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Structural mechanical and thermal hydraulic aspects on the behaviour of crack like leaks in piping

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ABSTRACT

The evaluation of fluid flow rates through crack-like leaks in pressurized components of NPPs plays an important role for leak-before-break considerations. When using available simplified methods for the estimation of critical discharge flow rates, a suitable friction factor has to be chosen. Guidelines are given in the German code KTA 3206 based on investigations of leak rate experiments summarized in this paper. The frictional pressure loss in different leak flow approaches has to be chosen consistently in order to obtain comparable results with different models.

Thermal hydraulic and structural mechanical analyses were performed for a postulated leak in the pressurizer surge line (SL) of a PWR Konvoi type under design basis accident conditions. The leak was postulated in form of a through-wall crack in circumferential direction. The size of the leak was calculated in the framework of Finite Element calculations with the code ADINA using an analysis model of a cooling loop of Konvoi type. With the calculated leak size, an ATHLET calculation was conducted, also examining the influence of the consideration of a variable leak size depending on the system pressure and mechanical loads. In the investigated case, the implication of the decreasing leak size, especially on the course of the remaining system pressure, cannot be neglected. The reduction of the leak area amounts in the transient examined to ca. 25% after about 1 h due to both the system pressure and temperature decrease and leads therefore also to an approximately 23% smaller leak rate. These results are dependent on the assumed position of the leak.

Concerning the determination of the leak rates as critical flow-through rates with simplified methods good agreement has been achieved although the approaches differ considerably in parts. Relevant influence factors are the inflow losses in the crack channel, the consideration of the hydraulic diameter in connection with the leak area and the assumptions on the flow resistance coefficient due to the roughness of the crack surfaces.

1. Introduction

For the demonstration of break preclusion for pressure retaining components in NPPs, the technical rule KTA 3206 (KTA 3206, August 2013) includes the requirements for the leak-before-break verification. For this procedure, it has to be ensured that a wall-penetrating crack is subcritical with respect to instable growth, and that the resulting leakage under stationary operation conditions can be detected by a leak detection system. Whether a leak can be detected on time depends mainly on the actual flow rate. Methods for the analysis of leak areas and leak rates, which are validated on experimental basis, have to be provided. For a conservative assessment of a leak concerning its detectability, the real flow rate has to be underpredicted rather than overestimated. This can be achieved with available simplified methods for the estimation of critical discharge flow rates (see Section 2) through a suitable resistance coefficient (see Section 3).

The work summarized in this paper is concentrated on one-dimensional leak rate models, in which the thermal-hydraulic variables (e.g. pressure, temperature, void fraction) are resolved over the flow path length. The question whether the critical discharge flow will be reached or whether a subcritical flow exists, can only be assessed within the frame of refined thermal hydraulic analysis methods. Work has been started to use higher dimensional approaches (see Section 6).

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Crack-like leaks in piping of the pressure retaining boundary of nuclear power plants cause loss of coolant accidents (LOCA), which are characterised by changes of global system parameters like internal pressure and fluid temperature as well as local physical quantities within the leak area. The time-dependent changes of internal pressure and fluid temperature in the cooling circuit due to a postulated leak are computed by thermal hydraulic codes. In thermal hydraulic calculations, it is common practice to assume a leak size which is constant during the LOCA.

With Finite Element (FE) analysis tools like ADINA (ADINA (Automatic Dynamic Incremental Nonlinear Analysis), September 2010) or ANSYS Mechanical (ANSYS® Mechanical Release 14.0, 2012), the time-dependent leak opening and the leak area during a LOCA can be calculated with high accuracy (see Section 4). For subcritical crack-like leaks with small leak openings, the change of the leak area during a LOCA can be significantly, which may affect global as well as local system parameters. Therefore, first investigations on the necessity to consider fluid–structure interaction (FSI) in case of fluid flow through crack-like leaks have been performed.

2. Basics for leak rate calculations

The flow of (subcooled) water (i.e. fluid temperature is below saturation temperature) through a crack-like leak is characterised by strong gradients of pressure, void fraction and phase temperatures inside the leak. The thermal hydraulic processes of the discharge are illustrated in Fig. 1.

Immediately behind the entrance into the crack-like flow channel, the flow is constricted in comparison to the cross section (vena contracta). In case of pressurized water conditions, the originally subcooled liquid becomes saturated and significantly superheated due to the strong pressure drop caused by both friction and acceleration losses of the flow. Evaporation may start within the flow channel or at the outlet. Frictional pressure losses enhanced by the crack face surface roughness are crucial for the correct evaluation of leak rates (see Section 3).

Often critical two-phase flow conditions are assumed to describe the leakage (Isbin et al, 1957; Faletli and Moalton, 1963; Reimann, 1984); this is usually the case if the speed of sound is reached within the flow path. The flow rates can be described with one-dimensional models developed by e.g. Moody (1965), Pana and Müller (1978) or Henry (1970), as well as with the mechanistic 1D finite-difference CDR-model (Critical Discharge Rate) of the ATHLET code (ATHLET User's Manual, 2012), the delayed equilibrium model (Feburie et al., 1993) or the phenomenological model developed by Müller (Grebner et al., 1999). The flow models differ in the assumptions regarding the flow regime and the thermal hydraulic description, as well as in the considered crack geometry. It is known that these intrinsic model differences may lead to large discrepancies in results of leak rate calculations (Grebner et al., 1995).

To ease the handling of simplified structural mechanical methods and leak rate calculation methods, the interactive computer program WinLeck has been developed in order to use various methods under a common graphical user interface (GUI). The program contains different models for the determination of leak areas as well as leak rates of through-wall cracks. Furthermore, the program allows the estimation of critical crack lengths for through-wall cracks in both circumferential as well as longitudinal direction in piping and the estimation of failure pressures of piping with surface cracks. The capabilities of WinLeck are summarised in the User Handbook (Heckmann et al., July 2013).

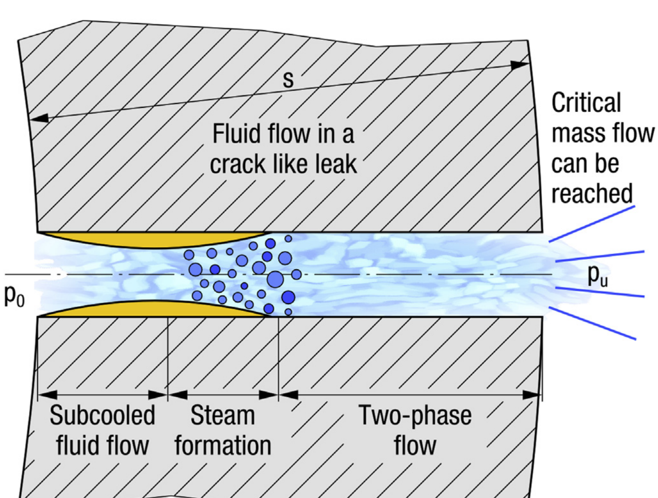

Fig. 1. Schematic presentation of the discharge flow through a crack.

3. Derivation of covering values for the friction factor

Several experimental studies have been performed in the past to measure the friction factor describing the flow resistance resulting from crack-like flow channels with rough surfaces. Fundamental publications are from Nikuradse (1933), Button et al. (1978), Gardner and Tyrrell (1986), John et al. (1988), Kefer et al. (1988) and Westphal (1991). In all these studies, the correlation between the flow cross section geometry, the roughness of the channel walls and the resulting flow resistance is documented.

The reports have been evaluated to obtain a dependence of the friction factor as a function of the ratio of the hydraulic diameter (measure for the crack width) and the roughness R_z. The results of this work are shown in Fig. 2 including the proposed covering curve, which has been included in KTA 3206 (KTA 3206, August 2013).

The friction factor describing the resistance resulting from the rough surfaces of a crack is usually modelled in the same way for two-phase as for single-phase flow. More details on the performed work are given in (Grebner et al., June 2014).

4. Comparative leak rate calculations on a test series

For the validation of different leak rate models, different approaches have been applied to test series described in (John et al.,

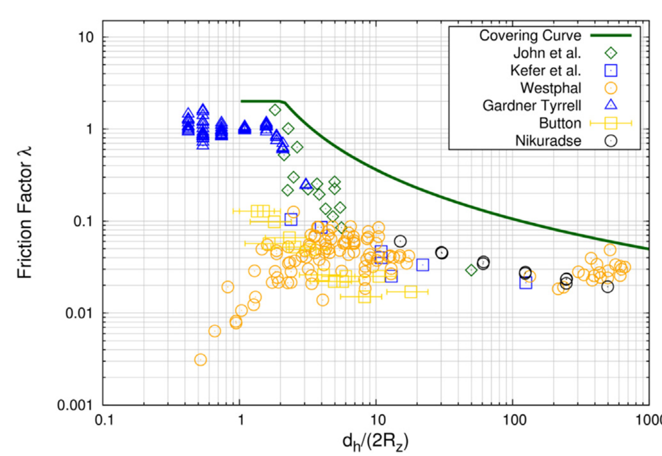

Fig. 2. Measured friction factors λ for different $d_h/2R_z$ from various experiments and covering curve included in KTA 3206 (KTA 3206, August 2013).