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SPECIMEN TESTING FOR STEAM GENERATOR TUBE LEAKS WITH MEASUREMENT OF FLOW PATTERNS

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ABSTRACT

Leak testing has been done at the FSI (Fluid-Structure-Interaction) test rig at MPA University of Stuttgart using specimen with fatigue cracks, circular holes and slits, for fluid conditions up to 8 MPa and temperatures up to 250 °C with atmospheric environment conditions. The mass flow rates are measured and flow pattern at the outlet is recorded with a high-speed camera. These tests cover a range of different relative leak openings L/d_h (ratio of wall thickness to hydraulic diameter), allowing to study the discharge flow regimes of leaks at thin walls. The high-speed camera allows to show that dependent on the stagnation conditions and the relative leak opening (L/d_h) the outlet region is characterized by a free-jet combined with two-phase flow. In tests with relatively small L/d_h the free-jet proportion in the outlet region is large. A stable liquid jet (as seen for Freon in Fauske and Min, 1963) is only seen for small subcooling, even for very small L/d_h.

INTRODUCTION

This work was triggered by reportable events related to linear indications from eddy current testing of steam generator tubes at the German plant GKN II in 2018, 2019 and 2020 (Ministry of Environment, Climate and Energy Economy Baden-Württemberg, 2020). In August 2018, the annual revision was carried out at GKN II. The plant holds four steam generators with each containing about 4100 steam generator tubes (SGT) with a wall thickness of 1.2 mm. As a part of the annual revision eddy current testing was performed on the steam generator tubes resulting in several indications with different damage characteristics including wall thinning. In 2017, the required 20 % testing scope according to KTA 3201.4, was extended to 100 % after indications were found on the cold side of the tubes in one steam generator. Steam generator tubes with a wall thickness weakening of bigger than 30 % were plugged – no crack-like indications were detected. One year later again, wall thickness weakening was detected at all of the four steam generators. The indications could be divided into two main damage characteristics including volumetric, point or cone-like and linear circumferentially oriented crack-like wall thickness weakening phenomena. The flaws had a depth of up to 91% of the wall thickness of 1.2 mm. All of these originate from the secondary side. A list of measures was seized and fracture mechanic analyses were applied to estimate the residual load capacity. Until 2020 improved testing and evaluation methods were established and a safety assessment with the demonstration of physical integrity was again conducted. Although the tightness of the SGT was ensured, the observed degradations motivated the focussed investigation of the consequences of SGT leakages.

In case of a wall-penetrating damage in a steam generator tube during commercial operation, fluid from the activity-retaining reactor coolant system passes to the secondary water/steam cycle. Activity monitoring of the secondary cycle with several independent and sensitive measuring devices enables the system to be taken-out of service at very low activity concentrations. In August 2019 a first project proposal was worked out at MPA and GRS to investigate leak rates at thin-walled structures like steam generator tubes. Within the reactor coolant pressure boundary (RCPB) of a pressurized water reactor, the SGT are the thinnest components. In case of a wall-penetrating defect in one of these tubes, the primary coolant will leak to the secondary loop, which is operated at a lower pressure. While the mass flow through leaks in thicker walls is well studied and understood (Schmid et al., 2021), the flow pattern was expected to differ significantly in the case of a SGT leak. Therefore, several investigations concentrated on this topic (Majumdar et al., 2001, Revankar and Riznic, 2019, and Zhang et al., 2019) and measured the flow through leaks in thin structures. This paper contributes specific tests on thin specimens with the measurement of flow rate, pressure field, and optical observations, which are also used in the related work of Heckmann et al., 2022b.

This paper describes the test facility in different configurations as well as the specimen that were used and shows a selection of the results that were evaluated from the measured data. Also, a selection of results of the leak rate investigations are described. One major work item of these investigations were the optical recordings of the discharge at thin-walled specimens with pin holes. The paper concludes with a summary section.

FSI TEST FACILITY

The testing has been done at the FSI (Fluid-Structure-Interaction) test rig at MPA University of Stuttgart, which was built up as a modular test stand for component testing under fatigue loading in hot and cold water cycling environmental condition and upgraded for also allowing leak rate testing in a previous project (Silber et al., 2017). A detailed description of the FSI test rig at MPA University of Stuttgart is given by Schmid et al., 2021. Due to the requirements concerning the investigations that were planned for this project, some major adaptions had to be realised at the test rig. This section explains the different setups of the FSI test rig that were realised in order to meet the requirements for the investigations. The leak rate test configuration allows for measurement of leak rates using Coriolis-flow meters and a leakage collecting vessel for up to 200 g/s as well as measurement of pressure up to 75 bar and temperature in the stagnation volume up to 270 °C. In Figure 1 the experimental setup is shown.

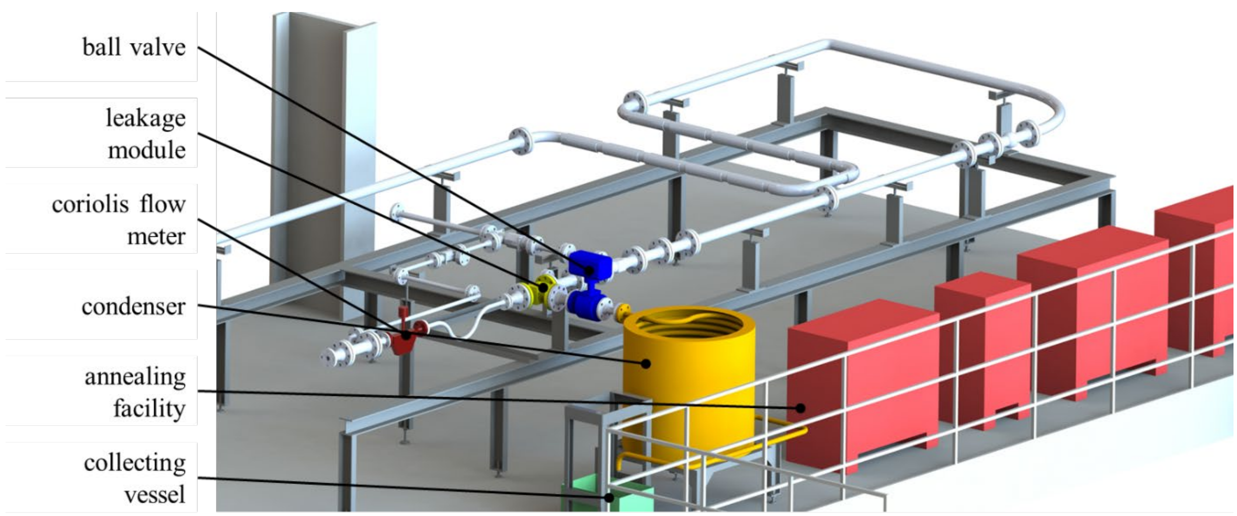

Figure 1. FSI test rig configuration for leak rate investigations

One extension aims at the optical investigation of the discharge. Therefore, the ball valve and the condenser were replaced by an acrylic glass housing and a high-speed camera. The acrylic glass housing drains the steam away from the high-speed camera equipment and allows a partial condensation of the leakage. Additionally, the high-speed camera equipment was shielded from heat radiation and steam by metal sheets. Furthermore, a blower was used to force water droplets back to the acrylic glass housing and protect the lens, see Figure 3. The setup for these investigations did not allow for closing the leak. The leakage module with the specimen was held open throughout a test series at one constant temperature level and selected pressure levels.

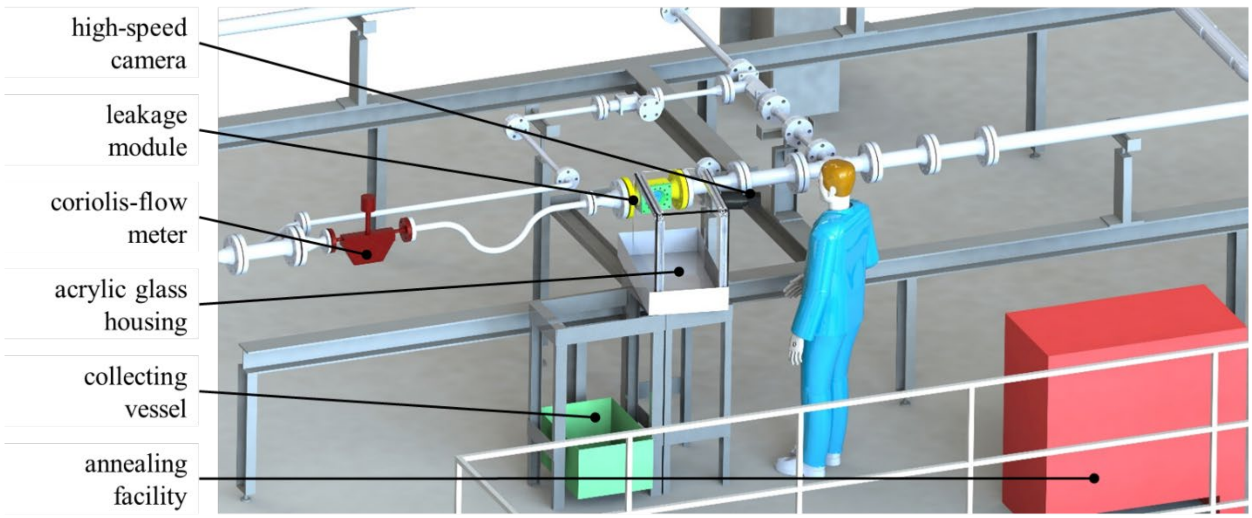

Figure 2. FSI test rig configuration for optical investigation (free discharge, high-speed camera)

One further aim was to investigate a possible influence of discharge into a water vessel on the measured leak rate instead of free discharge into air. Therefore, a discharge vessel was designed, equipped with a spill over tube. This setup (see Figure 4) is mainly capable for leak rate measurements at temperatures up to 90 °C but can be used at higher temperatures in the short term. Leak rates were measured using the Coriolis-flow meters as well as the leakage collecting vessel fed by the spill over tube.

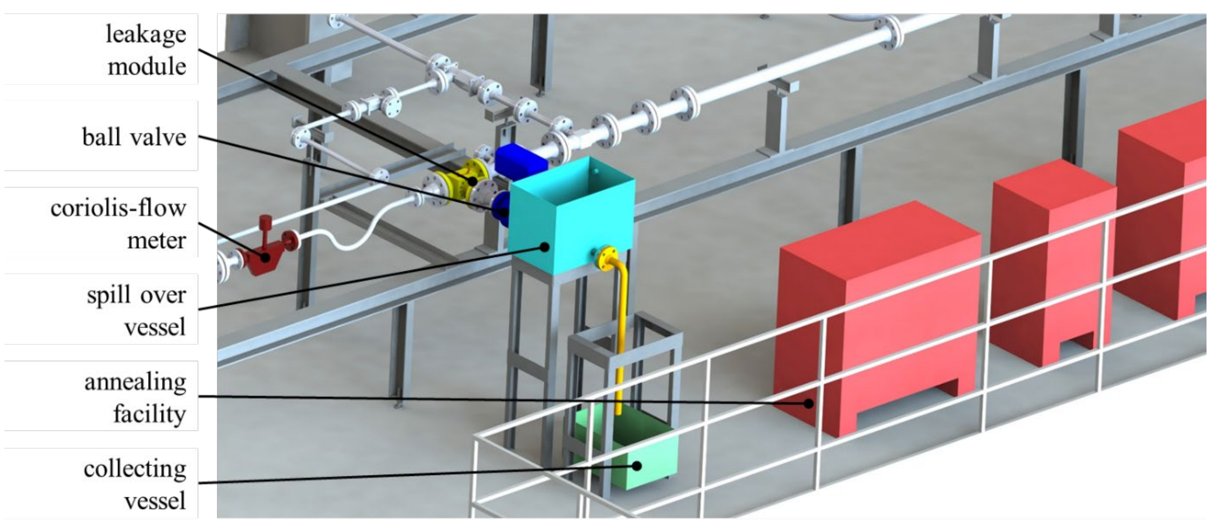

Figure 3. FSI test rig configuration for investigation of discharge into water

SPECIMENS

Three different types of specimen with wall thicknesses of around 1.2 mm and less were manufactured, most of which with circular holes but also three with defined slits and one with a fatigue crack. In addition, two specimen with wall thickness of 8.0 mm of a recent research project were included and investigated using the high-speed camera. Within this section all three types of specimen are depicted and described shortly. Table 1 gives the hydraulic diameter and thickness as well as type of the specimen. Pin hole specimen were manufactured by sinker EDM using base plates of 8 mm thickness. A wall thickness of 1.2 mm was manufactured only in a centre hole of 5 mm in diameter. Metal sheets of 1.3 mm were partly welded together keeping a constant distance in order to manufacture specimen with defined slits. These were attached to a support plate of 8 mm thickness and seal welded. One specimen was equipped with a fatigue crack. The fatigue crack was grown, originating from a semi elliptical flaw, into a plate with a thickness of 16 mm. In a final process, material was worked off using sinker EDM, leaving a fatigue crack in a wall of around 1.3 mm, see Figure 5.

Table 1. Geometry of the leaks

Specimen	Type	Hydraulic diameter in mm		Wall thickness in mm
		Upstream	Downstream	
VS000		0.5	0.5	0.2
VS030		0.304	0.302	1.24
VS040		0.41	0.396	1.22
VS045	pin hole	0.446	0.476	0.65
VS055		0.626	0.592	1.2
VS060		0.634	0.646	8.0
VS115		1.21	1.204	8.0
010T001	defined slit	0.248	0.54	1.25
020T001		0.719	0.468	1.25
010T001M		0.503	0.504	1.89
R4	fatigue crack	0.1	0.156	1.3

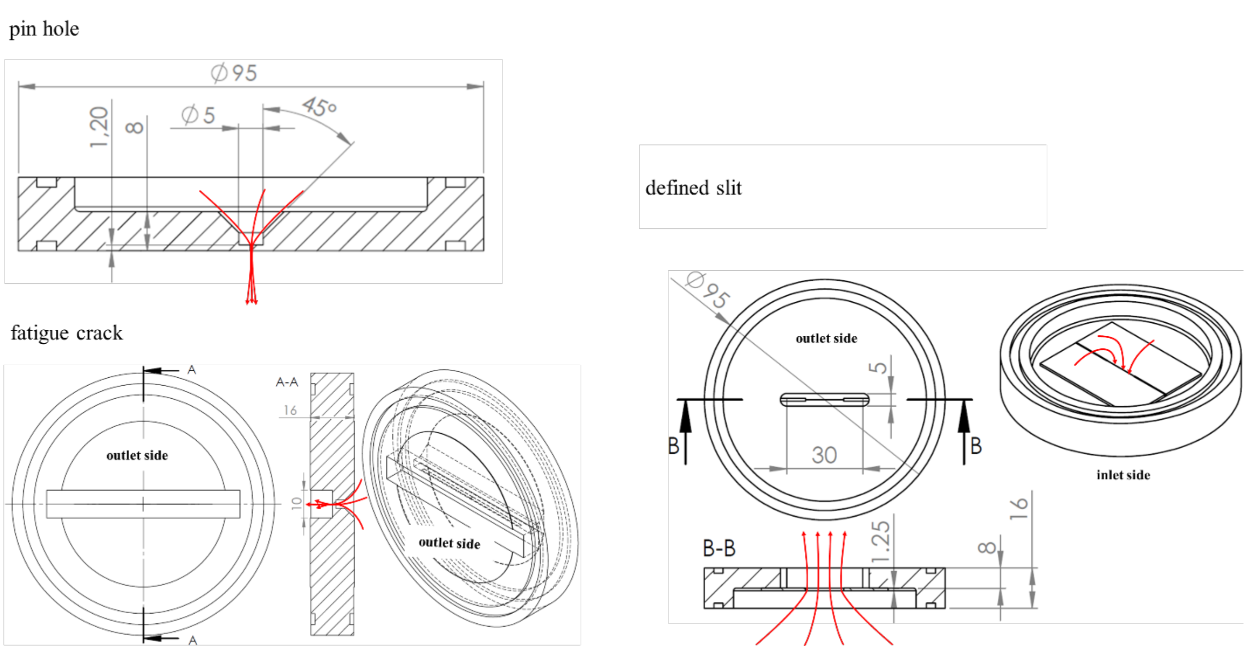

Figure 4. Technical drawing of specimen with pin hole, defined slit and fatigue crack

LEAK RATE INVESTIGATIONS

The experimental setup used for the leak rate measurement investigations is shown in Figure 1. Leak rate measurements were carried out in the temperature range from 20 °C to 270 °C for pressures between 5 and 80 bar. The leak mass flow was guided into the condenser, which approximately corresponds to free discharge in air environment.

While the leak flow rate results for all specimens are documented in Heckmann et al. (2022a), this section provides a detailed description of the leak rate investigations of specimen R4. The test specimen R4 with a fatigue a crack is shown in Figure 5. The geometric parameters of the specimen are given in Table 1. All specimens were measured regarding the geometry of the inlet and outlet side using a light microscope. Figure 8 and Figure 9 show stitched images that represent the entire inlet and outlet area of the fatigue crack of specimen R4. More than 160 individual leak rate measurements were carried out, including also repeated measurements. In the repeated measurements, considerable deviations occurred in some cases which could be traced back to particles that were used in the FSI test rig for particle image velocimetry (PIV) measurements in past experiments and remained in the system despite cleaning and filtering. These particles caused a reduction of the leak cross section over time and thus a reduction in leak rate. This phenomenon only occurred for fatigue cracks and could not be observed for pin hole and defined slit measurements with parallel leak channel flanks. Apart from the above-mentioned particles, no relevant changes to the crack, the inlet or outlet area, caused by flow during the leak rate investigations, could be observed, see Figure 10.

Figure 5. Stitched images of the fatigue crack of R4 from the inlet side after leak rate measurement with a full crack length of around 42 mm

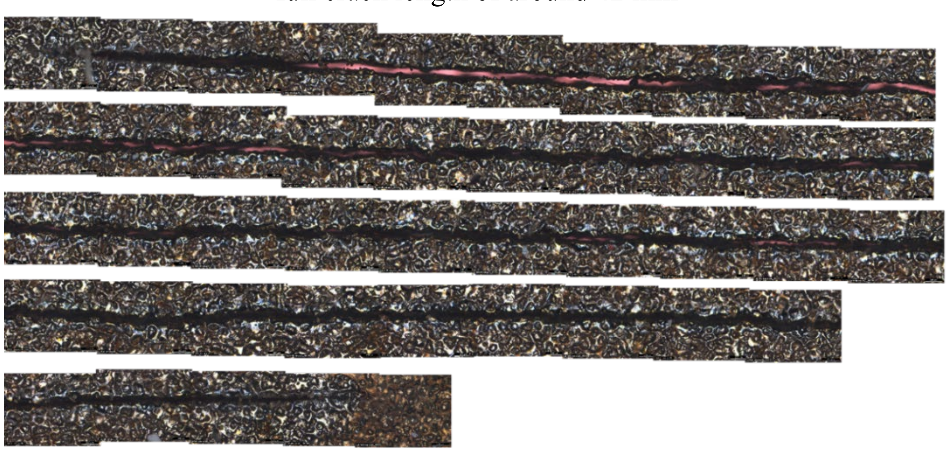

Figure 6. Stitched images of the fatigue crack of R4 from the outlet side after leak rate measurement with a full crack length of around 44 mm

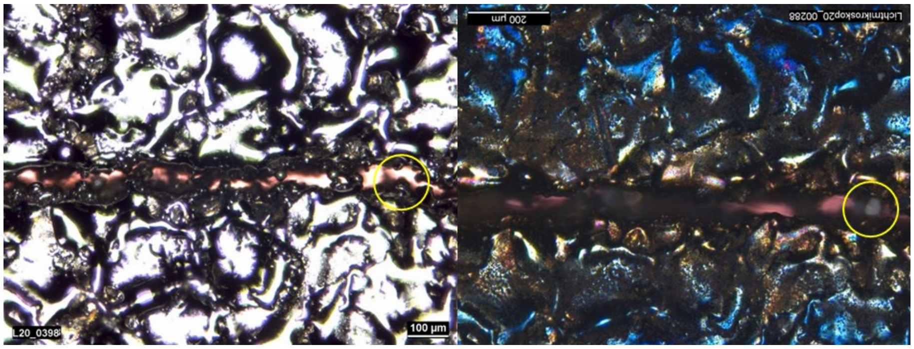

Figure 7. Image of the inlet at specimen R4 before (left) and after (right) leak rate measurement with particle from PIV measurements

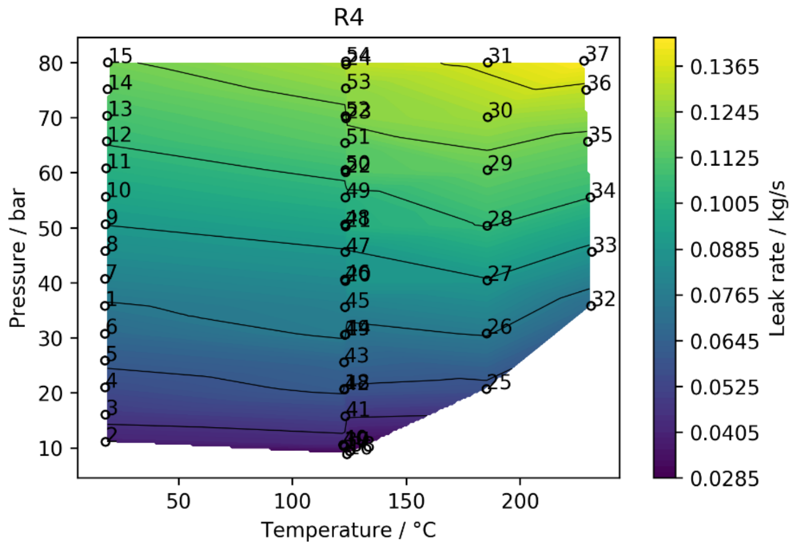

Figure 8. Measured leak rates at specimen R4

The leak tests with discharge into a water tank was done with selected specimens. No effect on the leak flow rate measurement was measured when comparing discharge into air and into water.

OPTICAL INVESTIGATIONS - OBSERVED FLOW PATTERN

The optical investigations were carried out to underpin the model assumptions for the Metastable Jet Model described in Heckmann et al. (2022b). The aim is to observe liquid water above the evaporation temperature (metastable liquid) at the leak exit. For a selection of specimens, discharge investigations at the outlet were performed using the high-speed camera within the complete parameter range of the FSI test rig. The testing has been carried out with pin hole like leaks only. The rotationally symmetric discharge allows for repeatable recording angles and better comparability of different specimen with the high-speed camera. Figure 12 gives an overview of the three different discharge flow patterns that were observed and distinguished for specimen VS030. For temperatures below 105 °C in the stagnation volume, discharge flow forms a single jet. Within the transition range from 105 to around 145 °C both, a jet as well as a steam cone can be observed. For temperatures above 145 °C, the jet disappears, and a steam cone develops. These three flow patterns can also be observed for specimen VSV055, see Figure 13. However, for specimen VS055, a jet still forms up to temperatures of around 117 °C.

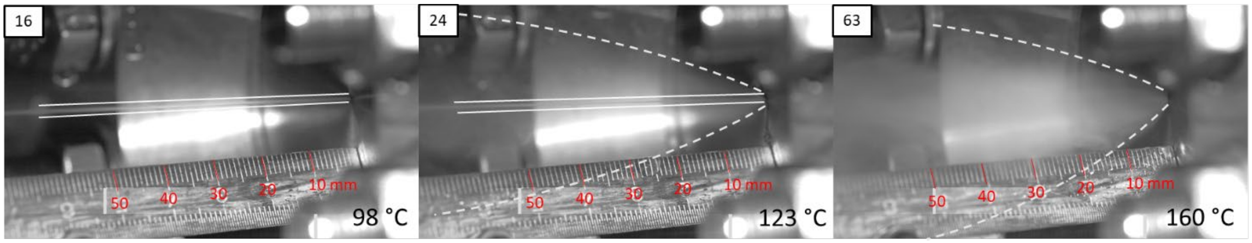

Figure 9. Flow pattern at around 50 bar for specimen VS030 at 98 °C, 123 °C and 160 °C

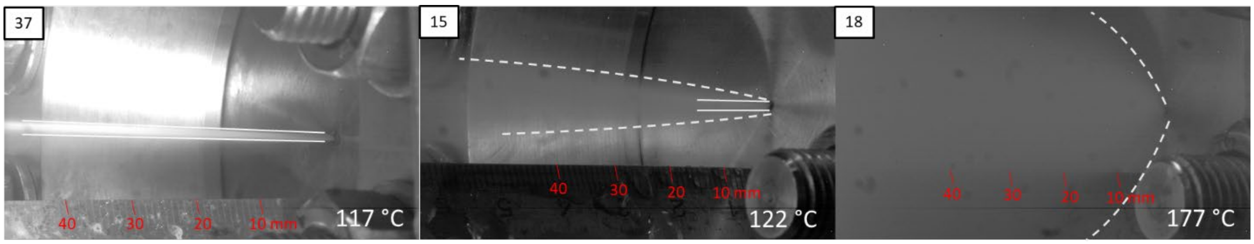

Figure 10. Flow pattern at around 50 bar for specimen VS055 at 117 °C, 122 °C and 177 °C

Figure 14 gives a summary in form of two diagrams for all investigated parameters with specimen VS030 and VS055. Each dot in the diagram refers to a video of 20 s length. A python script was then used to handle these videos and extract one frame out of every video. This frame was then evaluated manually, guided by the python script. The positions of the vertical lines, that mark the border of the three flow patterns, were defined manually by evaluating the coloured dots in the diagram. As can be seen from Figure 14, this change in flow pattern seems to be independent of pressure and is primarily driven by temperature for the investigated parameter range (although the transition temperatures are different for VS030 and VS055).

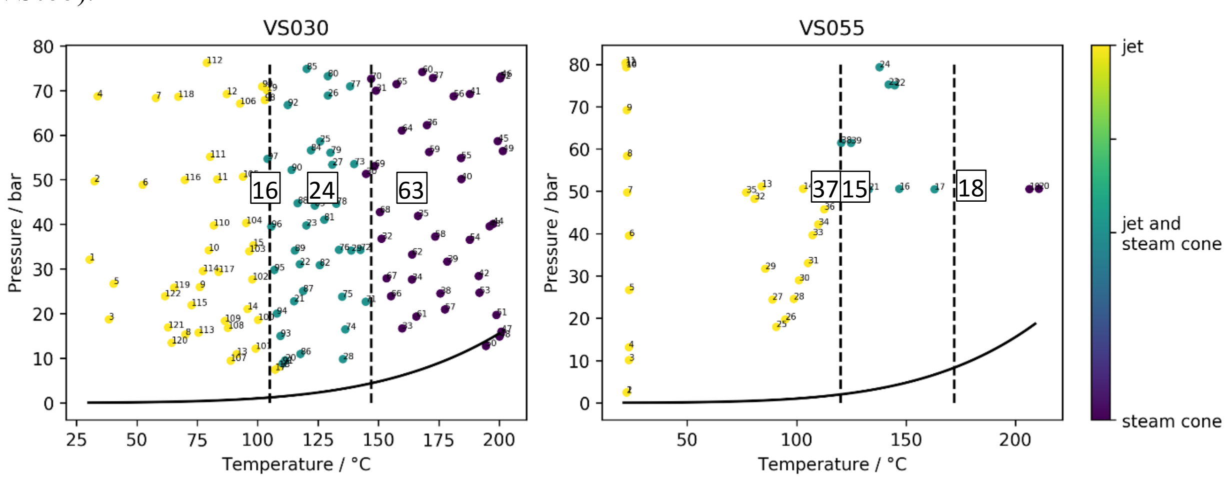

Figure 11. Categorization of discharge flow pattern for specimen VS030 and VS055, the numbers in squares refer to the numbers in Figure 12 and Figure 13.

Hence, the flow patterns from Figure 12 and Figure 13 show a dependence mainly on temperature and on relative flow length, which can be plotted in a diagram, see Figure 15. It appears that for smaller values of the relative flow length L/d_h,a metastable jet forms up. This leak type is also referred to as gate-like whereas larger values of relative flow length are referred to as tunnel-like leaks. These behave fundamentally different as no metastable phase can be observed on the outlet.

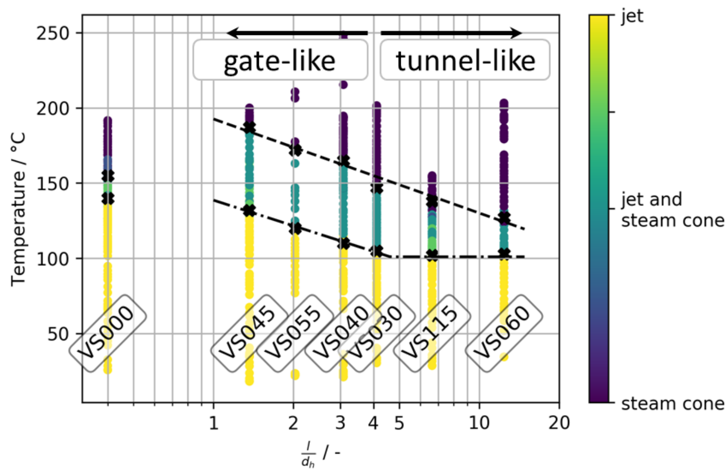

Figure 12. Flow pattern dependent on relative flow length (l/d_h)

SUMMARY AND CONCLUSION

This paper gives an overview about the experimental setting of the FSI test rig and the applied investigations at MPA University of Stuttgart. Measurements were carried out with specimen containing fatigue cracks, circular pin holes and slits, for fluid conditions up to 80 bar and temperatures up to 250 °C with atmospheric and environment conditions. Results for a fatigue crack specimen are presented in detail. Three different experimental settings were realized for thin-walled specimens equivalent to wall thicknesses of SGT. The first one allows leak rate measurements in the full parameter range of the FSI test rig using a condenser which drains and condenses the leakage. A second setup allows for investigations of discharge flow pattern with a high-speed camera. The high-speed camera allows to show that dependent on the stagnation conditions and the relative leak opening (L/d_h) the outlet region is characterized by a free jet combined with two-phase flow. These tests cover a range of relative leak openings L/d_h(ratio of wall thickness to hydraulic diameter) from 0.4 to 12. In tests with relatively small L/d_h the free-jet proportion in the outlet region is large. A stable liquid jet (as seen for Freon in Fauske and Min, 1963) is only seen for small subcooling, even for very small L/d_h. One measurement series was carried out to investigate influence of water environment conditions to the leak rate at room temperature – no deviations caused by the water environment could be found within these investigations. The results of these experiments deliver a contribution to develop computational approaches such as the Metastable Jet Model and assumptions for gate-like leaks are underpinned. Further, experiments with tight cracks, regarding fatigue as well as stress corrosion, at steam generator tubes are planned with secondary side pressure.

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