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Original Article

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

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A B S T R A C T

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

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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]:

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

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

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, υ_{gc} and υ_{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:

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

where:

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

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:

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

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:

$$D_H = \frac{4 \times area}{wetted\ perimeter}, \quad (6)$$

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:

$$p_e = \frac{G_o^2 \upsilon_{Lo}}{2C_D^2}, \quad (7)$$

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:

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

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:

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

Considering the relation$A_o G_o = A_c G_c$, Eq. (9) becomes:

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

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

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

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]: