Heat Transfer Analysis of the European Pressurized Water Reactor

(EPR) Core Catcher Test Facility Volley

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ABSTRACT

The EPR is designed to cope with severe accidents, involving core meltdown. A specific melt spreading area has been designed within the containment. This core catcher will be flooded by water, which transfers the decay heat to the containment heat removal system. To improve cooling, horizontal flow channels made of cast iron are located also below the core catcher. STUK, the radiation and nuclear safety authority in Finland, wanted an independent study of the functionality of the core catcher design. Effect of the presence of insulation material and boric acid in the cooling water was to be studied, as well as the general behavior of the system in different phases of the flooding of the core melt spreading area.

To verify the function of the core catcher design, a scaled down test facility was built at Lappeenranta University of Technology. Since there are some physical restrictions of a test facility computational tools were applied especially for the tests where steady state conditions could not be reached without endangering the integrity of the test facility.

This paper introduces the Volley test facility, computational simulations and compares them with the test results. Simulated temperatures of those Volley tests, which could be run until steady state conditions, are very close to the measured temperatures. It can be concluded also, that the temperatures are evidently below the cast iron melting point with heat fluxes used in the tests, if there is a small flow inside the cooling channels or even in case when only a few adjacent cooling channels are totally dry.

1 INTRODUCTION

The European Pressurized Water Reactor (EPR) is a Pressurized Water Reactor (PWR) in the 1,600 MWₑ class. Its design is primarily based on the French N4 and the German KONVOI reactors. The EPR is designed in such a way that during extremely severe accidents, involving core meltdown and piercing of the steel reactor vessel, molten core (corium) behaviour and cooling can be managed. In practise this has been settled so that if any part of the core is molten and escaping from the reactor vessel, it will be passively collected and retained, and then cooled in a specially designed area inside the containment.

The main purpose of this area, the core catcher, is to handle these extreme situations in such a way that the accident would be confined within the reactor containment building and the probability of radionuclide’s spreading from the containment to the environment will be minimized. For that purpose, the EPR includes a large ex-vessel core catcher. The molten corium is temporarily retained and accumulated below the pressure vessel. After the melt plug is destroyed the molten corium flows down through the melt discharge channel. Finally, the molten corium is retained and cooled down on the
spreading compartment. The spreading compartment will also be flooded by cooling water in order to achieve more effective heat transfer. Most of the heat will be transferred from the molten corium upwards to water and finally to the containment, but cooling has been made more effective by horizontal water-filled cooling channels which are located below the core catcher bottom. The bottom (area 170 m²) and sides (area 50 m²) of the spreading compartment are assembled with cooling elements made of cast iron. The coolant (1700 ppm concentrated boron-rich water) is driven by gravity from the In-containment Refueling Water Storage Tank (IRWST). Figure 1 shows the main components of the EPR core catcher and Figure 2 the structure of the cooling elements.

![Figure 1. Main components of the EPR core catcher [1].](image1)

![Figure 2. Structure of the cooling elements [1].](image2)

Originally thermal hydraulic tests were performed by the EPR vendor to prove the proper functioning of the core catcher design [1]. However, these tests were executed by using pure water as a coolant. To prove the chemical stability of the core catcher, some additional tests had to be executed by using boron-rich and mineral wool treated water. To further verify the function of the core catcher, a test facility (Volley) was designed and constructed at Lappeenranta University of Technology, Finland.
The purpose of the Lappeenranta tests was to clarify:

- the thermal hydraulic behavior of the cooling channels,
- the possibility of boric acid accumulation in different parts of the cooling channels,
- the effect of insulation material mixed in water, and
- the effect of cooling channel inclination.

2 VOLLEY EXPERIMENTAL SETUP

The test rig contained of two full-scale (length 5 m, cross-section 50x100 mm) horizontal cooling channels made of cast iron. The cooling channels simulated the finned construction of the cooling elements. The heat from molten corium was simulated with 68 cartridge heaters, mounted inside the upper part of the core catcher plate. The heaters are 180 mm long (the width of the catcher plate), have a diameter of 20 mm and maximum heating power of 2.2 kW each. The maximum heat flux in the core catcher plate is approximately 160 kW/m². The coolant was drained by gravity from the boron solution tank (total volume 2.4 m³) down to the cooling channels. There are viewing windows along the side of the catcher plate for visual observation of the cooling channel. The core catcher plate is insulated with 100 mm thick mineral wool to reduce heat losses. Table 1 shows the main dimensions of the test rig compared to the EPR plant conditions. Physical properties of the grey cast iron EN-GJL-150 are shown in Table 2. 3D-sketches of the initial and modified test rig construction are presented in Figure 3 and Figure 4, correspondingly. In Figure 3 seen type of a test facility construction simulates the events early after melt discharge into the spreading area when the cooling channels are filled with water and the water level in the spreading room rises but stays below the top of the sidewall cooling elements. After the modifications, Figure 4, test facility construction simulated the events in the later phase of a possible core melt accident in the EPR plant conditions i.e. the spreading room is filled with water.

<table>
<thead>
<tr>
<th>Protection material</th>
<th>Test rig</th>
<th>EPR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of the cooling channels</td>
<td>2</td>
<td>360</td>
</tr>
<tr>
<td>Total length of the cooling channels [m]</td>
<td>10</td>
<td>1700</td>
</tr>
<tr>
<td>Cross-section of the cooling channels (w[mm] x h[mm])</td>
<td>50x100</td>
<td>50x100</td>
</tr>
<tr>
<td>Distance between two cooling channels [mm]</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>Heated horizontal area [m²]</td>
<td>0.93</td>
<td>170</td>
</tr>
<tr>
<td>Heated vertical area [m²]</td>
<td>-</td>
<td>50</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>7100</td>
<td>10⁻⁶</td>
<td>500</td>
<td></td>
</tr>
<tr>
<td>100</td>
<td></td>
<td>52.5</td>
<td></td>
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</tr>
<tr>
<td>200</td>
<td></td>
<td>51</td>
<td></td>
<td></td>
</tr>
<tr>
<td>300</td>
<td></td>
<td>50</td>
<td></td>
<td></td>
</tr>
<tr>
<td>400</td>
<td></td>
<td>49</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

In literature the die casting cast iron roughness has been announced to be 0.8 – 60 μm [3, 4].
Figure 3. Initial EPR core catcher test facility (Volley04).

Figure 4. Modified EPR core catcher test facility (Volley05).
3 TEST PROGRAMME

The VOLLEY core catcher studies were performed during years 2004 – 2005 in two phases that are related to different stages of the core melt accident. In the first phase (Volley 2004 tests), the top of the outflow pipe construction was connected to the atmosphere. This type of a test facility construction simulates the events in the early phase of a possible core melt accident i.e. the cooling channels are filled with water and water level in the spreading room is raising but the level stays still below the top of the sidewall cooling elements. For the second phase (Volley 2005 tests) the test rig design was modified. After the modifications, the test facility construction simulates the events in the later phase of a possible core melt accident in the EPR plant conditions i.e. the spreading room is totally filled with water.

During the tests heat flux, coolant flow rate and coolant temperature were varied and both pure water and boron rich (boron concentration 1700 ppm) and mineral wool treated water (mineral wool concentration 50 mg/l) were used as coolant. Also the effect of core catcher plate inclination (1°) was studied. Initial test parameters are shown in Table 3.

### Table 3. Initial parameters for the Volley04 and Volley05 tests.

<table>
<thead>
<tr>
<th>Test</th>
<th>Heating power [kW]</th>
<th>Coolant flow rate [kg/min]</th>
<th>Coolant temp. [°C]</th>
<th>Water level in the buffer tank [m]</th>
<th>Flow elbow in end the outflow pipe [°]</th>
<th>Inclination [°]</th>
<th>Initial Boron concentration [ppm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volley04 test 1</td>
<td>70</td>
<td>2</td>
<td>20</td>
<td>-</td>
<td>-</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Volley04 test 2</td>
<td>70</td>
<td>2</td>
<td>80</td>
<td>-</td>
<td>-</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Volley04 test 3</td>
<td>70</td>
<td>10</td>
<td>20</td>
<td>-</td>
<td>-</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Volley04 test 4</td>
<td>95</td>
<td>3</td>
<td>80</td>
<td>-</td>
<td>-</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Volley04 test 5</td>
<td>95</td>
<td>3</td>
<td>20</td>
<td>-</td>
<td>-</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Volley04 test 6</td>
<td>95</td>
<td>2</td>
<td>20</td>
<td>-</td>
<td>-</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Volley04 test 7</td>
<td>35</td>
<td>2</td>
<td>80</td>
<td>-</td>
<td>-</td>
<td>0</td>
<td>1700</td>
</tr>
<tr>
<td>Volley04 test 8</td>
<td>35</td>
<td>2</td>
<td>80</td>
<td>-</td>
<td>-</td>
<td>0</td>
<td>1700</td>
</tr>
<tr>
<td>Volley04 test 9</td>
<td>35</td>
<td>2</td>
<td>80</td>
<td>-</td>
<td>-</td>
<td>0</td>
<td>1700</td>
</tr>
<tr>
<td>Volley05 test 1</td>
<td>35</td>
<td>2</td>
<td>80</td>
<td>0.32</td>
<td>180</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Volley05 test 2</td>
<td>70</td>
<td>2</td>
<td>20</td>
<td>0.47</td>
<td>180</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Volley05 test 3</td>
<td>35</td>
<td>2</td>
<td>80</td>
<td>0.32</td>
<td>90</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Volley05 test 4</td>
<td>35</td>
<td>2</td>
<td>80</td>
<td>0.47</td>
<td>90</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Volley05 test 5</td>
<td>70</td>
<td>10</td>
<td>20</td>
<td>0.32</td>
<td>90</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Volley05 test 6</td>
<td>35</td>
<td>2</td>
<td>80</td>
<td>0.32</td>
<td>90</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Volley05 test 7</td>
<td>70</td>
<td>2</td>
<td>80</td>
<td>0.32</td>
<td>90</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Volley05 test 8</td>
<td>95</td>
<td>2</td>
<td>80</td>
<td>0.32</td>
<td>90</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Volley05 test 9</td>
<td>35</td>
<td>2</td>
<td>80</td>
<td>0.32</td>
<td>90</td>
<td>0</td>
<td>1700</td>
</tr>
<tr>
<td>Volley05 test 10</td>
<td>35</td>
<td>2</td>
<td>80</td>
<td>0.32</td>
<td>90</td>
<td>0</td>
<td>1700</td>
</tr>
</tbody>
</table>

4 THEORETICAL REVIEW

4.1 Convection

The convection heat transfer mode has been described as energy transfer occurring within a fluid due to the combined effects of conduction and bulk fluid motion. Typically, the energy that is being transferred is the sensible or internal thermal, energy of the fluid. However, there are convection processes for which there is, in addition, latent heat exchange. This latent heat exchange is generally associated with a phase change between the liquid and vapour states of the fluid. Two special cases are boiling and condensation. For example, convection heat transfer results from fluid motion induced by vapour bubbles generated at the bottom of a pan of boiling water.

The appropriate rate equation for the convection heat transfer is of the form of the equation 1.
\[ q^* = h(T_s - T_a) \] (1)

where \( q^* \), the convective heat flux, is proportional to the difference between the surface and fluid temperatures \( (T_s > T_a) \). This expression is known as Newton’s law of cooling, and proportionality constant \( h \) is termed the convection heat transfer coefficient. It depends on conditions in the boundary layer, which are influenced by surface geometry, the nature of the fluid motion, and an assortment of fluid thermodynamic and transport properties. Typical \( h \) values are given in Table 4 [5, 6].

**Table 4. Typical values of the convection heat transfer coefficient.**

<table>
<thead>
<tr>
<th>Process</th>
<th>( h ) [W/m(^2)K]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Free convection</td>
<td></td>
</tr>
<tr>
<td>Gases</td>
<td>2-25</td>
</tr>
<tr>
<td>Liquids</td>
<td>50-1 000</td>
</tr>
<tr>
<td>Forced convection</td>
<td></td>
</tr>
<tr>
<td>Gases</td>
<td>25-250</td>
</tr>
<tr>
<td>Liquids</td>
<td>100-20 000</td>
</tr>
<tr>
<td>Convection with phase change</td>
<td></td>
</tr>
<tr>
<td>Boiling or condensation</td>
<td>2 500-100 000</td>
</tr>
</tbody>
</table>

4.2 Pool Boiling Correlations

A widely used correlation for pool nucleate boiling, which was developed by Rohsenow [7, 8, 9] is equation 2.

\[ q^* = \mu_f h_{fg} \left[ \frac{g(\rho_f - \rho_g)}{\sigma} \right]^{0.5} \left( \frac{c_{p,f} \Delta T_e}{C_{S,f} h_{fg} Pr_f^{n_f}} \right)^3, \] (2)

where coefficient \( C_{S,f} \) and the exponent \( n_f \) depend on the surface-liquid combination. In the reference [8] it is explained that this correlation applies only for clean surfaces and errors can amount to ±100%.

Although these several attempts of theoretical type equations utilizing the fluid, this type correlation found unsuitable for the current work. These correlations required various physical property data and these are often unavailable for designer’s problem. Correlations are inherent uncertainly due to the surface conditions and this why complicated to evaluate in this case. For these reasons and several unable measurable parameters it was reasonable to find other kind correlation.

A simpler approach, widely used by designers, is based on the work of Borishanski [10, 11] who utilized the law of corresponding states. His correlation is given as equation 3.

\[ h = A^* \cdot q^{0.7} F(P_r), \] (3)

where \( F(P_r) \) is a function of reduced pressure \( P_r \), and \( A^* \) is a constant evaluated at the reference reduced pressure \( P_r = 0.0294 \). Mostinski [12] and Collier [13] have modified factors \( A^* \) and \( F(P_r) \) giving them the following expressions.
According to literature [6, 14] it is safe and commonly recommended to drop the last two polynomial terms from equation 6. The Mostinski method is at least as accurate as any of the correlations based on physical properties and it is much simpler to use.

Another, newer and more accurate correlation of heat transfer coefficient is developed by Cooper [6]. His correlation is given in equation 7.

\[
    h = 55 P_r^{0.12 - 0.4343 \ln(R_p)} (-0.4343 - \ln(P_r))^{-0.55} M^{-0.5} q^{0.67},
\]

where \( M \) is the molecular weight of the liquid and \( R_p \) is the surface roughness parameter in \( \mu \text{m} \). For an unspecified surface \( R_p \) is set equal to 1.0 \( \mu \text{m} \). The correlation covers reduced pressures from 0.001 to 0.9 and molecular weights from 2 to 200 g/mol. This is the recommended method to use for water and refrigerants and for organic fluids with poorly defined physical properties.

The Gorenflo [6] method is an alternative approach for predicting nucleate pool boiling coefficients. It is based on a reference heat transfer coefficient \( h_0 \) at the following standard conditions: reduced pressure \( P_{r0} = 0.1 \), surface roughness \( R_{p0} = 0.4 \mu \text{m} \) and heat flux \( q_0 = 20000 \text{ W/m}^2 \). The reference value of \( h_0 \) is given for water as 5600 W/m²K. To obtain coefficient at other conditions, the following equation 8 is used.

\[
    h = h_0 F_{PF} \left( \frac{q}{q_0} \right)^{nf} \left( \frac{R_p}{R_{p0}} \right)^{0.133},
\]

where surface roughness of actual surface \( R_p \) is in micrometers and can be set to 0.4 \( \mu \text{m} \) for an unknown surface. The pressure correlation factor \( F_{PF} \) for water is correlated as equation 9.

\[
    F_{PF} = 1.2 P_r^{0.27} + 2.5 P_r + \frac{P_r}{1 - P_r}
\]

The heat flux correlation term has an exponent \( nf \) given as equation 10 for water.

\[
    nf = 0.9 - 0.3 P_r^{0.15}
\]

5 CALCULATION METHODS

Decisions done during the simulations are described in this chapter. For studying the heat transfer behaviour of the test facility during the tests it is appropriate to use 2D model of the bulk. It was clear that in this case the main problem was the heat transfer. Fluent was chosen as the simulation program to be used because it is sophisticated enough to solve simple heat transfer problem. Use of Finite Element Method (FEM) programs should give only a small advantage compared to Computational Fluid Dynamics (CFD) programs, like Fluent.

5.1 Mesh

The mesh used in the simulation was generated by Fluent Inc. program GAMBIT 2.2.30. After setting all vertexes in correct dimensions and scale, they are connected by edges, as shown in Figure 5. All edges are created symmetrically to make the generation of the mesh simpler. Cooling channel
walls are also split into several edges since, as described later, in different heights of cooling channel there may be different properties. Now they can be set in the water channel edge by edge.

The whole bulk is also split half in horizontally by tree interior edges, as seen in Figure 5 (horizontal green lines in the middle of the bulk). This is also done to make symmetric mesh generation easier. Two faces are generated in the bulk, upper and lower ones, split by the interiors. These faces are meshed with symmetric size quad elements in a way that size of the computing area of every cell is 1 mm².

Figure 5. Mesh of Volley bulk created by GAMBIT.

5.2 Fluent simulation

In this work Fluent Inc's Fluent 6.2.16 program 2D version has been used to simulate heat transfer phenomena. First, case is read from the file and the dimensions of the mesh are checked to be scaled in millimetres. 2D space and steady time have to be chosen in Models and in Solver menus. Energy equation option has to be set on. Radiation settings don’t need to be on in these temperatures. No proper bulk material in the Fluent database is available for this application. For this reason a new solid material has to be created in the Materials menu bar. For this material, named as iron, density is 7100 kg/m³, specific heat capacity is 500 J/kgK. Thermal conductivity is set piecewise-linear as shown in Table 2.

5.2.1 Boundary conditions

Boundary conditions for each wall in the bulk are set separately. The heat flux from the wall at the top of the channel is set to the value which is defined in each test case from the heating power of cartridge heaters. For example in the Volley test 7/04 the heat flux is 38 000 W/m². The heat flux in other outer walls could be set negative due to the heat losses, but in these tests the bulk was covered by mineral wool, so the effect of the heat losses is insignificantly small.

The walls of the cooling channels were split into several edges, to be able to set different properties for them, as mentioned before. In different height of cooling channel could be set different heat transfer coefficient to simulate water level in the channel. This work the heat transfer coefficient between cast iron and steam/air was set zero. Because the heat transfer coefficient between iron and steam comparing to the heat transfer coefficient between iron and water is insignificant. In chapter 4.2
three different heat transfer correlations for pool boiling are presented. These correlations give rather similar values, but in this work every case was simulated with all three different values. Channel walls required also boundary conditions for free stream temperature. Measured coolant temperatures in the tests and free stream temperatures are read from measuring data. Bulk wall materials have to be set to be of the right material.

5.2.2 Heat transfer coefficients

As mentioned, the heat transfer coefficients are calculated in all cases with three different correlations given by Borishanski, Cooper and Gorenflo correlations. Examples of these heat transfer coefficients with different heat fluxes are presented in Table 5.

<table>
<thead>
<tr>
<th>Heat flux [W/m$^2$]</th>
<th>Pressure [bar]</th>
<th>Borishanski*</th>
<th>Cooper*</th>
<th>Gorenflo**/**</th>
</tr>
</thead>
<tbody>
<tr>
<td>38 000</td>
<td>1.09</td>
<td>4915</td>
<td>5907</td>
<td>4139 – 7350</td>
</tr>
<tr>
<td>75 000</td>
<td>~0.7</td>
<td>7338</td>
<td>8505</td>
<td>6248-11094</td>
</tr>
<tr>
<td>102 000</td>
<td>1.05</td>
<td>9749</td>
<td>11453</td>
<td>8730-15502</td>
</tr>
</tbody>
</table>

* Depends on the pressure of cooling.
** Depends on the used cast iron roughness.

After setting all boundary conditions and options, the case was initialised and at least 100 iterations were run although the iteration converged after about 30-40 iterations.

One example of the temperature contours is presented in Figure 6. To compare numerical information from simulation with experimental results, measuring points were set in the mesh to same places as the thermocouples in the test facility. Locations of the measuring points in the bulk are presented in Figure 7.

6 COMPARISON OF THE EXPERIMENTAL RESULTS WITH THEORETICAL CALCULATIONS

In this chapter three video recorded Volley tests measurements are compared with the simulation results. Parameters needed in the simulation are the heating power, free stream
temperature in the cooling channel, and information about the water level in the cooling channel. Heating power and fluid temperatures in the cooling channel are measured during the tests. Information about water levels requires a visual observation in these tests. Plane 3 was selected for the comparisons of the measurements and simulation (see Figure 8), because on both sides of this plane there is a viewing window and the water level in the measuring plane can be estimated in some accuracy.

![Figure 8. Core catcher plate.](image)

6.1 Experimental results of Volley test 7/04

Volley tests before Volley test 7/04 were carried out with higher heating power and every time the tests had to be terminated due to the broken observation window or in order to save the test facility. The reason for this was violent the water hammers occurring during the tests. Therefore the purpose of the seventh test was to attain a steady state temperature distribution in the core catcher plate. The test was executed with the lowest heating power of 35 kW, coolant flow rate of 2 l/min and coolant temperature of 80 °C. The heating power was increased slowly to the value 35 kW (at 480 s). The coolant flow was initiated at 1530 s. After some steam was formed in the upper part of the channel, water started to oscillate.

At 2640 s, the outflow pipe was drained totally and stratified flow occurred. Water surface started to rise slowly. Temperatures in the upper part of the channel (T15, T26 and T36 in Figure 9) and in the core catcher structures (Figure 10) started to rise indicating dry-out. At 2980 s a water column started to develop inside the outflow pipe. At 3040 s the outflow pipe was drained totally again and stratified flow occurred.

At 9000 s, a maximum temperature was attained in the core catcher plate, see Figure 10. Because a 100 °C steady state temperature was attained on the bottom of the core catcher plate (T44), steam bubbles formed on the bottom of the cooling channel.
Volley Test 7/04: Temperatures of coolant

Figure 9. Temperatures of coolant in test 7/04.

Volley Test 7/04: Temperatures in the core catcher plate

Figure 10. Temperatures in the core catcher plate in test 7/04.
6.2 Simulation of Volley test 7/04

Heating power in Volley test 7/04 was set to 35 kW/m² and temperatures of the fluids can be seen from Figure 9. Water level in the cooling channel can be approximated from video recordings. Observing was carried out in that time scale when core catcher plate temperatures were in the steady state. Figure 10 shows that there is no real steady state in this test, but video recordings show that water level during period from 9000 s to 12000 s is very stable, see Figure 11 taken at 11114.2 s.

![Figure 11. Water level in the cooling channel during the steady state at 11114.2 s in Volley test 7/04.](image1)

Heat transfer coefficient was calculated with Borishanski, Cooper and Gorenflo correlations and used in same level as water was observed from the video recorded. For comparing measurements and calculations, simulations were done with different water levels. All simulations were initialized before running. Results of the simulations with different water levels and the measured temperatures of the test are shown in Figure 12.

![Figure 12. Temperatures of the simulation comparing measured temperatures test 7/04.](image2)
Similarity of the three different heat transfer correlations can be seen from Figure 12. Difference of values is difficult to see because simulation points are very close to each other, and all T44 simulation points are almost in the same group. Figure 12 show that simulations with 70 mm water level in the cooling channel give very similar results as measured temperatures. The video recording (Figure 11) shows that water level is clearly lower than 100 mm, but it seems to be little higher than 50 mm. This observation supports the simulation sensibility. Measured temperatures in the point T24 are higher than in the point T25 and this indicates that the cooling channel is not full of water. The video recording shows that in the top of cooling channel there is a layer of steam and air. This layer insulates the top part of the cooling channel and for this reason T24 temperatures rise higher than T25.

6.3 Experimental results of Volley test 6/05

The test was carried out with 1° inclined core catcher to clarify if inclination has an effect to the test results, particularly water hammer phenomenon.

The test was executed with a heating power of 35 kW, coolant flow rate of 2 l/min and coolant temperature of 80 °C. Water level in the buffer tank was 0.32 m. Due to the inclination of the core catcher occurring of condensation-induced water hammer was negligible. Therefore there was no risk for windows to break and the test was carried out normally until the moment of 18000 s. Saturated water temperature was reached in the buffer tank at 5500 s.

A steady state temperature distribution in the core catcher structures was reached after 6000 s, see Figure 13. Figure 14 shows precise temperatures in the middle part of the core catcher, which are used in the comparison with the simulation. Figure 15 shows temperatures of coolant in the channel.

Figure 16 shows steady state temperature profiles along the core catcher in Volley test 3/05 and test 6/05. In the test 3/05 temperatures in the beginning of the core catcher structures got notable higher than in the end indicating occurring of a dry-out. Meanwhile, during test 6/05 very steady temperature profiles along the core catcher were measured. Also temperatures measured 10 mm above the frontal cooling channel showed approximately 5 °C lower values than temperatures measured at the same height in the middle of the core catcher plate (above channels in legend) indicating no dry-out along the top part of the cooling channel.

Figure 13. Temperatures in the core catcher plate in Volley test 6/05.
Figure 14. Temperatures in the middle part of the core catcher plate in Volley test 6/05.

Figure 15. Temperatures of coolant in Volley test 6/05.
Figure 16. Steady state temperature profiles along the core catcher in Volley test 3/05 and test 6/05.

### 6.4 Simulation of Volley test 6/05

Through the viewing windows it was seen how water oscillated strongly back and forth as long as the test was carried out. Due to the inclination upper edge of the cooling channel was wetted at few seconds’ intervals also in the beginning part of the core catcher, see Figure 17.

Again the heat transfer coefficients are calculated using Borishanski, Cooper and Gorenflo correlations. Results of the simulation in different water levels and the measured temperatures of the test are shown in Figure 18.
Figure 18 shows how simulations give similar results with measuring when full cooling channel are calculated. Simulated temperatures at the point T44 are higher than measured. Reason for this could be a sensor which was connected to core catcher plate only partially.

7 SIMULATIONS EXTENDED TO THE STEADY STATE CONDITIONS

The purpose of this chapter is to present how terminated Volley04 tests might behave if they could have been continued long enough to reach steady state conditions. Water level in the cooling channel is unknown as well as coolant temperature. These parameters have to be varied and estimated. Volley tests 1/04, 2/04 and 4/04 were simulated and the steady state temperature were estimated. Volley test 3/04 could not be simulated due to inadequate temperature information. In Volley tests 5/04 and 6/04 the parameters for simulation did not differ from the test 4/04. In these tests the coolant flow rate and temperature varied but these are not simulation parameters. Therefore it was not necessary to carry out these simulations.

7.1 Simulations with the empty cooling channels

Finally, some simulations were executed with empty cooling channels. In the situation when cooling channels are empty, only bottom walls of one or both cooling channels are wetted. Figure 19 shows simulation temperatures of the measuring points with three different heat fluxes, when only bottom walls of both channels are wetted. As Figure 19 shows, the melting temperature of cast iron is not reached.
When considering the situation, where only bottom wall of one channel is wetted, the temperature distribution will change. Figure 20 shows the situation in which the cooling channel on the side of the measuring points (right) is wetted and the other side (left) is totally dry. The heat flux in this case was 102 000 W/m². Smaller heat flux gives smaller temperatures. In the contrary situation the temperature distribution is the same but like a mirror image. In the Table 6 there are listed simulation temperatures from both the cases.
Table 6. Measuring points’ temperatures when one cooling channel is wetted and another is dry.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature if the channel below</td>
<td>985.05</td>
<td>936.38</td>
<td>909.45</td>
<td>394.18</td>
</tr>
<tr>
<td>of the measuring points is wetted</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Temperature if the channel below</td>
<td>1021.85</td>
<td>976.66</td>
<td>909.23</td>
<td>390.43</td>
</tr>
<tr>
<td>of the measuring points is dry</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cast iron melting temperature</td>
<td>1250</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Simulation results show that there is no immediate risk of melting of the cooling channel element if the channel is at least partly wetted. But if several parallel cooling channels are totally dry then the structure temperature will probably rise to the melting temperature.

8 CONCLUSIONS

This work concentrated on theoretical and computational study of the EPR core catcher test facility (Volley) designed and constructed at Lappeenranta University of Technology. Work included examination of various correlations of heat transfer coefficient in the pool boiling conditions. Three different correlations were found, which could be used when only few measured parameters are available. It can be mentioned that difference of used heat transfer correlations seems to be small, at least in this test facility scale and compare to the measuring accuracy.

The second part of the work consisted of the Volley 04 test simulations. The simulation method was first validated by calculating such Volley 04 and 05 tests, which could be continued to thermal hydraulic steady state and had video recorded information of the coolant level in the cooling channel. The simulations gave fine results. The most interesting observation was that in the situation, in which the cooling water oscillated strongly back and forth, the results corresponded with the case when the cooling channel is full of water. Simulations and measurement results were the same within two or three Celsius degrees. Results were good even if the heat transfer coefficient between cast iron and steam/air was set zero. This is because the heat transfer coefficient between iron and steam is very low compared to the coefficient between iron and water. Simulations also support the observation that the full cooling channel gives different order of values for the temperature measurements T24 and T25 above the cooling channels than the only partly wetted channel.

In general it can be said that simulation results of Volley tests 04 and 05, which have been video recorded and could be run until the steady state conditions, are very close to the measured temperatures. But simulations of tests done without visualising do not give comprehensive results. From the results the magnitude of the temperatures in the measuring points can be deduced.

It also can be concluded, that if there is even a small water flow inside the cooling channels or only a few adjacent cooling channels are totally dry, the core catcher cannot melt with heat fluxes used in the tests.

REFERENCES


