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Steam Line Rupture Experiments with the PPOOLEX Test Facility

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Abstract

The results of the steam line rupture experiment series in 2007 with the scaled down PPOOLEX test facility designed and constructed at Lappeenranta University of Technology are reported. The test facility is a closed stainless steel vessel divided into two compartments, dry well and wet well. Air was blown into the dry well compartment and from there through a DN200 blowdown pipe to the condensation pool. Altogether five experiments, each consisting of several blows (tests), were carried out.

The main purpose of the experiment series was to study the initial phase of a postulated steam line break accident inside a BWR containment. Specifically, thermal stratification in the dry well compartment and ejection of water plug from the blowdown pipe were of interest. In addition, the effect of counterpressure on bubble dynamics was studied.

A temperature difference of approximately 15 °C between the upper and lower part of the dry well was measured. In the wet well gas space, a temperature difference of more than 30 °C was registered. These were measured during the compression period of the tests. Towards the end of the tests the temperature differences tended to disappear. To get a more detailed picture of temperature distribution in the wet well, especially close to the water level, a dense net of measurements is required in future experiments. In longer experiments, heat conduction to structures and heat losses to surroundings should also be taken into account.

Ejection of water plugs from the blowdown pipe did not cause notable loads to the structures due to the suppressing effect of the dry well compartment. The maximum measured pressure pulse at the pool bottom was only 10 kPa and the maximum strain amplitude at the pool bottom rounding was negligible both in axial and circumferential direction.

As the counterpressure of the system increased, but the flow rate remained the same, the maximum size of the air bubbles at the blowdown pipe outlet got smaller and smaller. Furthermore, the magnitude of pressure oscillations in the wet well pool decreased with increasing counterpressure. Correspondingly, the formation frequency of bubbles increased with increasing counterpressure. Meanwhile, flow rate had no effect on the bubble formation frequency.

Key words

condensation pool, steam/air blowdown, non-condensable gas, steam line rupture

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STEAM LINE RUPTURE EXPERIMENTS WITH THE PPOOLEX TEST FACILITY

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The results of the steam line rupture experiment series in 2007 with the scaled down PPOOLEX test facility designed and constructed at Lappeenranta University of Technology are reported. The test facility is a closed stainless steel vessel divided into two compartments, dry well and wet well. Air was blown into the dry well compartment and from there through a DN200 blowdown pipe to the condensation pool. Altogether five experiments, each consisting of several blows (tests), were carried out.

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A temperature difference of approximately 15 °C between the upper and lower part of the dry well was measured. In the wet well gas space, a temperature difference of more than 30 °C was registered. These were measured during the compression period of the tests. Towards the end of the tests the temperature differences tended to disappear. To get a more detailed picture of temperature distribution in the wet well, especially close to the water level, a dense net of measurements is required in future experiments. In longer experiments, heat conduction to structures and heat losses to surroundings should also be taken into account.

Ejection of water plugs from the blowdown pipe did not cause notable loads to the structures due to the suppressing effect of the dry well compartment. The maximum measured pressure pulse at the pool bottom was only 10 kPa and the maximum strain amplitude at the pool bottom rounding was negligible both in axial and circumferential direction.

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PREFACE

Condensation pool studies started in Nuclear Safety Research Unit at Lappeenranta University of Technology (LUT) in 2001 within the Finnish Research Programme on Nuclear Power Plant Safety (FINNUS). The experiments were designed to correspond to the conditions in the Finnish boiling water reactors (BWR) and the experiment programme was partially funded by Teollisuuden Voima Oy (TVO). Studies continued in 2003 within the Condensation Pool Experiments (POOLEX) project as a part of the Safety of Nuclear Power Plants - Finnish National Research Programme (SAFIR). The studies were funded by the State Nuclear Waste Management Fund (VYR) and by the Nordic Nuclear Safety Research (NKS).

In these research projects, the formation, size and distribution of non-condensable gas and steam bubbles in the condensation pool was studied with an open scaled down pool test facility. Also the effect of non-condensable gas on the performance of an emergency core cooling system (ECCS) pump was examined. The experiments were modeled with computational fluid dynamics (CFD) and structural analysis codes at VTT.

A new research project called Condensation Experiments with PPOOLEX Facility (CONDEX) started in 2007 within the SAFIR2010 - The Finnish Research Programme on Nuclear Power Plant Safety 2007 – 2010. The CONDEX project focuses on different containment issues and continues further the work done in this area within the FINNUS and SAFIR programs. For the new experiments, a closed test facility modeling the dry well and wet well compartments of a BWR containment was designed and constructed. The main objective of the CONDEX project is to increase the understanding of different phenomena inside the containment during a postulated main steam line break (MSLB) accident. The studies are funded by the VYR and NKS.

CONTENTS

LAPPEENRANTA UNIVERSITY OF TECHNOLOGY

NOMENCLATURE

A	area
F	flow rate
p, P	pressure
Q	volumetric flow rate
q_m	mass flow rate
S	strain
T	temperature
z	vertical movement

Greek symbols

Δ	change
ε	strain

Abbreviations

AVI	audio video interleave
BWR	boiling water reactor
CCTV	closed circuit television
CFD	computational fluid dynamics
CONDEX	condensation experiments with PPOOLEX facility project
DCC	direct contact condensation
ECCS	emergency core cooling system
FINNUS	Finnish Research Programme on Nuclear Power Plant Safety
fps	frames per second
LOCA	loss-of-coolant accident
LUT	Lappeenranta University of Technology
MSLB	main steam line break
NKS	Nordic nuclear safety research
PACTEL	parallel channel test loop
POOLEX	condensation pool test facility, condensation pool experiments project
PPOOLEX	containment test facility
PWR	pressurized water reactor
RAM	random access memory
SAFIR	Safety of Nuclear Power Plants – Finnish National Research Programme
SAFIR2010	The Finnish Research Programme on Nuclear Power Plant Safety 2007 – 2010
SLR	steam line rupture
SRV	safety/relief valve
TVO	Teollisuuden Voima Oy
USB	universal serial bus
VTT	Technical Research Centre of Finland
VYR	State Nuclear Waste Management Fund
VVER	Vodo Vodjanyi Energetitseskij Reaktor

1 INTRODUCTION

During a postulated main steam line break accident inside the containment a large amount of non-condensable (nitrogen) and condensable (steam) gas is blown from the upper drywell to the condensation pool through the blowdown pipes in the Olkiluoto type BWRs. The wet well pool serves as the major heat sink for condensation of steam. Figure 1 shows the schematic of the Olkiluoto type BWR containment.

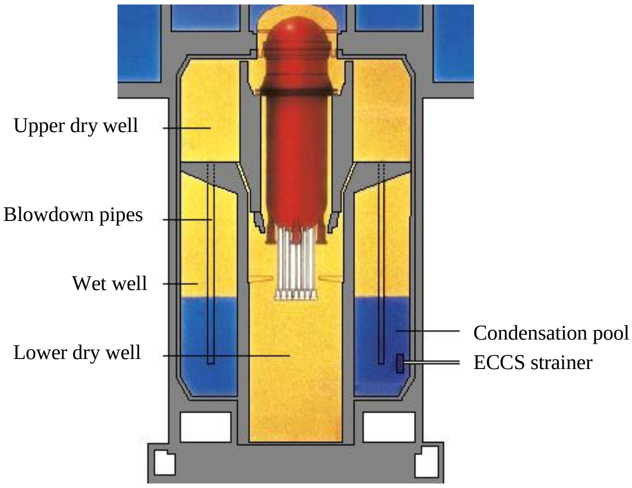

Figure 1. Schematic of the Olkiluoto type BWR containment.

The main objective of the CONDEX project is to increase the understanding of different phenomena inside the dry well and wet well compartments of a BWR containment during a steam line break accident. These phenomena could be connected, for example, to bubble dynamics issues, thermal stratification and mixing, wall condensation and interaction of parallel blowdown pipes. Steam bubbles interact with pool water by heat transfer, condensation and momentum exchange via buoyancy and drag forces. Pressure oscillations due to rapid condensation occur frequently. Investigation of the steam/gas 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. Experience of suitable instrumentation and visualization equipment was achieved already during the preceding research projects dealing with condensation pool issues.

Experiment results of the CONDEX project can be used for the validation of different numerical methods for simulating gas/steam injection through a blowdown pipe into liquid. Experimental studies on the process of formation, detachment and break-up and the simultaneous direct contact condensation (DCC) of large steam bubbles as well as on the stratification and mixing phenomena in the pool are still sparse. However, the improvement of models is necessary for the reduction of uncertainties in predicting containment behaviour during gas/steam injection. Some of the bubble dynamics models are applicable also outside the BWR scenarios, e.g. for the quench tank operation in the pressurizer vent line of a Pressurized Water Reactor (PWR), for the bubble condenser in a VVER-440/213 reactor system, or in case of a submerged steam generator pipe break.

The development work of 3D two-phase flow models for CFD codes can be assisted by the CONDEX experiments. Furthermore, the (one-directional or bi-directional) coupling of CFD and structural analysis codes in solving fluid-structure interactions can be facilitated with the aid of load measurements of the steam blowdown experiments.

In 2006, a new test facility, called PPOOLEX, related to BWR containment studies was designed and constructed by Nuclear Safety Research Unit at LUT. It models both the dry and wet well (condensation pool) compartments of the containment and withstands prototypical system pressures. Experience gained with the operation of the preceding open POOLEX facility was extensively utilized in the design and construction process of the new facility.

Experiments with the new PPOOLEX facility were started in 2007 by running a series of characterizing tests. They focused on observing the general behaviour of the facility, on testing instrumentation and the proper operation of the automation, control and safety systems. These experiments are reported in reference [1].

The research programme was continued in November 2007 with five experiments (SLR series) focusing on the initial phase of a postulated steam line break accident inside the containment. Pure air was used as the flowing substance in these experiments. Thermal stratification in the dry well compartment and ejection of water plug from the blowdown pipe were of special interest. In addition, the effect of counterpressure on bubble dynamics was studied in one experiment. In this report, the results of these experiments are presented. First, chapter two gives a short description of the test facility and its measurements as well as of the data acquisition system used. The test programme of the SLR experiment series is introduced in chapter three. The test results are presented and shortly discussed in chapter four. Chapter five summarizes the findings of the experiment series.

2 PPOOLEX TEST FACILITY

Condensation studies at LUT started with an open cylindrical pool test facility (POOLEX) modeling the suppression pool of the BWR containment. During the years 2002-2006, the facility had several modifications and enhancements as well as improvements of instrumentation before it was replaced with a more versatile PPOOLEX facility in the end of 2006. The PPOOLEX facility is described in more detail in reference [2]. However, the main features of the facility and its instrumentation are introduced below.

2.1 TEST VESSEL

The PPOOLEX facility consists of a wet well compartment (condensation pool), dry well compartment, inlet plenum and air/steam line piping. An intermediate floor separates the compartments from each other but a route for gas/steam flow from the dry well to the wet well is created by a vertical blowdown pipe attached underneath the floor.

The main component of the facility is the ~31 m^3 cylindrical test vessel, 7.45 m in height and 2.4 m in diameter. The vessel is constructed from three separate plate cylinder segments and from two dome segments. The test facility is able to withstand considerable structural loads caused by rapid condensation of steam. The vessel sections modeling dry well and wet well are volumetrically scaled according to the compartment volumes of the Olkiluoto 1 and 2 containment buildings. The DN200 (∅ 219.1 x 2.5 mm) blowdown pipe is positioned inside the pool in a non-axisymmetric location, i.e. 300 mm away from the centre of the condensation pool. Horizontal piping (inlet plenum) for injection of gas and steam penetrates through the side wall of the dry well compartment. The length of the inlet plenum is 2.0 m and inner diameter 214.1 mm. There are several windows for visual observation in the walls of both compartments. A DN100 (∅ 114.3 x 2.5 mm) drain pipe with a manual valve is connected to the bottom of the vessel. A relief valve connection is mounted on the vessel head. The large removable vessel head and a man hole (DN500) in the wet well compartment wall provide access to the interior of the vessel for maintenance and modifications of internals and instrumentation. A sketch of the test vessel is presented in Figure 2. Table 1 lists the main dimensions of the test facility compared to the conditions in the Olkiluoto plant.

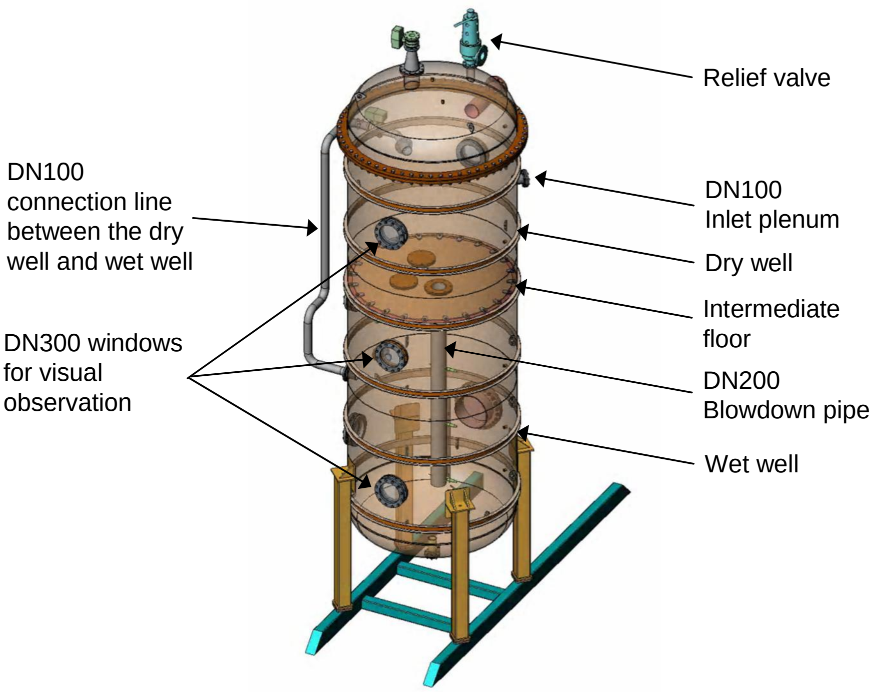

Figure 2. PPOOLEX test vessel.

Table 1. Test facility vs. Olkiluoto 1 and 2 BWRs

	POOLEX test facility	Olkiluoto 1 and 2
Number of blowdown pipes	1	16
Inner diameter of blowdown pipe [mm]	214.1	600
Suppression pool cross-sectional area [m^2]	4.45	287.5
Dry well volume [m^3]	13.3	4350
Wet well volume [m^3]	17.8	5725
Nominal water volume in suppression pool [m^3]	8.38*	2700
Nominal water level in suppression pool [m]	2.14*	9.5
Pipes submerged [m]	1.05	6.5
A_{pipes}/A_{pool}x100%	0.8**	1.6

* Water volume and level can be chosen according to the experiment type in question. The values listed in the table are based on the ratio of nominal water and gas volumes in the plant.
** With one blowdown pipe.

2.2 PIPING

In the plant, there are vacuum breakers between the dry well and wet well compartments in order to keep the pressure in the wet well compartment in all possible accident situations less than 0.05 MPa above the dry well pressure In the PPOOLEX test facility, pressure difference between the compartments is regulated through a connection line (Ø 114.3 x 2.5 mm) installed between the dry well and the gas volume of the wet well. A remotely operated valve in the connection line can be programmed to open with a desired pressure difference according to test specifications. However, the pressure difference across the separating floor between the compartments should not exceed the design value of 0.2 MPa.

Steam needed in the experiments is produced with the nearby PACTEL [3] test facility, which has a core section of 1 MW heating power and three steam generators. Steam is led through a thermally insulated steam line, made of sections of standard DN80 (Ø 88.9 x 2.0 mm) and DN50 (Ø 60.3 x 2.0 mm) pipes, from the PACTEL steam generators towards the test vessel. The steam line is connected to the DN200 inlet plenum with a 0.47 m long cone section. Accumulators connected to the compressed air network of the laboratory can be used for providing non-condensable gas injection. A schematic illustration of the air and steam line piping is presented in Figure 3.

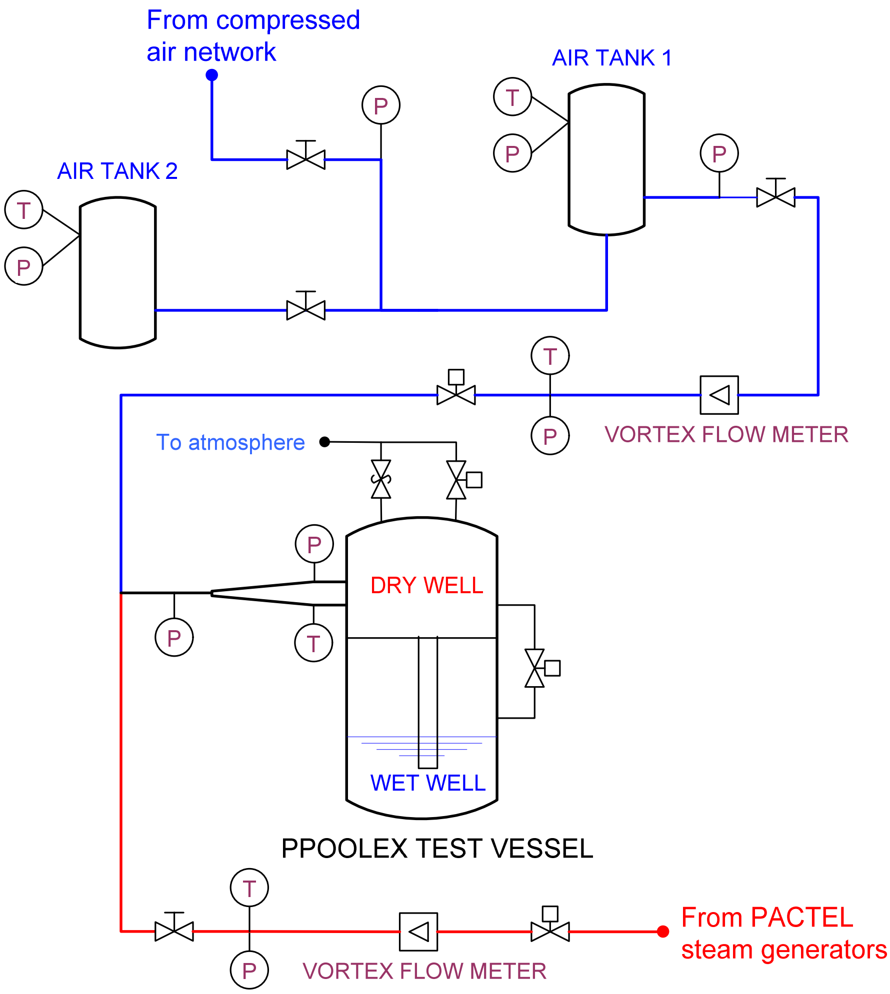

Figure 3. Arrangement of air and steam supply in the PPOOLEX facility.

2.3 MEASUREMENT INSRUMENTATION

The applied instrumentation depends on the experiments in question. Normally, the test facility is equipped with several thermocouples (T) for measuring air/steam and pool water temperatures and with pressure transducers (P) for observing pressure behavior in the dry well compartment, inside the blowdown pipe, at the condensation pool bottom and in the gas phase of the wet well compartment. Steam and air flow rates are measured with vortex flow meters (F) in the steam and air lines. TORBAR measurement in the inlet plenum provides another mean to estimate the injection flow rate. Additional instrumentation includes, for example, strain gauges (S) on the pool outer wall and valve position sensors. Strains are measured both in circumferential and axial direction. After the characterizing test series, three thermocouple measurements were added to the dry well compartment for capturing the temperature distribution in more detail. A list of different types of basic measurements in the PPOOLEX test facility is presented in Table 2. The figures in Appendix 1 show the exact locations of the measurements and the table in Appendix 1 lists the identification codes and error estimations of the measurements used in the SLR series. The error estimations are calculated on the basis of variance analysis. The results agree with normal distributed data with 95% confidence interval.

Table 2. Instrumentation of the PPOOLEX test facility

Quantity measured		No.	Range	Accuracy
Pressure	Dry well	1	0-6 bar	±0.06 bar
	Wet well	3	0-6/0-10 bar	±0.4/0.5 bar
	Blowdown pipe	1	0-10 bar	±0.7 bar
	Inlet plenum	1	0-6 bar	±0.06 bar
	Steam line	1	1-51 bar	±0.5 bar
	Air line	2	0-6/1-11 bar	±0.06/0.1 bar
	Air tanks 1&2	2	0-16/0-11 bar	±0.15/0.11 bar
Temperature	Dry well	4	-40-200 °C	±3.2 °C
	Wet well	5	0-250 °C	±2.0 °C
	Pool water	1	0-200 °C	±2.6 °C
	Blowdown pipe	3	0-250 °C	±2.0 °C
	Inlet plenum	1	-40-200 °C	±3.2 °C
	Steam line	1	0-400 °C	±3.6 °C
	Air line	1	-20-100 °C	±2.8 °C
	Air tanks 1&2	2	-20-100/200 °C	±2.8/3.1 °C
	Vessel wall	1	0-200 °C	±2.9 °C
Mass flow rate	Steam line	1	0-285 l/s	±4.9 l/s
	Gas line	1	0-575 m^3/h	±18 g/s
	Inlet plenum*	1	0.002-0.018 bar	±99 g/s
Water level in wet well		1	0-30000 Pa	±0.06 m
Pressure difference across the floor		1	-499-505 kPa	± 9.7 kPa
Loads on structures		4	N/A	N/A
Vertical movement of the pool		1	N/A	N/A

* TORBAR (used only occasionally as a supplementary measurement)

2.4 CCTV SYSTEM

For more accurate observation of air/steam bubbles at the blowdown pipe outlet, the test facility is furnished with a Citius Imaging digital high-speed video camera (model C10) [4]. The camera is controlled with a PC. The PC is also used for displaying and storing of video data. The camera is a single unit and it is connected to the PC through a USB bus.

The high-speed video recording is at first stored to the RAM-memory in the camera (in AVI-format). From there it is transferred to the PC hard disk. The camera is furnished with the largest possible amount of memory; 2 GB. The camera can achieve over 10000 frames/second (fps) recording speed and up to 652x496 pixels resolution with 256 shades of gray. However, speed and maximum recording time depend on the resolution used.

Standard video cameras, digital videocassette recorders and a quad processor supplement the visual observation system. By using a digital color quad processor it is possible to divide the TV screen into four equal size parts and look at the view of four cameras on the same screen.

2.5 DATA ACQUISITION

National Instruments PCI-PXI-SCXI PC-driven measurement system is used for data acquisition. The system enables high-speed multi-channel measurements. The maximum number of measurement channels is 96 with additional eight channels for strain measurements. The maximum recording speed depends on the number of measurements and is in the region of 300 thousand samples per second. Measurement software is LabView 7.1. The data acquisition system is discussed in more detail in reference [5].

Separate HPVee based 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.

In the steam line break experiments (SLR series), the used data recording frequency of LabView was either 10 Hz (during SLR-02) or 5 kHz depending on the objective of the experiment. For the temperature measurements the data recording frequency was 10 Hz (in SLR-02) or 50 Hz. The temperature measurements are therefore averages of 100 measured points when recording frequency of 5 kHz was used. The rest of the measurements (for example in the air line) were recorded by HPVee software with the frequency of 2 Hz.

A separate measurement channel is used for the air line valve position information. Approximately 3.6 V means that the valve is fully open, and approximately 1.1 V that it is fully closed. Voltage under 1.1 V means the valve is opening. Both HPVee and LabView record the channel.

A separate measurement channel is also used for the digital high-speed video camera triggering. When the camera gets a signal from the trigger it starts to record. Depending on the adjustment, the camera either records the events from the triggering moment towards the future or from the past until the triggering moment. Boundary signal for the camera is approximately 3.5 V.

3 TEST PROGRAMME

The test program with air discharge in November 2007 focused on the initial phase of a postulated steam line rupture accident inside a BWR containment and consisted of five experiments (labeled from SLR-01 to SLR-05). Experiments SLR-02 and SLR-05 dealt with thermal stratification in the dry well and wet well compartments and experiments SLR-01 and SLR-03 with a water plug ejection from the blowdown pipe. In experiment SLR-04, the effect of counterpressure on bubble dynamics was investigated. Each experiment included several separate blows (tests) of air. The experiments were carried out by using the DN200 blowdown pipe. Accumulators, filled with the help of the compressed air network of the laboratory, provided the air flow needed in the experiments.

Before each experiment the condensation pool (wet well) of the facility was filled with water to the level of 2.14 m i.e. the blowdown pipe outlet was submerged by 1.05 m. This air/water distribution corresponds to the scaled gas and liquid volumes in the containment of the reference plant. Pool water bulk temperature was about 22 °C. The throttle valve in the air line was fully open in experiments SLR-01 and SLR-02. The valve was replaced with a straight pipe section for the experiments SLR-03 and SLR-05. In SLR-04, the position of the valve was adjusted before each blow so that the desired air flow rate would be achieved. Flow rate was controlled also with the initial pressure level of the air accumulators.

After the correct initial pressure level in the air accumulators had been achieved the remote-controlled shut-off valve in the air line was opened. As a result, the inlet plenum was filled with air that immediately pushed its way to the dry well compartment and mixed there with the initial air content. Pressure build-up in the dry well then pushed water in the blowdown pipe downwards and after a while the pipe cleared and air flow into the wet well compartment started.

In the eighth blow of SLR-04, some noise was observed in the fast temperature measurement signal. All other measurements worked properly during the test program. Table 3 shows the initial parameters of the experiments in the SLR series.

Table 3. Initial parameters of the steam line rupture experiments in the PPOOLEX facility

Experiment	Air accumulator initial pressure [MPa]	Initial pool water level [m]	Pool water [°C]	Comments
SLR-01	0.4 – 0.8	2.14	~ 23	-
SLR-02	0.4 – 0.8	2.14	~ 22	Connection to compressed air network open in test 3
SLR-03	0.4 – 0.8	2.14	~ 22	-
SLR-04	0.6 – 0.8	2.14	~ 21	Noise in temperatures during test 8
SLR-05	0.8 – 1.2	2.14	~ 21	-

4 ANALYSIS OF THE EXPERIMENTS

The following chapters give a more detailed description of the experiment program and also try to analyze the observed phenomena.

4.1 EXPERIMENTS ON THERMAL STRATIFICATION (SLR-02, SLR-05)

In experiments SLR-02 and SLR-05, thermal stratification in the dry well and wet well gas space was studied. SLR-02 and SLR-05 consisted of three and two separate blows, correspondingly. The digital high speed camera with a recording speed of 195.2 fps was used in SLR-05 for capturing air bubbles at the blowdown pipe outlet. Table 4 summarizes the values of main parameters during the experiments SLR-02 and SLR-05.

Table 4. Main parameters during SLR-02 and SLR-05

Test	Accumulator initial pressure [MPa]	$q_{m,air,max}$ [g/s]	Blow duration [s]	Dry well ΔT_{max} [°C]	Wet well gas space ΔT_{max} [°C]
SLR-02-1	0.4	290	79	12	10
SLR-02-2	0.8	610	57	14	20
SLR-02-3	0.8	620	544	15	32
SLR-05-1	0.8	430	55	15	22
SLR-05-2	1.2	800	53	16	23

The initial gas atmosphere in the dry well compartment and in the gas space of the wet well heats-up due to compression after air discharge from the accumulators starts. As the temperatures increase, they also stratify notably in both compartments. The general behavior in the test vessel is similar in all individual blows of SLR-02 and SLR-05. Some minor differences may come from the fact that the initial temperatures in the dry well and wet well gas space differ by a few degrees from one test to another.

The duration of the blow is the longest (544 seconds) in test SLR-02-3. Therefore, this test gives the most representative results concerning thermal stratification and is selected for analysis here. The measured temperatures between 0…10 seconds give the temperature distribution in the facility before the test. All the thermocouples show temperatures of approximately 20…22 °C indicating isothermal conditions.

The air blow is initiated at 10 s. At first, the air mass flow rate reaches the value of 620 g/s (Figure 4). As the test progresses and the pressure difference between the air accumulators and the test vessel diminishes, the flow rate decreases. For instance, at 100 s the flow rate is 90 g/s and at 200 s 25 g/s. When the blow is terminated at 554 s, the flow rate is no more than 22 g/s. Most of the pressure build-up in the test vessel happens, of course, during the high flow period. After 100 s, the pressure increase is quite small. Figure 5 shows the pressure behavior in the wet well compartment during the whole test.

Figure 6 presents the temperature distribution in the dry well and Figure 7 in the wet well gas space. Generally speaking, temperatures increase more on the upper measurement elevations than on the lower elevations. In the dry well, there is one exception to this. Measurement T1109 (dry well lower middle) is located approximately on the same level as the inlet plenum. During the first hundred seconds of the test, flow from the inlet plenum hits quite straight to the thermocouple of T1109 and cools it effectively. Therefore it heats-up only about half of that of the measurement T1105 in the dry well top.

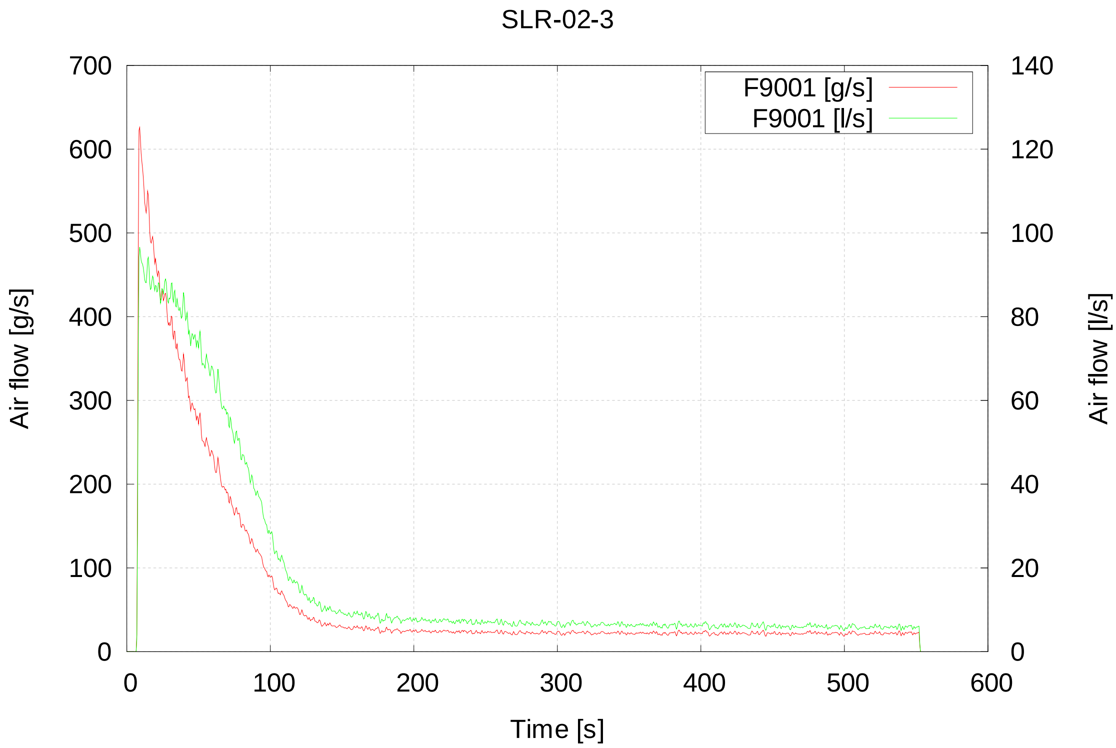

Figure 4. Volumetric and mass flow rate of air in SLR-02-3.

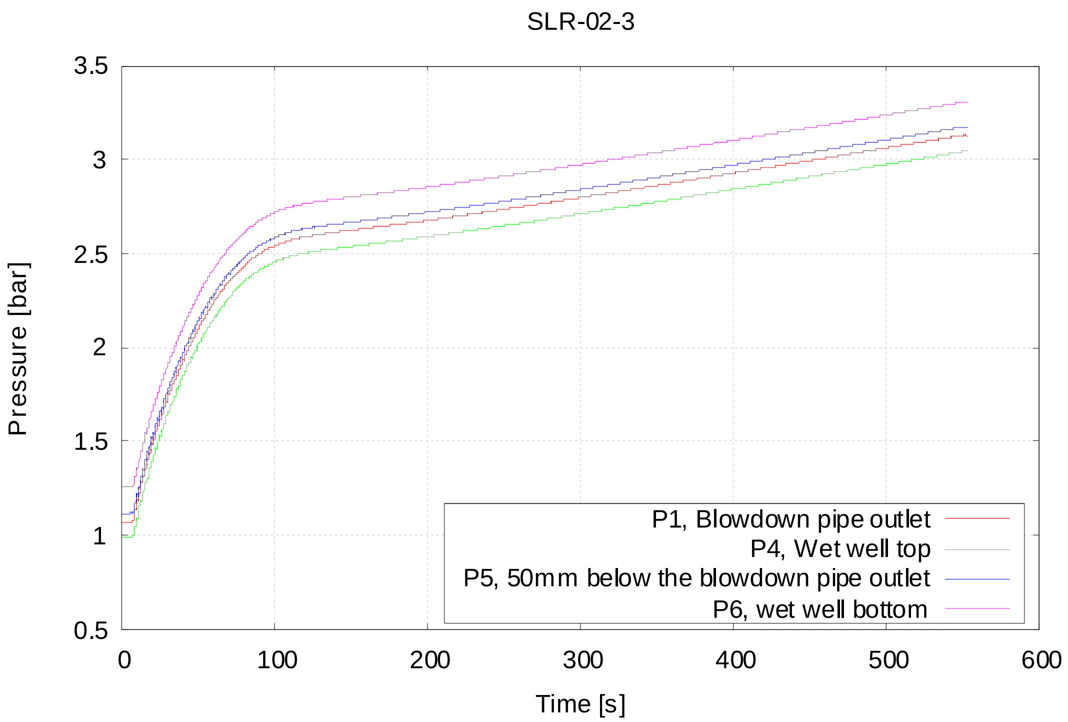

Figure 5. Pressure build-up in the wet well compartment in SLR-02-3.

Temperatures increase for about 100 seconds (duration of the effective compression period) and then start to cool off. Measurements T1107 (dry well middle) and T1108 (dry well bottom) behave similarly during the heat-up phase but diverge from each other as the cool-off period begins. At 230 s, the measurement close to the dry well bottom (T1108) drops below the above mentioned T1109 affected by inflow of air. At the end of the test, all other measurements in the dry well but T1108 indicate almost uniform temperatures of about 33 °C. The reading of T1108 is about 5 °C below that.

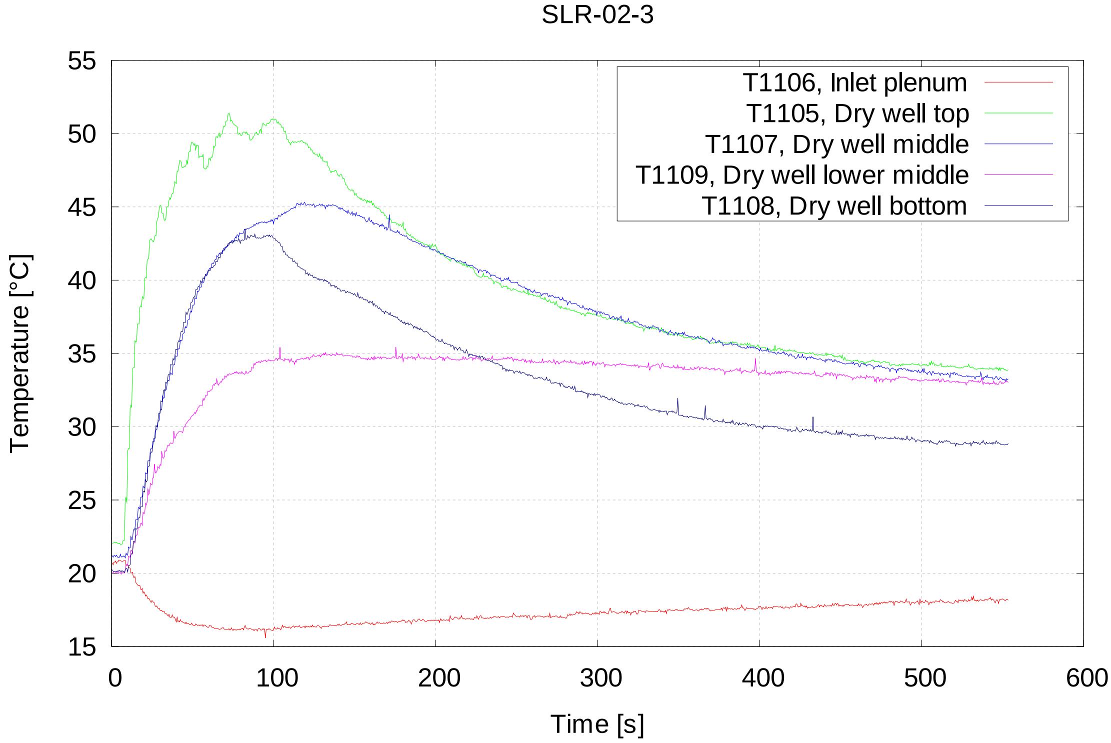

Figure 6. Temperatures in the inlet plenum and in the dry well in SLR-02-3.

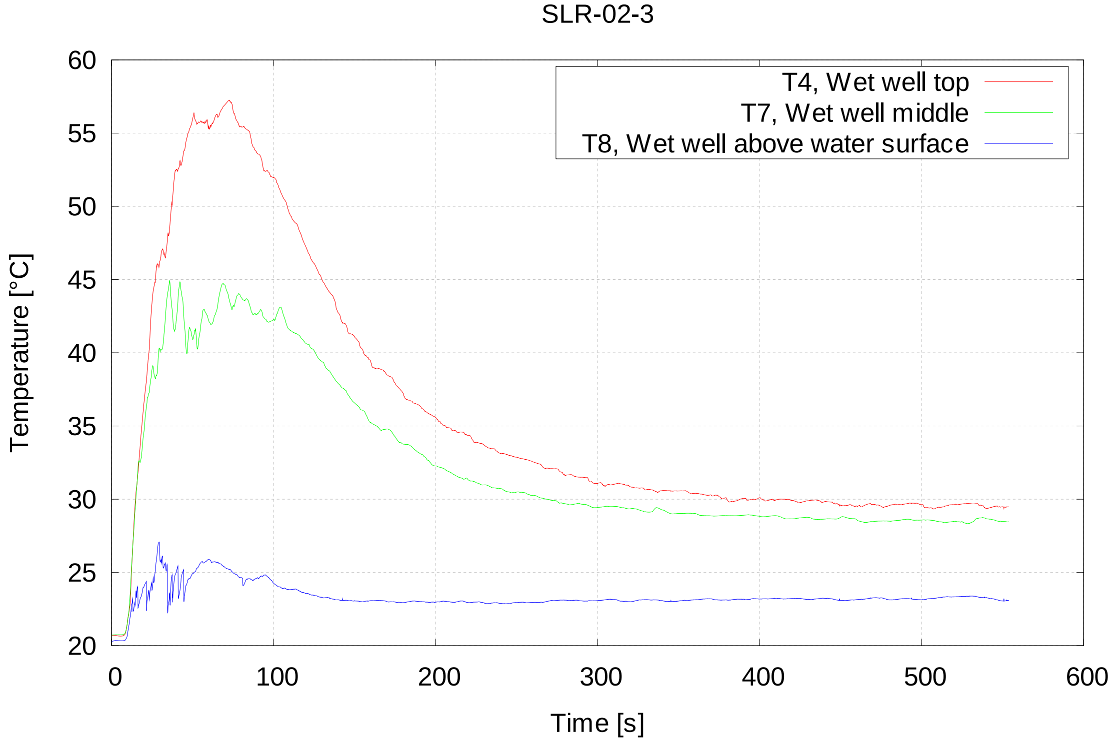

Figure 7. Temperatures in the wet well gas space in SLR-02-3.

The maximum temperature difference between the upper (T1105) and lower part (T1108) of the dry well compartment is 15 °C and it is measured during the heat-up period at about 20…25 s. At 100 s, when the temperatures start to decrease, the difference between T1105 and T1108 is only about 6-7 °C. After cooling off for about 450 s, T1105, T1107 and T1109 end up showing almost the same temperature, as already mentioned above.

T1106 in the inlet plenum has the same initial temperature but behaves differently as the measurements in the dry well compartment (Figure 6). During the high flow period in the beginning of the test it cools off by about 5 °C due to the expansion effect of the flow in the valves and in the cone section of the air line. During the rest of the test, it heats-up slightly but never even reaches the original initial temperature.

In the wet well gas space, the highest temperature rise (about 37 °C) during the compression period is experienced by T4 close to the wet well top. T8, just above the water level of the condensation pool, indicates only an increase of about 6 °C while T7 in the middle elevation of the gas space heats-up by about 25 °C. The maximum temperature difference (T4 - T8) is 32 °C and it is measured at about 72…74 s. At the end of the test, the temperature difference is only about 6 °C, since the two topmost measurements have cooled off to a value below 30 °C and T8 is a few degrees above the initial value of 21 °C.

In test SLR-05-2, the initial pressure of the air accumulators was increased to 1.2 MPa. As a result, the air mass flow rate was somewhat higher in the beginning of the blow than in the other tests. This had, however, no magnifying effect on the thermal stratification process. On the contrary, the maximum temperature difference between T4 and T8 in the wet well gas space was almost 10 °C smaller than in test SLR-02-3, because the temperatures of the wet well top increased less.

So far there has been only one temperature measurement in the vicinity of the water surface in the condensation pool. Cold structures near the water surface elevation and the cold water itself prevent extensive heat-up. To get a more detailed picture of temperature distribution close to the water level a dense net of measurements is required in future experiments. In longer experiments, the effect on stratification of heat conduction to structures and heat losses to surroundings should also be taken into account.

4.2 EXPERIMENTS ON WATER PLUG EJECTION (SLR-01, SLR-03)

In experiments SLR-01 and SLR-03, effects of water plug ejection from the blowdown pipe to the wet well bottom in the beginning of the tests was studied. Both SLR-01 and SLR-03 consisted of three separate air blows. The total duration of the blows was short, between 10 and 25 seconds, since the effects of the investigated phenomenon died away quite soon. In SLR-01, the throttle valve in the air line was fully open. In SLR03, the valve was replaced with a straight pipe section. The data recording frequency of LabView measurement program was 5 kHz in both experiments. Table 5 summarizes the values of main parameters during the experiments.

In the experiments, neither the pressure transducer at the pool bottom nor the strain gauges on the pool outer wall measure high loads. The maximum amplitude of pressure pulses at the pool bottom is no more than 10 kPa, Figure 8. As expected, it was measured with the highest used initial pressure (0.8 MPa) of the air accumulators in SLR-03-3. The pressure measurement P5

(50 mm below the blowdown pipe outlet) registers higher values than P6 (at the pool bottom). P5 is at the range of direct influence of air bubbles forming at the blowdown pipe outlet. As the bubbles detach from the pipe and partly break up oscillating pressure behavior can be observed even though there is no condensation related phenomena present. This is true especially in the beginning of the blow when the forming air bubbles are large. The wavy form of the P4 measurement (in the wet well gas space) is a result of the formation of air bubbles and consequent lift-up to the water surface in the wet well pool.

Table 5. Main parameter during SLR-01 and SLR-03

Test	Accumulator initial pressure [MPa]	$q_{m,air,max}$ [g/s]	Δp_{max} at the wet well bottom [kPa]	$\Delta\varepsilon_{max}$ [μS]	Δz_{max} [mm]
SLR-01-1	0.4	250	2	~ 0	0.15
SLR-01-2	0.6	450	4	~ 0	0.3
SLR-01-3	0.8	580	8	~ 0	0.3
SLR-03-1	0.4	250	5	~ 0	0.15
SLR-03-2	0.6	360	7	~ 0	0.3
SLR-03-3	0.8	450	10	~ 0	0.3

Measured strains due to water plugs hitting to the pool bottom are negligible both in axial and circumferential direction. Only very small oscillation can be seen in the strain curves during the first ten seconds of the blow, Figure 9. However, the effect of pressure increase inside the test vessel, as the tests progress further, can be noticed from the strain values (particularly from S1 and S4). Vertical movement of the pool is quite small, too (Figure 10). The maximum movement is not always measured with the first water plug. In SLR-03-3, the largest vertical movement is, for example, concurrent with the fourth plug, as Figure 10 shows. The lift-up of air bubbles to the surface has also some effect on the vertical movement of the pool.

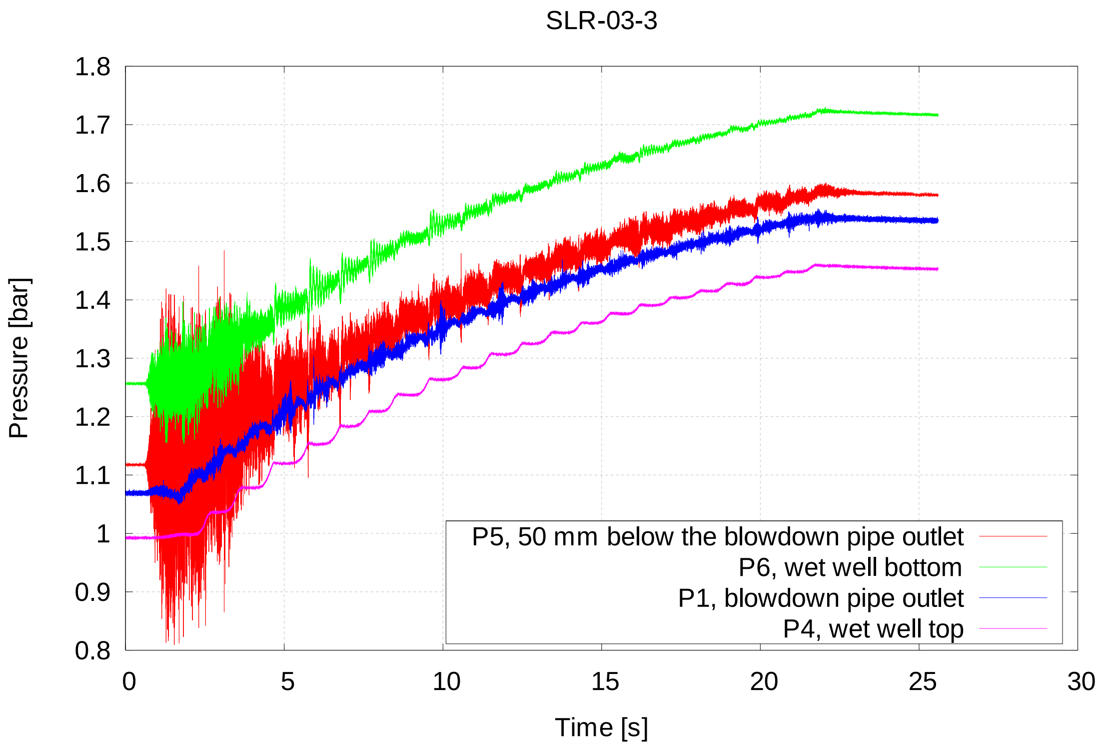

Figure 8. Pressures in the wet well in SLR-03-3.

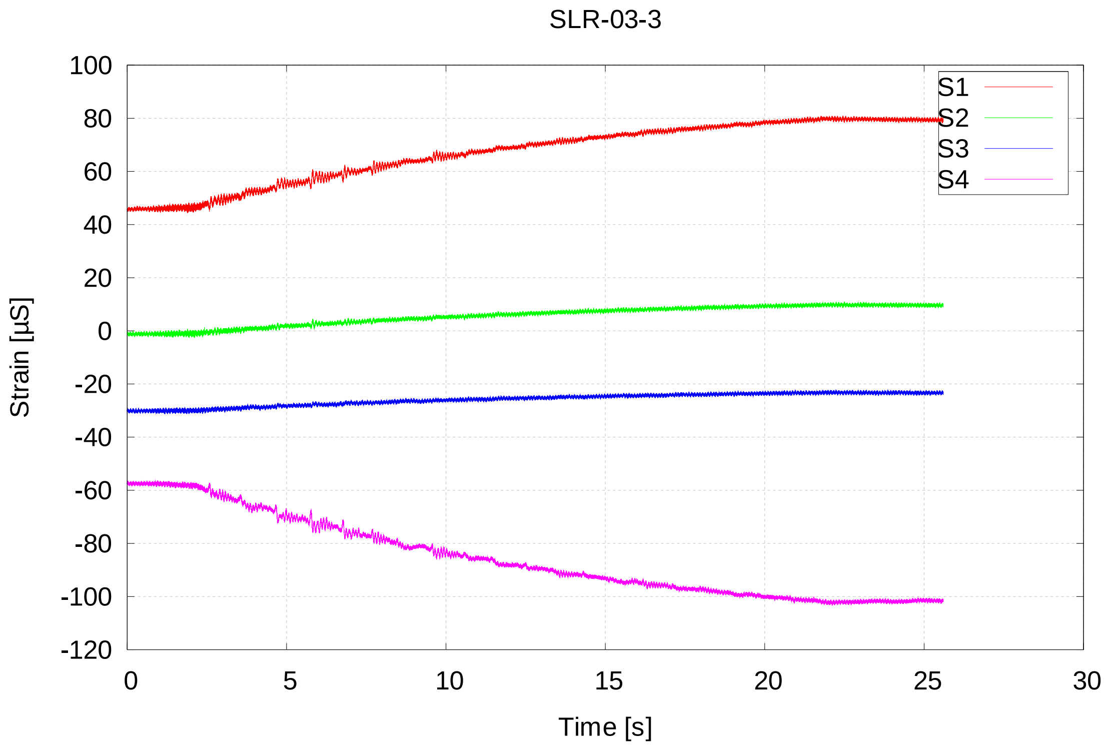

Figure 9. Strains in SLR-03-3.

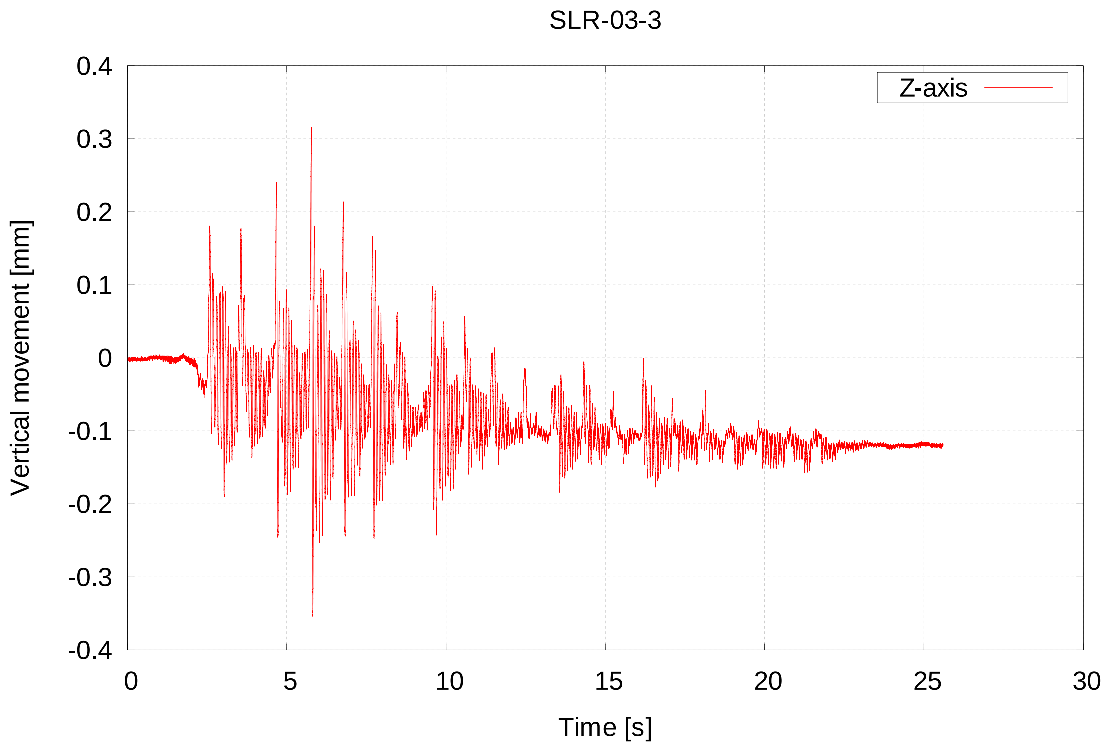

Figure 10. Vertical movement of the pool in SLR-03-3.

The maximum measured pressure pulses due to water plugs can be compared to the corresponding measurement in the preceding POOLEX experiments with the open pool test facility. The values measured then are roughly one order of magnitude bigger than the values registered now, when the initial pressure of the air/steam source is about the same in the tests. Even two orders of magnitude bigger values than now were measured when the initial pressure of the PACTEL steam generators was high (3 MPa). In the open pool steam discharge experiments, strain values in the range of 300 µS were measured as a result of water plugs with high initial steam source pressures. The reason for notably smaller pressure pulses and strains in the PPOOLEX tests is the suppressing effect caused by the dry well compartment as well as the different wall thickness and shape of the bottom section. Furthermore, in the open pool tests air/steam was discharged directly into the blowdown pipe.

4.3 EXPERIMENTS ON COUNTERPRESSURE EFFECTS (SLR-04)

In experiment SLR-04, the effect of counterpressure on bubble dynamics was studied. SLR-04 consisted of 12 separate air blows. In the experiment, four different counterpressure (approximately 100, 200, 300 and 400 kPa) and three air mass flow rate values (approximately 130, 270 and 400 g/s) were used. The extent of opening of the throttle valve in the air line was varied to produce the different flow rates. The initial pressure of the air accumulators was between 0.6-0.75 MPa. The data recording frequency of LabView measurement program was 5 kHz. The digital high speed camera with a recording speed of 196.3 fps was used for capturing the behavior of air bubbles at the blowdown pipe outlet. Table 6 summarizes the values of main parameters during SLR-04.

Table 6. Main parameters during SLR-04

Test	Accumulator initial pressure [MPa]	$q_{m,air,av}$ [g/s]	Dry well abs. pressure [kPa]	Wet well gas space abs. pressure [kPa]	Air bubble formation frequency [Hz]	Δp_{max} at the wet well bottom / blowdown pipe outlet [kPa]
SLR-04-1	0.75	140	100…150	100…135	1.0	2 / 4
SLR-04-2	0.65	130	195…205	180…195	1.3	1 / 3
SLR-04-3	0.60	120	295…305	280…295	1.4	1 / 2
SLR-04-4	0.65	130	400...410	385...400	1.6	1 / 2
SLR-04-5	0.75	300	100...135	100...125	1.0	4 / 8
SLR-04-6	0.70	280	195...225	180...215	1.3	2 / 5
SLR-04-7	0.65	270	295...320	285...305	1.4	2 / 4
SLR-04-8	0.65	250	390...415	380...405	1.5	1 / 4
SLR-04-9	0.75	400	100...150	100...140	1.0	5 / 10
SLR-04-10	0.75	420	195...235	185...225	1.2	3 / 8
SLR-04-11	0.75	420	295…340	285…330	1.4	2 / 6
SLR-04-12	0.75	400	385…430	375…420	1.5	2 / 6

Figure 11 shows some typical air bubbles at the blowdown pipe outlet before break-up in consecutive tests (SLR-04-9…SLR-04-12) where the counterpressure in the wet well compartment is increased from 100 kPa to about 400 kPa but the gas flow rate into the dry well is practically kept the same. As one can be expect, the maximum size of the forming air bubbles at the blowdown pipe outlet gets smaller and smaller as the counterpressure increases. Based on visual observation with the help of the high speed video, it can be estimated that the maximum diameter of unbroken bubbles decreases about 40 % as the counterpressure rises from 100 kPa to 400 kPa. Also, the final shape of the air bubbles before break-up changes from a spherical one to a doughnut like shape as the counterpressure increases.

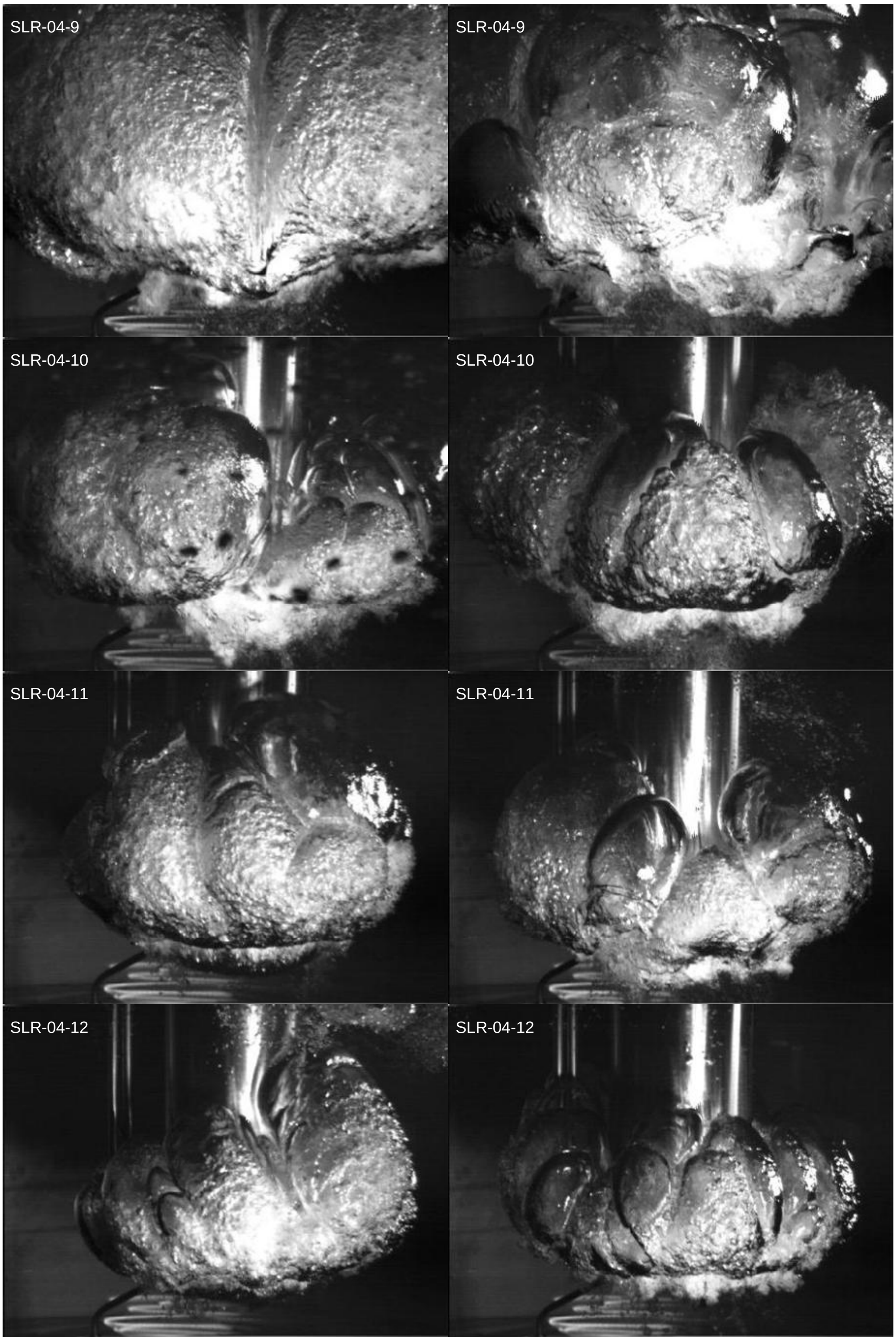

Figure 11. Frame captures of high speed video from SLR-04-9…SLR-09-12.

Pressure behavior in the dry and wet well compartments in SLR-04-9 and SLR-04-12 is presented in Figure 12 and Figure 13, respectively. From the pressure measurement in the wet well gas space (P4) it can be seen that the formation frequency of air bubbles increases with increasing counterpressure. By counting the "waves" of the P4 curves from a certain interval in

Figures 12 and 13 one can conclude that the bubble formation frequency changes from 1 Hz to 1.5 Hz as the counterpressure rises from 100 kPa to 400 kPa. Meanwhile, the air flow rate seems to have no effect on the air bubble formation frequency, see Table 6.

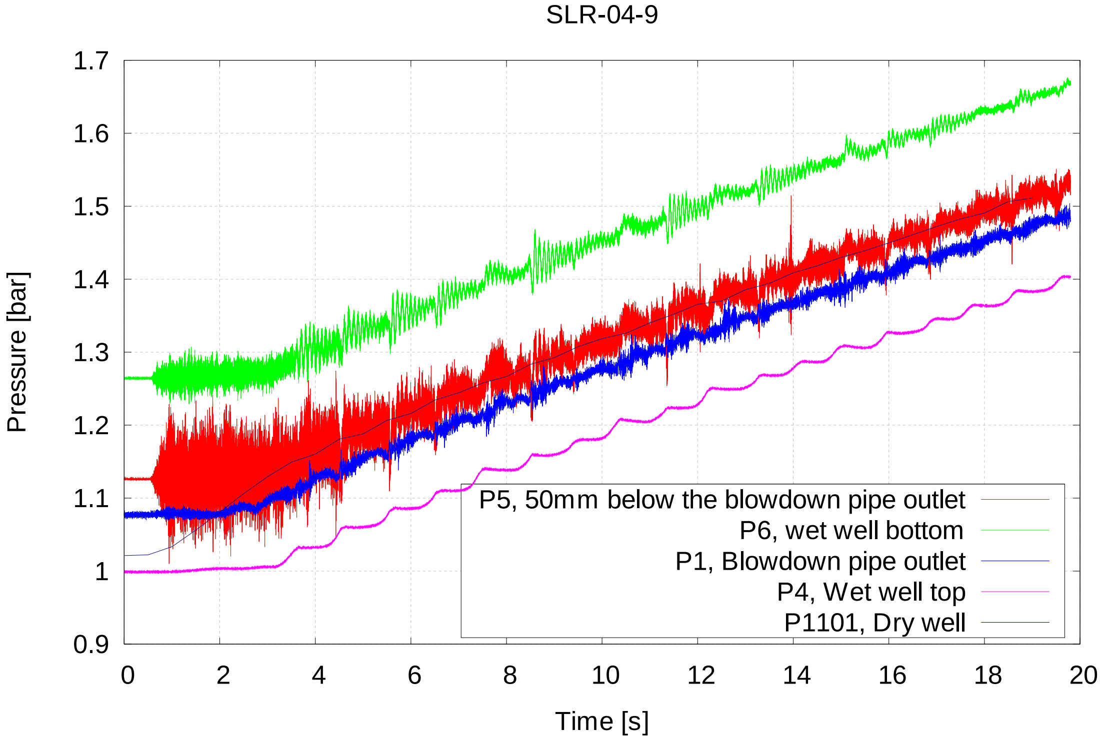

Figure 12. Pressures in the dry and wet well in SLR-04-9.

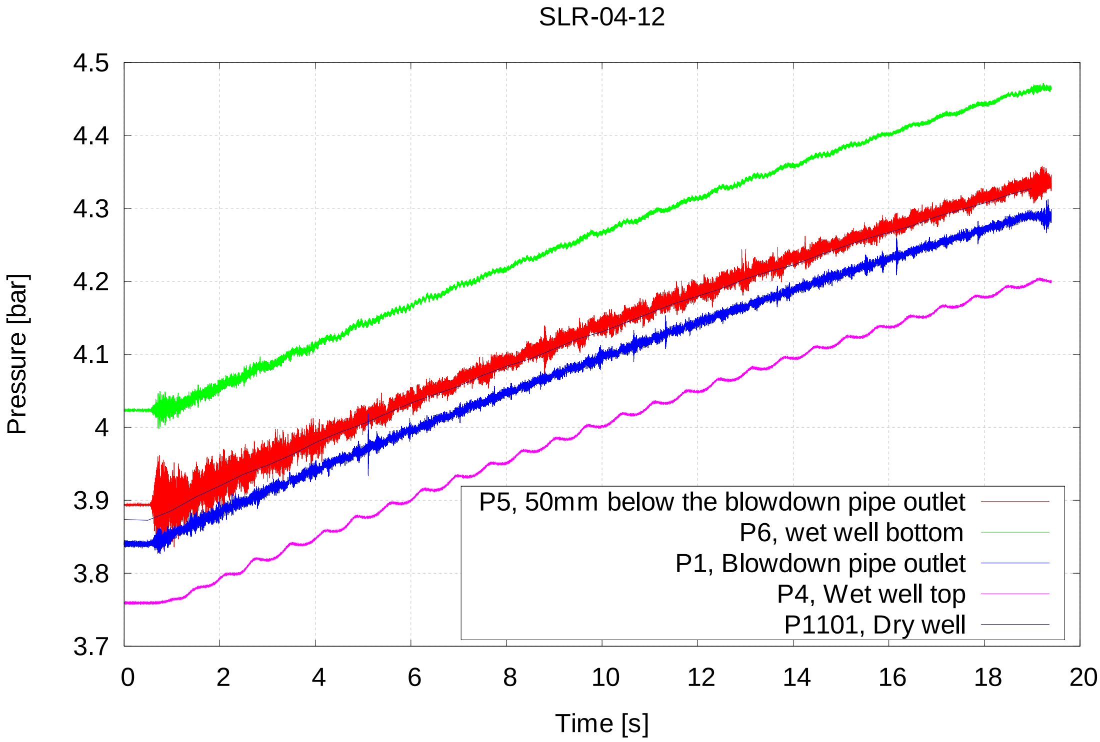

Figure 13. Pressures in the dry and wet well in SLR-04-12.

The amplitude of pressure oscillations in the wet well pool decreases as the counterpressure increases. Pressure oscillations are, however, very small (10-20 kPa at the most) in these experiments.

5 SUMMARY AND CONCLUSIONS

This report summarizes the results of the steam line rupture experiment series in 2007 with the scaled down PPOOLEX test facility designed and constructed at Lappeenranta University of Technology. The test facility is a closed stainless steel vessel divided into two compartments, dry well and wet well. During the experiments of the SLR series the test facility was equipped with basic high frequency measurement instrumentation for capturing different aspects of the investigated phenomena. Accumulators filled with the help of the compressed air network of the laboratory were used as the source of air.

In the experiments air was blown into the dry well compartment and from there through the DN200 blowdown pipe to the condensation pool. Altogether five successful experiments, each consisting of several blows (tests), were carried out.

The main purpose of the experiment series was to study the initial phase of a postulated steam line break accident inside a BWR containment. Specifically, thermal stratification in the dry well compartment and ejection of water plug from the blowdown pipe were of interest. In addition, the effect of counterpressure on bubble dynamics was studied in one experiment.

In the thermal stratification experiments, a temperature difference of approximately 15 °C between the upper and lower part of the dry well was measured. In the wet well gas space, a temperature difference of more than 30 °C was registered. These were measured during the compression period of the tests. Towards the end of the tests the temperature differences tend to disappear due to cooling off of the system. In the dry well compartment, temperatures at the elevation of the inlet plenum increase less than anticipated during the compression period due to the cooling effect of the inflow. To get a more detailed picture of temperature distribution in the wet well compartment, especially close to the water level, a dense net of measurements is required in future experiments. In longer experiments, the effect of heat conduction to structures and heat losses to surroundings should also be taken into account.

During the tests water plugs were ejected into the pool after initiating the air blows. This did not cause notable loads to the test facility structures due to the suppressing effect of the dry well compartment. The maximum measured pressure pulse at the pool bottom was only 10 kPa and the maximum strain amplitude at the pool bottom rounding was negligible both in axial and circumferential direction. Vertical movement of the pool was quite small, too. In the preceding open pool experiments, where the discharge flow was directly injected into the blowdown pipe, the maximum loads due to water plugs were, depending on the test conditions, one or two orders of magnitude larger.

As the counterpressure of the system increases, but the flow rate into the dry well compartment remains the same, the maximum size of the forming air bubbles at the blowdown pipe outlet gets smaller and smaller. Furthermore, the magnitude of pressure oscillations in the wet well pool decreases with increasing counterpressure. Correspondingly, the formation frequency of air bubbles increases with increasing counterpressure. Meanwhile, air flow rate seems to have no effect on the air bubble formation frequency.

The dry and wet well compartments of the PPOOLEX test facility have been volumetrically scaled according to the corresponding containment volumes of the reference plant. Before each experiment the condensation pool (wet well) of the facility was filled with water to the level of 2.14 m i.e. the blowdown pipe outlet was submerged by 1.05 m. This air/water distribution corresponds to the scaled gas and liquid volumes during normal operation in the containment of the reference plant. However, the behavior of the test facility deviates from that of the reference containment in certain situations. Therefore, conclusions concerning the effect of different phenomena observed in the test facility cannot be directly transferred to the plant scale. The lack of thermal insulation on the test vessel outer walls distorts the temperature behavior both in the dry well and wet well compartments. Heat losses to environment as well as heat being stored in structures are different from those in the reference plant. Furthermore, the non-condensable gas flow rate into the condensation pool is smaller in the test facility than in the (scaled down) reference case of a main steam line break inside the containment. Further modifications and additions of equipment are needed to broaden the applicability of the test facility for system scale studies.

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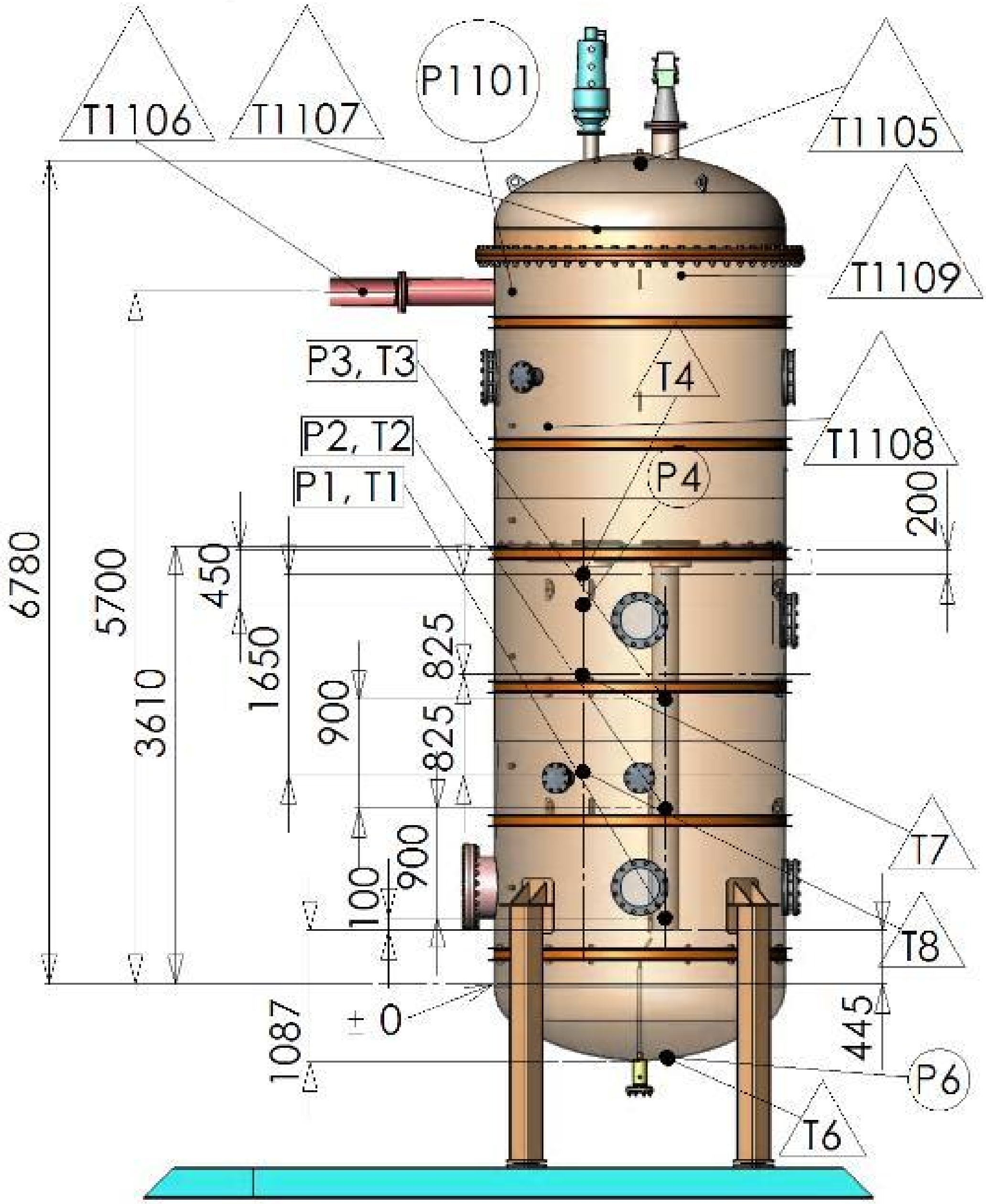
APPENDIX 1: INSTRUMENTATION OF THE PPOOLEX TEST FACILITY



Test vessel measurements.

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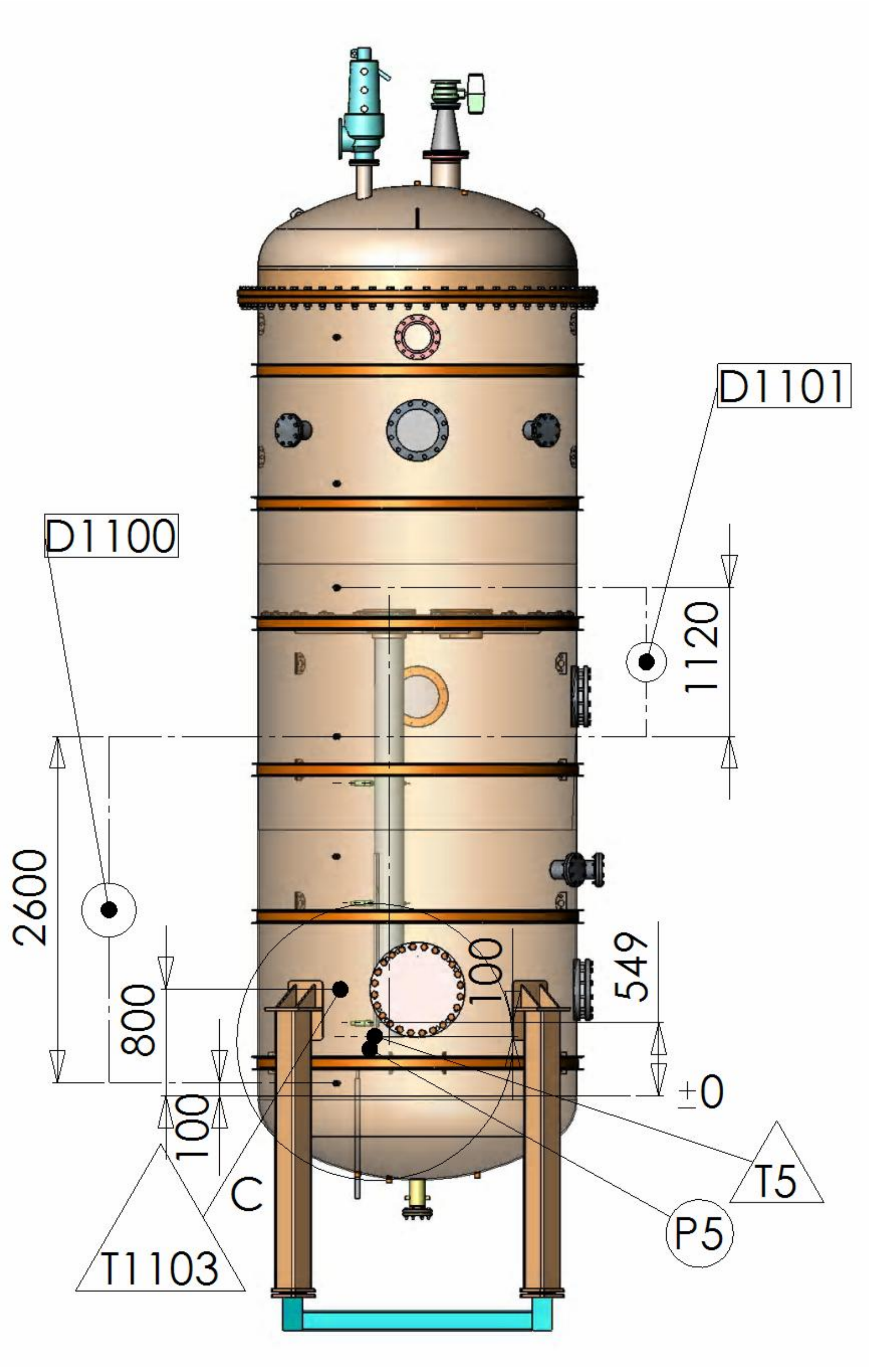
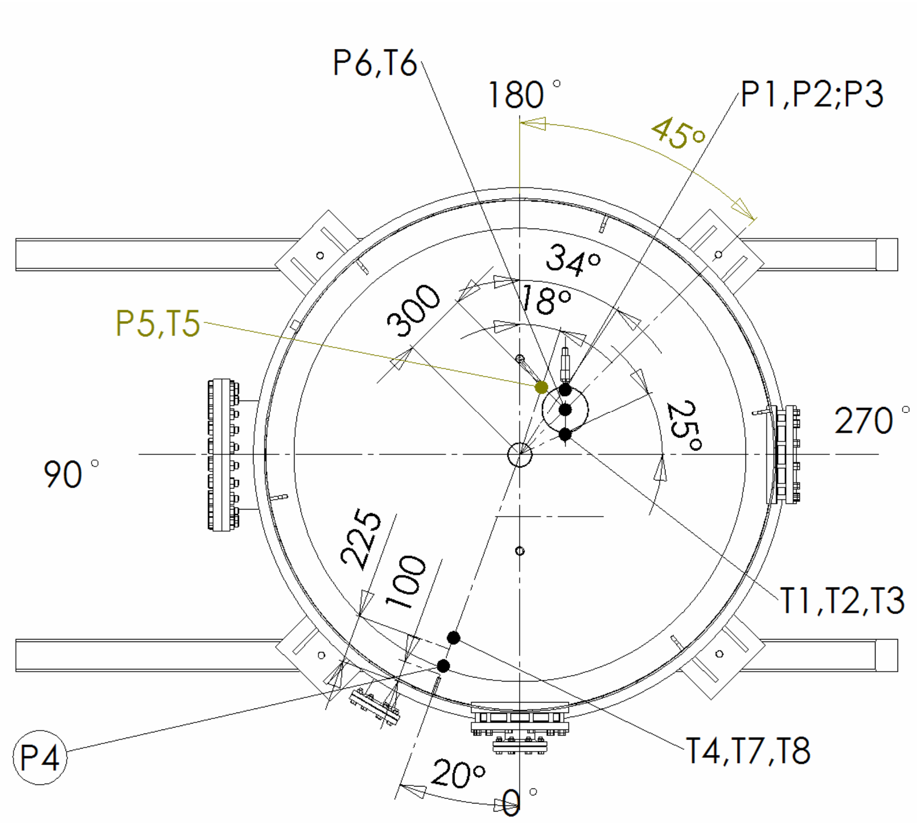
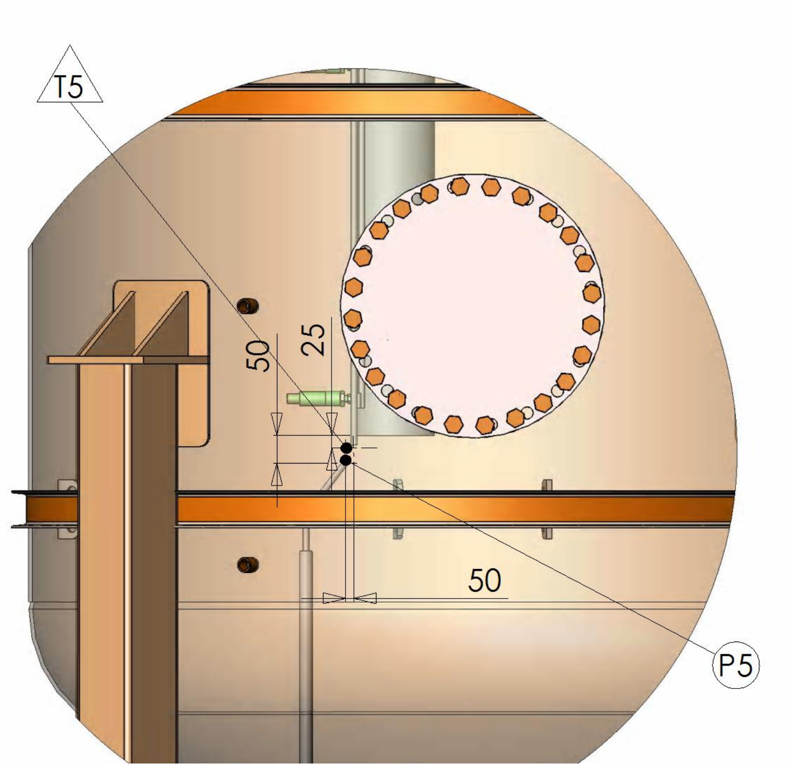


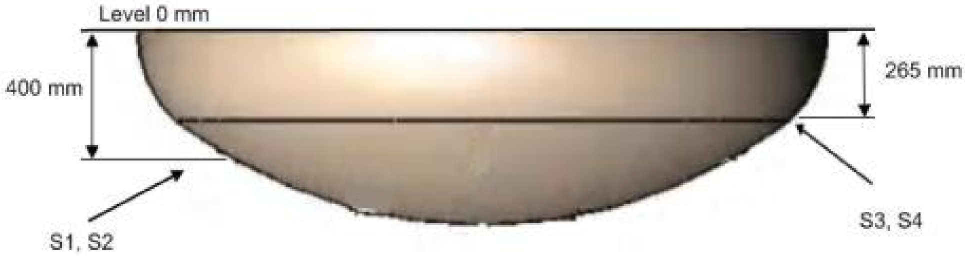
Test vessel measurements.

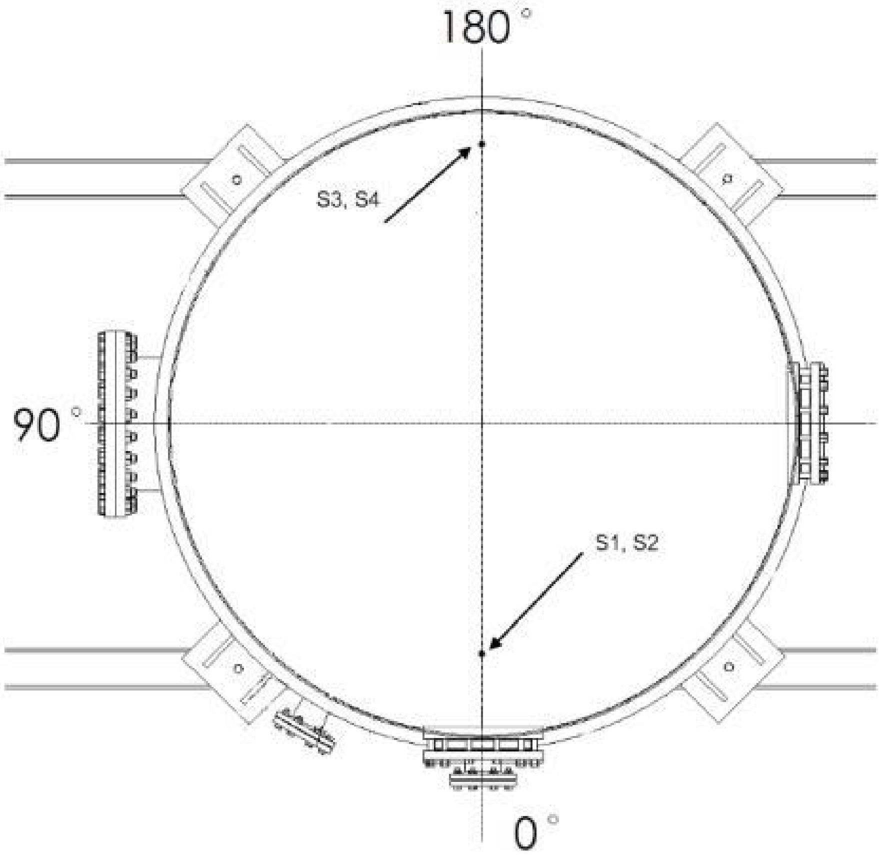


Measurement directions.



Pressure and temperature at the blowdown pipe outlet.



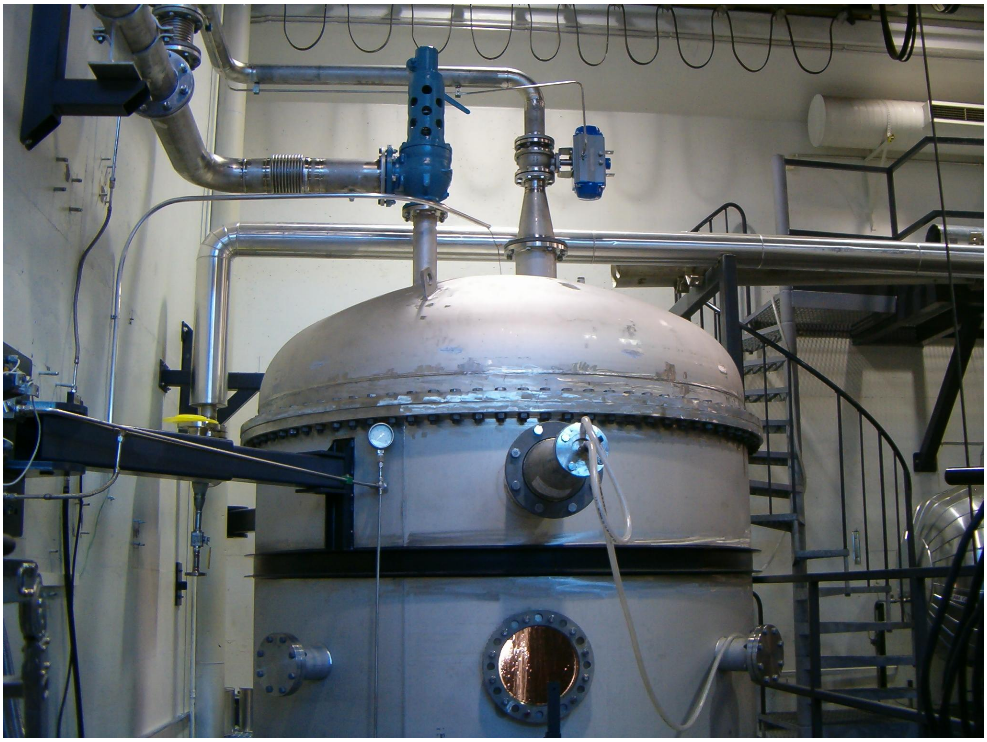


Strain gauges on the outer wall of the pool.

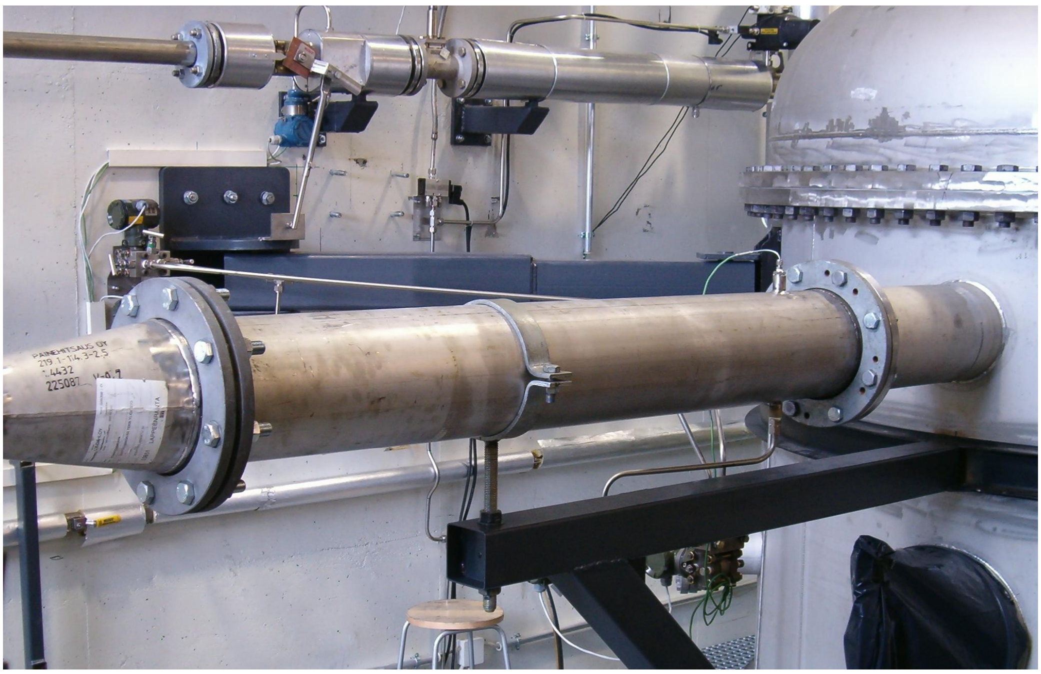
Measurement	Code	Elevation	Angle	Location	Error estimation
Pressure	P1	545	214	Blowdown pipe	±0.7 bar
Temperature	T1	545	245	Blowdown pipe	±1.8 °C
Temperature	T2	1445	245	Blowdown pipe	±1.8 °C
Temperature	T3	2345	245	Blowdown pipe	±1.8 °C
Pressure	P4	3160	20	Wet well gas space	±0.4 bar
Temperature	T4	3410	20	Wet well gas space	±1.8 °C
Pressure	P5	395	198	Blowdown pipe outlet	±0.7 bar
Temperature	T5	420	198	Blowdown pipe outlet	±1.8 °C
Pressure	P6	-1060	225	Wet well bottom	±0.5 bar
Temperature	T6	-1060	225	Wet well bottom	±1.8 °C
Temperature	T7	2585	20	Wet well	±1.8 °C
Temperature	T8	1760	20	Wet well	±1.8 °C
Pressure	P1101	5700	90	Dry well	±0.06 bar
Temperature	T1104	-245	180	Outside wall	±2.9 °C
Temperature	T1105	6780	-	Dry well top	±3.2 °C
Temperature	T1107	6085	45	Dry well middle	±3.2 °C
Temperature	T1108	4600	120	Dry well bottom	±3.2 °C
Temperature	T1109	5790	225	Dry well lower middle	±3.2 °C
Temperature	T1103	800	120	Wet well	±2.9 °C
Flow rate	F1101	5700	-	Inlet plenum	±99 g/s
Pressure	P1102	5700	-	Inlet plenum	±0.06 bar
Temperature	T1106	5700	-	Inlet plenum	±3.2 °C
Pressure	P1103	-	-	Air/steam line	±0.06 bar
Pressure diff.	D1100	100-2700	120	Wet well	±0.06 m
Pressure diff.	D1101	2700-3820	120	Across the floor	±0.10 bar
Flow rate	F1100	-	-	Steam line	±4.9 l/s
Temperature	T1102	-	-	At the steam line vortex	±3.6 °C
Pressure	P1100	-	-	At the steam line vortex	±0.5 bar
Flow rate	F9001	-	-	Air line	±2.7 l/s / ±30 g/s
Temperature	T9001	-	-	At the air line vortex	±3.0 °C
Pressure	P9002	-	-	At the air line vortex	±15.6 kPa
Pressure	P9000	-	-	Air tank 1	±10.8 kPa
Temperature	T9000	-	-	Air tank 1	±3.0 °C
Pressure	P9001	-	-	Air tank 2	±10.8 kPa
Temperature	T0460	-	-	Air tank 2	±3.0 °C
Strain	S1	-400	0	Bottom segment	Not defined
Strain	S2	-400	0	Bottom segment	Not defined
Strain	S3	-265	180	Bottom segment	Not defined
Strain	S4	-265	180	Bottom segment	Not defined
Vertical pool movement	Z-axis	-	-	Below pool bottom	Not defined
Valve position	X1100	-	-		Not defined

Measurements in the PPOOLEX facility.

APPENDIX 2: TEST FACILITY PHOTOGRAPHS



Dry well compartment and relief valves.



Inlet plenum.

Blowdown pipe and intermediate floor.

Pressure and temperature measurements at the blowdown pipe outlet.

Title	Steam Line Rupture Experiments with the PPOOLEX Test Facility
Author(s)	Jani Laine and Markku Puustinen
Affiliation(s)	Lappeenranta University of Technology, Nuclear Safety Research Unit, Finland
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No. of illustrations	13+9
No. of references	5

Abstract

The results of the steam line rupture experiment series in 2007 with the scaled down PPOOLEX test facility designed and constructed at Lappeenranta University of Technology are reported. The test facility is a closed stainless steel vessel divided into two compartments, dry well and wet well. Air was blown into the dry well compartment and from there through a DN200 blowdown pipe to the condensation pool. Altogether five experiments, each consisting of several blows (tests), were carried out.

The main purpose of the experiment series was to study the initial phase of a postulated steam line break accident inside a BWR containment. Specifically, thermal stratification in the dry well compartment and ejection of water plug from the blowdown pipe were of interest. In addition, the effect of counterpressure on bubble dynamics was studied.

A temperature difference of approximately 15 °C between the upper and lower part of the dry well was measured. In the wet well gas space, a temperature difference of more than 30 °C was registered. These were measured during the compression period of the tests. Towards the end of the tests the temperature differences tended to disappear. To get a more detailed picture of temperature distribution in the wet well, especially close to the water level, a dense net of measurements is required in future experiments. In longer experiments, heat conduction to structures and heat losses to surroundings should also be taken into account.

Ejection of water plugs from the blowdown pipe did not cause notable loads to the structures due to the suppressing effect of the dry well compartment. The maximum measured pressure pulse at the pool bottom was only 10 kPa and the maximum strain amplitude at the pool bottom rounding was negligible both in axial and circumferential direction.

As the counterpressure of the system increased, but the flow rate remained the same, the maximum size of the air bubbles at the blowdown pipe outlet got smaller and smaller. Furthermore, the magnitude of pressure oscillations in the wet well pool decreased with increasing counterpressure. Correspondingly, the formation frequency of bubbles increased with increasing counterpressure. Meanwhile, flow rate had no effect on the bubble formation frequency.

Key words: condensation pool, steam/air blowdown, non-condensable gas, steam line rupture

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