Steam Blowdown Experiments with the Condensation Pool Test Rig

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ABSTRACT

During a possible loss-of-coolant accident (LOCA) a large amount of non-condensable (nitrogen) and condensable (steam) gas is blown from the upper drywell of the containment to the condensation pool through the blowdown pipes at the boiling water reactors (BWRs). The wetwell pool serves as the major heat sink for condensation of steam. The blowdown causes both dynamic and structural loads to the condensation pool. There might also be a risk that the gas discharging to the pool could push its way to the emergency core cooling systems (ECCS) and undermine their performance.

1 INTRODUCTION

An intensive test programme for the investigation of BWR containment dynamics has been carried out in 1970’s with the Marviken containment system in Sweden [1]. Recent studies include, for example, small scale experiments with air and steam performed by Meier in connection with the development work of a two-dimensional computational fluid dynamics (CFD) model [2]. Youn, Ko, Lee, Kim, Bae and Park have studied direct contact condensation of steam, and pressure oscillations at low mass flux using a horizontal pipe and an injection nozzle submerged in a pool containing sub-cooled water [3]. Experimental work on the subject during the last two decades has, however, been quite rare.

Condensation pool studies have been performed in the Nuclear Safety Research Unit at Lappeenranta University of Technology (LUT) between 2001 and 2005 in the framework of two successive Finnish national research programmes (FINNUS and SAFIR) on nuclear power plant safety. The tests have been designed to correspond to the conditions of a postulated accident in Finnish BWRs.

In the first tests, the formation, size and distribution of non-condensable gas bubbles in the condensation pool has been studied experimentally with a scaled down pool test facility. In the Condensation Pool Experiments (POOLEX) project, belonging to the latter national programme, steam instead of non-condensable gas has been injected into the condensation pool test rig. The main objective of the POOLEX project is to increase the understanding of different phenomena in the condensation pool during steam injection. These phenomena could be connected to bubble dynamics issues such as bubble growth, upward acceleration, detachment and break-up. The bubbles interact with pool water by heat transfer, steam condensation and possibly evaporation, and momentum exchange via buoyancy and drag forces. Pressure oscillations due to rapid condensation are also among the issues of interest.
The investigation of the steam injection phenomenon requires high-grade measuring techniques. For example, to estimate the loads on the pool structures by condensation pressure oscillations the frequency and the amplitude of the oscillations have to be measured. With the aid of high-speed video observations the validity of correlations for steam bubble size and break-up heights as a function of total volumetric flow-rate and pool sub-cooling can be investigated. In determining condensation rates during bubble formation direct measurement of heat and mass transfer is desirable, but virtually impossible. However, the process of direct-contact condensation of large steam bubbles in water is well suited for visual observation. Interfaces are macroscopic and well visible. To some extent, condensation rates can be determined indirectly from volume rates-of-change estimated from video images.

Experiment results of the POOLEX project can be used for the validation of different numerical methods for simulating steam injection through a blowdown pipe into liquid. The development work of 3D two-phase flow models for computational fluid dynamics (CFD) codes can be assisted by the POOLEX experiments. Furthermore, the coupling of CFD and structural analysis codes in solving fluid-structure interactions could be facilitated with the aid of load measurements of the steam blowdown experiments.

2 CONDENSATION POOL TEST RIG

The test facility consists of a large, cylinder shaped, uninsulated water pool with an open top and a conical bottom, of a blowdown pipe, and of a steam line connecting the test section to the nearby PACTEL facility [4], whose three steam generators are acting as a steam source (see Figure 1). There are several circular windows in the pool wall for visual observation of the interior. Disc springs are installed under the four stands and the pool is connected to the laboratory walls by using five tie rods. The main geometrical dimensions of the test rig are listed in Table 1.

Figure 1: Schematic of the test rig setup for the condensation pool experiments
Table 1: Main dimensions of the condensation pool test rig

<table>
<thead>
<tr>
<th>Blowdown pipes:</th>
<th>Length:</th>
<th>4.0 m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inner diameter (DN80 / DN100 / DN200):</td>
<td>85 / 110 / 214 mm</td>
<td></td>
</tr>
<tr>
<td>Water pool:</td>
<td>Height:</td>
<td>5.0 m</td>
</tr>
<tr>
<td>Inner diameter:</td>
<td></td>
<td>2.4 m</td>
</tr>
<tr>
<td>Pool cross-sectional area:</td>
<td>4.52 m²</td>
<td></td>
</tr>
<tr>
<td>Total volume:</td>
<td></td>
<td>20.6 m³</td>
</tr>
<tr>
<td>Water volume at normal water level of 3.7 m from the bottom:</td>
<td>15.4 m³</td>
<td></td>
</tr>
<tr>
<td>Wall thickness:</td>
<td></td>
<td>4 mm</td>
</tr>
<tr>
<td>Bottom wall thickness:</td>
<td></td>
<td>5 mm</td>
</tr>
</tbody>
</table>

At the moment, there are three options available for the blowdown pipe size, DN80, DN100 and DN200. The axial position of the blowdown pipe inside the pool is asymmetrical i.e. it is placed 300 mm away from the pool centre axis. Steam injection is initiated by opening a remotely controlled valve in the steam line.

2.1 Description of Measurements

The test facility is equipped with Ø0.5 mm K-type thermocouples for measuring steam and pool water temperatures (T), with high frequency pressure transducers (P) for observing pressure behaviour in the blowdown pipe and at the pool bottom, and with one pressure transducer (DP) for detecting the pool water level. Steam flow is measured with a vortex flow meter in the DN50 steam line. Additional instrumentation includes four strain gauges on the pool outer wall, valve position sensors and a high-speed video camera trigger. Figure 2 shows the measurement locations.

Figure 2: Positioning of instrumentation inside the blowdown pipe and on the pool bottom
2.2 Digital High-Speed Video Camera

The investigation of the steam injection phenomenon requires high-grade measuring techniques. A Citius Imaging C10 digital high-speed video camera is used for visual observation of the pool interior. The camera works in close connection with a PC, which is used for controlling, display and storage. The camera is furnished with the maximum amount of memory available (2 GB) and it can achieve over 10000 frames/second (fps) recording speed and up to 652x496 pixels resolution with 256 shades of grey. However, speed and maximum recording time depend on the resolution used. During the experiments a recording speed of approximately 220 fps with a resolution of 400x338 has mostly been used. With this set-up the maximum recording time is 73 seconds (29 MB/s).

2.3 Data Acquisition [5]

A National Instruments PCI-PXI-SCXI data acquisition system is used to enable high-speed multi-channel measurements. It is a PC-driven measurement system with a LabView 7.1 user interface. The maximum number of measurement channels is 96 with additional eight channels for strain measurements. The maximum recording frequency depends on the number of measurements and is in the region of 300 kHz for all the measured channels combined. Separate software is used for monitoring and recording the essential measurements of the PACTEL facility producing the steam. Both data acquisition systems measure signals as volts. After the experiments, the voltage readings are converted to engineering units by using special conversion software.

The data recording frequency of LabView has usually been 10 kHz for other than temperature measurements. For temperatures the frequency has been 200 Hz. The temperature measurements are therefore averages of 50 measured points. Residual measurements are recorded by HPVee software with the frequency of 1 Hz. A separate measurement channel is used both for the steam line valve position information and for the digital high-speed video camera triggering.

A high data recording frequency produces a large amount of measurement data. With the used data recording frequency and the number of measurement channels (10 kHz / 12 channels and 200 Hz / 5 channels for temperature readings) LabView produces approximately 17 MB of data per a 10 second time interval. As a comparison, HPVee produces no more than 1 kB of data / 10 seconds. To avoid problems due to the large amount of measurement data a high performance PC for processing and a lot of disk space for archiving are essential.

3 TEST PROGRAMME

The pool test rig was originally designed and constructed from the point of view of structural integrity for the experiments with steam. However, it was first used for the investigation of the behavior of non-condensable gas in the initial phase of the blowdown. After some modifications to the pool and its instrumentation, the rig has now been used for steam injection studies. Several preliminary experiments with the three different blowdown pipes have been executed in 2003-2004 [6, 7] before the actual test series on steam injection. In the pre-tests, experimental procedures have been developed and rehearsed and extra requirements for instrumentation or data acquisition have been assessed.

The actual test programme has started in December 2004 [8]. It contains so far five experiments at initial steam pressures between 0.3 and 3.0 MPa and at water pool temperatures between 11 and 76 °C. Steam mass flux has ranged from 4 to 13 kg/m²s. In the beginning of each experiment, the water level in the pool has been approximately 3.5 m, i.e.
the blowdown pipe has been submerged by 2 m. Each experiment consists of four to ten individual steam blows. All the actual experiments have been performed by using the DN200 blowdown pipe. During the pressure build-up phase and between individual steam blows the steam line has been heated with a small by-pass flow.

In the handbook of thermal hydraulics of BWRs, Lahey and Moody present a map of condensation modes that have been observed during either LOCA or safety/relief valve (SRV) steam discharge [9]. In that map, condensation modes are categorized based on steam mass flux and pool bulk temperature. Due to steam discharge, the pool water temperature rises in the course of the accident. In Figure 3, individual steam blows from those four experiments with the condensation pool test rig, where the flow rate have been measured, are marked on the map of Lahey and Moody as colored crosses. In the DN200 blowdown pipe, the attainable steam mass flux is quite small due to the limited steam production. As a result, all blows are located in the lower end of the x-axis. However, with increasing pool water temperature and with quite high initial pressures of the steam source four different regions of the map can be covered; condensation within vents or blowdown pipes, chugging, condensation oscillations and transition region.

![Diagram of condensation modes](image)

Figure 3: Placement of separate steam blows from four different experiments with the condensation pool test rig on the condensation mode map of Lahey and Moody [9]

### 3.1 Boundary Conditions

Boundary conditions of the individual experiments depend on the used facility configuration and test parameters. Steam pressure and temperature either in the PACTEL steam generator or in the steam line at the flow meter can be used as inlet conditions. Another available inlet condition is the measured steam flow rate, except in those few experiments where the measurement range of the flow meter was exceeded. No inlet conditions for the moisture content of steam or for the amount of droplets among the flow are available, because there is no void measurement in the steam line. Saturated conditions at the flow meter may be assumed, for example, to calculate the steam velocity. Since the steam line is insulated, heat losses between the steam generator and the top part of the blowdown pipe can be assumed negligible. Instead, heat losses from the water pool must be taken into account in the simulation calculations. Atmospheric pressure on the pool water surface or hydrostatic pressure (in brief individual steam blows where the level rise is minimal) in the pool bottom
corresponding to the height of the water volume in the pool can be used as an outlet boundary condition. The pool water temperature rises during the steam blows, and therefore it cannot be used as an outlet boundary.

4 TEST RESULTS

The five actual experiments are briefly presented in Table 2 in a collective form i.e. separate steam blows are not itemized. Beside the initial conditions, the last columns of the table give the maximum pressure peaks measured inside the blowdown pipe and at the pool bottom as well as the highest strain values.

Table 2: Measured values from the steam injection experiments

<table>
<thead>
<tr>
<th>Exp.</th>
<th>Initial steam pressure [MPa]</th>
<th>$T_{\text{pool}}$ [°C]</th>
<th>$G_{\text{steam}}$ [kg/m²s]</th>
<th>$p_{\text{max}}$ in the DN200 pipe [MPa]</th>
<th>$\Delta p_{\text{max}}$ on the pool bottom [kPa]</th>
<th>$\Delta \varepsilon_{\text{max}}$ [$\mu$S]</th>
</tr>
</thead>
<tbody>
<tr>
<td>STB-13</td>
<td>0.5 – 0.6</td>
<td>15…27</td>
<td>4…12</td>
<td>1.6</td>
<td>30</td>
<td>not known</td>
</tr>
<tr>
<td>STB-14</td>
<td>0.5</td>
<td>37…68</td>
<td>8…12</td>
<td>1.3</td>
<td>40</td>
<td>220</td>
</tr>
<tr>
<td>STB-15</td>
<td>0.4 – 0.5</td>
<td>49…76</td>
<td>5…12</td>
<td>1.3</td>
<td>60</td>
<td>240</td>
</tr>
<tr>
<td>STB-16</td>
<td>0.3 – 0.5</td>
<td>11…17</td>
<td>4…13</td>
<td>3.9</td>
<td>40</td>
<td>90</td>
</tr>
<tr>
<td>STB-17</td>
<td>1.0 – 3.0</td>
<td>22…37</td>
<td>not known</td>
<td>1.8</td>
<td>390</td>
<td>330</td>
</tr>
</tbody>
</table>

4.1 Condensation inside the Blowdown Pipe

In those cases, where the pool water temperature has been below 30 °C and the steam mass flux close to the lower end of the used range of 4…13 kg/m²s, steam has mainly condensed within the blowdown pipe. The rapid condensation process generates an underpressure lasting up to 0.5 s. Due to the collapse of the steam volume, a water hammer develops and propagates inside the blowdown pipe. As a result, a high pressure pulse occurs when the pipe is filled with water. The maximum registered pressure pulse inside the blowdown pipe has been 3.9 MPa, see Figure 4.

![Figure 4: Pressure behavior inside the blowdown pipe and on the pool bottom during steam injection into cold water](image-url)
During the test steam-water interface moves strongly up and down inside the pipe as the pressure pulses follow each other, see Figure 5. This is characteristic of the condensation mode in question: condensation within vents or blowdown pipes, see Figure 3. No high loads on the pool bottom have been measured by the pressure sensor or the strain gauges in those cases where the condensation takes place inside the blowdown pipe.

![Figure 5: Steam-water interface movement up and down inside the blowdown pipe as indicated by temperature measurements](image)

4.2 **Steam Bubbles at the Blowdown Pipe Outlet**

As the pool water temperature or steam mass flux increase the condensation mode changes to chugging and steam bubbles start to form at the blowdown pipe outlet. First, the bubbles are small but with rising pool water temperature they become larger and larger. The maximum observed bubble diameter in the condensation pool experiments so far has been about two and a half times the DN200 blowdown pipe diameter. Frame captures from the high speed video in Figure 6 show some typical steam bubbles as a function of increasing pool water temperature while the other test parameters are almost constant. (Variation in steam mass flux between the blows is less than 20%).

The time needed for the bubbles to collapse (condense) increases with the bubble size and pool water temperature. However, no noticeable change in the steam bubble formation frequency (0.5 Hz) with increasing pool water temperature (from 50 to 70 °C) but with constant steam flux has been observed. This observation is made from a continuous blowdown lasting for 3000 s but it is valid only for the overlapping area of the chugging and transition regions, see Figure 3.

After the bubbles at the pipe outlet collapse, water is sucked into the blowdown pipe and pressure pulses induced by a water hammer propagating inside the pipe are registered again. This time, however, they are smaller (maximum value 1.3 MPa) than in the case of the whole condensation taking place inside the blowdown pipe.

As the pool water temperature still rises, no more sudden collapses of the steam volume inside the blowdown pipe occur and no significant underpressure or water hammer phenomena develop. Highest pressure loads (40 kPa) and strains (240 µS) at the pool bottom are observed in connection with the collapse of some of the largest bubbles at the pipe outlet after the pool water temperature has risen over the value of 70 °C.
4.3 Condensation Oscillations

When the steam flow rate is high enough, it prevents water ingress into the blowdown pipe i.e. the whole condensation process takes place in the pool. To achieve these conditions in the test rig, the initial pressure of the steam source was increased up to 3.0 MPa and the
control valve in the steam line was kept fully open during the blows ignoring the fact that the measurement range of the flow meter would be exceeded. In the last two blows of the fifth experiment, water ingress into the pipe was minimal and steam-water interface oscillated at the pipe outlet. The observed condensation mode belongs to region three on the map of Lahey and Moody i.e. condensation oscillations. The next mode, quasi-steady condensation (region 4), was not fully achieved in the experiment. Figure 7 illustrates how the behaviour of the steam-water interface inside the blowdown pipe develops as the condensation mode changes from chugging to condensation oscillations.

5 SUMMARY AND CONCLUSIONS

Five experiment series have been carried out to study steam injection into a large water pool with a scaled down test facility designed and constructed at Lappeenranta University of Technology. In the experiments, dynamics issues of steam bubbles, such as bubble growth and maximum size have been studied. Pressure oscillations and loads to pool structures due to rapid condensation have also been among the issues of interest. The initial system pressure of the steam source has ranged from 0.3 to 3.0 MPa and the water bulk temperature in the pool from 11°C to 76°C. The size of the blowdown pipe has been DN200. Wide frequency band instrumentation and a fast data acquisition system have produced detailed measurement data. A digital high-speed video camera has been used for the accurate observation of the forming steam bubbles during the blows.

During the experiments, three different condensation modes have been observed; condensation inside the blowdown pipe, chugging and condensation oscillations. Which one of these condensation modes is dominating, is determined by the pool water temperature and steam mass flux.

With cold water and low steam mass flow, the condensation process takes place already inside the blowdown pipe. Condensation-induced water hammer develops inside the blowdown pipe and high pressure pulses can be registered.

As the pool water temperature and/or steam flow gets higher, transition to chugging mode takes place. In this mode, steam flow pushes steam-water interface downwards inside the blowdown pipe and a steam bubble forms at the pipe outlet. The bubble condenses rapidly and the steam-water interface moves upwards inside the blowdown pipe until the steam pressure is high enough to stop the interface and push it downwards again. Chugging phenomenon causes dynamic loads to the pool structures.

Further increase of steam flow causes a transition to condensation oscillations mode. In this mode, steam-water interface undergoes a condensation event totally in the pool. A steam bubble forms at the pipe outlet and begins to collapse. The high steam flow rate prevents water re-entry into the blowdown pipe. The next bubble is formed after the condensation event and the cycle is repeated. Condensation oscillations mode causes dynamic loads to the pool structures, too.

The condensation modes observed in the experiments correspond nicely to the different regions on the map of Lahey and Moody (Figure 3). More experiments, for example on the chugging phenomenon, will be carried out in the near future in the POOLEX project to assist the development work of two-phase flow models for CFD codes and to facilitate the coupling of CFD and structural analysis codes in solving fluid-structure interactions.
REFERENCES


