\epsilon_0} = \frac{\sigma}{\sigma_0} + \alpha\left(\frac{\sigma}{\sigma_0}\right)^n, \tag{25}$$

where $\epsilon_0 = \sigma_0/E$ and σ_0 is the reference stress, which usually has the same value as yield strength. Other COD solutions when bending moment is applied with or without axial load can be found in [14].

If the cross-sectional shape of the flow path is assumed to be elliptical, COA can be calculated from COD using the following equation:

$$A = \frac{\pi}{2}\delta b, \tag{26}$$

where b is the half crack length.

3. Program development

A program was developed to estimate the leak rate through a circumferential crack in a pipe using the Henry–Fauske flow model and modified Henry–Fauske flow model. In order to solve Eqs. (1) and (2), the thermodynamic properties of water should be known. For this purpose, the program developed by Riemer et al. [15] was used.

In order to obtain the probabilistic distribution characteristics of the leak rate, the Monte Carlo simulation method was used. In this method, the crack morphology parameters given in Table 1 were treated as normally distributed random variables and new values of parameters were generated in each leak rate calculation. The cumulative distribution function was obtained using the simulated leak rate values for the given crack length. In the program, the normally distributed parameters were generated using the algorithm proposed by Box and Muller [16]. The program was written in C++.

After developing the program, the obtained leak rate was compared with the leak rate from the PRAISE program in order to check its accuracy. In this case, the Henry–Fauske flow model and the COA solution of Eq. (22) were used. It was found that the difference between the two leak rate results was < 1%.

4. Numerical results

4.1. Comparison of COA solutions

In the analysis, the pipe material is assumed to be ASME SA351 CF8M. The material properties and pipe geometries

Table 1 – Mean and standard deviation of crack morphology parameters [13].

Crack morphology variable	Corrosion fatigue		IGSCC		PWSCC–base		PWSCC–weld	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
μ_L (μm)	8.814	2.972	4.70	3.937	10.62	9.870	16.86	13.57
μ_G (μm)	40.51	17.65	80.0	39.01	92.67	65.26	113.9	90.97
n_L (mm^{-1})	6.730	8.070	28.2	18.90	8.043	2.043	5.940	4.540
K_G	1.017	0.0163	1.07	0.100	1.060	0.095	1.009	0.011
K_{GL}	1.060	0.0300	1.33	0.170	1.327	0.249	1.243	0.079

Table 2 – Geometry and material data used in the analysis.

Geometries and material properties	Input data
Yield strength (MPa)	201.1
Ultimate strength (MPa)	529.2
Elastic modulus (GPa)	215
α	12.22
n	4.84
Outer diameter of pipe (mm)	878.8
Thickness of pipe (mm)	71.1

used are given in Table 2. In Table 2, α and n are parameters in the Ramberg–Osgood relationship. Normal operating pressure is assumed to be 15.51 MPa. The applied axial stress from deadweight is 14.34 MPa and the stress from deadweight and restraint of thermal expansion is 59.2 MPa.

Fig. 1 shows two COA solutions for a through-wall circumferential obtained using Eqs. (22) and (26). When the half crack length, b, is small, the two equations give similar COA values. As b increases, however, the COA from Eq. (26) becomes larger than that from Eq. (22).

4.2. *Comparison of two flow models*

Mass flux ${}_cG_c$ was calculated for a through-wall circumferential crack with crack length 2b using the Henry–Fauske model described in earlier. Multiplying the obtained mass flux by COA, the leak rate was obtained as a function of half crack length. Eq. (22) was used for COA calculation in order to get a similar leak rate as the PRAISE program. The leak rate was also obtained using the modified Henry–Fauske model described earlier and the handbook COA solution of Eq. (26) was used as an improved COA solution. The two leak rate results were plotted in Fig. 2 as a function of the half crack length. It can be noted that both results show a similar leak rate when the half crack length, b, is small. However, the leak rate from the modified Henry–Fauske model becomes much larger than that from the original Henry–Fauske model as b increases.

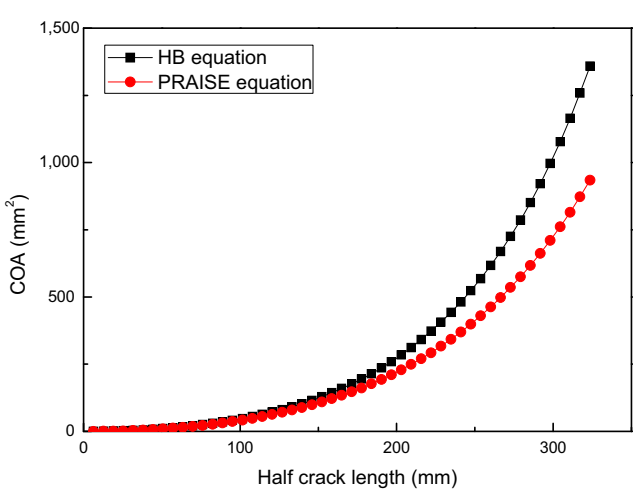

Fig. 1 – Comparison of COA solutions obtained from PRAISE equation and handbook solution. COA, crack opening area.

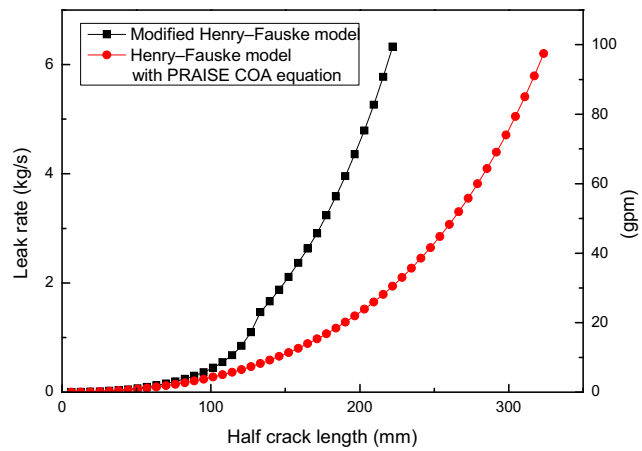

Fig. 2 – Comparison of leak rates obtained from Henry–Fauske flow model and modified Henry–Fauske flow model.

Fig. 3 shows variation of normalized pressure loss terms as the half crack length increases for the Henry–Fauske model. The pressure loss terms are normalized with the crack entrance pressure, p_o. In the Fig. 3, p_t is the total pressure loss. The pressure loss due to entrance effects, p_e, was excluded because the term was too small in comparison to the other terms. When the half crack length is small, p_f is the dominant pressure loss. As the half crack length increases, however, p_f decreases rapidly to a small value. However, p_k increases rapidly and becomes the dominant pressure loss term.

Fig. 4 shows variation of normalized pressure loss terms for the modified Henry–Fauske model. The model shows a similar variation trend in each pressure loss term compared with the previous result of Fig. 3. When the half crack length is short, p_f is the dominant pressure loss. However, p_k becomes the dominant pressure loss term as the half crack length increases. It can be noted that the total pressure loss

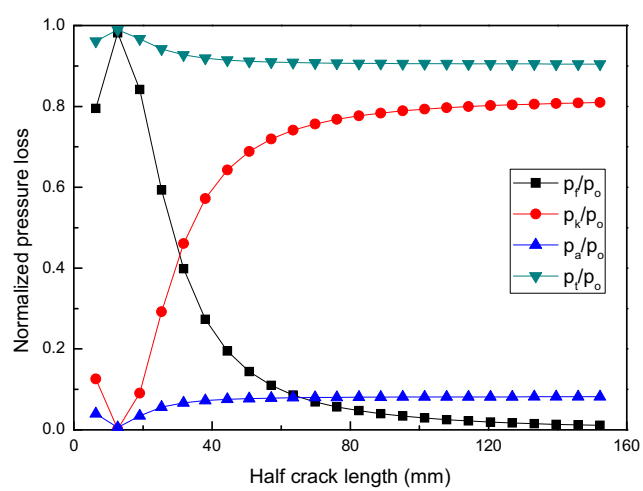

Fig. 3 – Variation of normalized pressure loss terms in Henry–Fauske flow model.

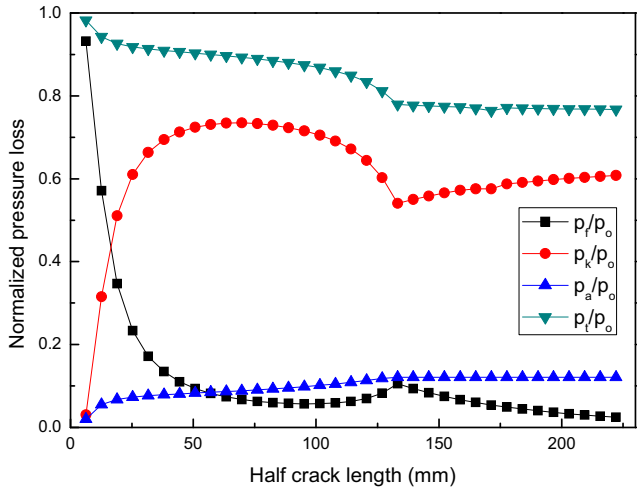

Fig. 4 – Variation of normalized pressure loss terms in modified Henry–Fauske flow model.

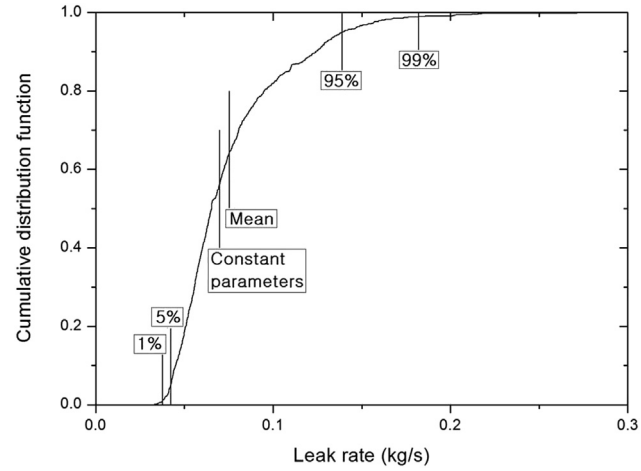

Fig. 5 – Probability density function of leak rate for crack morphology variables of corrosion fatigue when the half crack length is 50.8 mm.

from this model is less than that from the Henry–Fauske model.

4.3. *Distribution of leak rate*

As Collier et al. [12] indicated, the leak rate model agrees relatively well with the measured flow rate if the mean value is considered. However, the measured flow rate shows significant scatter. In order to simulate the scattering characteristics of the measured flow rate data, the crack morphology parameters should be treated as random variables.

In order to examine the statistical distribution characteristics of leak rate, 1,000 leak rate values were generated for the given crack geometries and material properties using a Monte Carlo simulation. In the simulation, the crack morphology parameters were assumed to be normally distributed random variables. The mean and standard deviation values for crack morphology parameters are given in Table 1. The modified Henry–Fauske model and the handbook COA solution of Eq. (26) were used in the calculation. Geometric, material, and loading data were the same as the previous analysis.

The first crack morphology parameters for corrosion fatigue in Table 1 were used. Fig. 5 shows the cumulative density function of the leak rate when the half crack length is 50.8 mm. The 1st, 5th, 95th, and 99th percentiles and the mean value are also indicated in Fig. 5. The line corresponding to the constant parameter indicates the leak rate obtained when constant crack morphology parameters were used in the calculation. Several important statistical properties are given in Table 3. If we compare the median value of 0.0654 kg/s with the 5th percentile of 0.0424 kg/s and the 95th percentile of 0.1389 kg/s, it can be noted that the leak rate is widely distributed. The probability density functions and statistical properties when the half crack lengths are 101.6 mm and 152.4 mm are also given in Figs. 6 and 7 and Table 3.

In order to demonstrate the scattering behavior, the leak rate values obtained from the analysis are plotted in Fig. 8. Open symbols represent the leak rates obtained when the crack morphology parameters were treated as random variables. The crack morphology data for SCC fatigue in Table 1 were used. In Fig. 8 and 10 leak rate results are plotted for each half crack length and the error bars are also plotted to represent the mean and the standard deviation of the 10 obtained leak rate values. The solid curve represents the leak rate when constant mean values were used for crack morphology parameters. It can be seen that the simulated leak rate exhibits significant scatter.

The leak rates were also obtained when the crack morphology data for primary water stress corrosion cracking (PWSCC) weld in Table 1 were used. The results are plotted in Fig. 9. It was found that this simulated leak rate also exhibits significant scatter. The statistical properties are given in Table 4.

If crack morphology parameters are considered as random variables we can demonstrate significant scatter in the leak rate. If we estimate the leak rate with constant crack morphology parameters, a large discrepancy between the estimated value and the observed value will be expected. When leak rate estimation is necessary for LBB or LOCA

Table 3 – Characteristics of distribution of leak rate for crack morphology parameters of corrosion fatigue.

Properties	Leak rate for corrosion fatigue (kg/s)		
	$b = 50.8$ mm	$b = 101.6$ mm	$b = 152.4$ mm
Mean	0.0753	0.509	1.939
Standard deviation	0.0320	0.233	0.752
5th percentile	0.0424	0.238	0.971
10th percentile	0.0451	0.263	1.169
Median	0.0654	0.456	1.787
90th percentile	0.1241	0.813	2.85
95th percentile	0.1389	0.966	3.55

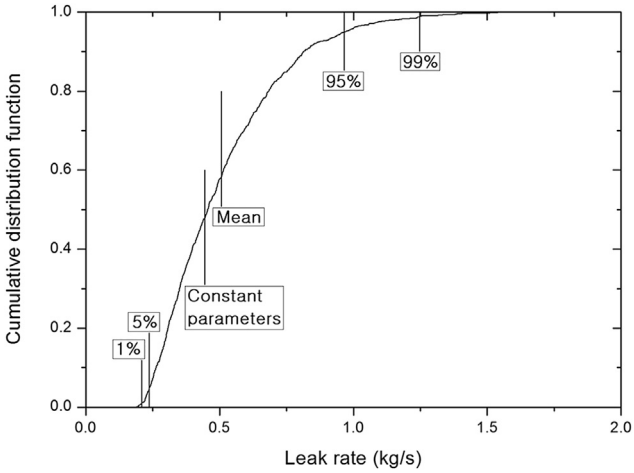

Fig. 6 – Probability density function of leak rate for crack morphology variables of corrosion fatigue when the half crack length is 101.6 mm.

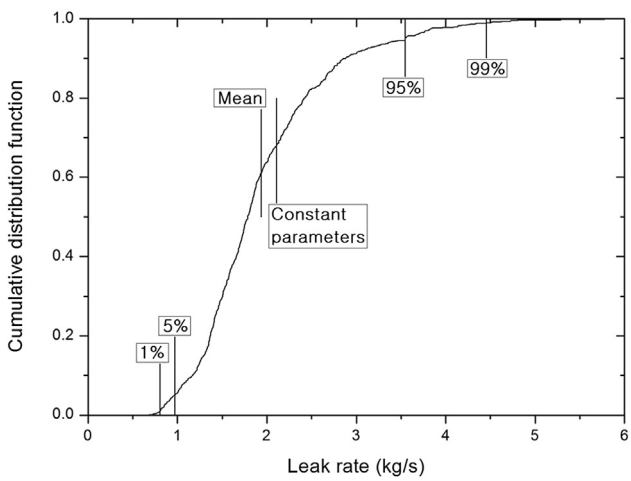

Fig. 7 – Probability density function of leak rate for crack morphology variables of corrosion fatigue when the half crack length is 152.4 mm.

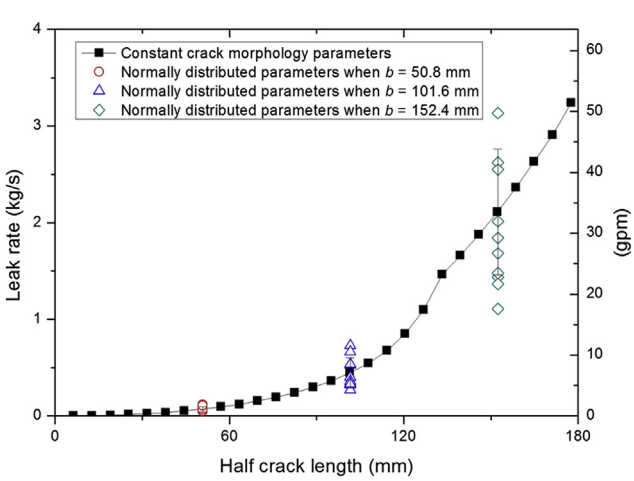

Fig. 8 – Leak rates for normally distributed crack morphology variables of corrosion fatigue.

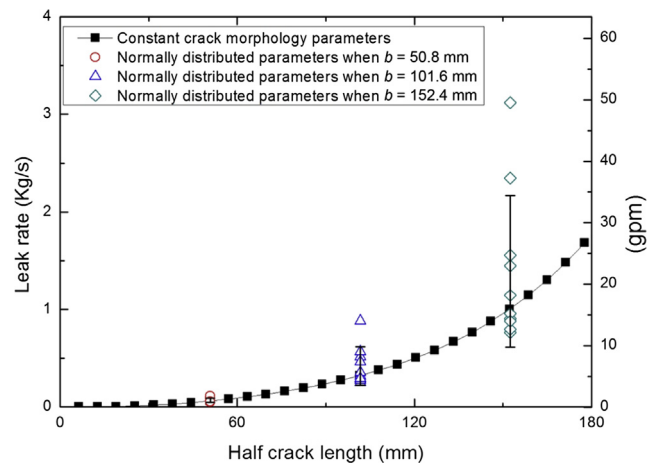

Fig. 9 – Leak rates for normally distributed crack morphology variables of PWSCC weld.

Table 4 – Characteristics of distribution of leak rate for crack morphology parameters of PWSCC weld.

Properties	Leak rate for PWSCC weld (kg/s)		
	$b = 50.8$ mm	$b = 101.6$ mm	$b = 152.4$ mm
Mean	0.0675	0.385	1.242
Standard dev.	0.0270	0.1861	0.632
5th percentile	0.0431	0.217	0.638
10th percentile	0.0455	0.234	0.694
Median	0.0592	0.318	1.021
90th percentile	0.0979	0.660	2.12
95th percentile	0.1322	0.799	2.50

analysis, the leak rate should be obtained as a probability distribution function. In order to improve the accuracy of leak rate analysis, accurate crack morphology parameters should be known.

5. Conclusion

(1) A program was developed in order to obtain the leak rate through a circumferential crack using the Henry–Fauske model and modified Henry–Fauske model; (2) the modified Henry–Fauske model using an improved COA solution gives a similar leak rate to the Henry–Fauske model when the crack length is short, but the model gives a larger leak rate than the Henry–Fauske model as the crack length increases; (3) significant scatter was demonstrated in the estimated leak rates when the crack morphology parameters are treated as normally distributed random variables; and (4) by using the crack morphology parameters for SCC fatigue and PWSCC weld, cumulative density functions were obtained for leak rate.

Conflicts of interest

All authors have no conflicts of interest to declare.

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