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BEHAVIOUR OF A PRESSURE VESSEL NOZZLE WITH THERMO-SLEEVE UNDER THERMAL LOADING INDUCED BY STRATIFIED FLOW

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1 INTRODUCTION

Startup at low reactor power may give rise to stratified flow conditions in pipes of boiling water and pressurized water reactors. Stratified flow regimes cause a steep temperature gradient between the cold and the hot fluid layer. This temperature gradient produces high axial stresses which, in the case of intermittent feeding of cold water and an appropriate number of repetitions, in principle may initiate cracking in the feedwater pipe and close to the feeding nozzle. Thermosleeves have been installed in a number of reactors to mitigate thermally induced stresses; they reduce the intensity of thermal transients by means of an insulating fluid annulus developing between the sleeve and the nozzle. In order to measure the temperature and stress gradients occurring in the region of the nozzle edge, the so-called TEMS experiments were carried out under realistic operating conditions, and with different cold water levels within the framework of German research activities in the field of reactor safety at the HDR test facility. The experiments served to simulate the physics phenomena by means of a FE-program /1/ and to verify the computational approach by comparisons of measurements and calculations.

2 EXPERIMENTAL FACILITY

Fig. 1 shows the isometry of the test piping system adjacent to the reactor pressure vessel (RPV) for the TEMS experiments. The test section was located in the area of the nozzle S (DN 450) /2/. A stratified flow regime was achieved in the horizontal section of the pipe between the nozzle S and the first pipe bend. Fig. 2 shows the design of the thermosleeve and the nozzle with a fluid gap of about 7,5 mm between nozzle and sleeve. The RPV-nozzle is fabricated of 23 NiMoCr 3 6 similar to ASTM 508 Cl 2 nuclear grade steel and is cladded with austenitic steel X 10 CrNiNb 18 9 of about 7 mm thickness. Fig. 2 shows also the sensor distribution in the nozzle region. In cross-section TS2 and TS4, the temperatures in the sleeve and on the cladding of the nozzle were measured. At the bottom of the nozzle, the axial strains and circumferential strains were measured at cross-section ES1-ES3. As the heat transfer coefficient exerts a major influence on the thermal gradients in the sleeve and also in the nozzle, a measurement probe was installed in the sleeve. This measurement probe allowed the temperature distribution in the boundary layer and, from this, the heat transfer coefficient on the inside of the sleeve to be determined.

3 TEST MATRIX

Two different heights of cold water levels (10% and 30% of the inner sleeve diameter) were studied to assess the load acting on the nozzle as a result of thermal shock loads induced by stratified flow regimes. The boundary conditions were T_H = 240 °C, T_C = 50 °C, p = 10.8 MPa. The mass flows used to achieve the necessary heights of the two different cold water levels were 1.8 t/h and 45 t/h, respectively.

4 TEST EVALUATION AND RECALCULATION

Inside the sleeve the steep temperature gradients found were identical with those known from earlier studies /3/. Fig. 3 shows the measured and the calculated temperature distributions in the sleeve and at the nozzle for the 30% cold water level at the time 600 s after the onset of feed for cross section TS2. The steep temperature gradient on the inside of the sleeve in the transition area between the hot and the cold layer is clearly evident. In the plane of separation temperature fluctuations occur as a result of wave formation. The temperature fluctuation measured at the inner wall of the sleeve was ΔT = 15 K. On the outside of the sleeve and the inside of the nozzle, temperature gradients are much flatter. For better explanation of the temperature distribution in the nozzle with a sleeve it is necessary to consider the fluid dynamics in the water annulus between the nozzle and the sleeve. Feeding cold water cools the sleeve and, consequently, also the fluid in the annulus. As a consequence of the differences in temperature and, hence, also in density between the fluid in the annulus and the hot fluid in the reactor pressure vessel,the cooler fluid flows from the annulus into the RPV. For reasons of continuity the hot fluid from the RPV must enter the fluid annulus at the same time. This influx into the fluid annulus was simulated also in numerical terms /4/ by presetting the temperature reduction inside the sleeve. Fig. 4 is a plot of the velocity distribution in the fluid annulus at 30% cold water level. It is evident that, in the region of the plane of separation, there is a very pronounced influx from the RPV into the fluid annulus, as a result of which the nozzle is continuously supplied with heat. Superimposed upon this U-shaped influx is a convection flow in the circumferential direction at the bottom of the annulus, Fig. 5. This so-called Benard convection arises out of the difference in temperatures of the sleeve and the nozzle. The fluid in the annulus cools off at the sleeve and, because of the increasing density, begins to drop. The fluid heats up at the hot nozzle wall and rises along the nozzle wall. If one compares the flow velocity in the circumferential direction, due to the axial U-shaped influx, with that of the Benard convection, one sees that the Benard convection can be generated only in a narrow angular sector of $\Delta\varphi = 10°$ on both sides of the bottom of the nozzle. Benard convection causes a pronounced heat transport from the sleeve to the nozzle, as a result of which there is pronounced cooling of the nozzle only in this region, see Fig. 3.

The fluid dynamics findings can be used to calculate the distribution of temperatures and stresses in the nozzle by means of a FE-structural program /5/. The temperature reduction at the nozzle was measured to be 60 K at the TS2 cross-section, which is described quite well by numerical simulation, Fig. 3. Fig. 6 shows the measured and the calculated strain range for 10% and 30% cold water levels. With increasing cold water levels, also higher thermal stresses arise, because an increasing height of the cold water layer gives rise to a higher mass flow, and, consequently, also an increased heat transfer from the sleeve to the nozzle. At cross-section ES2 measurements indicate a maximum axial strain range, $\Delta\varepsilon_{ax} = 0.86 \cdot 10^{-3}$ m/m and a circumferential strain range, $\Delta\varepsilon_{\varphi} = 0.51 \cdot 10^{-3}$ m/m. The finite element calculations show that the highest stress in the area of the nozzle occurs at the nozzle edge. At that point, the load composed of heating, internal pressure and thermal shock gives rise to a circumferential stress of $\sigma_{\varphi} = 260$ MPa for a cold water level of 30%.

5 CONCLUSION

In a realistic experiment, the load exerted on a nozzle equipped with a thermosleeve was examined under stratified flow conditions. The experiment as well as extensive recalculations indicated the good protective action of the thermosleeve. Because of the difference in densities in the fluid annulus between the sleeve and the nozzle under conditions of cold water feeding, a flow is induced from the RPV into the fluid annulus. This flow carries heat into the annulus, thus producing a very mild cooling effect on the nozzle with low shock stresses. In the area of the nozzle edge, the findings indicate a circumferential stress, $\sigma_{\varphi} = 260$ MPa at the cladding, from the superimposed load comprised of heating to 240 °C, internal pressure, and thermal shock. The numerical calculations produced good agreement with the measured data. If the heat transfer coefficient on the inside of the sleeve is known, it is possible to calculate, by means of a FE-program, the axial influx and, hence, the amount of heat introduced into the fluid annulus between the sleeve and the nozzle. These data then allow the temperature and stress distributions in the nozzle to be determined. This approach can be used to calculate the load imposed on the nozzle also for different cold water levels and different modes of operation.

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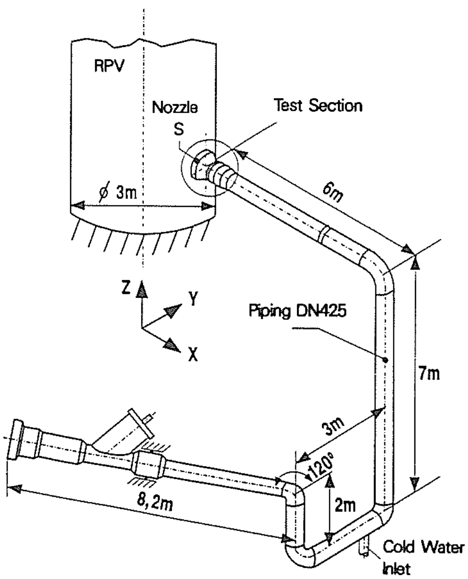

Fig. 1: Isometry of the piping system

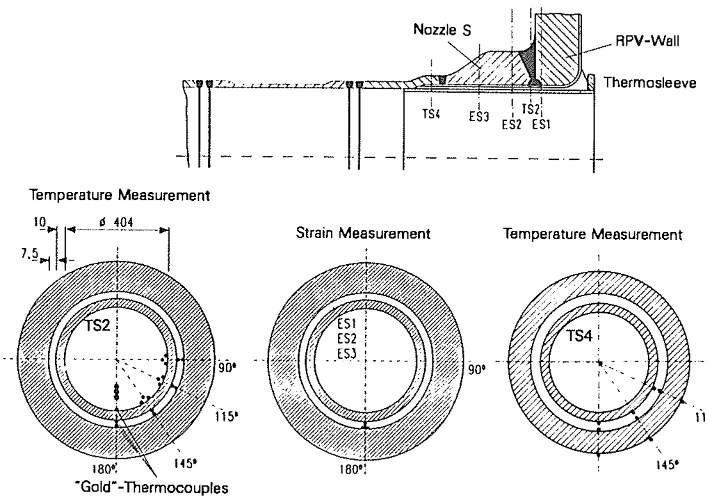

Fig. 2: Design of the nozzle with thermosleeve and sensor distribution

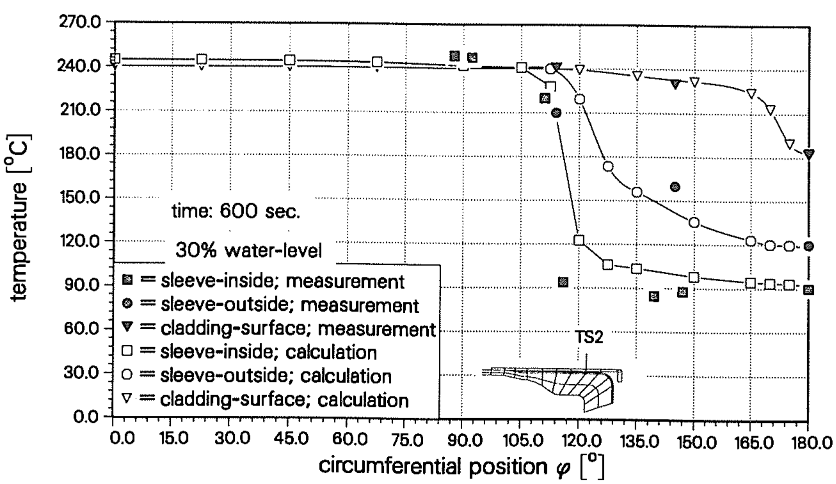

Fig. 3: Comparison calculation measurement of the temperature distribution at the sleeve and the nozzle in cross section TS2

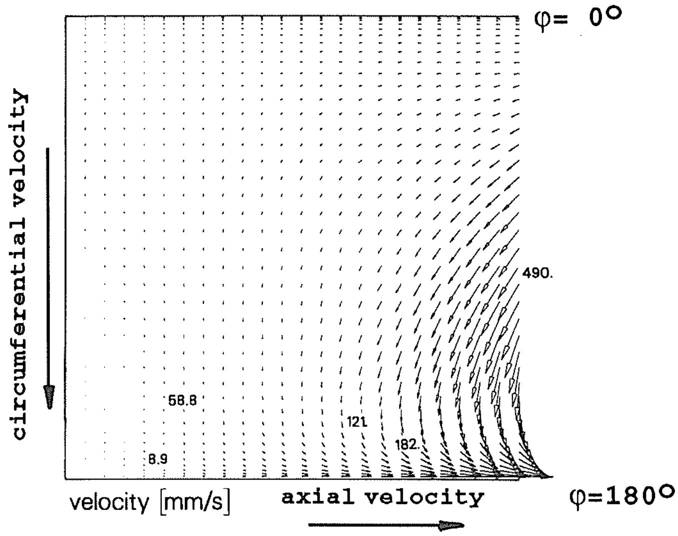

Fig. 4: Circumferential velocity distribution for 30% water level (U-shaped)

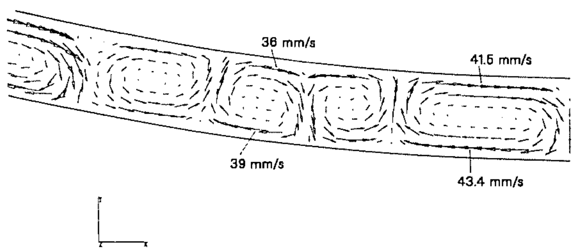

Fig. 5: Benard vortex in the lower part of the annulus for 30% water level

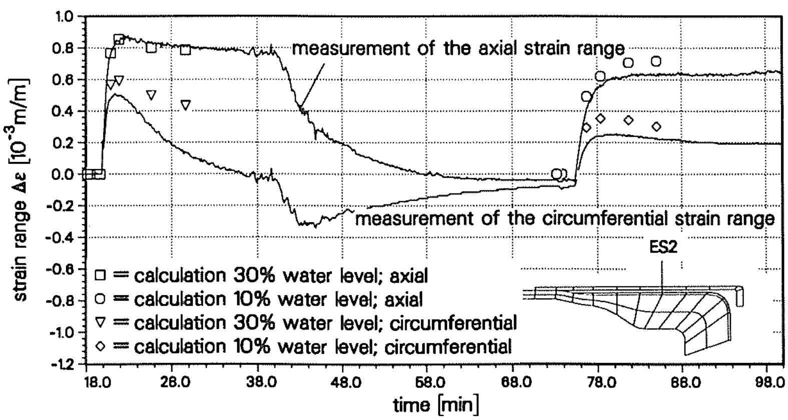

Fig. 6: Comparison calculation measurement of the strain range at the nozzle at point ES2