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Original Article

Estimation of Leak Rate Through Cracks in Bimaterial Pipes in Nuclear Power Plants

Jai Hak Park [a,*], *Jin Ho Lee* [b], *and Young-Jin Oh* [c]

[a] *Department of Safety Engineering, Chungbuk National University, 1 Chungdae-ro, Seowon-gu, Cheongju, Chungbuk 362-763, South Korea*
[b] *Department of Mechanical and Material Assessment, Korea Institute of Nuclear Safety, 62 Gwahak-ro, Yuseong-gu, Daejeon 305-338, South Korea*
[c] *Department of Structural Integrity and Materials, KEPCO Engineering and Construction Company, 269 Hyeoksin-ro, Gimcheon, Kyeongbuk 740-220, South Korea*

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ABSTRACT

The accurate estimation of leak rate through cracks is crucial in applying the leak before break (LBB) concept to pipeline design in nuclear power plants. Because of its importance, several programs were developed based on the several proposed flow models, and used in nuclear power industries. As the flow models were developed for a homogeneous pipe material, however, some difficulties were encountered in estimating leak rates for bimaterial pipes. In this paper, a flow model is proposed to estimate leak rate in bimaterial pipes based on the modified Henry–Fauske flow model. In the new flow model, different crack morphology parameters can be considered in two parts of a flow path. In addition, based on the proposed flow model, a program was developed to estimate leak rate for a crack with linearly varying cross-sectional area. Using the program, leak rates were calculated for through-thickness cracks with constant or linearly varying cross-sectional areas in a bimaterial pipe. The leak rate results were then compared and discussed in comparison with the results for a homogeneous pipe. The effects of the crack morphology parameters and the variation in cross-sectional area on the leak rate were examined and discussed.

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1. Introduction

The accurate estimation of leak rate through cracks is crucial in applying the *leak before break* (LBB) concept to pipeline design in nuclear power plants. Because of its importance, many flow models were proposed and used in several programs, such as PICEP [1,2], SQUIRT [3], and PRAISE [4,5]. In the SQUIRT and PRAISE programs, the Henry–Fauske flow model [6–8] was used. In this model, nonequilibrium vapor generation rates were considered and also the pressure loss terms due to friction, bends, and protrusions in the crack flow path were included in the governing equations.

Rahman et al [9] introduced a new flow model after modifying the Henry–Fauske flow model. In the previous

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

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model, the crack morphology parameters were assumed to be constant along the flow path. In the new model, however, the crack morphology parameters are assumed to be a function of crack opening displacement (COD). This modified Henry–Fauske model was implemented in the PRO-LOCA program [10], which is a probabilistic fracture mechanics program for pipes, and also in the program developed by Park et al. [11].

In the previous flow models, only pipes made of a single material were considered. Therefore, it was difficult to estimate the flow rate through cracks in bimaterial pipes using the developed program. In this paper, the modified Henry–Fauske flow model was extended further to consider different crack morphology parameters in two parts of a flow path in a bimaterial pipe. In addition, a program was developed based on the proposed flow model. The proposed model can be used to estimate the leak rate of steam–water mixture through cracks in pipes or vessels. Using the program, the leak rate was calculated for through-thickness cracks with a constant or linearly varying cross-sectional area in a bimaterial pipe. In addition, the results were compared with the results for a homogeneous pipe. The default crack morphology parameters of corrosion fatigue and intergranular stress corrosion cracking (IGSCC) in the PRO-COCA program [10] were used in the calculation. The effects of the crack morphology parameters and the variation of cross-sectional area along a flow path on the leak rate were examined and discussed.

2. Materials and methods

2.1. Flow model for bimaterial pipes

To estimate leak rates for through-thickness cracks in bimaterial pipes, a new flow model was proposed by modifying the Henry–Fauske flow model, which was developed to estimate the leak rate of steam–water mixture in pipes and vessels in nuclear power plants. The flow path considered in the proposed model is illustrated in Fig. 1. The flow path in each material can have different crack morphology parameters and also can have a linearly varying cross-sectional area. Let the cross-sectional areas at the entrance, interface, and exit planes be A_o, A_m, and A_c,respectively, and let the pressures at each plane be p_o, p_m, and p_c.

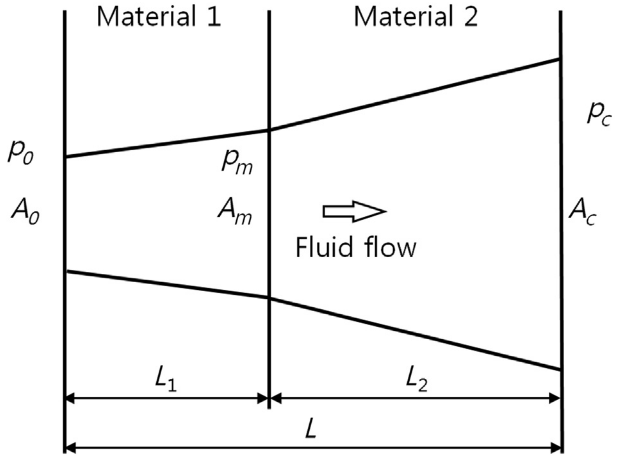

Fig. 1 – Flow path in a bimaterial pipe.

The Henry–Fauske flow model can be described using the following equations [3,6–8]:

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

$$p_c + p_e + p_a + p_f + p_k + p_{aa} - p_o = 0 \tag{2}$$

where G is mass flux, p is pressure, υ_{gc} and υ_{Lc} are specific volumes of saturated vapor and saturated liquid, respectively, and γ_o is the isentropic expansion coefficient. The subscripts o and c are the values at the crack entrance plane and at the crack exit plane, respectively. Therefore, p_o and p_c are the pressure values at the crack entrance and exit planes, respectively.

In Eq. (1), X_c is the nonequilibrium vapor generation rate and X_E is defined by $X_E = (S_o - S_{Lc})/(S_{gc} - S_{Lc})$ [6]. 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, N_c is N at the crack exit plane (N is defined by $N = 20X_E$ for $X_E < 0.05$ and $N = 1.0$ for $X_E \geq 0.05$) [6]. 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.

In Eqs. (1) and (2), mass flux at crack exit plane, G_c, and pressure at the crack exit plane, p_c, are unknown variables. The leak rate through a crack can be estimated by multiplying G_c with the crack opening area at the crack exit plane, A_c. The pressure at the interface plane, p_m, is also an unknown variable and must be determined while solving the equations.

The detailed definition of each term in Eqs. (1) and (2) for homogeneous pipes can be found in elsewhere (see [6,11]). Each term needs to be modified for a flow path in a bimaterial pipe.

2.2. Pressure loss terms

The pressure loss due to entrance effects, p_e, is given by [3].

$$p_e = \frac{G_o^2 \upsilon_{Lo}}{2C_D^2} \tag{3}$$

where C_D is the coefficient of discharge and $C_D = 0.95$ is used in this study.

The pressure losses due to friction in the flow paths in Materials 1 and 2, p_{f1} and p_{f2}, respectively, are given by

$$p_{f1} = \left(f_1 \frac{L_1}{D_H}\right) \frac{\overline{G}_1^2}{2} \left[(1-\overline{X})\overline{\upsilon}_L + \overline{X}\overline{\upsilon}_g\right]_1 \tag{4}$$

$$p_{f2} = \left(f_2 \frac{L_2}{D_H}\right) \frac{\overline{G}_2^2}{2} \left[(1-\overline{X})\overline{\upsilon}_L + \overline{X}\overline{\upsilon}_g\right]_2 \tag{5}$$

where f_1 and f_2 are the friction factors in the flow paths in Materials 1 and 2, respectively, and L_1 and L_2 are the lengths of the flow paths in Materials 1 and 2, respectively; X is the fluid quality, and a bar on the variable means the average value in

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