Abstract

In Pressurized Water Reactors and in CANDU reactors steam generator (SG) tubes represent a major fraction of the reactor primary coolant pressure boundary. 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. In this study an experimental program and analysis methods were developed to measure and assess the choking flow rate of subcooled water through simulated steam generator tube crack geometries. Experiments were conducted on choking flow for various simulated crack geometries for vessel pressures up to 7 MPa with various subcoolings. Measurements were done on 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.

Keywords: flashing flow; choking flow; steam generator tube; cracks; experiments; Burnel model.

1. Introduction

In Pressurized Water Reactors and in CANDU reactors steam generator (SG) tubes represent a major fraction of the reactor primary coolant pressure boundary. 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. In this study an experimental program and analysis methods were developed to measure and assess the choking flow rate of subcooled water through simulated steam generator tube crack geometries. Experiments were conducted on choking flow for various simulated crack geometries for vessel pressures up to 7 MPa with various subcoolings. Measurements were done on 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.

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. There are many identified degradation mechanisms related to SG tubes which include; intergranular attack and outside diameter stress corrosion cracking (SCC), primary water stress corrosion cracking, tube fretting and wear, foreign material wear, pitting, high cycle fatigue, and wastage or thinning. Of these, environmentally induced degradation through intergranular SCC and intergranular attack is the most serious degradation process at present. This degradation commonly occurs in crevice regions at tube support plates and tube sheet locations or under sludge piles, although intergranular SCC has also been observed in the free span of the tubes.

Damage to a steam generator tube impairs its ability to perform its required safety function in terms of both structural integrity and leakage integrity. They must maintain more than 6.9 MPa pressure differential between the inside and outside tube wall during normal operation. In the event of a main steam line break (MSLB) where the secondary side drops to atmospheric pressure, the tube wall differential pressure can be more than double that of normal operation. Traditionally, steam generators and steam generator tubes were designed with a sufficient safety margin against rupture. The design requirements of ASME code and the Nuclear Regulatory Commission (NRC) for steam generator tubes is 1.4P_{MSLR} > 25 MPa [1]. These safety margins are based on the rupture or burst pressure of an unflawed tube. A typical unflawed Alloy 600 tube has an industry expected burst pressure of ~86 MPa [2].

A sufficient safety margin in design against tube rupture was originally the basis to maintaining a suitable level of plant safety and reliability. Steam generator operability requires the completion of steam generator tube inspections using non-destructive techniques, usually eddy current examination, in intervals ranging from 12 to 40 months. There are also further steam generator tube integrity assessment guidelines which provide assessment procedures and criteria for assessing tube integrity for burst/collapse and through wall leakage, loading definitions, and design margins [3]. The final result is that steam generators operate under the leak-before-break concept, which demonstrates that a crack can grow through-wall, resulting in a leak, and that this through-wall flaw will be detected by leakage monitoring systems well before the flaw becomes unstable and the tube ruptures. Much research in the area of steam generator tube integrity is therefore related to the burst characterization of tubes with flaws [4]. Literature survey shows that most of the data on simulated steam generator cracks is carried out with the tube ultimately leading to burst [5]. The break geometry characterization is not properly carried out to associate the discharge data with a well characterized break. Thus prediction and benchmarking the predictions of leak rates through SG cracks with data is challenging.

There is very limited data on the steam generator tube leak rate measurement. Most studies of subcooled choking flow are related to long tubes with large L/D and nozzles [6-8]. The survey shows that this geometry has been studied over a large range of pressures and liquid subcoolings however, as can be seen, these data focus on L/D geometries greater than 15. Also, all of those data have a channel length greater than 10 mm, which is not indicative of steam generator tubing. Steam generator tubes have a wall thickness typically less than 3 mm. In view of this an experimental program was carried out where the simulated steam generator tube crack geometry were well characterized and choking flow of subcooled water tests were performed.

2. Experimental Facility

Design of a test facility to measure leak rates of through-wall cracks was based on the following goals. (1) The test facility should be modular so that various crack geometries can be studied. (2) The pressure differential across the break should be similar to the prototype about 6.8 MPa (1000 psi). (3) Facility should be such that tests can be easily repeated. Based on these goals a test facility is designed. A schematic of the test facility can be seen in Figure 1.

2.1. Pressure Vessel

The pressure vessel was constructed from a single 3.5 inch diameter schedule 160 316SS seamless pipe. It is 3.05 m in length and has numerous inlet and outlet ports including a 1 inch NPT port for connection to the test section specimens and ¼ inch ports for pressure measurement and thermocouples.

The vessel is equipped with one pressure relief valve with manufacturer preset of 8.3 MPa. The pressure vessel is pressurized using compressed nitrogen bottles connected via 3/8 inch SS tubing. A single stage regulator with downstream pressure gauge range of 0-13.8 MPa is used to keep a constant regulated pressure during a given experimental run.
2.2. Pressure Measurement

One differential pressure transducer and one gauge pressure transmitter are used for pressure data acquisition. The differential pressure transducer is a Honeywell ST3000® smart transducer used to measure the water level in the pressure vessel. A gauge pressure transmitter, located at P2 in Fig. 1 is used to measure the pressure just before the choking plane. The transmitter was manufactured and calibrated by Ashcroft®, with a range of 0-13.8 MPa with accuracy of 1.0%. Other pressure measurements are also available through needle gauges. As stated above, there is a pressure gauge on the nitrogen regulator. Also, a WIKA® brand needle gauge with a range of 0-6.9 MPa is located at P1. This allows for redundant monitoring of the vessel pressure.

2.3. Vessel Heating

Due to the high pressure and temperature at the extreme end of the range of experiments performed, submersible type heaters were not able to be used. The vessel water was heated from outside the pressure vessel using three band heaters 3 inches wide with and I.D. of 4.5 inches. The band heaters are Watlow® brand thin band ceramic insulated heaters. Each heater is capable of producing 1200 Watts and run in parallel off a 240 volt power supply. The entire pressure vessel and piping to the test section are insulated with 2 inches of mineral wool variety insulation.

Fig. 1. Schematic of test facility with measurement locations and types
2.4. Temperature Measurement

Temperatures were measured using 5 K-type stainless steel sheathed thermocouples at locations T1-T5. Measurements were taken at a rate of 1 Hz. At TC5 a tee was used to allow both pressure and temperature to be measured at the same location just upstream of the test section break. All thermocouples were inserted to the centreline of the flow at their respective locations.

2.5. Leak Rate Measurement

A 25.4 cm bolted bonnet full port gate valve initiates the experiment and the steam produced in the test section break is piped to the weigh tank where it is condensed. This allows for the dynamic measurement of the mass of water in the weigh tank. The following describes the components involved in this measurement.

A 189.3 litre condensing tank is suspended from two high precision miniature load cells via steel cable at LC1 and LC2. The load cells work in both tension and compression and have a load capacity of 136.07 kg each. Both were manufacturer calibrated and in-house calibrated. Their full scale output is different for each, but is approximately 2.2 mV/V with a combined error of less than 0.1%. Over a 20 minute period their full scale creep is less than 0.05%. In order to increase the accuracy of the load cell data acquisition, a signal amplifier is used to amplify the signal before being recorded. All electronic components are allowed to warm up a sufficient amount of time before an experiment was conducted.

2.6. Data Acquisition

Two separate data acquisition boards made by Measurement Computing® were used for data acquisition. A PCI-DAS-TC board was used for thermocouple measurement. This board allows for 16 differential thermocouple input channels, with a resolution of 0.03 degrees C. The other board was used for the pressure transmitter, load cells, and differential pressure transducer. This board, a PCIM-DAS16JR/16 can handle up to 16 single ended or 8 differential analog inputs with 16 bit resolution. All data acquisition was streamed through and collected using a program written in Lab VIEW® software. Thermocouple data was taken at 1 Hz while all other data was taken at 20 Hz.

3. Test Samples

For obvious reasons, there are a limited number of actual steam generator tube cracks that are available for use in any experimental program. Cracked tubes that are removed from service have been studied by a limited number of groups [5, 10, 11]. These limited studies however use destructive examination and experimental techniques to establish modes of failure for the tubes with flaws. Actual tube flaws can vary in size (microscopic to macroscopic), shape, location, and roughness depending on the flaw type and morphology while in service. The flaws themselves are affected by the length of time they are in service, corrosion, vibrations and stress, as well as thermal-hydraulic conditions. This makes it difficult to study actual tube flaws in a laboratory environment, where many tests can be conducted under well controlled conditions. It is very difficult to reproduce crack-like flaws whether they are very tight, deep, corrosion, or pitting type. It is very important and advantageous however to study leak rates in well controlled environment with a well characterized crack geometry as crack opening area plays an important role in flow rates. The test samples produced in this study represent partially opened relatively large pitting flaws and axial cracks. They are machined using advanced tools which are near the lower limit of sizes capable of being produced without chemical etching techniques. This allows for precise flaw characterization.

Two types of test specimens were used in the experimental program. One is a round hole and the other is rectangular slit. The hole was drilled using a micro drill bit and the 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 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 2. The orifice hole can be seen in Figure 3. The average hole diameter was estimated as 475.5 micrometers (μm). As mentioned before, the slits were cut by laser. This technique cannot produce a uniform cross section through the depth of the cut due to melting effects in the material. Therefore, one side of the cut will have a slightly different area than the other. For completeness, the laser cut slit is shown with the measure slit dimensions indicated on the figure. The effective cross sectional flow area was calculated by averaging the front and back cross sections of the slits.
4. Test Results

4.1. Cold Water Discharge Tests

Flow discharge tests were carried out with water at room temperature (20 °C). Since the water is discharged to atmospheric pressure, the upstream pressure represents total pressure drop across the slit. Using the flow rate data the Reynolds number $Re$, and the discharge coefficient $C_d$ for the slit is calculated as

\[ Re = \frac{G D}{\mu} \]

\[ C_d = \frac{G}{\sqrt{2 \rho D P}} \]

(1)
(2)

where, $G$ is mass flux, $D$ is slit hydraulic diameter, $\rho$ is the fluid density and $\mu$ is viscosity. The data on discharge coefficient as function of pressure showed that a square-root fit to the pressure showing that in both cases the mass flux increases as a square root of pressure. The discharge coefficient for pinhole #1 varied 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. In Figure 4 Typical discharge coefficient $C_d$ as function of Reynolds number for slit #4 is shown.

Fig. 2. Slit crack test specimen #2.

Fig. 3. Pin hole crack test specimen #1

Fig. 4. Discharge coefficient $C_d$ as function of Reynolds number for slit #4.

4.2. 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. A comparison between cold water discharge tests and heated tests for slit #2 can be seen in Figure 5. Subcooling for the tests carried out on slit #2 varied from 15 to 29 °C. Data for measured discharge rate for slit #6 at four different subcoolings near the same pressure can be seen in Figure 6. This allows for the dependence of mass discharge rate on subcooling to be examined. The variance of pressure for these runs was less than 0.08 MPa. In Figure
7, the choking mass flux is 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.

4.3. Experimental Uncertainty Analysis

Experimental data uncertainty analysis was carried out for measured data such as, diameter, pressure temperatures, and mass using instrument measurement uncertainties and for the uncertainties in calculated parameters such as mass flux, error propagation method was employed. The total relative error in the mass flux data using the weight tank measurement method ranged from 1.17 % to 1.95 % for all experimental runs. Errors for a representative case are shown in Table 1. The error contributions from the different parameters of interest for the same run are shown in Table.2.

![Fig. 5. Cold water discharge mass flux and subcooled flashing mass flux for slit # 2](image)

5. Choking Flow Model for Slits

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 vapour generation. With these considerations, a homogeneous equilibrium model (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 vapour generation. Alamgir and Lienhard [11] proposed a model for flashing inception based on pressure undershoot. They found that the liquid phase depressurizes below the saturation value, corresponding to the superheat required for vapour generation. Figure 7 show a comparison of the model predictions with SG simulated tube data of Revankar et al. [12] and channel
length of 3.17mm. 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. 6. Choking flow in slit geometry for 7MPa tests.](image)

Table 1. Error for a representative test case, $P = 6.7277$ MPa, $G=6.5707 \times 10^4$ kg/m$^2$s

| Parameter      | Value (1) | Standard Error (2) | Relative Error (2)/(1) |
|----------------|-----------|--------------------|------------------------|
| Mass flux $G$ (kg/m$^2$s) | 65707.5   | 1279.3             | 0.01947                |
| Pressure $P$ (Pa)    | 6727738   | 67277.38           | 0.01                   |
| Temperature $T$ (°C) | 237.04    | 1                  | 0.0042                 |

Table 2. Error Contribution for a representative test case

| Parameter      | Standard Error | Error Contribution |
|----------------|---------------|--------------------|
| Mass flux $G$, (kg/m$^2$s) | 1279.3        | Mass 1 (kg)  | Mass 2 (kg) | Area (m$^2$) |
|                |               | 456.627           | 465.627     | 314.572      |

6. Conclusions

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. A literature survey showed that there are few data sets available on crack geometries related to steam generator tubing. An experimental program was carried out measuring subcooled flashing flow rate through well defined simulated crack geometries with $L/D<5.5$. As subcooling increases the flashing discharge rate also increases. A homogeneous non-equilibrium model for flashing flow in steam generator tube crack was modelled. The prediction from HENM agreed well within 10% of experimental data for choking discharge rates from such geometries.

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Fig. 7. Comparison of HENM with experimental data

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