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Comparison of Two-Phase Critical Flow Models for Estimation of Leak Flow Rate through Cracks

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***Abstract*—**The estimation of leak flow rates through narrow cracks in structures is of importance for nuclear reactor safety, since the leak flow could be detected before occurrence of loss-of-coolant accidents. The two-phase critical leak flow rates are calculated using the system analysis code, and two representative non-homogeneous critical flow models, Henry-Fauske model and Ransom-Trapp model, are compared. The pressure decrease and vapor generation in the crack, and the leak flow rates are found to be larger for the Henry-Fauske model. It is shown that the leak flow rates are not affected by the structural temperature, but affected largely by the roughness of crack surface.

***Keywords*—**Crack, critical flow, leak, roughness.

I. Introduction

The leak-before-break concept is of importance for the structural integrity of nuclear reactor systems. The leakage from the surface of reactor components could be detected even for very small leakage, and the loss-of-coolant accidents are avoided. The temperature and pressure in the reactor components are very high, and those in the outside are in the atmospheric conditions. The leak flows through the cracks are generally two-phase critical flows. The estimation of two-phase critical leak flow rates is thus important for nuclear reactor safety.

The leak flow rates are estimated by the simple flow models for the structural analyses [1]-[4]. The simple flow models are based on the equilibrium two-phase flow models or homogeneous two-phase flow models. The crack size is determined by the structural analyses, and the leak flow rates are calculated as a function of the hydraulic diameter of cracks.

The two-phase critical flows are also important for the safety evaluation of nuclear reactors including accident analyses, and calculated by the system analysis codes [5]. The two-phase critical flow models used in the system analysis codes have been developed based on a large number of theoretical and experimental analyses [6], [7]. These models are based on the non-homogeneous two-fluid models, and give reliable two-phase critical flow rates [7]. The system analysis codes or the two-phase critical flow models used in the codes are complicated, and usually not used for leak flow estimation.

In this study, the system analysis code RELAP [6] is used to calculate the two-phase critical leak flows through narrow cracks. Two representative critical flow models, Henry-Fauske model [8], [9] and Ransom-Trapp model [6], are compared with the simple model. The flow phenomena such as pressure distribution and vapor generation in the crack are shown. The effects of structural temperature and surface roughness of the crack are also shown.

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II. Critical Flow Model

The Henry-Fauske and Ransom-Trapp critical flow models are used in this study as the representative non-homogeneous two-fluid models. These models are much complicated, but the outlines are briefly described here [7].

A. Henry-Fauske Model

The Henry-Fauske critical flow model is based on the one dimensional momentum and mass conservation equations, and the mass flow rate G is given by:

$$G^2 = \left\{\frac{N}{G_{HE}} - u_v x \frac{dN}{dp}\right\}^{-1} \quad (1)$$

where N, G_{HE}, u_v, x and p are, respectively, the non-equilibrium parameter, critical flow rate given by the homogeneous equilibrium theory, vapor velocity, quality and pressure. The non-equilibrium parameter is given by:

$$N = \frac{u_l}{x(1-\alpha)u_v} \quad (2)$$

where u_l and α are the liquid velocity and void fraction, respectively.

B. Ransom-Trapp Model

The Ransom-Trapp critical flow model, which was developed for the system analysis code RELAP [6] to simulate the discharge flows through breaks during the loss-of-coolant accidents of nuclear reactors, is based on the momentum equations for liquid and vapor phases and the mass and energy equations for mixture. The matrix representation of these governing equations is:

$$A(U)\frac{\partial U}{\partial t} + B(U)\frac{\partial U}{\partial x} = 0 \quad (3)$$

where U indicates a variable vector consisting of densities and velocities for liquid and vapor phases and void fraction. The following condition is necessary for the above equation:

$$det(A\mu - B) = 0 \quad (4)$$

where μ indicates the characteristic root. The critical flow condition is obtained when the maximum value of the characteristic root is zero.

III. Cracks and Flow Condition

The leak flows through the cracks in the nuclear reactor piping system are estimated in this study. Two pipes with different diameter, 4 inch and 6 inch, are used as the sample cases [2]. The thickness of pipe wall is 8.6 mm for 4 inch pipe and 11.0 mm for 6 inch pipe, and this thickness is regarded as the crack length. The inside flow is assumed to be saturated under the boiling water reactor condition: 7.24 MPa and 561.15 K. These conditions are the inlet conditions of the crack. The outside conditions, which are the outlet conditions of the crack, are the atmospheric conditions.

The crack in the pipe wall is modeled as a flow channel as shown in Fig. 1: the length is 8.6 mm for 4 inch pipe and 11.0 mm for 6 inch pipe. This flow channel is divided by 60 calculation mesh cells. The mesh cells near the outlet are finer than those near the inlet. The mesh cell size is determined by the preliminary calculations so that the calculated results are not affected by the mesh cell size. The time step size is 1.0 μs. The steady state is established in less than 1 ms, but the calculations are continued to 2 ms in the following. The flow area is a function of the hydraulic diameter, and the hydraulic diameter is varied from 0.1 mm to 1.0 mm. The roughness of the inside surface of the crack is assumed to be 30 μm for the base case calculations, and varied for the sensitivity calculations. The heat conduction in the pipe wall is also calculated. The initial temperature of the pipe wall is the same as the fluid temperature for the base case calculations, and varied for the sensitivity calculations.

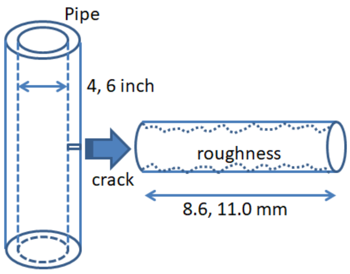

Fig. 1 Schematic model of pipe crack

IV. Results and Discussion

The calculated flow conditions in the crack and the leak flow rates through the crack are shown in this section. The leak flow rates are compared with those by the simple model used for the structural analysis. The effects of pipe wall temperature and crack surface roughness on the leak flow rates are also shown by sensitivity calculations.

A. Flow Conditions in Crack

The calculated flow conditions in the crack are shown in Figs. 2 and 3 for the 4 inch pipe case. The results by Henry-Fauske model are indicated by H-F and those by Ransom-Trapp model by R-T in these figures. The pressure distribution is shown in Fig. 2. The pressure decreases from the inlet to the outlet, and the critical flow conditions are established at the outlet. The flows in crack are not affected by the outlet conditions, and the pressure near the outlet is much higher than the outlet pressure. The pressure decrease in the crack is shown to be larger for the H-F model in Fig. 2.

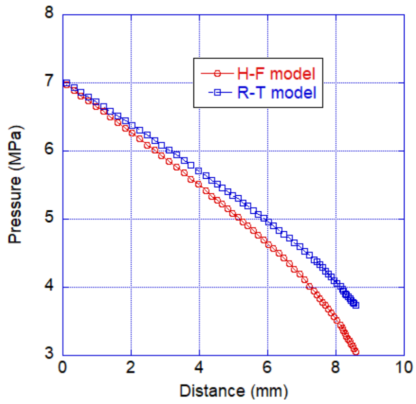

Fig. 2 Pressure distribution in 4 inch pipe crack

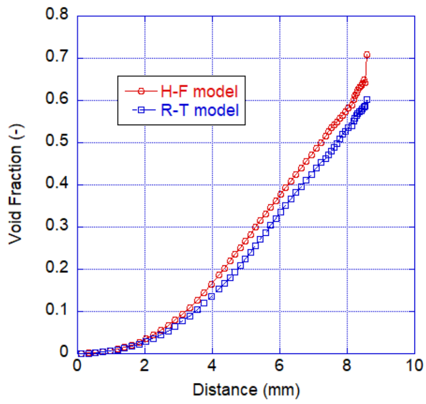

Fig. 3 Void fraction distribution in 4 inch pipe crack

The void fraction distribution is shown in Fig. 3. The void fraction indicates the volume fraction of vapor, and thus the vapor generation. The crack inlet flow is saturated water, and the vapor generation occurs along the crack channel. The void fraction increases from the inlet to the outlet. It is shown in Fig. 3 that the void fraction and vapor generation are larger for the H-F model, since the pressure decrease is larger for the H-F model as shown in Fig. 2. The outlet flow rates are calculated by the critical flow models, and the flow velocities in crack for two phases are defined by the outlet flow rate. The pressure decreases due to the acceleration and friction are then defined by the outlet flow rate. The flow conditions in crack are thus much affected by the critical flow model as shown in Figs. 2 and 3.

B. Leak Flow Rate

The calculated leak flow rates are shown in Figs. 4 and 5 as a function of hydraulic diameter of the crack, respectively for 4 inch pipe and 6 inch pipe cases. The flow rates obtained by the Moody model, which is the simple model used for structural analyses [2], [3], are also shown in Figs. 3 and 4. The flow rates are expressed in the unit of gpm/mm^2 since this expression is common for the structural analyses [1]-[3]. It is shown in Figs. 3 and 4 that the flow rates by H-F model are larger than those by R-T model. This is because the pressure decrease and the vapor generation in crack are larger for the H-F model as shown in Figs. 2 and 3. The flow rates by the simple model are almost in between those by H-F and R-T models.

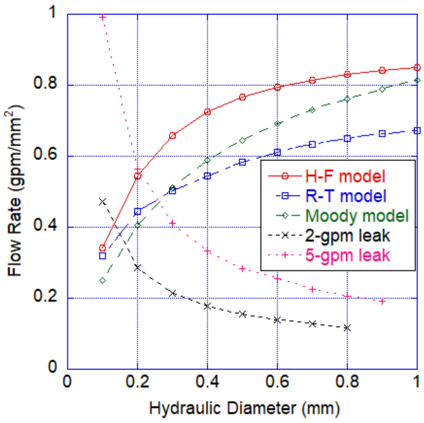

Fig. 4 Leak flow rate in 4 inch pipe crack

The detectable leak flow rates in the unit of gpm are assumed in the structural analysis [2], [3], and the flow rates in the unit of gpm/mm^2 are calculated as a function of the hydraulic diameter. The two cases with different detectable leak flow rates, 2 gpm and 5 gpm, are shown in Figs. 4 and 5 along with the leak flow rates obtained by H-F, R-T and Moody models. In the structural analysis, the leak flow rates are determined as the intersection of two curves: the detectable leak flow rate curve and the Moody model curve. For instance in Fig. 5, if the detectable leak flow rate is 5 gpm, the simple Moody model gives the leak flow rate about 0.4 gpm/mm^2, while the R-T model and H-F model give higher leak flow rates of about 0.43 and 0.49 gpm/mm^2, respectively. The hydraulic diameters corresponding to the leak flow rates are 0.25 mm, 0.22 mm, and 0.19 mm, respectively for the Moody model, R-T model and H-F model. These trends for the leak flow rates and hydraulic diameters are the same for the 4 inch pipe case as shown in Fig. 4.

From the view point of structural analysis, these intersections of the detectable leak flow rate curve and the flow rate curve by the critical flow models are of importance. The leak flow rates at these intersections shown in Figs. 4 and 5 are the largest for the H-F model and the smallest for the simple Moody model, and the R-T model is in between these two models. The hydraulic diameters corresponding to the leak flow rates are, on the contrary, the largest for the simple Moody model and the smallest for the H-F model.

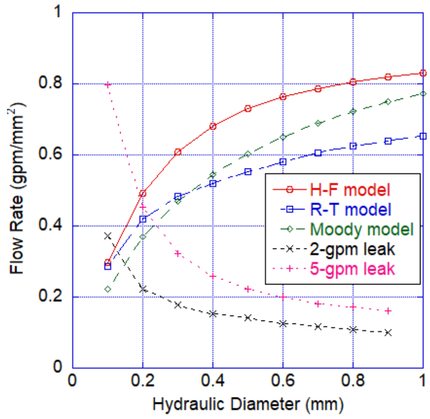

Fig. 5 Leak flow rate in 6 inch pipe crack

C. Effect of Pipe Wall Temperature

The effect of pipe wall temperature is evaluated using the heat structure module provided by the code. The heat structure is connected to the crack channel shown in Fig. 1. Two large heat structures are assumed around the crack channel: one is stainless steel and the other is glass wool as a heat insulator. The heat transfer rate at the outside of the heat insulator is assumed to be 10 W/m^2/K. The initial pipe temperature is varied in the following.

It is shown in Figs. 4 and 5 that the hydraulic diameters corresponding to the intersections of the detectable leak flow rate curve and the critical flow rate curve are around 0.2 mm. The effect of pipe wall temperature is thus calculated for the hydraulic diameter of 0.2 mm in Fig. 6. Two cases with different pipe diameter are shown: 4 inch and 6 inch. The inlet temperature is 615.15 K, and the adiabatic pipe wall was assumed in the previous calculations. The initial pipe wall temperature is reduced by 50 K from 615.15 K to 315.15 K in Fig. 6. It is clearly shown in Fig. 6 that the effect of pipe wall temperature is negligibly small and the calculated flow rates are almost the same as the adiabatic case.

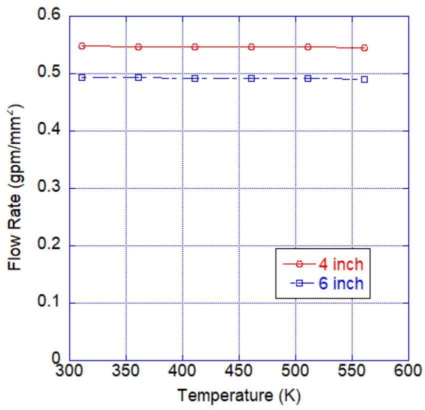

Fig. 6 Effect of pipe temperature

The effect of crack surface roughness is shown in Fig. 7 for the hydraulic diameter of 0.2 mm. The surface roughness of 30 µm was used in the previous calculations, but is changed in Fig.

7. The surface roughness of 0 μm corresponds to the smooth channel without roughness, and the flow rate is the maximum. The flow rate decreases as the surface roughness increases as shown in Fig. 7. The effect of surface roughness is shown to be larger than that of pipe wall temperature shown in Fig. 6. The surface roughness of crack is generally not known, but the leak flow rate is shown to be much affected by the surface roughness as show in Fig. 7. It is thus found that the crack surface roughness is one of the important parameters for the leak flow estimation.

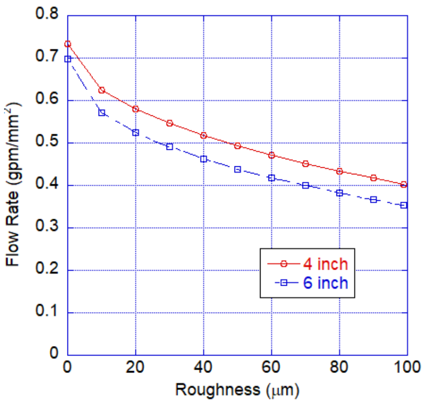

Fig. 7 Effect of crack surface roughness

V. CONCLUSION

The two-phase critical leak flow rates have been calculated using the system analysis code RELAP, and the representative non-homogeneous critical flow models, Henry-Fauske model and Ransom-Trapp model, were compared. The hypothetical crack in the 4 inch and 6 inch pipe walls were calculated. The pressure decrease and vapor generation in the crack, and thus the leak flow rates were found to be larger for the Henry-Fauske model. It was shown that the leak flow rates were not affected by the pipe wall temperature, but affected largely by the roughness of crack surface. It was thus found that the crack surface roughness is the important parameter for the estimation of two-phase critical leak flow rates in narrow cracks.

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