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COUPLED FLUID-STRUCTURE SIMULATION OF AIR-STEAM LEAKAGE IN SMALL-SCALE CONCRETE SPECIMENS

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ABSTRACT

At the Materials Testing and Research Institute (MPA Karlsruhe) of the Karlsruhe Institute of Technology (KIT) air-steam leakage experiments with small-scale concrete specimens split by a single penetrating crack were performed. Thermocouples were cast into the concrete specimen to measure the temperatures, which are developing through a heating air-steam flow. Additionally, the mass flow rate of the air and steam phase were measured over time. Through a coupled simulation scheme, the temperature development within the specimen and the related deformation as well as the leakage flow, including fluid-structure interaction (FSI), have been calculated. To simulate the leakage flow and the heat transfer from fluid to solid the thermal-hydraulic system software ATHLET (GRS, 2017), which has been developed and validated by GRS, is used. The thermal and structural response of the concrete specimen is calculated with the finite element program ANSYS Mechanical.

INTRODUCTION

The containment of a nuclear power plant is the last barrier to prevent the release of radioactive substances to the environment, especially in case of a severe accident. Therefore, leak-tightness of containments is a safety relevant issue. In plant designs with concrete containment structures it is a challenge to assure leak-tightness, because concrete structures will always have cracks even during normal operation. In some cases, this may lead to a very small amount of leakage, when there is a big enough pressure difference applied across the wall. The amount of leakage must be known to decide, if this is within acceptable bounds or not.

Many researchers investigated the leakage process through cracked concrete structures to predict the leakage rate with empirical formulas including several simplifying assumptions (Rizkalla et al., 1984; Suzuki et al., 1992; Greiner and Ramm, 1995; Badoux, 2002). First, the complex geometry of a crack in a concrete structure, which may include the branching of one leakage path into multiple leakage paths or vice versa, or a nonuniform crack width w along the surface and through the depth, is reduced to a prismatic volume through the thickness of the wall. Furthermore, it is assumed, that the crack surface length b is much bigger than the crack width ($b \gg w$), and the crack depth l, which is equal to the wall thickness in a containment building, is much bigger than the hydraulic diameter d_h of the leakage flow ($l \gg d_h$). But most importantly, the empirical formulas are derived from air leakage experiments and can be applied to steam leakage only with reservations.

Riva et al. (Riva et al., 1999) compared the application of several published empirical formulas to calculate the steady state value of air and air-steam leakage. In case of air-steam leakage, the value of dynamic viscosity input in the calculation is adopted to the experiment. The empirical formula proposed by Rizkalla et al. (Rizkalla et al., 1984) showed the best results in the comparison. Simon et al. (Simon et al., 2007) employed a coupled simulation scheme to calculate air-steam leakage of large-scale cracked concrete specimens. The flow simulation, which was solved with a finite difference approach, was coupled to a thermal-structure mechanical simulation performed with the finite element code CAST3M. A linear profile with an adapted friction factor was used in the flow calculation. Niklasch and Herrmann (Niklasch and Herrmann, 2009) employed the software ADINA, where a directly coupled finite element scheme for fluid-structure interaction is implemented, to simulate air-steam leakage of large-scale cracked concrete specimens. Because ADINA contains no multiphase flow models, the flow conditions inside the cracks are described by the Homogenous Equilibrium Model (HEM). A linear profile of the crack channel was assumed, where the effect of roughness of the crack wall was reproduced through the turbulence model. The flow in the crack channel was modelled with 2D FCBI (flow-condition based interpolation) elements.

The motivation of the work presented in the following is to address the specifics of hot air-steam leakage, namely the heat transfer from hot steam to the initially cold structure and the condensation of steam along the crack channel. The leakage flow within the crack as well as the flow in the inlet and outlet tubes up to the flow measurement is simulated with the 1D thermal-hydraulic system code ATHLET (GRS, 2017), which has been developed at GRS to simulate accident behavior in the primary circuit of a nuclear power plant. ANSYS Mechanical (ANSYS, Inc., 2018) is used to simulate the thermal and structure mechanical behavior of the concrete specimen. A two-way coupling scheme is established with the help of PYTHON scripts.

AIR-STEAM LEAKAGE EXPERIMENTS

The concrete specimens, which were investigated in the experiments, were cast from CEM III cement and had a cuboid shape with dimensions 4.0 cm x 4.0 cm x 11.0 cm. They were cracked into two halves by a single penetrating crack. Hence, the leakage path had a length of more than 4.0 cm and the crack surface length was more than 4.0 cm depending on the detailed crack geometry. The specimen halves were mounted in a sealed steel casing to be able to adjust the crack width through threaded bars. An inlet tube was sealed onto the top surface of the specimen, an outlet tube was sealed to the bottom surface. Figure 1 shows the schematic setup.

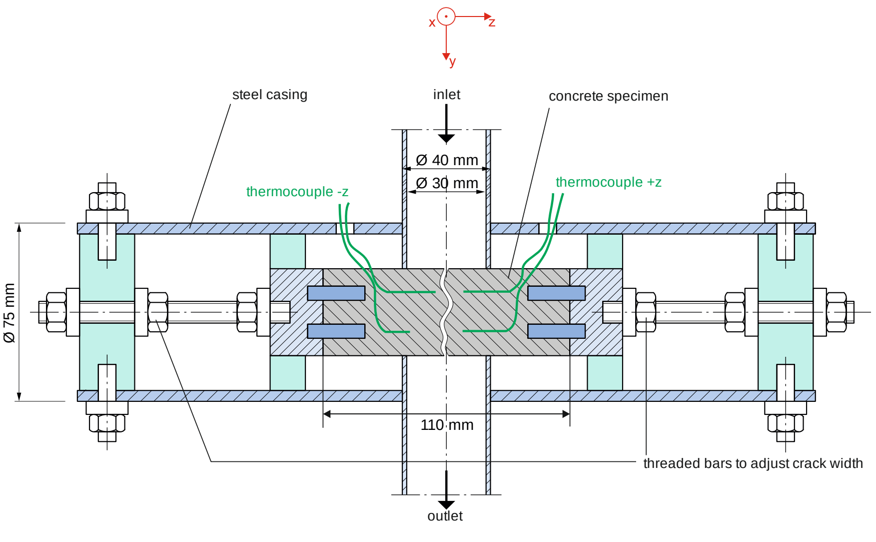


Figure 1: Setup of the air-steam leakage experiments with cracked concrete specimen and embedded thermocouples.

In Figure 2 concrete specimens with embedded thermocouples (green wires), which were dismounted after leakage experiments, are displayed in the left-hand side picture. Brown stains of epoxy resin, that was used to seal the specimen into the steal casing, can be seen on the surface. On each side face of the specimen a piston with a threaded bar was glued on. The right-hand side picture shows a view into the inlet tube and onto the cracked specimen. The threaded bars to adjust the crack width can be seen on the sides of the steel casing.

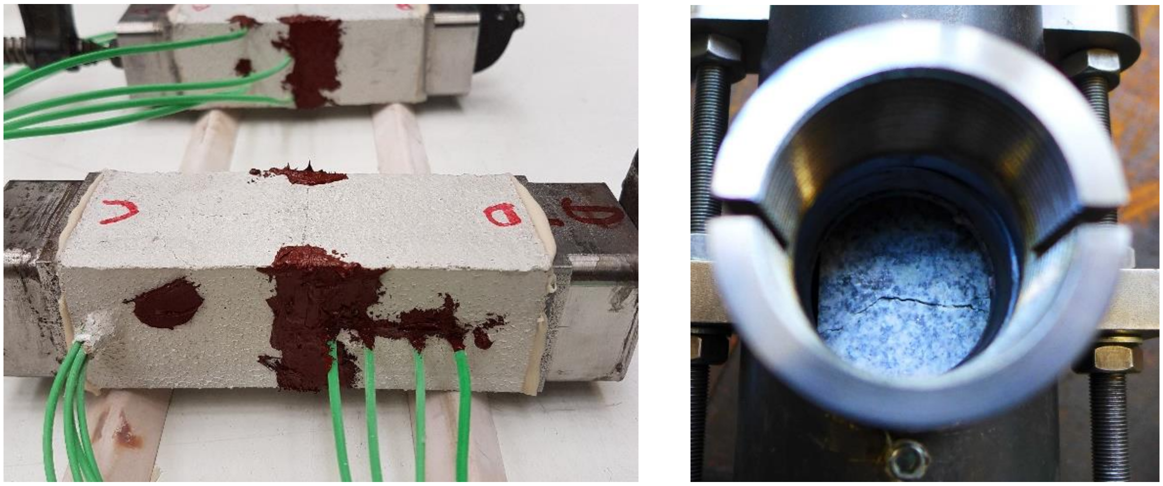


Figure 2: Concrete specimens with embedded thermocouples (green wires) and
glued on pistons with attached threaded bars (left).
Top view onto a cracked specimen mounted and sealed into the steel casing (right).

Pressurized hot air and steam are generated separately and mixed together with a constant steam mass ratio of 0.6 in a pressure chamber. Temperature and pressure of the air-steam mixture is controlled, the mixture is fed into the inlet tube and through the cracked concrete specimen. The flow measurements are performed downstream of the specimen. To be able to measure the steam and air phase separately a cooling coil with a length of 48.5 m is attached to the outlet tube. From the mass of the condensed water collected over time the steam mass flow rate is computed. The air mass flow rate is measured directly from the flow discharging from the cooling coil. The experimental setup was modified from a setup to investigate long duration leakage and self-healing of concrete cracks (Zemann et al., 2017). Furthermore, flow velocity measurements at the crack exit were performed (Bahr et al., 2018b).

The aim of the experimental procedure was to adjust the boundary conditions in such a way, that the hot air-steam mixture heats the initially cold specimen, resulting in a thermal expansion of the specimen within the stiff bearing and subsequently a decrease in the crack opening and thus leading to a measurable reduction of the leakage rate.

SIMULATING AIR-STEAM LEAKAGE

The geometrical discretization of the fluid flowing through the cracked specimen is shown schematically in Figure 3. As indicated the fluid flows from a reservoir at the top of the specimen downwards through the cracked specimen. The crack width is scaled up disproportionately to better indicate the local coupling variables solid temperature T_s, heat flow q and crack opening displacement Δy. Additionally, the location of the sensing tips of the thermocouples, which were employed in the presented experiment, are marked in the thermal-structure mechanical mesh.

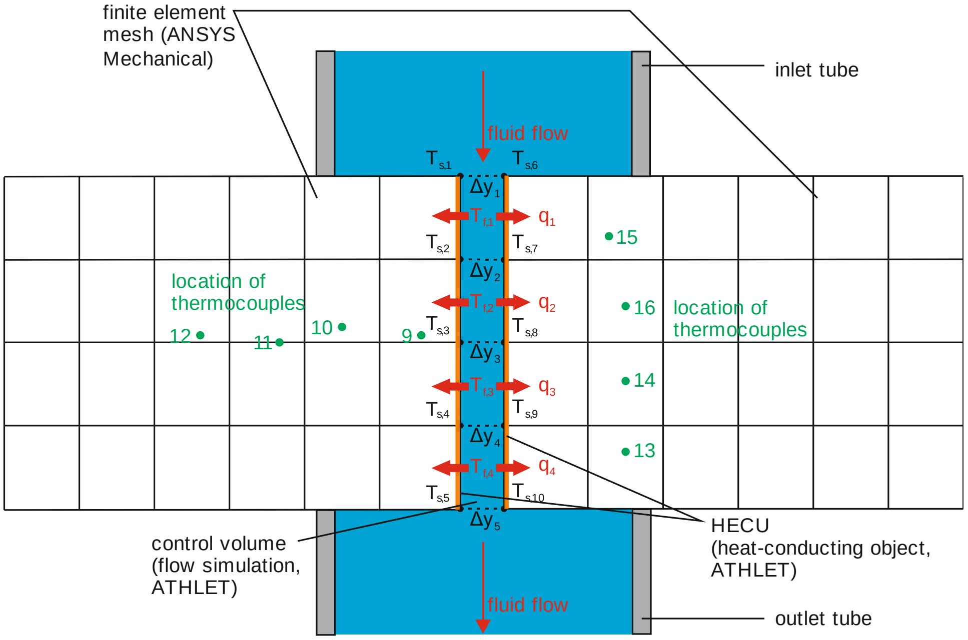


Figure 3: Modelling of the leakage flow in ATHLET and the thermal and structure mechanical response of the cracked concrete specimen in ANSYS Mechanical (T_s: solid temperature [°C], T_f: fluid temperature [°C], q: heat flow [W/m²], Δy: crack opening displacement [m]).

Simplifications are made in both structure mechanical and flow modelling. A cuboid crack channel is assumed; the one-dimensional flow is modelled as pipe flow with rough walls and hydraulic diameter in ATHLET. The value of roughness is determined according to standard (DIN EN ISO 4288, 1998). Thus, the exact 3D structure of the crack channel is not considered. The value of heat flow is computed in ATHLET through a heat-conducting object (HECU) attached to the flow channel.

The two halves of the cuboid concrete specimen, which are separated by the crack channel into two separate meshes, are modelled by planar 2D elements in ANSYS Mechanical. For higher accuracy 8-node elements (PLANE223) instead of 4-node elements (PLANE13) have been used. The elements have both displacement and temperature degrees of freedom, which are coupled by thermal expansion. In the simulation, the structural degrees of freedom of the right and left sides of the specimen are fixed representing the stiff bearing within the steel casing. In flow direction, the discretization of the flow channel matches the element size in the structural mesh, i.e. 4 fluid control volumes face on each side 4 matching structural elements.

In a coupled simulation run, at first ATHLET is started. An automated time step algorithm is implemented in ATHLET; the effective time-step size is computed based on the current flow physics. Independent from the time step in the flow simulation, a coupling time step is defined, which is considerably larger. When the coupling time step is reached, the ATHLET run is interrupted and the heat flow from the fluid to the structure is output to a text file. The PYHTON script reads in the data and inserts the values into the ANSYS input as boundary condition. The ANSYS Mechanical run is triggered individually for the duration of each coupling time step, i.e. at the end of each ANSYS run, a restart file is written, which is read in the following run. In addition, at the end of the coupling time step, the wall temperatures and crack widths computed by ANSYS Mechanical are written to text files, which in turn are evaluated by the PYTHON control script and passed to ATHLET. Wall temperature and flow channel width are adapted, and the flow simulation continues.

RESULTS

In total seven experiments with four specimens were conducted. A detailed description of the experiments and further analysis can be found in (Bahr et al., 2018a). In the experiment presented in the following, a pressure of 5.2 bar was selected at the inlet, at the outlet a pressure of 1,0 bar was maintained. The air-steam mixture had a temperature of 140°C; the crack width was adjusted to 0.15 mm at the initially cold specimen.

In the experimental setup, the mass flow of the steam phase is not measured directly, but the steam discharged from the cracked specimen is condensed in a cooling coil, which is attached to the outlet tube. Thereafter, the mass of the collected condensate is measured over time. The displayed mass flow rate of the condensed water is calculated by numerically differentiating the recorded mass signal in respect to time. Because the recorded mass time signal showed significant noise a stabilized derivative with regularization as proposed by (Chartrand, 2011) was employed, which resulted in the displayed step-like signal.

Figure 4 shows the measured and simulated mass flow rates of the condensed water and the air. The simulated air mass flow rates agree well with the measured values except that the simulated signal shows a more pronounced peak at the beginning, which indicates that not all details concerning air mass flow measurement are included in the simulation. Measured and simulated condensed water flow rates show significant differences especially in the first 80 s. This is due to the fact, that the end of the cooling coil tube was directed perpendicular downwards into the collection container, which was placed upon the measuring scale. Once the flow reached the container, the flow exerted an initially increasing pressure upon the scale. This finding was confirmed by an air-only leakage experiment, where a similar initial value showed up in the time derivative of the mass scale signal, which has nothing to do with condensed water.

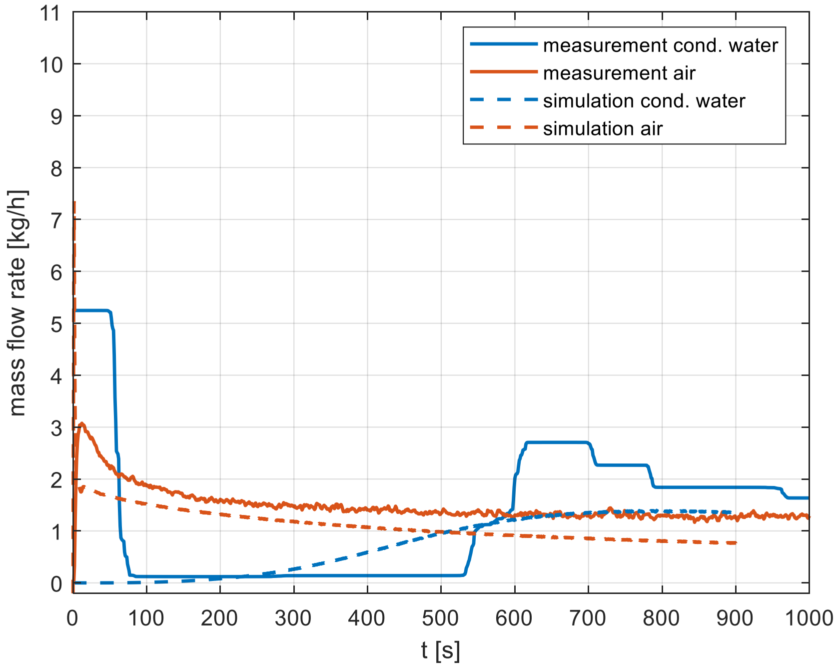


Figure 4: Measured and simulated condensed water (steam) and air mass flow.

The process of condensation introduces significant inertia into the overall system, so that the condensation in the cooling coil was included in the simulation model to be able to match the measured signal. In the ATHLET input, the multiphase flow through the tube sections with their respective cross-sections as well as the condensation process was included.

Figure 5 shows the evolution of the heat transfer coefficients calculated in the four heat-conducting objects (HECU) from the local wall temperature and physical quantities such as the fluid temperature and the flow velocity. Through the heat transfer from the fluid to the structure the fluid is cooled down on its way from the inlet (HECU 1) to the outlet (HECU 4). The heat transfer coefficient and connected with it the heat transfer initially decreases from inlet to outlet. After about 600 s, the heat transfer coefficient in the HECU 4 object drops abruptly because the structure near the outlet has been heated up to such an extent and the air-steam mixture has expanded so far that the heat transfer almost comes to a standstill. Connected with this, the condensation also comes to a standstill there.

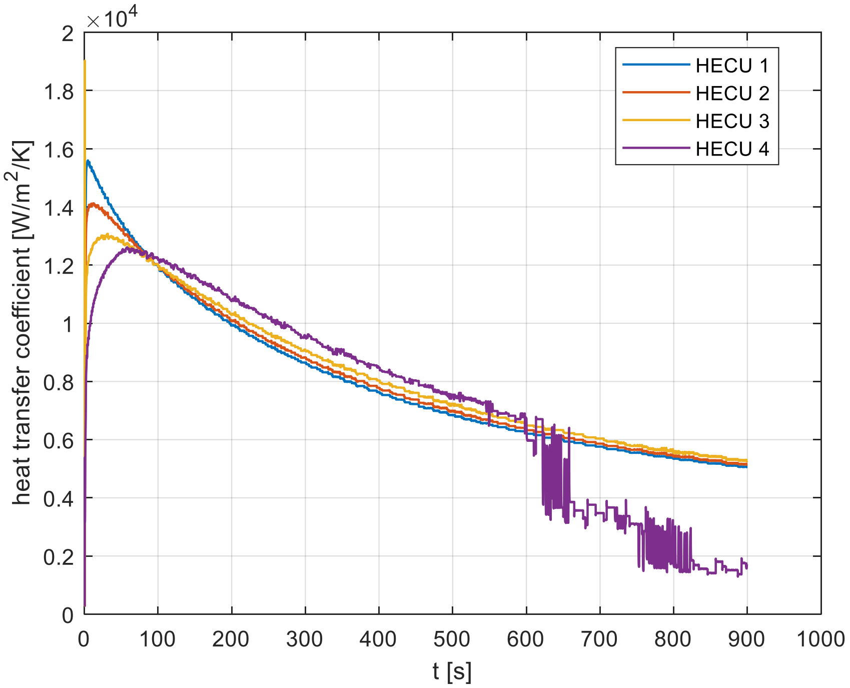


Figure 5: Heat transfer coefficient (from fluid to structure) for the 4 heat-conducting objects utilized in the flow simulation in ATHLET.

Figure 6 shows the measured temperature time signals of the thermocouples embedded in the specimen as well as the simulated temperatures at the respective measurement locations. In one of the specimen halves, the thermocouples are embedded in the mid-plane between top and bottom face with increasing distance to the crack surface in the order 9-10-11-12. In contrast, the thermocouples in the other specimen half are situated at about 1.3 cm from the crack surface along the flow direction in the order of 15-16-14-13 (from inlet to outlet). In general, the calculated temperatures agree well with the measured values. Near the inlet (thermocouple 15) the largest discrepancies appear, which may be explained by inaccurate values of heat capacity and heat conductivity and more likely uncertainties in the calculation of the heat transfer coefficients.

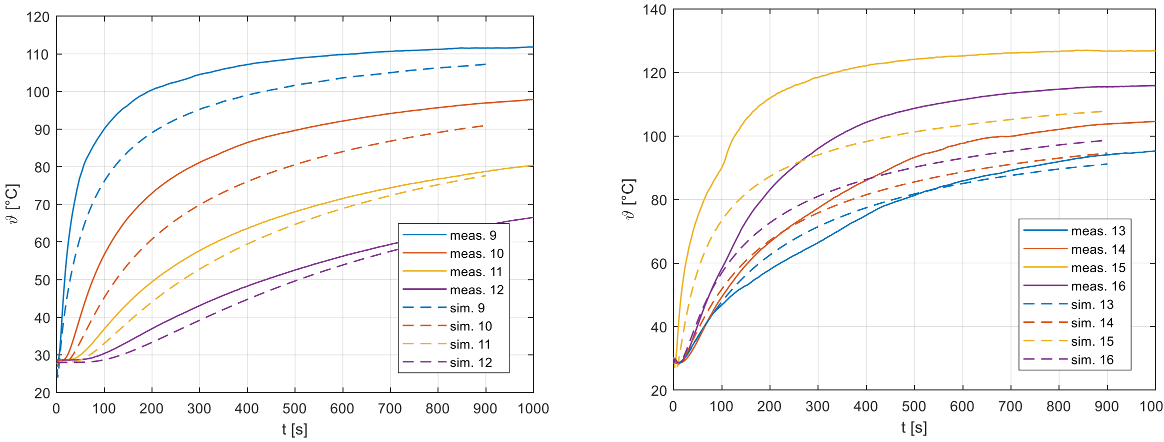
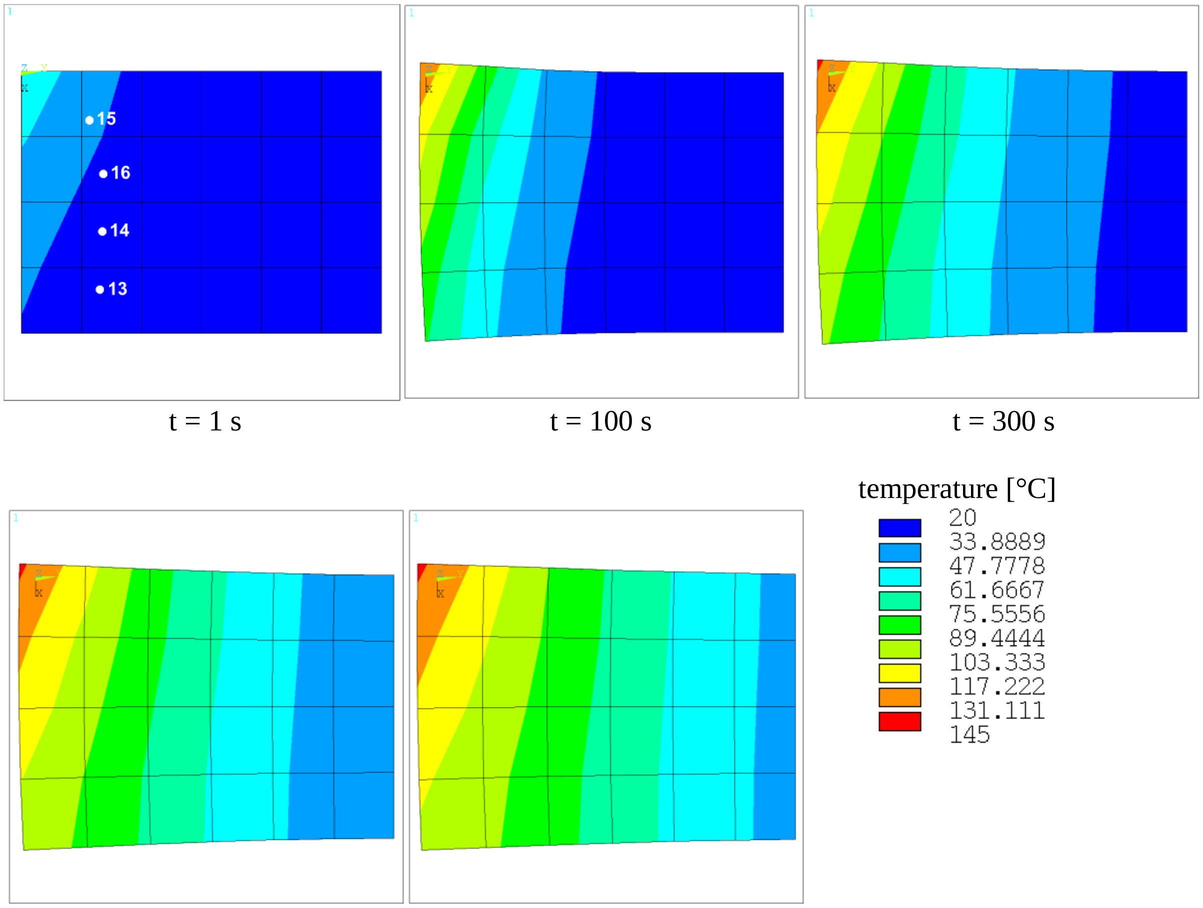


Figure 6: Temperature evolution at thermocouples 9-10-11-12 (left specimen half) and 15-16-14-13 (right specimen half).



t = 1 s

t = 100 s

t = 300 s

t = 600 s

t = 900 s

Figure 7: Simulated temperature distribution in the right specimen half at various times (Crack channel on the left side, flow direction from top to bottom).

Figure 7 shows the simulated temperature distribution of the right specimen half at various times of the simulation period; the deformations are scaled up by a factor of 100. The specimen halves were meshed with PLANE223 elements. The crack channel is situated next to the left side of the displayed specimen half. The flow direction is top to bottom. In the first plot the measurement locations, i.e. the sensing tip, of the four thermocouples embedded in the right specimen half are marked.

Due to the progressive cooling of the fluid on the passage from inlet to outlet an uneven heating develops along the crack surface resulting in a curved shape of the mesh. The smallest crack opening distance is reached at 1 cm from the inlet, i.e. after one quarter of the crack flow. After 900 seconds the initial crack opening displacement of 0.15 mm is reduced by 37 %.

With the help of simulation, the flow variables can be examined in more detail irrespective of the measurements undertaken in the experiment. Figure 8 shows the mass flow of the condensed water, steam and air phases at the inlet and the outlet of the crack. Over the entire simulation period, the steam and air mass flow rate steadily decreased because the crack opening displacement was reduced (fluid-structure interaction). A comparison of the water and steam mass flows before and after the crack reveals a low condensation in the crack during the experiment.

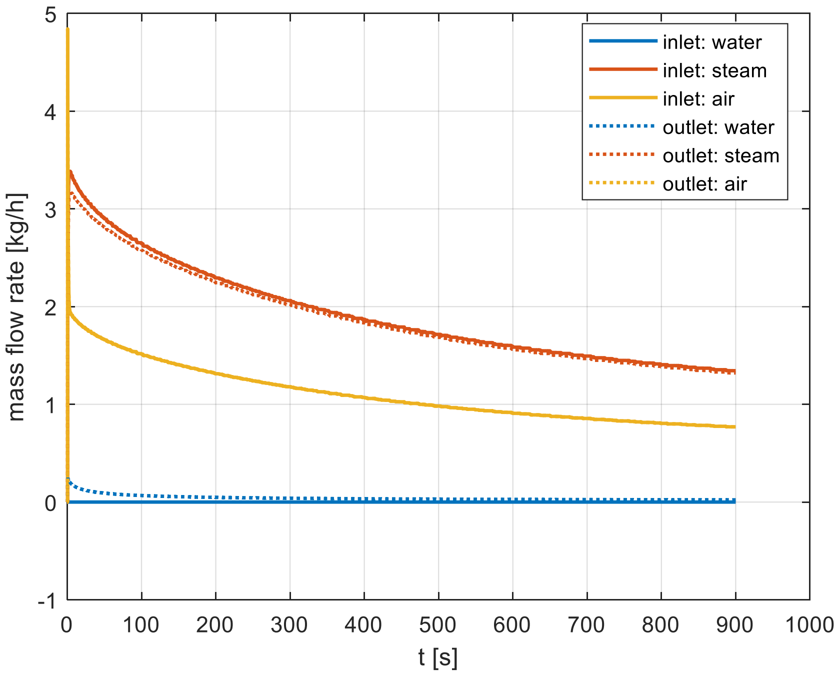


Figure 8: Simulated mass flow rate of water, steam and air directly in front of the inlet and directly after the outlet.

CONCLUSION

With the presented coupled simulation scheme the leakage of steam and air-steam mixtures through cracked concrete structures can be simulated. The simulation model includes phase changes of the steam along the flow path as well as changes of the cross-sectional area of the flow channel due to heat exchange and thermal expansion of the surrounding structure. Small-scale experiments were performed, where the described phenomena occurred. In simulations of the experimental procedure the calculated time dependent temperature distribution in the specimen as well as the air component of the total mass flow rate compare well with measured values. Differences between simulation and measurement arise for the steam respectively condensed water mass flow rate, which can partly be attributed to features of the experimental setup. In future experiments a steam mass flow rate measurement close to the crack exit would be desirable.

With the FSI simulation methodology details about the flow within the crack can be calculated, which needs further validation by experiments. Furthermore, research activities are needed to transfer the methodology to larger scale, e.g. a containment building with multiple through-wall cracks.

ACKNOWLEDGMENT

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REFERENCES

ANSYS, Inc., 2018. ANSYS Mechanical, Finite element analysis (FEA) of stress, thermal, vibration and fatigue simulations.

Badoux, M., 2002. SwissMetro-Air permeability of cracked concrete plates, in: Proceedings of MAGLEV. Presented at the MAGLEV.

Bahr, L., Heckmann, K., Bläsius, C., Sievers, J., 2018a. Improvement of the chain of analysis methods to evaluate the integrity and leak tightness of prestressed reinforced concrete containments with and without liner under severe accident loading, GRS Research Report (GRS-486), in German.

Bahr, L., Sievers, J., Zemann, M., Herrmann, N., 2018b. Investigations on leakage experiments with small-scale cracked concrete specimens including fluid structure interaction, in: TINCE 2018 – Technological Innovations in Nuclear Civil Engineering. Paris-Saclay, France.

Chartrand, R., 2011. Numerical Differentiation of Noisy, Nonsmooth Data. ISRN Applied Mathematics 2011, 1–11. https://doi.org/10.5402/2011/164564

DIN EN ISO 4288, 1998. Geometrical Product Specifications (GPS) - Surface texture; Profile method - Rules and procedures for the assessment of surface texture (ISO 4288: 1996); German Version EN ISO 4288: 1997).

Greiner, U., Ramm, W., 1995. Air leakage characteristics in cracked concrete. Nuclear Engineering and Design 156, 167–172.

GRS, 2017. ATHLET Version 3.1A, Analysis of THermal-hydraulics of LEaks and Transients. Gesellschaft für Anlagen- und Reaktorsicherheit gGmbH.

Niklasch, C., Herrmann, N., 2009. Nonlinear fluid–structure interaction calculation of the leakage behaviour of cracked concrete walls. Nuclear Engineering and Design 239, 1628–1640. https://doi.org/doi:10.1016/j.nucengdes.2008.09.001

Riva, P., Brusa, L., Contri, P., Imperato, L., 1999. Prediction of air and steam leak rate through cracked reinforced concrete panels. Nuclear Engineering and Design 192, 13–30.

Rizkalla, S.H., Lau, B.L., Simmonds, S.H., 1984. Air leakage characteristics in reinforced concrete. Journal of Structural Engineering 110, 1149–1162.

Simon, H., Nahas, G., Coulon, N., 2007. Air–steam leakage through cracks in concrete walls. Nuclear Engineering and Design 237, 1786–1794. https://doi.org/doi:10.1016/j.nucengdes.2007.03.025

Suzuki, T., Takiguchi, K., Hotta, H., 1992. Leakage of gas through concrete cracks. Nuclear Engineering and Design 133, 121–130.

Zemann, M., Herrmann, N., Willers, K., Gerlach, L., Müller, H.S., 2017. Cracks in concrete containment - comparing the self-healing potential under variable air and steam loads between real scale and laboratory scale, in: Transactions of the 24th International Conference on Structural Mechanics in Reactor Technology (SMiRT 24). Busan, Korea.