EXPERIMENTAL AND COMPUTATIONAL INVESTIGATION OF COOLABILITY OF BALLONED BUNDLES WITH PELLET RELOCATION

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ABSTRACT

During a LOCA incident the high pressure in the fuel rods can lead to clad ballooning and the debris of fuel pellets can fill the enlarged volume. The evaluation of the role of these two effects on the coolability of VVER type fuel bundles was the main objective of the experimental series. The “CODEX-COOL” experiment launched in AEKI focused on the last phase of such LOCA transient. The experimental results confirmed that a VVER bundle with even 86% blockage rate remains coolable. The ballooned section creates some obstacles for the cooling water during reflood of the bundle, but this effect causes only a short delay in the cooling down of the hot fuel rods. The accumulation of fuel pellet debris in the ballooned volume results in a local power peak, which leads to further slowing down of quench front. The effect of local power peak seems to be less significant on the delay of cooling down than the effect of ballooning bottom of the reactor core.

The experimental results confirmed that the VVER bundle with even 86% blockage rate remains coolable after such LOCA event.

The coolability of ballooned VVER type bundles were analysed also by the APROS code. The model of the studied system was built in the Finnish APROS thermohydraulic code. The numerically results showed also that a VVER bundle with even 86% blockage rate remains coolable after a LOCA event.

1 INTRODUCTION

The coolability of fuel assemblies must be guaranteed during design basis accidents. There are two basic phenomena which may have important influence on the coolability of nuclear fuel under loss-of-coolant-accident (LOCA) conditions:

The high internal pressure in the fuel rods, the fast decrease of reactor pressure and the rise of temperature can lead to ballooning of the fuel cladding. The size of deformation depends on several parameters (e.g. pressure increase rate, degree of cladding oxidation, pressure difference between inside and outside of cladding, temperature). In case of large
deformations the flow cross section between the fuel rods can be partially blocked and this may create an obstacle for cooling water in the reflood phase of the LOCA.

In case of high burnup fuel the fragmentation of fuel pellets and relocation of fragments into the ballooned section may occur. The accumulation of debris in the ballooned section will produce a local power peak and this effect may also influence the coolability of the ballooned bundle.

2 TEST FACILITY

The basic requirement against the experimental facility was the reproduction of LOCA conditions in an out-of-pile configuration. The CODEX facility was built for simulation of severe accident conditions. The main components of this facility were used in the coolability tests after significant reconstruction. The current tests series are identified as LOCA-“CODEX-COOL” experiments.

2.1 Test bundle

The test bundle represents the VVER fuel geometry. The fuel rod diameter is 9.1 mm, the pitch size 12.2 mm and the height of spacer grid 10 mm. The thickness of cladding is 0.6 mm. The fuel rods are arranged on a triangular lattice and the bundle has a hexagonal cross section. The bundle is covered by shroud. The bundle included 19 electrically heated fuel rod simulators (Figure 1).

![Figure 1: Cross section of bundle](image1)

![Figure 2: Hollow sleeves](image2)

The heater bars are positioned in the center of fuel rods, with the diameter of bars of 4mm. The heater bars are covered by alumina pellets and stainless steel cladding. Thermal insulation are applied around the bundle to limit heat losses and to produce more uniform radial power profile. The total length of the fuel rods is 1000 mm. and the length of the heated section 932 mm. The total power applied in the tests was 9 kW, which was derived from the decay heat of VVER fuel during LOCA. The simulation of ballooning is solved by using hollow sleeves that are fixed on the external surface of the cladding. The length of the sleeves is 50mm. The neighbouring sleeves are in direct contact on 30 mm length (Figure 1 and 2). The thickness of sleeves in the direction of neighbour rods is 3.1mm. using these sleeves 86% blockage rate could be reached in the bundle (Figure 3). This very high blockage rate could be considered as a conservative upper value for ballooned VVER bundles. The blocked section is positioned in the upper section of the bundle 200mm below the top. The local power peak in the ballooned area is produced by the reduction of cross section of heater bars (Figure 4.). The diameter of the bars is 4mm in the main part of the rods and 2.8mm in the ballooned region.
This technical solution produces 100% additional heat in that section. The reduction of diameter increases the gap between the power source and alumina pellets. In spite of that, most of the power produced in the heater bar is released in radial direction through the pellets, cladding and sleeves. The increase of the gap size could cause only some delay in the heat-up of the cladding when the power is increased from the pre-heating conditions to the nominal test power.

Figure 3: Cross section of bundle without (left) and with (right) sleeves

Figure 4: Schematic view of cladding (left), cross section of heater bar (center) and axial power profile (right)

The power increase rate is derived from geometrical considerations. The ballooned section of the bundle has about 200% of the original tube volume for the given length. Accordingly the local power peak is also 200% as if UO₂ debris could fill perfectly the ballooned volume.

2.2 Experimental loop

The test section of the facility included the 19 rod bundle in vertical position. The main components of the experimental loop(Figure 5) were the following:

- steamgenerator,
- superheater,
- test section,
- expansion volume,
- condensator,
- water supply system with pump
The instrumentation of the facility included 44 thermocouples and several other devices for the measurement of pressure, flowrate and water levels in different positions. The detailed measurement of temperature field enabled the tracking of quench front during the reflood phase of the facility.

2.3 Execution of tests

The scenario of the experiments started with a preheating period in order to establish a stable and as much as possible uniform temperature distribution in the bundle. The target temperature in the first series of tests was 600 ºC (Figure6).

It must be noted that, the ballooning of fuel bundles does not appear at 600 ºC. It was supposed that during the first part of the LOCA transient the temperature was reached between 800 and 1000 ºC and the ballooning took place that time. Only the final quench by water came at 600 ºC. So the currently applied 600 ºC is not the peak clad temperature during the LOCA, but the temperature when the quench front reached the bottom of the fuel rods. The next series of experiments will be carried out at higher temperatures in order to cover a wider range of temperatures.
The bundle power was varied between 600-1500 W in the preheating phase. The steam supply from the steam generator and superheater section produced 600 ºC steam flow. The hot steam entered the test section in the bottom and left at the top. The outlet steam was condensed in the condenser unit and the water was collected in a volume beneath the condenser. The reflood phase was initiated in the tests with the increase of bundle power to 9 kW. The steam supply was terminated and water injection started from the bottom. The tests were continued until the quench front reached the top of the bundle. At the end of the test the electrical power was switched off and the facility was cooled down. The current experiments did not simulate the whole scenario of a loss-of-coolant accident. The blowdown phase with very fast temperature increase and a temporary peak with maximum temperature were not covered. The CODEX-COOL tests focused on the last phase of LOCA transient when the bundle is cooled down by cold water injected by the emergency core cooling system from the bottom of the reactor core.

3 EXPERIMENTAL RESULTS

The first series of tests included three configurations:
- Bundle without ballooning,
- bundle with ballooning and the uniform power profile,
- bundle with ballooning and the local power peak.

Each configuration was tested with three different flowrates. In the second and third configurations ballooning was simulated in all 19 rods of the bundle. The main question addressed in these tests was the coolability of bundles during quenching. It was considered that if the temperature increase in the vicinity of blocked section could be terminated than the bundle was coolable at the given temperature, power and flowrate conditions.

3.1 Tests without ballooning

The simple bundle without ballooning simulators was tested as a reference case. The three tests performed at 600 ºC were characterized by smooth cooling down of the bundle. In the test with high flowrate (Figure 8) the cool-down time was 6 s, while in case of low flowrate tests the cooling down took 18 s (Table1). Temperature measurements indicated in (Figure 7) correspond to different axial positions: T0 – 0 mm, TA – 143 mm, TB – 286 mm, TC – 429 mm, TD – 572 mm, TE – 715 mm, TF – 858 mm, where 0 mm is the bottom of the bundle.
3.2 Tests with ballooning and the uniform power profile

The bundle with ballooning simulators but without local power peak was quenched in longer times than the reference case. Comparing the Table 1 it can be seen that the bundle with ballooning required two time longer times for cool-down as the bundle without ballooning. In the test with low flowrate the cool-down time was 13 s, while in case of low flowrate tests the cooling period 32s. (Table1).

The increase of cool-down time in the tests with blockage could be explained first of all with the cross section reduction: the steam produced during quench in the bottom part of the bundle could not as easily escape from the bundle as in the reference case without blockage simulators. The pressure increase under the blocked section led to decrease of water penetration into the bottom of the bundle.

3.3 Tests with ballooning and local power peak

The application of local power peak in the ballooned bundle caused further delay in the cooling down of the high temperature bundle. In these tests – similarly to previous configurations – the test section was heated up to 600 °C in steam atmosphere and the bundle was quenched from the bottom by cold water. The effect of flowrate was investigated in the three runs (Table 1) In the test with low flowrate (Figure 8) down time was 41 s, which means about 30% increase in the delay of cooling down the bundle compared to the case without local power peak. The detailed analyses of the temperature profiles indicated that the section above the ballooned region was cooled down faster than the ballooned part itself (Figure 8). Positions of thermocouples in Figure 8 are the same as in Figure 7.
Table 1: Joint table of measured results

<table>
<thead>
<tr>
<th>Type of test</th>
<th>N° Tests</th>
<th>Flowrate g/s</th>
<th>Cool-down time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Without Ballooning and with Uniform Power Profile</td>
<td>M1/600/max</td>
<td>225</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>M1/600/6</td>
<td>150</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td>M1/600/3</td>
<td>80</td>
<td>18</td>
</tr>
<tr>
<td>With Ballooning and with Uniform Power Profile</td>
<td>M2/600/max</td>
<td>225</td>
<td>13</td>
</tr>
<tr>
<td></td>
<td>M2/600/6</td>
<td>150</td>
<td>12</td>
</tr>
<tr>
<td></td>
<td>M2/600/3</td>
<td>80</td>
<td>32</td>
</tr>
<tr>
<td>Tests with ballooning and local power peak</td>
<td>M/600/max</td>
<td>225</td>
<td>12</td>
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<tr>
<td></td>
<td>M3/600/6</td>
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</tr>
<tr>
<td></td>
<td>M3/600/3</td>
<td>80</td>
<td>41</td>
</tr>
</tbody>
</table>

4 COMPUTATIONAL ANALYSIS

The computation analysis of the experiment was made with the APROS v5.08 thermohydraulic code.

The test section was modelled with heated pipe modules called “Pipe with Heat Structure” in the code. 19 parallel pipes modelled the sub channels of the bundle. Inside radius of one sub channel was 4.9mm in the non-ballooned section, and 2.7 mm in the ballooned region. The hydraulic diameter of the sub channels (78 mm in the non-ballooned region, and 2.1mm in the ballooned region) and the heat capacity of the pipes correspond to the test section details. The blockage rate was 86%, and the linear heat power was two times higher in the ballooned region (0.18 kW/cm) than in the regions without local peak power (0.09 kW/cm). The length of the test section (950mm.) was divided into 101 nodes. The sensitivity of the results for the nodalization was investigated: the more detailed nodalization did not improve the results.

The A, B, C, D, E and F points are the equivalent of the test facility’s temperature measurement points.

The pressurizer above the test facility was modelled as a tank. Initially the whole test section is filled up with superheated steam (560-640 °C, 0.27 MPa). During the experiment, a safety valve limited the pressure in the test section to 0.45MPa. This was modelled with constant pressure outlet point and a check valve to prevent the flooding of the test section from the outlet if the pressure in the pressurizer goes under 0.45 MPa.

The coolability of the bundle was investigated at low flow rate. The cool down time was 46s but 41s in the experiment with the flow rate of 80 g/s (Figure 9) At the beginning of the experiment the colder steam produced at the lowermost nodes pushes out the higher temperature (550-620 °C) steam from the test section (Figure 10). Because of this effect the temperature of the steam decreases rapidly in the whole test section, while the temperature of the pipe wall decreases later, when the quenching front reaches the actual height. The comparison between the experimental and the model data is shown on Figure 11.
Figure 9: Calculated values of serial test M3/600/3, with parameters: cool down time: 46s, flow rate: 80 g/s, level: ”A”, ”B”, ”C”, ”D”, ”E”, ”F”, initial temperature: 550-620 °C

Figure 10: Calculated and measured temperatures of serial test, with parameters: cool down time: 46s, flow rate: 80 g/s, level: ”F”, initial temperature: 620 °C

Figure 11: The comparison between the experiment’s and the model’s data

Figure 12: Calculated and measuring dates of test N°M/3/600/3, level: “C”

Figure 13: The comparison between the experiment’s and the model’s data dates of test N°M/3/600/3, level: “E”

In the lower nodes of the test section the calculated and measured parameters show good agreement (Figure 12). In the upper nodes the deviation between the model end
experiment are larger. One possible explanation can be the erroneous simulation of the experiment, but further investigation are needed (Figure 13).

5 CONCLUSIONS

Integral experiments have been carried out with ballooned VVER bundles in order to investigate their coolability after LOCA. The effect of local power peak was simulated, too. The tests were carried out in the modified configuration of the CODEX facility using 19-rod electrically heated fuel rod bundles. Three series of CODEX-COOL tests were performed:

- Reference bundle with fuel rods without ballooning, with uniform power profile.
- Bundle with 86% blockage rate and with uniform power profile. The blockage rate was reached by superimposing hollow sleeves on all 19 fuel rods.
- Bundle with 86% blockage rate and with local power peak in the ballooned area. The local power peak was produced by the local reduction the cross section of the internal heater bar inside of the fuel rods.
- In all three bundle configurations three different cooling water flowrates were applied.
- The experimental results confirmed that a VVER bundle with even 86% blockage rate remains coolable after a LOCA event in the investigated range of parameters.
- The ballooned section creates some obstacles for the cooling water during reflood of the bundle, but this effect causes only a short delay in the cooling down of the hot fuel rods.
- The presented tests with local power peak indicated that it will delay the cooling down of the bundles. The maximum delay was about 30% compared to case without local power peak.
- The APROS v5.08 thermohydraulic code was validated, that it is convenient and possible to use for the simulation of quench processes.

REFERENCES
