Choking Flow through Steam Generator Cracks- Experiments and Models

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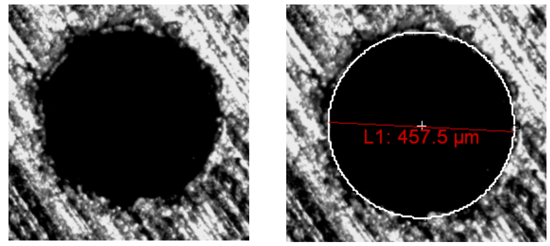
1. Introduction

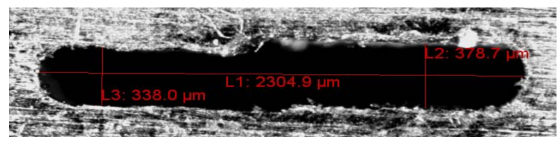
The steam generator (SG) tubes represent a major fraction of the reactor primary coolant pressure boundary surface area in both CANDU reactors and Pressurized Water Reactors (PWR). These tubes have an important safety role because they constitute one of the primary barriers between the radioactive and non-radioactive sides of the plant. The integrity of SG tubes is a safety-related issue, since the tubes are susceptible to corrosion and damage. The ability to estimate the leak rates from the through wall cracks in the steam generator tube is important in terms of radiological source terms and overall operational management of steam generators as well as demonstration of the leak-before-break condition [1]. In this study an experimental program and models were developed to measure and assess the choking flow rate of subcooled water through simulated steam generator tube crack geometries. Choking flow tests were conducted for various crack geometries for vessel pressures up to 7 MPa with various subcoolings and were compared with mechanistic models for short length to hydraulics diameter cracks.

2. Experimental Program

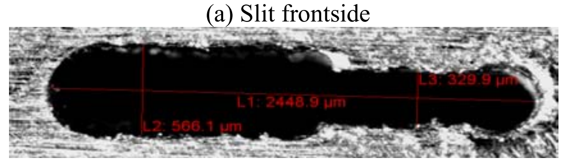
An experimental tests facility was developed that consisted of a pressure vessel designed for up to 10 MPa saturated water condition, a weighing tank that collects discharge water from crack sample and adequate instrumentation to measure the fluid conditions and chocking flow rates. Two types of test specimens were used in the experimental program. One is a round hole and the others were of rectangular slit geometry. The hole was drilled using a micro drill bit and a total of 5 slits were laser cut by machine on 316 SS plates of thickness 3.175 mm. The drilled hole is orifice like and represents a pitting type flaw, while the laser cut slits are representative of an axial stress corrosion crack that is partially opened. . The orifice hole can be seen in Figure 2. The average hole diameter was estimated as 475.5 micrometers(μm). The roughness was also estimated by measuring the valleys and peaks at the wall, and is estimated at 25 μm. The slit test specimens are numbered 2, 3, 4, 5, and 6 and increase in width respectively. Slit test specimen 2 is shown in Figure 3.



Fig, 1. Pin hole crack test specimen #1



(a) Slit frontside



(b) Slit backside
Fig. 2. Slit crack test specimen #2.

2.1 Cold Water Discharge Tests

Flow discharge tests were carried out with water at room temperature (20 °C). For the pinhole, the mass flux as a function of upstream pressure is shown in Figure 4. Since the water is discharged to atmospheric pressure, the upstream pressure represents total pressure drop across the slit. In Figures 5 and 6, the mass flux is shown as a function of pressure for slit #2 and slit #6 respectively. The trend lines show square root fit to the pressure showing that in both cases the mass flux increases as a square root of pressure. Using the flow rate data the Reynolds number and the discharge coefficient for the slit is calculated as

$$\mathrm{Re} = \frac{GD}{\mu} \qquad C_d = \frac{G}{\sqrt{2\rho\Delta P}}$$

The discharge coefficient for pinhole #1 varies from 0.45 to 0.48, for slit #2 it varies from 0.71 to 0.75 and for slit #6 it varies from 0.57 to 0.83.

2.2 Subcooled Flashing Discharge Tests

Test of flashing choking flow with heated water were carried out up to a vessel pressure of 6.8 MPa. Subcooling for the tests carried out varied from 25 to 50 °C. In Figure 3, the choking mass flux are shown as function of different subcooling for all slits. The choking mass flux increases as subcooling increases as expected due to a lower rate of vaporization at the test section exit. Also as the slit size increases the choking mass increases.

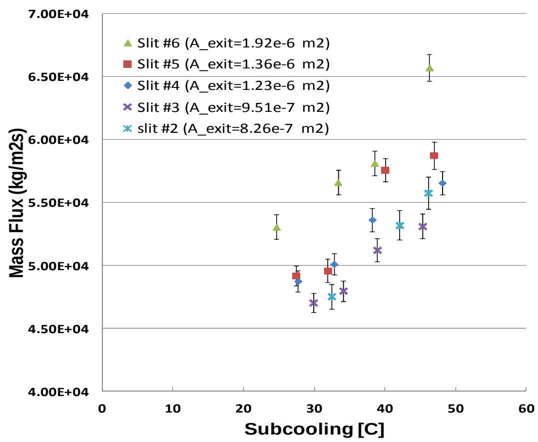


Fig. 3. Choking flow in slit geometry for 7MPa tests

3. Choking Flow Models

A one-dimensional model for two-phase choking flow was developed. A reservoir contains a fluid at constant pressure P_0 and temperature T_0 called the stagnation state. If the back pressure P_b is equal to P_0 then obviously no flow will occur in the channel. As P_b decreases, flow begins and a pressure gradient is established along the channel. Also, as P_b decreases, the flow rate increases until the back pressure reaches a critical pressure. At this point choking flow is obtained and any reduction in P_b beyond P_c does not change the flow rate or the pressure gradient in the channel. If the stagnation state is at saturation, then the entrance loss of the channel will cause the fluid to flash at the entrance. In this case, the channel only contains a two-phase mixture. In the case of higher subcooling, flashing will occur somewhere along the length of the channel. If one considers flashing to begin when the fluid reaches saturation, then flashing will occur at the point along the channel where the pressure drops below the corresponding saturation pressure at the stagnation temperature T_0. This is consistent with a homogeneous equilibrium model. This pressure drop is attributed to the single phase liquid frictional pressure drop along the channel. It is well known however that some amount of liquid superheat is required to produce and maintain vapor generation. With these considerations, a homogeneous equilibrium mode (HEM) is developed as well as a homogeneous nonequilibrium model (HNEM).

In case of HNEM for non-equilibrium effects to take place, the liquid must become superheated to allow for vapor generation. Alamgir and Lienhard proposed a model for flashing inception based on pressure undershoot [1]. They found that the liquid phase depressurizes below the saturation value, corresponding to the superheat required for vapor generation. Figure 6 show a comparison of the model predictions with SG simulated tube data of Revankar et al. and channel length of 3.17mm [2]. Again for the case of subcooled stagnation conditions and for much smaller channel length the HE model under predicts the critical mass flux data by as much as 27%. Again however, the HNEM model better predicts the data and is accurate to within 11% for the cases presented here.

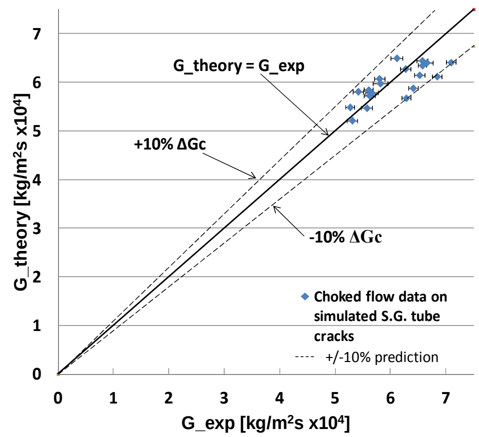


Fig. 4. Comparison of HENM with experimental data

4. Conclusions

An experimental program was carried out measuring subcooled flashing flow rate through well defined simulated crack geometries with L/D<5.5. Both homogeneous equilibrium and non-equilibrium mechanistic models were developed to model two-phase choking flow through slits. A comparison of the model results with experimental data shows that the HE based models grossly under predict choking flow rates in such geometries, while homogeneous non-equilibrium models greatly increase the accuracy of the predictions.

ACKNOWLEDGMENT

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