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Characterizing Experiments of the PPOOLEX Test Facility

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Abstract

This report summarizes the results of the characterizing test series in 2007 with the scaled down PPOOLEX facility designed and constructed at Lappeenranta University of Technology. Air and steam/air mixture was blown into the dry well compartment and from there through a DN200 blowdown pipe to the condensation pool (wet well). Altogether eight air and four steam/air mixture experiments, each consisting of several blows (tests), were carried out.
The main purpose of the experiment series was to study the general behavior of the facility and the performance of basic instrumentation. Proper operation of automation, control and safety systems was also tested.
The test facility is a closed stainless steel vessel divided into two compartments, dry well and wet well. The facility is equipped with high frequency measurements for capturing different aspects of the investigated phenomena.
The general behavior of the PPOOLEX facility differs significantly from that of the previous POOLEX facility because of the closed two-compartment structure of the test vessel. Heat-up by several tens of degrees due to compression in both compartments was the most obvious evidence of this. Temperatures also stratified.
Condensation oscillations and chugging phenomenon were encountered in those tests where the fraction of non-condensables had time to decrease significantly. A radical change from smooth condensation behavior to oscillating one occurred quite abruptly when the air fraction of the blowdown pipe flow dropped close to zero. The experiments again demonstrated the strong diminishing effect that non-condensable gases have on dynamic unsteady loadings experienced by submerged pool structures.
BWR containment like behavior related to the beginning of a postulated steam line break accident was observed in the PPOOLEX test facility during the steam/air mixture experiments. The most important task of the research project, to produce experimental data for code simulation purposes, can be satisfactorily fulfilled with the current version of the facility. Further modifications and additions of equipment and instrumentation are, however, needed to increase the applicability of the test facility for system scale studies, too.

Key words

condensation pool, steam/air blowdown, non-condensable gas, pressure oscillations

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CHARACTERIZING EXPERIMENTS OF THE PPOOLEX TEST FACILITY

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Condensation oscillations and chugging phenomenon were encountered in those tests where the fraction of non-condensables had time to decrease significantly. A radical change from smooth condensation behavior to oscillating one occurred quite abruptly when the air fraction of the blowdown pipe flow dropped close to zero. The experiments again demonstrated the strong diminishing effect that non-condensable gases have on dynamic unsteady loadings experienced by submerged pool structures.

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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 VYR and NKS.

CONTENTS

APPENDIXES:

NOMENCLATURE

A	area
F	flow rate
P	pressure
S	strain
T	temperature
z	vertical movement

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
SG	steam generator
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.

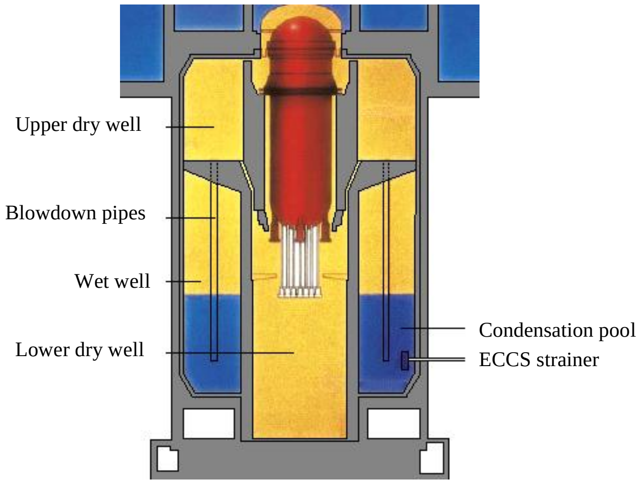

Figure 1. Schematic of the Olkiluoto type BWR containment.

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.

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. In this report, the results of those tests are presented. First, chapter two presents the different condensation modes in a BWR suppression pool during steam discharge. Chapter three 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 characterizing experiments is introduced in chapter four. The test results are presented and shortly discussed in chapter five. Chapter six summarizes the findings of the experiments.

2 CONDENSATION MODES DURING LOCA OR SAFETY/RELIEF VALVE BLOWDOWN

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, see Figure 2.

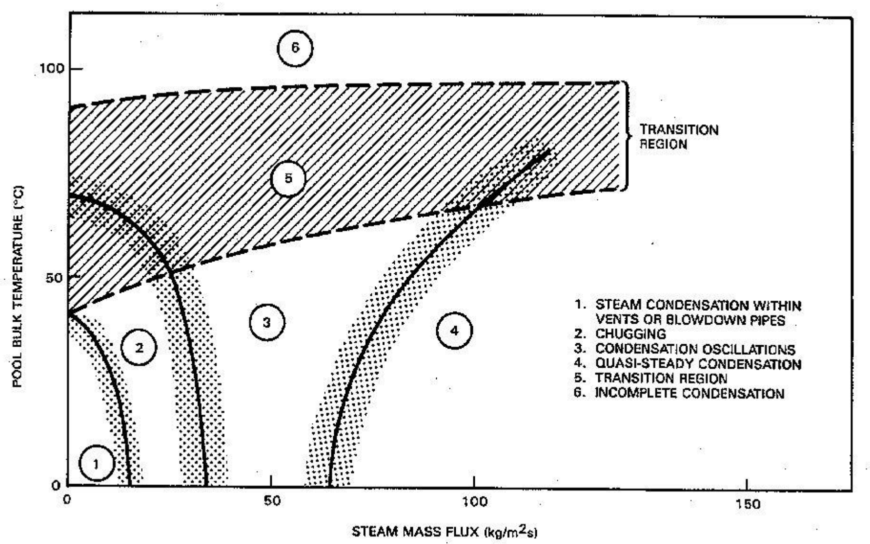

Figure 2. Condensation mode map for pure steam discharge [1].

With low steam mass flux and cold pool water temperature, condensation takes place within vents or blowdown pipes. A sharp drop in local steam pressure occurs as steam condenses rapidly when interacting with cold pool water. Because the condensation process is very rapid, an underpressure develops inside the blowdown pipe. Immediately after that, a condensation-induced water hammer is initiated as the pipe begins to fill with water. At the end of the collapse, a high pressure pulse occurs inside the pipe when it is filled with water. In this condensation mode, steam-water interface moves strongly up and down in the blowdown pipe.

As the steam mass flux increases, chugging or random condensation phenomena will commence. In chugging, the steam-water interface moves downwards inside the blowdown pipe and a steam bubble is formed at the pipe outlet (see steps 1-5 in Figure 3). The bubble condenses rapidly and an underpressure is generated (step 6). The steam-water interface begins to move upwards inside the pipe (steps 7-9) until the steam pressure is high enough to stop the interface and start to push it downwards again (step 10). Chugging imposes dynamic loads on submerged pool structures [1].

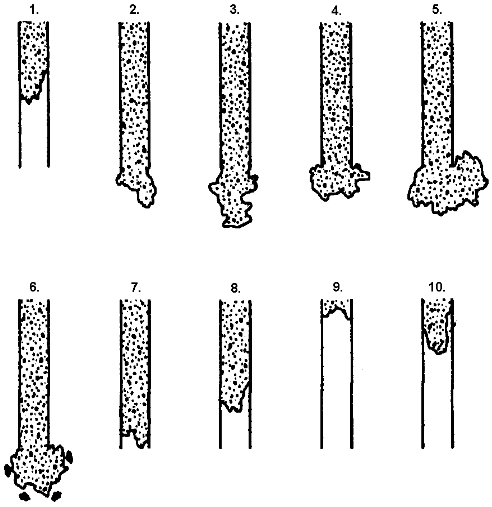

Figure 3. Sketch of the chugging phenomena [2].

Increasing the steam mass flux further leads to condensation oscillations. In this case, the steam-water interface undergoes a condensation event entirely in the pool. Steam bubble forms at the pipe outlet and begins to collapse. However, the high steam flow rate prevents water re-entry into the blowdown pipe. The next bubble is formed resulting to a condensation event and the cycle is repeated. Condensation oscillations cause unsteady loads on submerged pool structures [1].

With very high steam flows quasi-steady condensation is the dominating condensation mode. In this mode, high steam mass flux keeps the steam-water interface on the pipe outlet. Because the steam condenses steadily, no large loads are imposed on submerged pool structures.

3 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 [3]. However, the main features of the facility and its instrumentation are introduced below.

3.1 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 made of three separate plate cylinder segments and of two dome segments. The facility is able to withstand considerable structural loads caused by rapid condensation of steam. The vessel sections modeling dry and wet well are volumetrically scaled according to the volumes of the Olkiluoto 1 and 2 containment compartments. The DN200 (Ø 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. The original length of the inlet plenum was 0.5 m but it was replaced with the longer one during the characterizing test series (after the CHAR-06 experiment). There are several windows for visual observation in the vessel wall. A DN100 (Ø 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 4. Table 1 lists the main dimensions of the test facility compared to the conditions in the Olkiluoto plant.

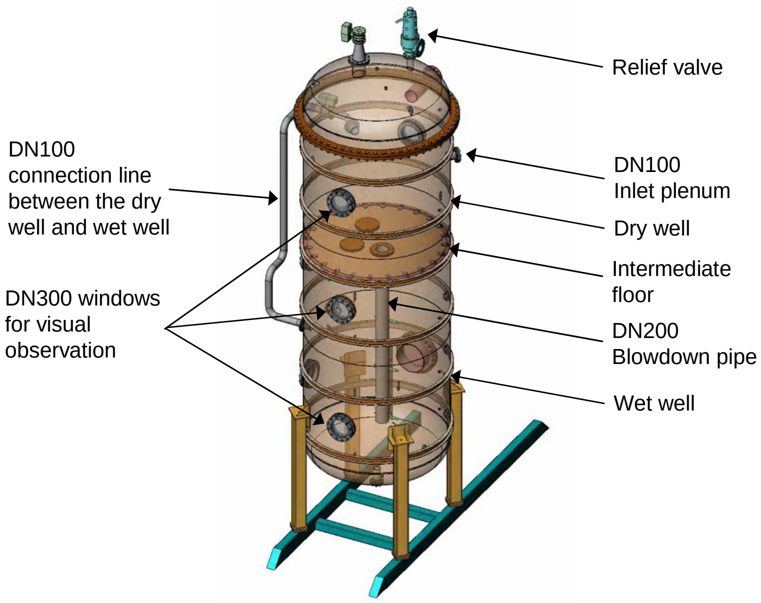

Figure 4. PPOOLEX test vessel.

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

	POOLEX 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

3.2 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 [4] 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 5.

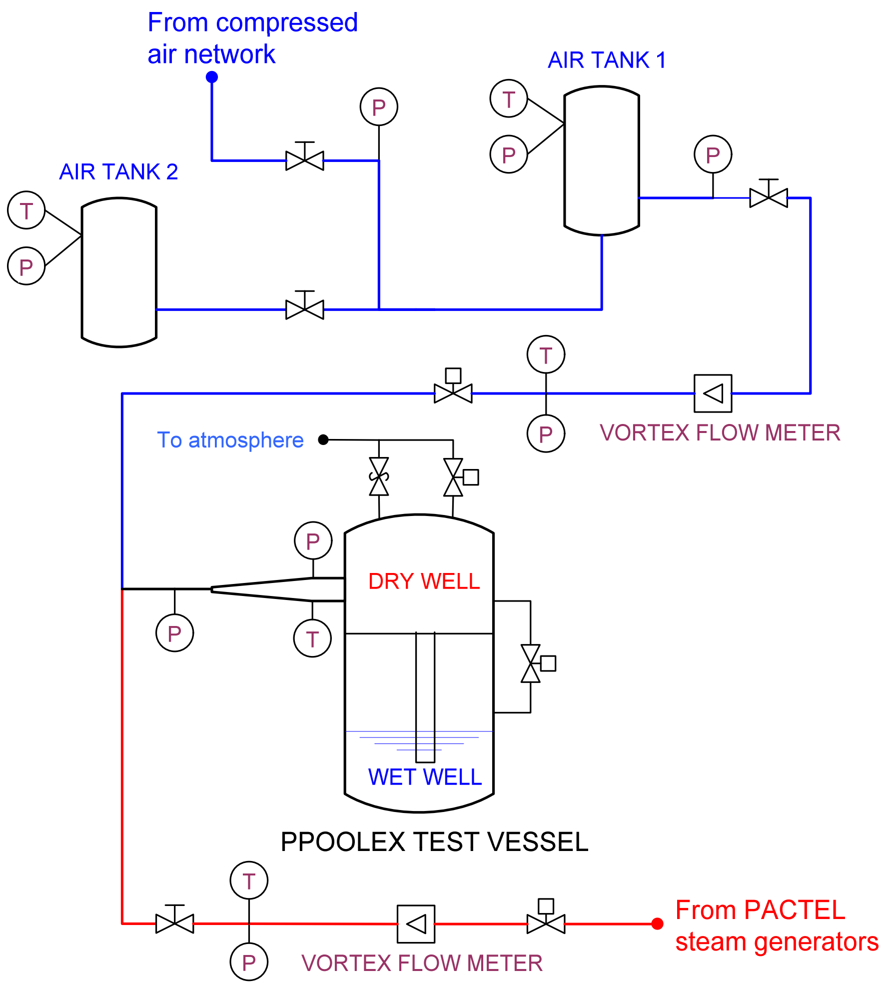

Figure 5. Arrangement of air and steam supply in the PPOOLEX facility.

3.3 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, inside the blowdown pipe, at the condensation pool bottom and in the gas phase of the wet well. 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. The strain measurements were added for the CHAR-12 experiment A list of different types of basic measurements used in the PPOOLEX facility during the characterizing experiment series 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.

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	1	-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)

3.4 CCTV SYSTEM

For more accurate observation of steam bubbles at the blowdown pipe outlet, the test facility is furnished with a Citius Imaging digital high-speed video camera (model C10) [5]. 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. (The high speed camera was not in use during the characterizing test series.)

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.

3.5 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 [6].

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. The voltage readings are converted to engineering units by using special conversion software.

In the characterizing tests, the data recording frequency of LabView was usually 1 kHz except for temperature measurements. For them the data recording frequency was 50 Hz. The temperature measurements are therefore averages of 20 measured points. In a couple of special test runs, the LabView frequency was either 5 or 10 kHz. The rest of the measurements (for example in the air/steam lines) are recorded by HPVee software with the frequency of 2 Hz in the air tests and 1 Hz in the steam/air mixture tests.

4 TEST PROGRAMME

The characterizing test program with air or steam/air mixture in 2007 consisted of 12 experiments. Experiments from CHAR-01 to CHAR-05 and from CHAR-07 to CHAR-09 dealt with air discharge and experiments CHAR-06, CHAR-10, CHAR-12 and CHAR-13 with steam/air mixture discharge. Each experiment included several separate blows (tests) of air or steam/air. Experiments were carried out by using a DN200 blowdown pipe. Air accumulators, filled with the help of the compressed air network of the laboratory, were used in the air discharge experiments. The three steam generators of the PACTEL test facility served as a steam source in the steam/air experiments.

Before each experiment the condensation pool 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 coolant volumes in the containment of the reference plant. The position of the throttle valve in the air or steam line was adjusted before each experiment so that the desired flow rate would be achieved. Flow rate was controlled also with the initial pressure level of the air accumulators and PACTEL steam generators. During pressure build-up of the steam generators and between the individual tests the steam line was heated with a small bypass flow.

After the correct initial pressure level in the air accumulators or in the steam generators had been achieved, the remote-controlled shut-off valve in the air/steam line was opened. As a result, the inlet plenum was filled with air or steam that immediately pushed its way to the dry well compartment and mixed there with the initial gas (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 flow into the wet well compartment started.

In CHAR-09, there was some noise in the measurement signals of T5, T6 and T8. All other measurements worked properly during the test program. Tables 3 and 4 show the initial parameters of the experiments.

Table 3. Initial parameters of the characterizing experiments with air discharge in the PPOOLEX facility in 2007

Experiment	Initial air accumulator pressure [MPa]	Initial pool water level [m]	Pool water temperature [°C]	Maximum air flow [g/s]	Comments
CHAR-01	0.3 – 0.8	2.14	~ 33	N/A	No flow rate measurement
CHAR-02	0.3 – 0.8	2.14	~ 50	N/A	No flow rate measurement
CHAR-03	0.3 – 0.8	2.14	~ 22	N/A	No flow rate measurement
CHAR-04	0.3 – 0.8	2.14	~ 20	N/A	No flow rate measurement
CHAR-05	0.4 – 0.8	2.14	~ 21	N/A	No flow rate measurement
CHAR-07	0.4 – 0.8	2.14	~ 21	~ 800	Maximum flow in test no. 4
CHAR-08	0.2 – 0.8	2.14	~ 20	~ 850	Maximum flow in test no.5
CHAR-09	0.8	2.14	~ 24	~ 830	Maximum flow in test no. 8 Noise in T5, T6, T8

Table 4. Initial parameters of the characterizing experiments with steam/air mixture discharge in the PPOOLEX facility in 2007

Experiment	Initial steam generator pressure [MPa]	Initial pool water level [m]	Pool water temperature [°C]	Maximum steam flow [g/s]	Comments
CHAR-06	0.15 – 0.2	2.14	~ 47	~ 130	
CHAR-10	0.2 – 0.4	2.14	~ 35	~ 1450	
CHAR-12	0.2 – 0.5	2.14	~ 19	~ 390	Measurement of strains and vertical movement added
CHAR-13	0.4 – 0.5	2.14	~ 20	~ 400	T1107 and T1108 added

5 EXPERIMENT RESULTS

The following chapters give a more detailed description of the characterizing experiment program and also try to analyze the observed phenomena. Not every experiment is gone through and discussed here. The most suitable experiments or individual blows (tests) from the point of view of the objectives of the characterizing test series are chosen for presentation.

5.1 EXPERIMENTS WITH AIR DISCHARGE

Eight air discharge experiments were executed. Each experiment had several separate air blow tests. Between the tests, the accumulators were filled again and the conditions in the test vessel were normalized with the help of forced ventilation. Usually, LabView recorded data only during the individual blows but HPVee recorded throughout the whole experiment. Visual material from the dry well, from the wet well gas space and of gas bubble formation at the blowdown pipe outlet was produced with standard video cameras through the vessel windows.

The main purpose of the experiments was to observe the general behavior of the facility, to assess the operation of instrumentation, automation, control and safety systems and to develop test procedures. To achieve these objectives different initial pressures in the air accumulators and final pressures in the test vessel, different flow rates by varying the position of the throttle valve in the air line and different pool water temperatures were used.

The initial pressure in the air accumulators ranged from 0.2 MPa to 0.8 MPa. The experiments were usually started with low initial pressure and continued by increasing the accumulator pressure in steps of 0.1 MPa or 0.2 MPa until the maximum available pressure of 0.8 MPa determined by the compressed air network was reached. The experiments were terminated either when the pressure difference between the accumulators and the test vessel had disappeared or when the test vessel pressure had reached a predetermined limit. This was the case when the connection to the compressed air network was left open. Since the design value for the vessel is 0.5 MPa, final pressures over 0.4 MPa were not used. In most cases, the pool bulk temperature was about 20 °C. A couple of experiments were executed with a higher pool water temperature.

Two tests from the characterizing air discharge experiments were selected for simulation with CFD codes both at VTT and LUT. Results of these calculations can be found from references [7] and [8].

5.1.1 General behavior of the facility

During the recorded blows the mass flow rate of air decreased as the pressure difference between the air accumulators and the test vessel decreased. The highest measured mass flow in the beginning of the blow with a maximum initial pressure of 0.8 MPa in the air accumulators and with a fully open throttle valve in the air line was about 0.85 kg/s. This corresponds to a mass flux value of 23.6 kg/m^2s in the inlet plenum. Before experiment CHAR-07 there was no flow meter in the air line. Almost constant air flows were experienced when the valve in the connection line to the compressed air network was left open during the experiment and at the same time the throttle valve in the air line was only partly open. With this arrangement, a constant air flow rate of about 0.2 kg/s was possible to achieve.

Figures 6 and 7 illustrate how the gas discharge flow into the dry well decreases as the pressure difference between the air accumulators and the test vessel disappears. The curves are from test CHAR-09-3, where the initial pressure of the accumulators was 0.8 MPa and the throttle valve in the air line was partly open.

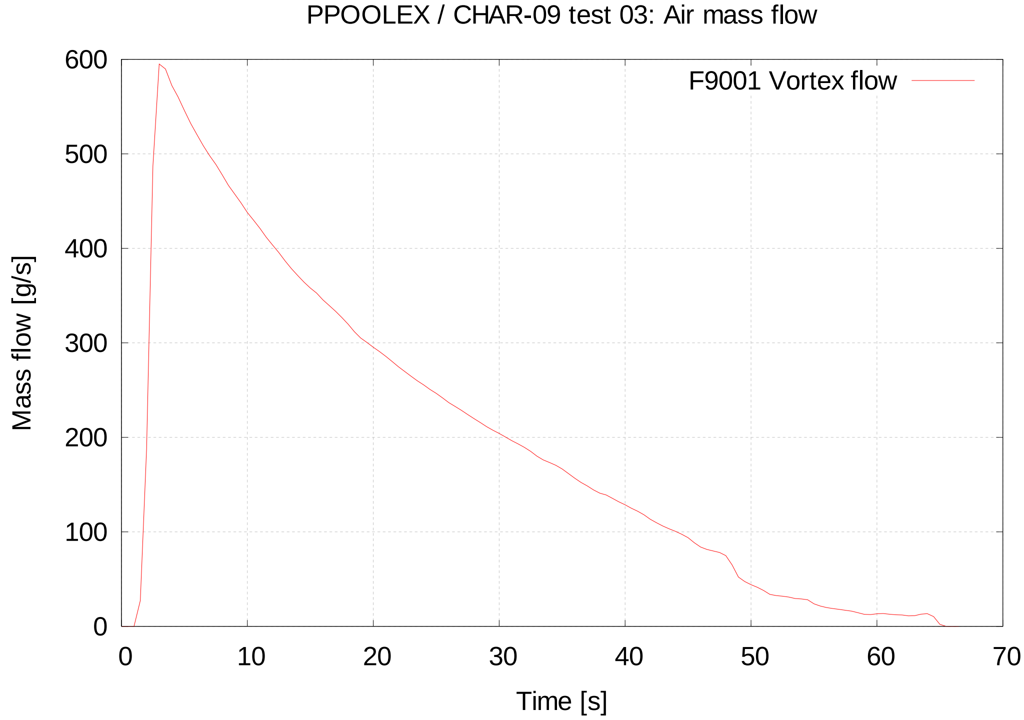

Figure 6. An example of decreasing flow into the dry well in air discharge test CHAR-09-3.

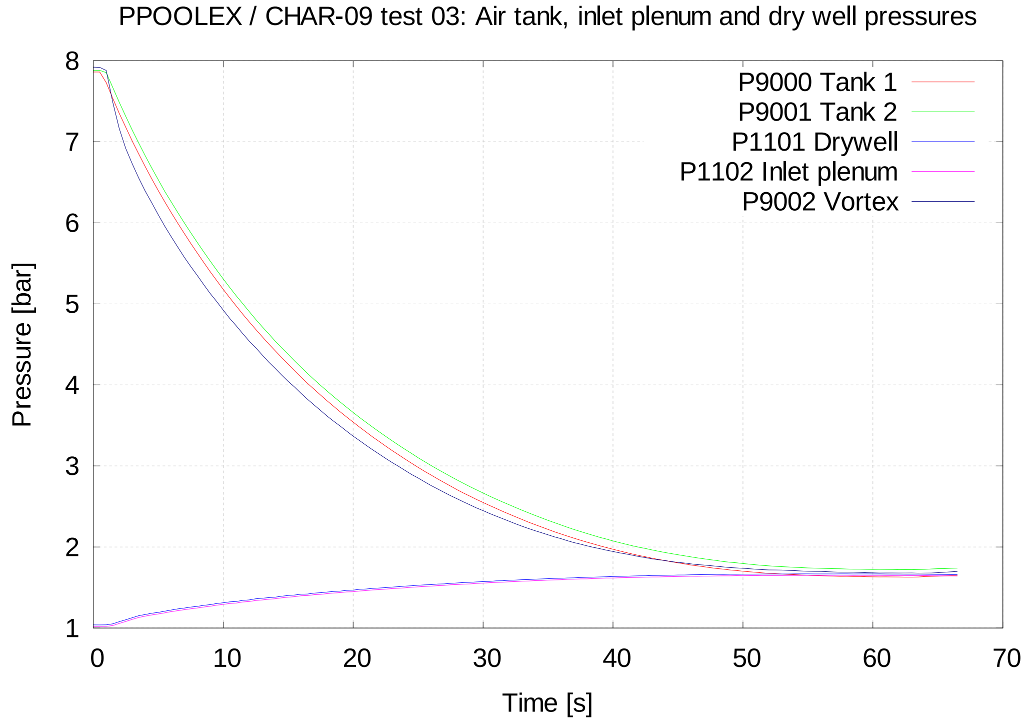

Figure 7. Disappearing pressure difference between the air accumulators and the test vessel in air discharge test CHAR-09-3.

The initial gas atmosphere in the dry well compartment and in the gas space of the wet well heated-up due to compression after air discharge from the accumulators had started. Up to 37 °C increase in temperature at the top of the dry well was observed in a test where the connection line to the compressed air network was left open and the final pressure of the test vessel was 0.4 MPa.

However, the peak temperature value was registered already at 200 seconds. This is before the pressure even reached 0.25 MPa (see Figure 8). After that, cooling by heat losses exceeded the effect of compression by pressure build-up. In the wet well compartment, the maximum temperature increase was 42 °C at highest. The temperature increase was a few degrees over 20 °C for both compartments if the connection to the compressed air network was closed.

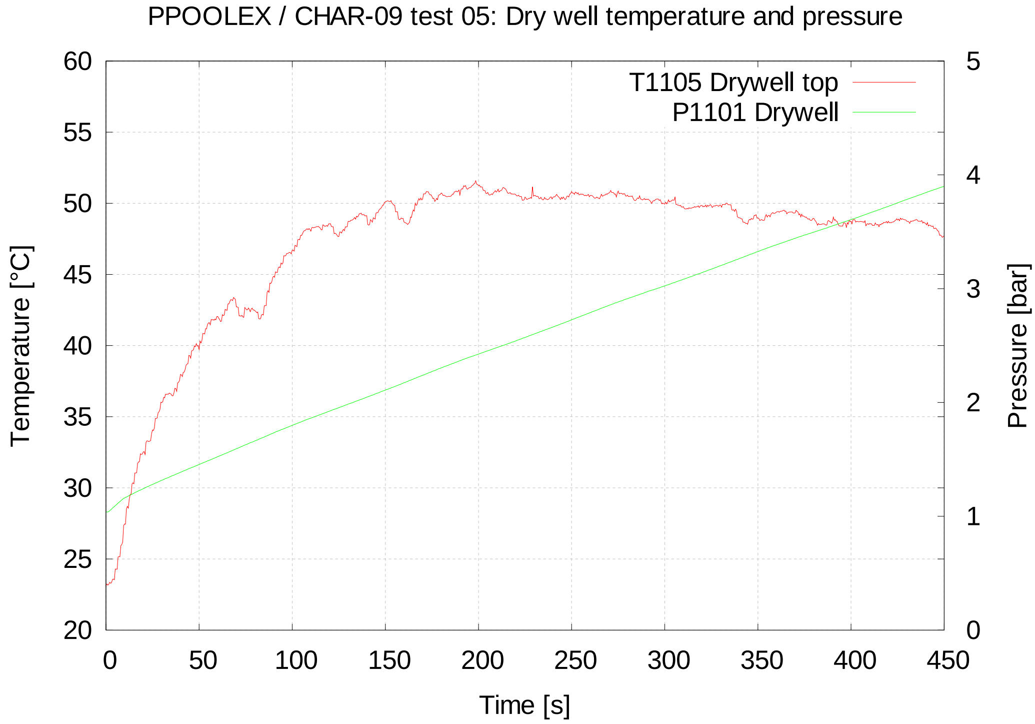

Figure 8. Temperature and pressure in the dry well during air discharge test CHAR-09-5.

5.1.2 Thermal stratification in the wet well gas space

As temperatures in the gas space of the wet well compartment increased during the air discharge tests, they also stratified. The temperature measurement just above the pool water level indicated an increase of only few degrees while the measurement close to the top of the compartment registered a rise even over 40 °C, when the test vessel pressure was let to increase to 0.4 MPa (from the initial pressure of 0.1 MPa). The temperature at the middle elevation of the wet well gas space was between the other two. In Figure 9, this development from a uniform initial temperature of the compartment to a strongly stratified situation at the end of the test can be clearly seen.

In most tests, stratification of temperatures in the wet well was very distinctive and followed the pattern described above. In a couple of tests, however, the two topmost measurements indicated almost equal values. No common explanation was found for this deviation from the general trend.

In the experiment with warmer pool water (CHAR-02), the thermocouple in the middle of the wet well gas space registered usually same values as the topmost thermocouple. Occasionally it indicated even higher values than the top measurement. In this case, the initial conditions could be the explaining factor. Because of a higher pool water temperature (50 °C), the wet well gas space is already at 42 °C in the beginning of the test and the rise in temperature due to compression is only about 25 °C. Furthermore, the structures of the wet well are also at a higher initial temperature than in other experiments.

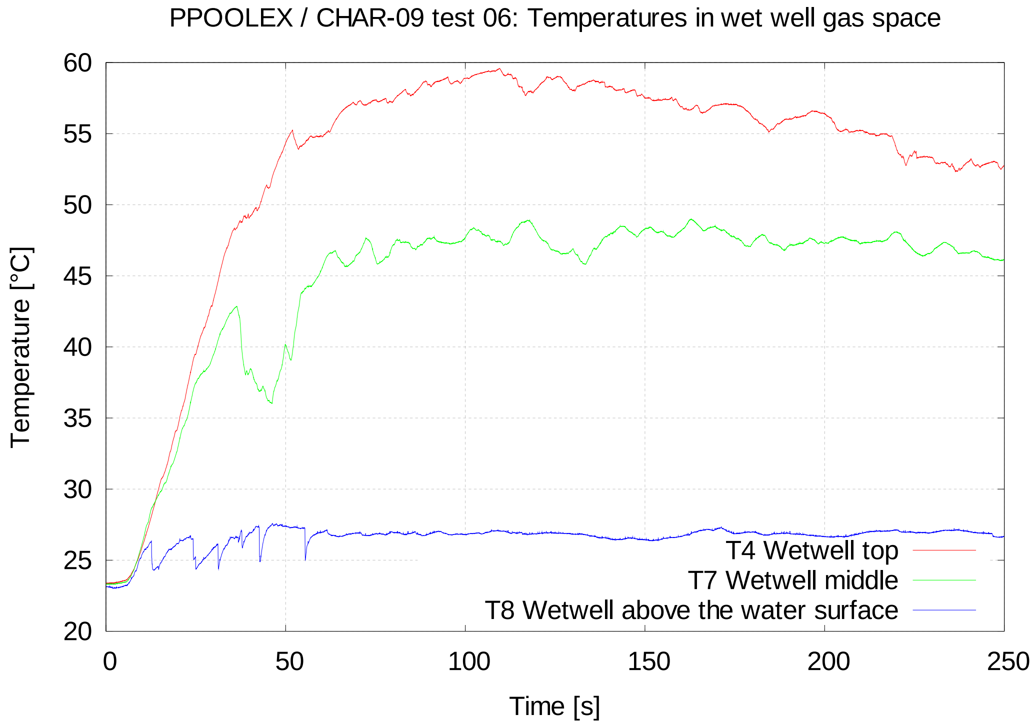

Figure 9. Stratification of temperatures in the wet well gas space in air discharge test CHAR-09-6.

Since the test vessel is not thermally insulated, heat losses to environment as well as heat being stored in structures soon start to have an effect on the wet well gas space temperatures as well as on the dry well temperatures. The decreasing trend can usually be observed after a couple hundred of seconds. Because of these phenomena, the behavior of the test facility deviates from that of the reference containment in certain situations. This must be taken into account when planning and carrying out future research with the facility, especially in case of such longer duration experiments where cooling by heat losses is not desired. Determination of heat losses will be conducted during 2008 and possible thermal insulation will be considered.

5.1.3 Effect of warm pool water

In the experiment CHAR-02, the pool water temperature was 50 °C, while it usually was only about 20 °C. No major system scale effects from this increased water temperature were observed apart from the above mentioned disturbance of the temperature stratification in the wet well gas space. However, with the pool water temperature in the region of 20 °C, the gas flowing from the dry well compartment through the blowdown pipe into the condensation pool is warmer than the pool water due to gas heat-up by compression. With the pool water temperature of 50 °C, the situation is the opposite. Warm water, that occupies the lower half of the blowdown pipe in the beginning of the test, is replaced with colder gas discharged from the dry well, see Figure 10. Measurements T1 and T2 inside the blowdown pipe indicate this clearly. Measurement T5, just below the pipe outlet, shows also some signs of colder gas flowing into the pool during the first 20 s of the test.

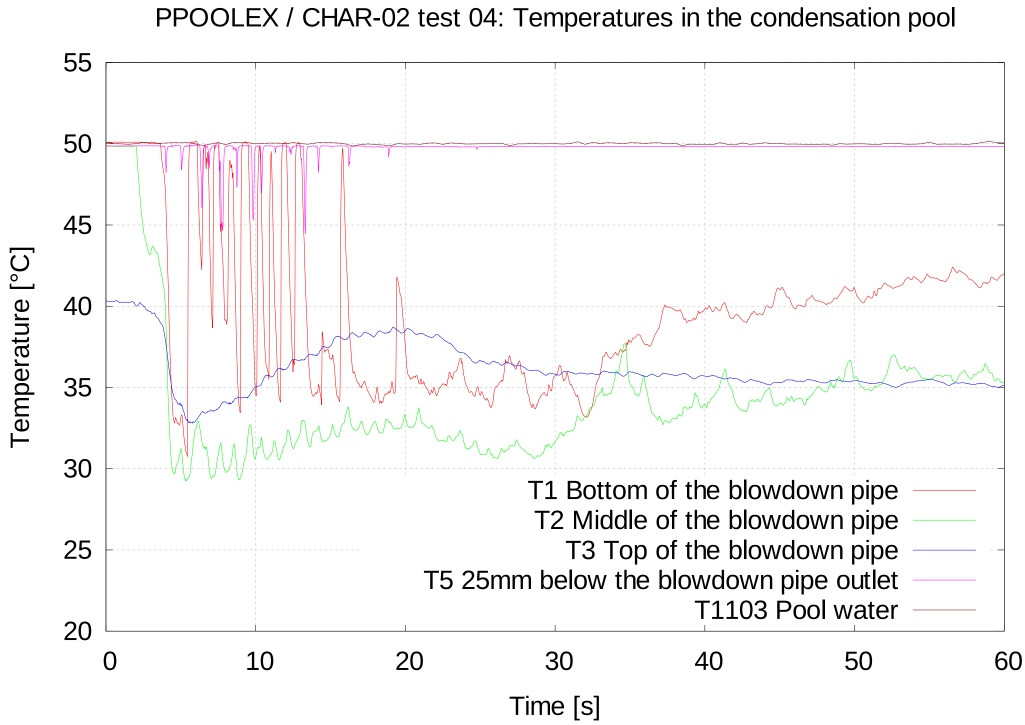

Figure 10. Temperatures in the blowdown pipe and pool in a test with warm pool water.

5.2 EXPERIMENTS WITH STEAM/AIR MIXTURE DISCHARGE

Four characterizing experiments with steam/air mixture discharge were executed. Each experiment had several separate blows (tests). Between the tests, the pressure in the PACTEL steam generators was let to restore and the conditions in the test vessel were normalized with the help of forced ventilation. Usually, LabView recorded data only during the individual blows but HPVee recorded throughout the whole experiment. Visual material from the dry well, from the wet well gas space and of steam/gas bubble formation at the blowdown pipe outlet was produced with standard video cameras through the vessel windows.

The main purpose of the experiments was to evaluate if containment like behavior can be established in the facility, to assess the operation of instrumentation, automation, control and safety systems and to develop test procedures. To achieve these objectives different initial pressures of the steam source and final pressures of the test vessel, different flow rates in the steam line and different pool water temperatures were used.

The initial pressure in the PACTEL steam generators ranged from 0.15 MPa to 0.5 MPa (all three SGs in use). The experiments were usually started with a low initial pressure and continued by increasing the steam source pressure in steps of 0.1 MPa. The experiments were terminated either when the pressure difference between the steam generators and the test vessel had disappeared or when the test vessel pressure had reached a predetermined limit. The highest used final pressure in the test vessel was about 0.27 MPa. The initial pool water bulk temperature was either about 20 °C, 35 °C or 50 °C. A small increase (2 °C – 5 °C) in the pool water temperature was experienced during the experiments due to the heating effect of steam discharge.

5.2.1 Containment like behavior of the facility

As the remotely operated valve in the steam line opened, the pressure and temperature in the dry well compartment immediately started to rise due to steam inflow. The increasing pressure difference between the dry and wet well compartments pushed water level in the blowdown pipe downwards until the pipe cleared. As a result, steam/air mixture flow through the pipe to the condensation pool began and the pressure and temperature started to rise there, too. In the beginning of the tests, condensation of steam took place also in the dry well due to cold structures. This was observed through the dry well windows as “falling rain” and water accumulation on the floor.

During the recorded blows the mass flow rate of steam slightly decreased as the pressure difference between the steam generators and the test vessel decreased. Otherwise, the steam flow was smooth and no fluctuations were present. The position of the throttle valve in the steam line was not changed at any time during the blows. The highest measured steam mass flow in the beginning of the blow with a maximum initial pressure of 0.5 MPa in the PACTEL steam generators and with an almost fully open throttle valve in the steam line was about of 1.45 kg/s. This corresponds to a mass flux value of 40.3 kg/m^2s in the inlet plenum. The steam source pressure could be kept constant by increasing the heating power of the PACTEL core section as the tests progressed. However, the steam flow rate into the dry well compartment had always a decreasing trend, because the pressure difference between the steam source and the test vessel slowly diminished along time.

In the very beginning of the tests, the flow through the blowdown pipe was almost pure air (that initially occupied the dry well). This could be verified even without any measurements of gas/steam fractions of the flow by looking at the bubble behavior at the blowdown pipe outlet. No signs of condensation were present and the formed bubbles started to rise towards the water surface after detachment. Soon, the fraction of steam among the flow started to increase and the behavior of the bubbles changed. Condensation related phenomena could be registered with pressure, temperature and strain measurements.

The same kind of temperature stratification as with the earlier pure air discharge experiments was experienced also now in the wet well gas space. A few tens of degrees difference in temperature between the water surface and the top of the compartment was measured.

Regardless of incomplete instrumentation one can say, that BWR containment like behavior related to the beginning of a postulated steam line break accident was observed in the PPOOLEX test facility during the steam/air mixture tests of the characterizing experiment series. Steam flow rates and temperatures were, however, smaller than in the (scaled down) reference case of a main steam line break inside the containment. The most important task of the research project, to produce experimental data for code simulation purposes, can be satisfactorily fulfilled even with the current version of the facility. Further modifications and additions of equipment and instrumentation broaden the applicability of the facility for system scale studies, too.

5.2.2 Smooth condensation vs. chugging

Depending on the test conditions (steam flow rate into dry well, pool temperature, non-condensable gas fraction of flow in the blowdown pipe) the behavior in the condensation pool was either quite stable or oscillating. In the first steam/air experiments with a small initial pressure in the steam generators, with warm (35 °C or 50 °C) pool water and with a high non-condensable gas fraction of the blowdown pipe flow (due to the short duration of blows) condensation was smooth and no oscillations related to chugging were observed. Pool water was not sucked back into the blowdown pipe and the upward/downward movement of the steam/water interface inside the pipe was minimal. This is well demonstrated in Figure 11, where the (steam) temperatures in the blowdown pipe end up on a uniform value and the pressure measurements don't indicate oscillations at all.

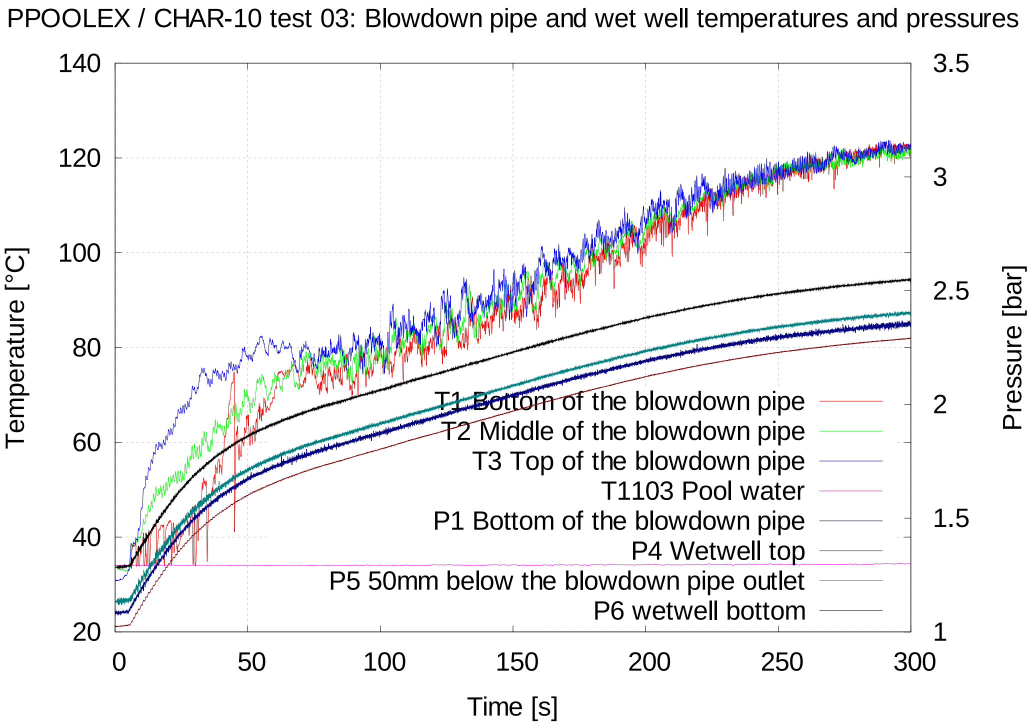

Figure 11. Uniform temperatures in the blowdown pipe during smooth condensation.

As the experiment series progressed towards longer tests, where the fraction of non-condensables had time to decrease significantly and condensation of steam bubbles at the blowdown pipe outlet began, condensation oscillations and chugging phenomenon were encountered. In these tests, a radical change from smooth condensation behavior to oscillating one with pressure pulses occurred quite abruptly when the air fraction of the blowdown pipe flow dropped close to zero. All pressure measurements below the water level registered this change. For example, in test CHAR-10-5, this happened at about 180 seconds, see Figure 12. The final stage of the longest experiments, when the flow was almost pure steam and had decreased close to zero, belonged to region 1 (condensation within vents or blowdown pipes) in the condensation mode map of Lahey and Moody (see Figure 2). Once again, the experiments demonstrated the strong diminishing effect that non-condensable gases have on dynamic unsteady loadings experienced by submerged pool structures. Air, in quantities even less than 1 %, reduces the condensation rate considerably, as was observed in the combined effects test series during the preceding research programme [9].

Amplitudes of the pressure pulses in the PPOOLEX experiments were not as high as measured during the POOLEX experiments (due to water hammer propagation) in the preceding research programme. This is due to the fact that the flow in the PPOOLEX experiments contained some amount of non-condensable gas during almost the whole duration of the tests. Furthermore, the dry well gas volume damped the oscillations inside the blowdown pipe by acting as a buffer. Some pressure pulses in the range of 0.7 MPa – 0.8 MPa were, however, measured during the chugging periods of the experiments (Figure 13).

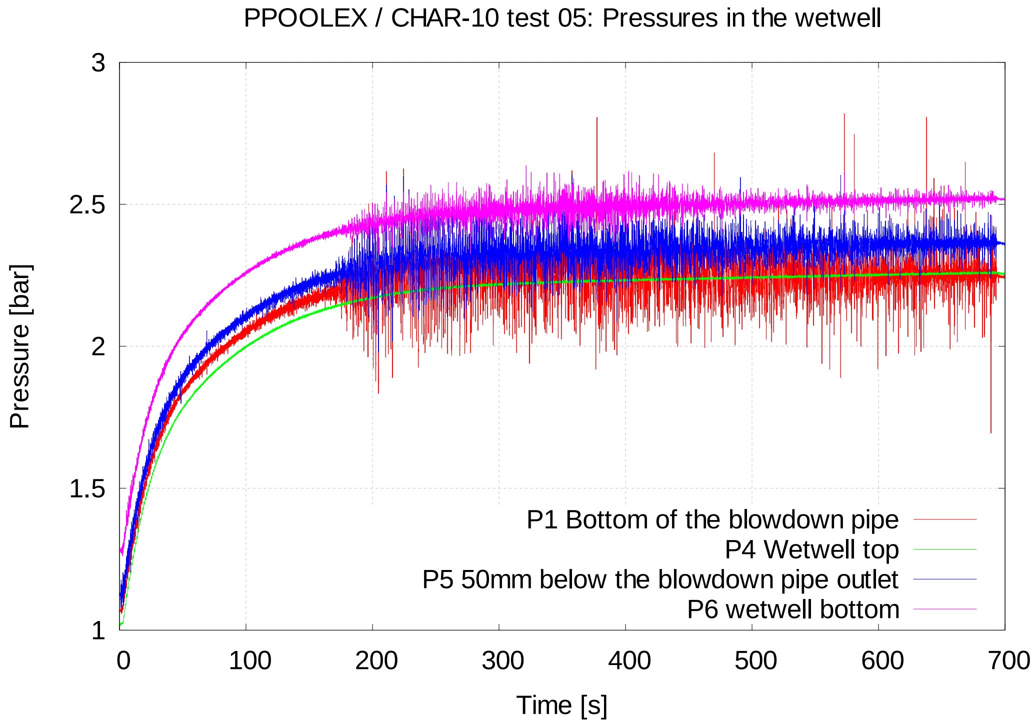

Figure 12. Radical change from smooth condensation to oscillating one as the air fraction of flow drops close to zero during a discharge of steam/air mixture.

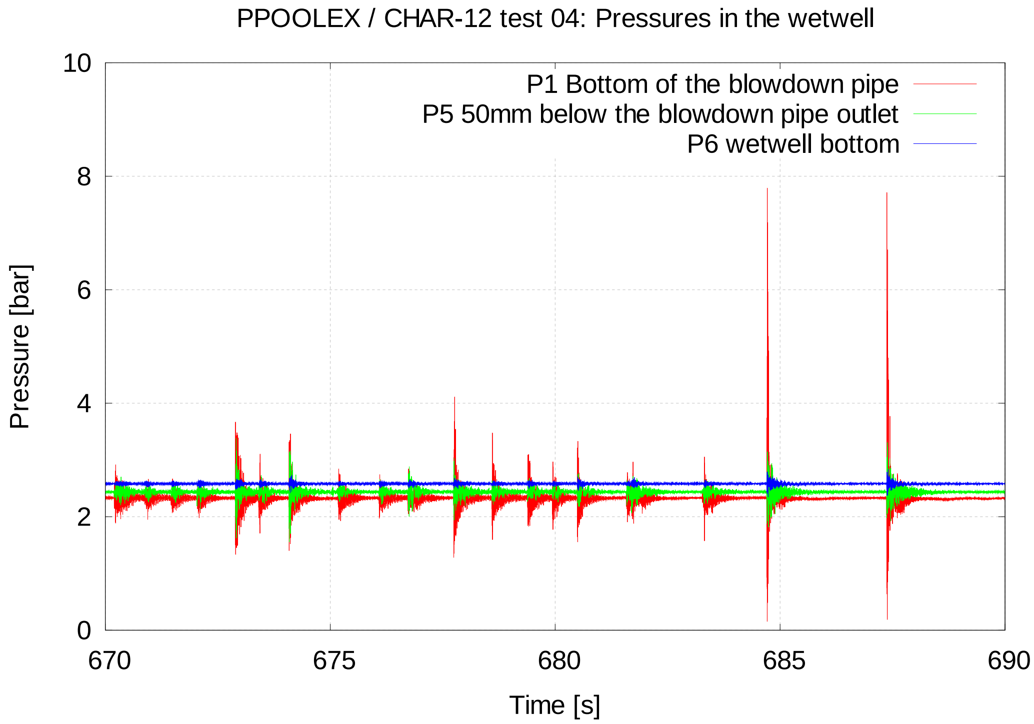

Figure 13. Pressure pulses in the wet well during chugging in a steam/air discharge test.

Figure 14 shows some pressure oscillations during a 0.2 s interval from the very final moments of the test CHAR-13-3, when the condensation mode is chugging. The oscillations in Figure 14 were measured after a collapse of a single steam bubble at the blowdown pipe outlet i.e. they all are some kind of secondary or sequel effects. Because a small amount of non-condensable gas was still among the blowdown pipe flow, the condensation process is somewhat continuous and the oscillations have no chance to die away. One can see that all the measured pressures in the pool liquid volume are in the same phase of oscillation but that the amplitude of the pool bottom measurement (P6) is much smaller than the amplitude of the measurements in (P1) and below (P5) the blowdown pipe. The constant pressure of the wet well gas space (P4) is also shown in Figure 14.

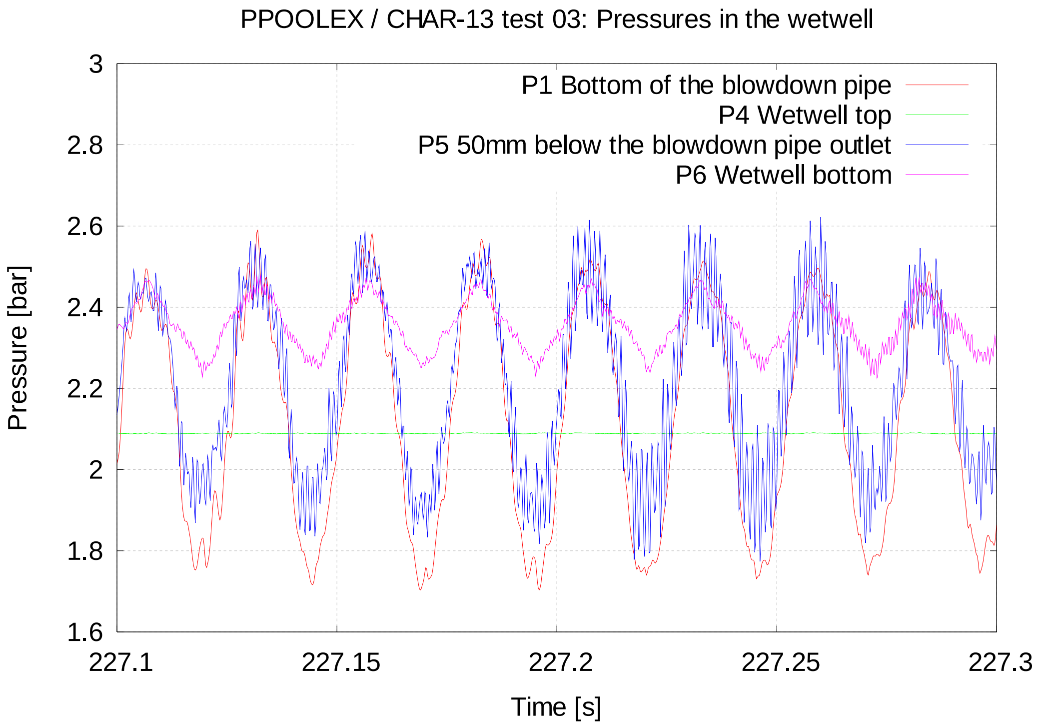

Figure 14. Pressure oscillations of the same phase in the wet well after a collapse of a steam bubble.

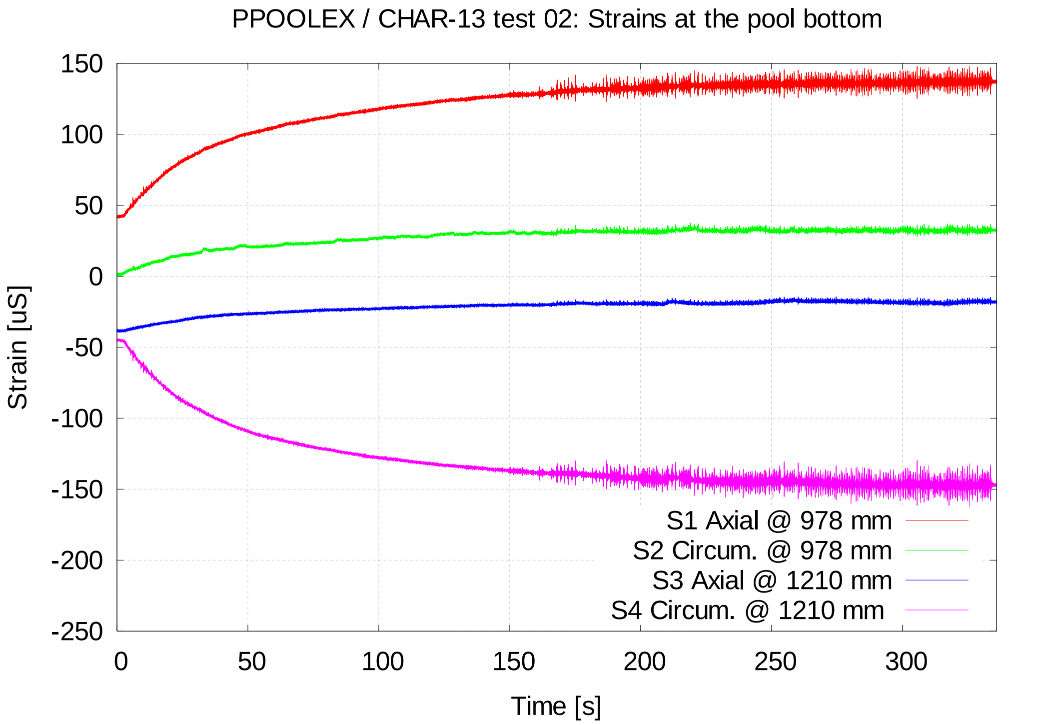

Figure 15. Strains at the test vessel bottom during a steam/air discharge test.

The strain measurements at the pool bottom (installed after CHAR-11) indicate only very small signs of pressure oscillations during the chugging periods. The overall pressure build-up of the test vessel can, however, be observed as an increasing or decreasing trend of the strain curves from the initial values, see Figure 15.

5.3 COMPARISON TO POOLEX EXPERIMENTS

The general behaviour of the PPOOLEX facility differs significantly from that of the previous POOLEX facility because of the closed two-compartment structure of the test vessel. In POOLEX, no heat-up or other effects due to compression by pressure build-up were present as is the case with PPOOLEX. Furthermore, the test types, conditions and parameters were not equal. Some observations concerning the similarity or dissimilarity of the test results can, however, be made.

As already discussed above, the amplitudes of pressure pulses in the PPOOLEX experiments were not as high as measured during the POOLEX experiments (due to water hammer propagation). In PPOOLEX, the dry well gas volume damped the oscillations inside the blowdown pipe by acting as a buffer. Furthermore, the flow contained some amount of non-condensable gas during almost the whole duration of the tests. This had a suppressing effect on the direct contact condensation phenomenon.

During the experiments dynamic unsteady loadings were caused to submerged pool structures due to chugging phenomenon. In addition, static loads were caused by the hydrostatic pressure of water. Maximum strain amplitudes in the experiments reported here are, however, clearly smaller than in the preceding POOLEX experiments dealing with chugging. This is mainly due to the suppressing effect of non-condensable gas (originating from the dry well compartment) among the flow. In the open POOLEX facility, pure steam was directly discharged into the blowdown pipe. The initial parameters and test conditions (cold pool water, large steam mass flux) were also more suitable in the earlier experiments for notable stresses to be generated. Direct comparison of the stress values is not useful due to the fact that the wall thickness is different in the two test facilities.

6 SUMMARY AND CONCLUSIONS

This report summarizes the results of the characterizing experiment series in 2007 with the 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, and it models a BWR containment. A DN200 blowdown pipe connects the compartments to each other. During the experiments the test facility was equipped with basic high frequency instrumentation for capturing different aspects of the investigated phenomena. Eight experiments with pure air discharge and four experiments with steam/air mixture discharge into the dry well were carried out. Each experiment consisted of several separate blows (tests). The main purpose of the experiment series was to study the general behavior of the facility, to evaluate if containment like behavior can be established, to assess the performance of basic instrumentation, automation, control and safety systems and to develop test procedures.

Before each experiment the condensation pool 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 varied from 20 °C to 50 °C. The maximum initial pressure of the air accumulators and of the steam source (the nearby PACTEL facility) before the blows was 0.8 MPa and 0.5 MPa, respectively. The highest measured mass flux in the inlet plenum in the beginning of the blow was 23.6 kg/m^{2}s in the air discharge experiments and 40.3 kg/m^{2}s in the steam/air mixture experiments. Visual material from air/steam bubble formation at the blowdown pipe outlet was produced with standard video cameras through the test vessel windows.

The general behaviour of the PPOOLEX facility differs significantly from that of the previous POOLEX facility because of the closed two-compartment structure of the test vessel. Heat-up due to compression in both compartments was the most obvious evidence of this. A temperature increase of several tens of degrees was experienced when the system pressure was let to rise from 0.1 MPa to 0.4 MPa. Temperatures also stratified in the gas space of the wet well compartment.

In the short duration steam/air mixture experiments with a high non-condensable gas fraction of the blowdown pipe flow condensation was smooth and no oscillations related to chugging were observed. Pool water was not sucked back into the blowdown pipe and the upward/downward movement of the steam/water interface inside the pipe was minimal. Condensation oscillations and chugging phenomenon were encountered in the longer tests where the fraction of non-condensables had time to decrease significantly. A radical change from smooth condensation behavior to oscillating one with pressure pulses occurred quite abruptly when the air fraction of the blowdown pipe flow dropped close to zero. However, the flow contained some amount of non-condensable gas during the whole duration of the tests.

The experiments again demonstrated the strong diminishing effect that non-condensable gases among the flow have on dynamic unsteady loadings experienced by submerged pool structures. Pressure pulses inside the blowdown pipe due to rapid condensation of steam bubbles and water hammer propagation during chugging were much smaller in the PPOOLEX steam/air mixture experiments than in the preceding POOLEX steam discharge experiments with the open pool test facility. Furthermore, the dry well gas volume damped the oscillations inside the blowdown pipe by acting as a buffer. The amplitude of oscillations measured by the pressure sensor at the pool bottom was considerably smaller, too.

BWR containment like behavior related to the beginning of a postulated steam line break accident was observed in the PPOOLEX test facility during the steam/air mixture experiments. Steam flow rates and temperatures were, however, smaller than in the (scaled down) reference case of a main steam line break inside the containment. The most important task of the research project, to produce experimental data for code simulation purposes, can be satisfactorily fulfilled even with the current version of the facility. However, further modifications and additions of equipment and instrumentation are needed to broaden the applicability of the test facility for system scale studies and to provide simulators with CFD-grade measurement data.

Since the test vessel is not thermally insulated, heat losses to environment as well as heat being stored in structures have an effect on the dry and wet well temperatures. The decreasing trend can usually be observed after a couple hundred of seconds. Therefore, the behavior of the test facility deviates from that of the reference containment in certain situations. This must be taken into account when planning and carrying out future research with the facility, especially in case of such longer duration experiments where cooling by heat losses is not desired.

The basic instrumentation, consisting of temperature, pressure, flow and strain measurements, have worked without major problems as well as the control, automation and safety systems. Additional measurements are, however, needed in order to get a full benefit from future experiments. Valuable information of applicable test procedures have been gained during the characterizing experiments.

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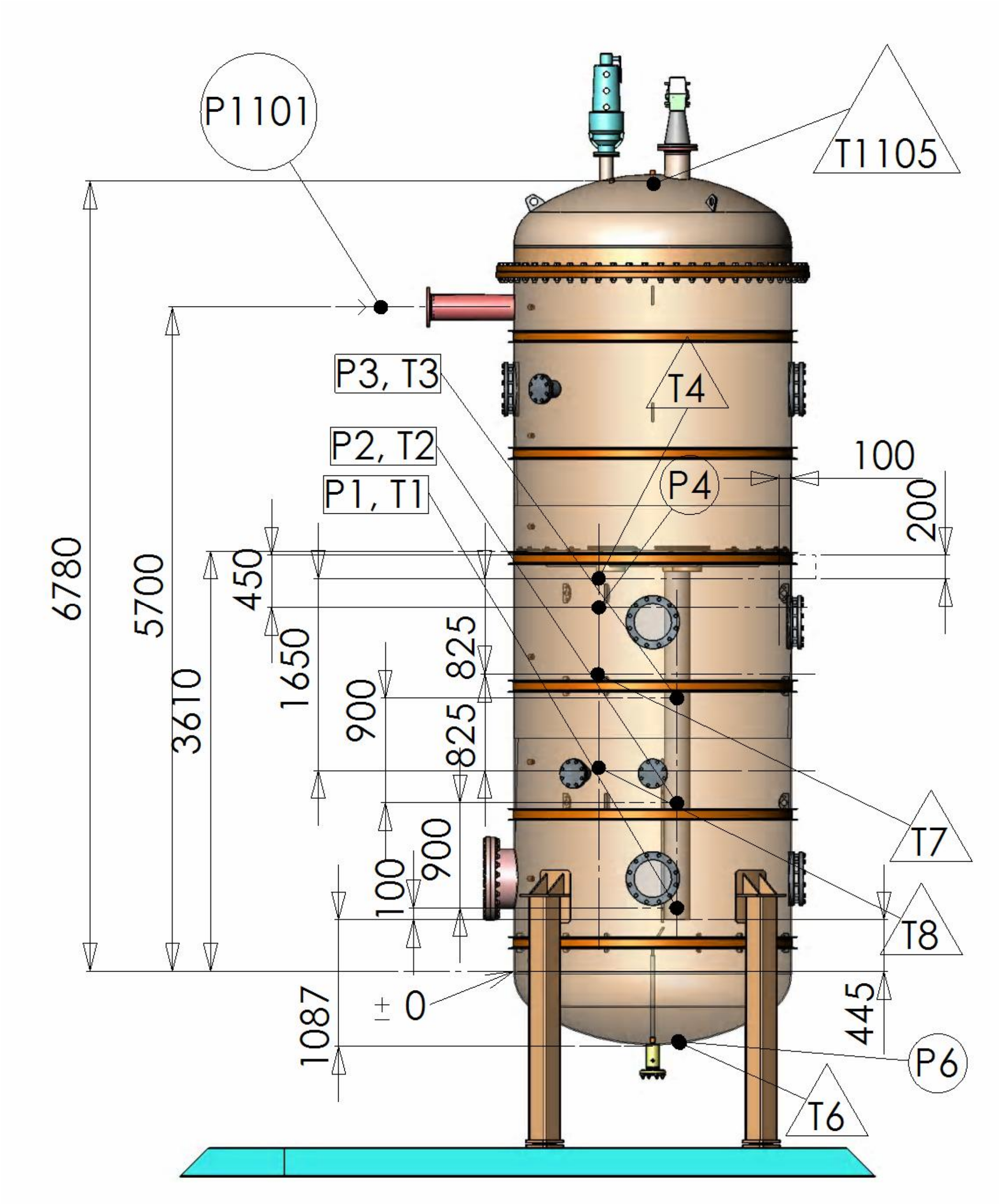
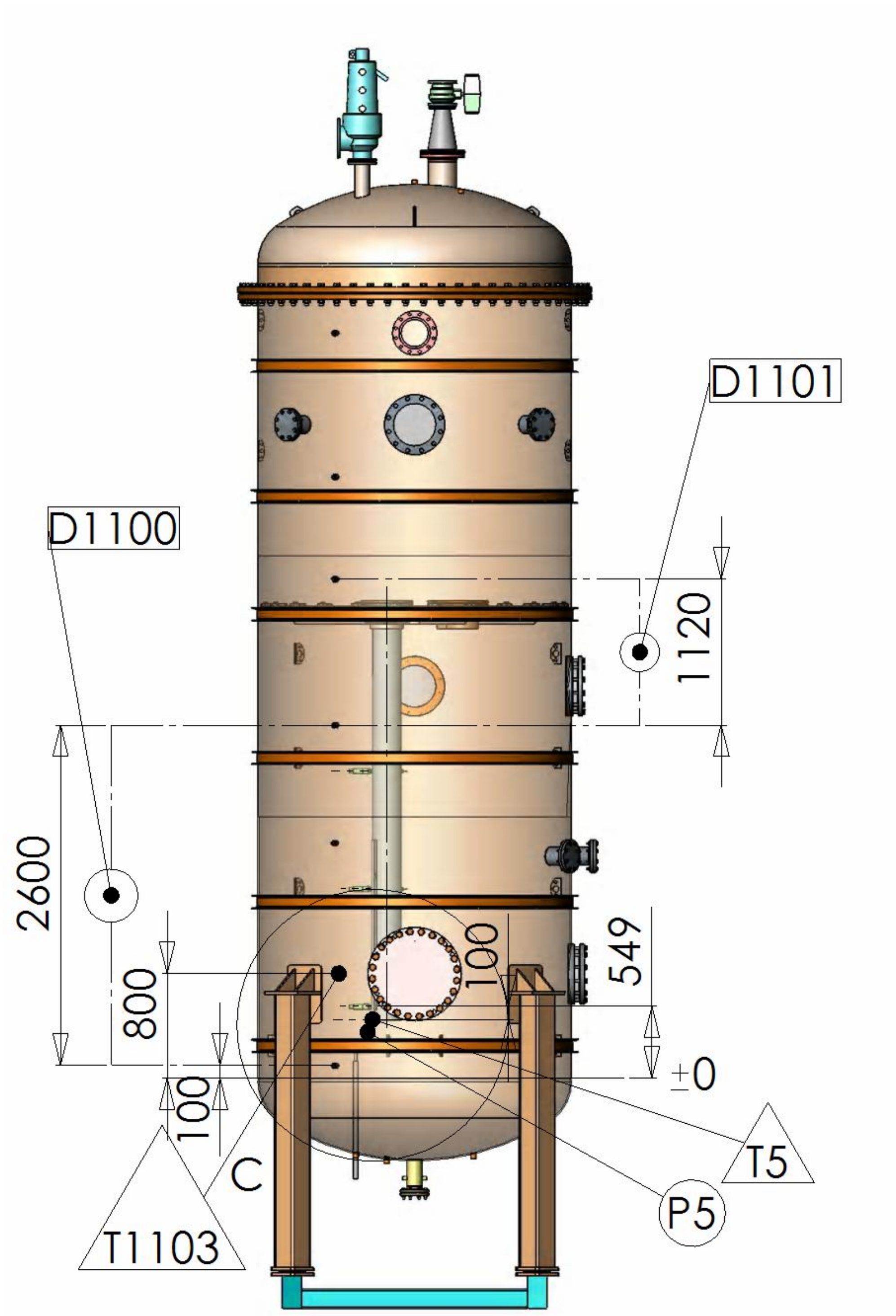
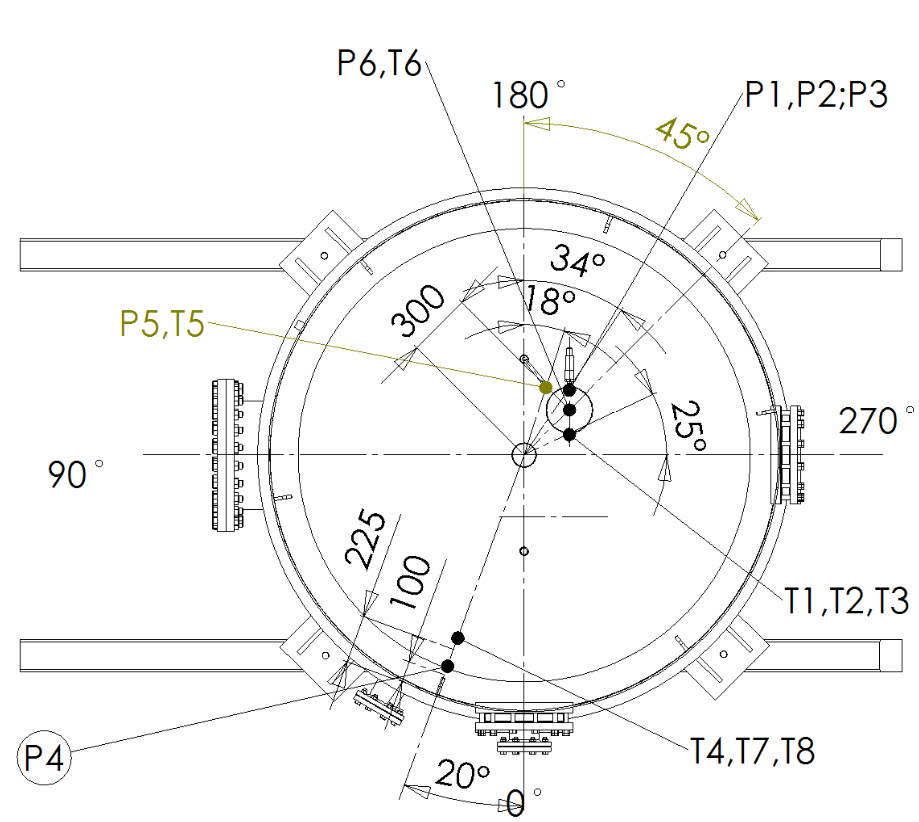
APPENDIX 1: INSTRUMENTATION OF THE PPOOLEX TEST FACILITY



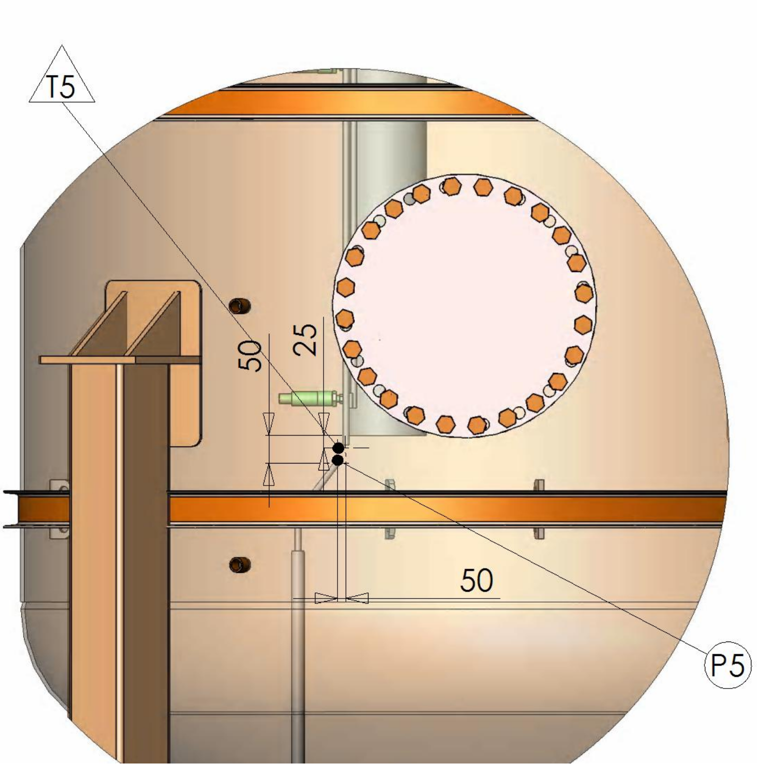
Test vessel measurements.



Test vessel measurements.



Measurement directions.

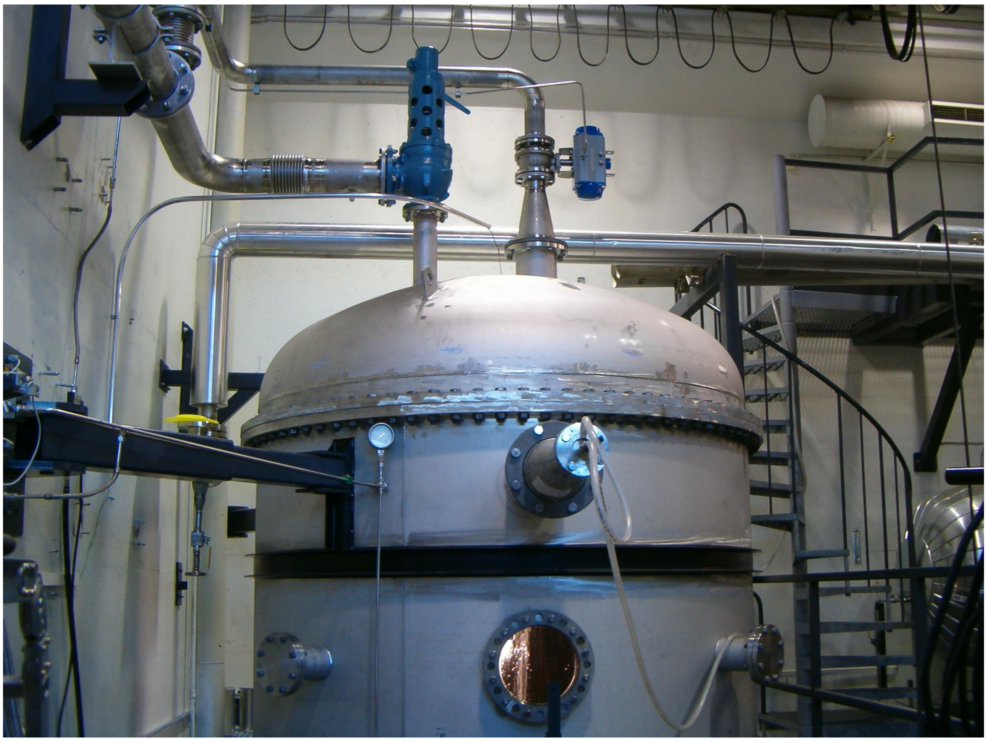


Pressure and temperature at the blowdown pipe outlet.

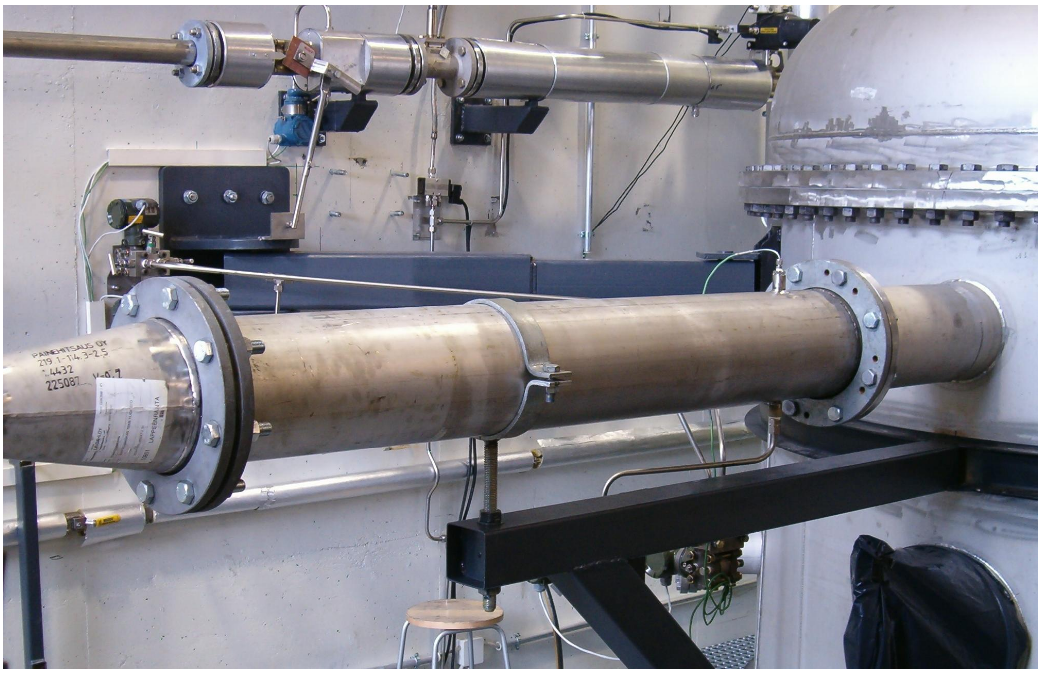
Measurement	Code	Elevation	Angle	Location
Pressure	P1	545	214	Blowdown pipe
Temperature	T1	545	245	Blowdown pipe
Temperature	T2	1445	245	Blowdown pipe
Temperature	T3	2345	245	Blowdown pipe
Pressure	P4	3160	20	Wet well gas space
Temperature	T4	3410	20	Wet well gas space
Pressure	P5	395	198	Blowdown pipe outlet
Temperature	T5	420	198	Blowdown pipe outlet
Pressure	P6	-1060	225	Wet well bottom
Temperature	T6	-1060	225	Wet well bottom
Temperature	T7	2585	20	Wet well
Temperature	T8	1760	20	Wet well
Pressure	P1101	5700	90	Dry well
Temperature	T1104	-245	180	Outside wall
Temperature	T1105	6780	-	Dry well top
Temperature	T1103	800	120	Wet well
Flow rate	F1101	5700	-	Inlet plenum
Pressure	P1102	5700	-	Inlet plenum
Temperature	T1106	5700	-	Inlet plenum
Pressure	P1103	-	-	Air/steam line
Pressure diff.	D1100	100-2700	120	Wet well
Pressure diff.	D1101	2700-3820	120	Across the floor
Flow rate	F1100	-	-	Steam line
Temperature	T1102	-	-	At the steam line vortex
Pressure	P1100	-	-	At the steam line vortex
Flow rate	F9001	-	-	Air line
Temperature	T9001	-	-	At the air line vortex
Pressure	P9002	-	-	At the air line vortex
Pressure	P9000	-	-	Air tank 1
Temperature	T9000	-	-	Air tank 1
Pressure	P9001	-	-	Air tank 2
Temperature	T0460	-	-	Air tank 2
Strain	S1	-400	0	Bottom segment
Strain	S2	-400	0	Bottom segment
Strain	S3	-265	180	Bottom segment
Strain	S4	-265	180	Bottom segment
Vertical pool movement	Z-axis	-	-	Below pool bottom
Valve position	X1100	-	-	-

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.

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Affiliation(s)	Lappeenranta University of Technology, Nuclear Safety Research Unit, Finland
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No. of illustrations	15+8
No. of references	9

Abstract

This report summarizes the results of the characterizing test series in 2007 with the scaled down PPOOLEX facility designed and constructed at Lappeenranta University of Technology. Air and steam/air mixture was blown into the dry well compartment and from there through a DN200 blowdown pipe to the condensation pool (wet well). Altogether eight air and four steam/air mixture experiments, each consisting of several blows (tests), were carried out.
The main purpose of the experiment series was to study the general behavior of the facility and the performance of basic instrumentation. Proper operation of automation, control and safety systems was also tested.
The test facility is a closed stainless steel vessel divided into two compartments, dry well and wet well. The facility is equipped with high frequency measurements for capturing different aspects of the investigated phenomena.
The general behavior of the PPOOLEX facility differs significantly from that of the previous POOLEX facility because of the closed two-compartment structure of the test vessel. Heat-up by several tens of degrees due to compression in both compartments was the most obvious evidence of this. Temperatures also stratified. Condensation oscillations and chugging phenomenon were encountered in those tests where the fraction of non-condensables had time to decrease significantly. A radical change from smooth condensation behavior to oscillating one occurred quite abruptly when the air fraction of the blowdown pipe flow dropped close to zero. The experiments again demonstrated the strong diminishing effect that non-condensable gases have on dynamic unsteady loadings experienced by submerged pool structures.
BWR containment like behavior related to the beginning of a postulated steam line break accident was observed in the PPOOLEX test facility during the steam/air mixture experiments. The most important task of the research project, to produce experimental data for code simulation purposes, can be satisfactorily fulfilled with the current version of the facility. Further modifications and additions of equipment and instrumentation are, however, needed to increase the applicability of the test facility for system scale studies, too.

Key words: condensation pool, steam/air blowdown, non-condensable gas, pressure oscillations

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