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MULTIPLE BLOWDOWN PIPE EXPERIMENTS WITH THE PPOOLEX FACILITY

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Abstract

This report summarizes the results of the experiments with two steel blowdown pipes carried out with the scaled down PPOOLEX test facility designed and constructed at Lappeenranta University of Technology. Steam was blown into the dry well compartment and from there through the blowdown pipes to the condensation pool.

The main purpose of the experiment series was to study chugging phenomena (rapid condensation) while steam is discharged through two parallel blowdown pipes into the condensation pool filled with sub-cooled water. Particularly, the aim was to study if the pipe material (polycarbonate) used in the earlier experiment series with two blowdown pipes has had an effect on the general chugging behaviour and measured loads.

In the experiments the initial temperature of the pool water was 20 ºC. The steam flow rate ranged from 220 g/s to 2 350 g/s and the temperature of incoming steam from 148 ºC to 207 ºC.

The formation and collapse of steam bubbles and the movement of the steam/water interface inside the pipes was non-synchronous. There could be even a 70 ms time difference between the occurrences of steam bubble collapses at the outlets of the two pipes. There was no clear pattern in which pipe the steam bubble first starts to collapse. Several successive bubbles could collapse first in either pipe but then the order changed for a single or several cycles.

High pressure loads were measured inside the blowdown pipes due to rapid condensation of the steam volumes in the pipes and resulting water hammer effects. The loads seemed to be higher in pipe 1 than in pipe 2. An explanation for this could be a possible unequal distribution of steam flow between the two pipes.

The pipe material has an effect on the condensation phenomena inside the blowdown pipes. A huge difference in the measured pressure curves inside the pipes could be observed compared to the experiments with the polycarbonate pipes. With the same test conditions the amplitude of the pressure pulses caused by water hammer was considerably larger in the steel pipe experiments. It seemed like the flow mode was different with the polycarbonate pipes from that with the steel pipes. Due to minimal heat conduction through the polycarbonate pipe wall condensation tended to happen at the pipe outlet and therefore no high pressure loads due to water hammer were experienced inside the pipe.

Key words

condensation pool, steam/air blowdown, chugging, dynamic loading

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This report summarizes the results of the experiments with two steel blowdown pipes carried out with the scaled down PPOOLEX test facility designed and constructed at Lappeenranta University of Technology. Steam was blown into the dry well compartment and from there through the blowdown pipes to the condensation pool. Seven experiments were carried out.

The main purpose of the experiment series was to study chugging phenomena (rapid condensation) while steam is discharged through two parallel blowdown pipes into the condensation pool filled with sub-cooled water. Particularly, the aim was to study if the pipe material (polycarbonate) used in the earlier experiment series with two blowdown pipes has had an effect on the general chugging behaviour and measured loads.

The PPOOLEX test facility is a closed vessel divided into dry and wet well compartments. The DN200 blowdown pipes (Ø219.1x2.5) were made of stainless steel and equipped with temperature and pressure measurements. In the experiments the initial temperature of the condensation pool water was 20 °C. The steam flow rate ranged from 220 g/s to 2 350 g/s and the temperature of incoming steam from 148 °C to 207 °C.

The formation and collapse of steam bubbles and the movement of the steam/water interface inside the pipes was non-synchronous. There could be even a 70 ms time difference between the occurrence of steam bubble collapses at the outlets of the two pipes. There was no clear pattern in which pipe the steam bubble first starts to collapse. Several successive bubbles could collapse first in either pipe but then the order changed for a single or several cycles.

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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 modelled 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 modelling the dry well and wet well compartments of 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, NKS and Nordic Nuclear Reactor Thermal-Hydraulics Network (NORTHNET).

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CONTENTS

NOMENCLATURE

c_p	specific heat capacity
k	thermal conductivity
p	pressure
Q	volumetric flow rate
q_m	mass flow rate
R_a	average surface roughness
T_m	melting temperature

Greek symbols

α	linear thermal expansion coefficient
Δ	change
ε	strain
ρ	density

Abbreviations

BWR	boiling water reactor
CCTV	closed circuit television
CFD	computational fluid dynamics
CONDEX	Condensation experiments
DCC	direct contact condensation
ECCS	emergency core cooling system
LOCA	loss-of-coolant accident
LUT	Lappeenranta University of Technology
MOV	QuickTime
MSLB	main steam line break
NKS	Nordic nuclear safety research
PACTEL	parallel channel test loop
PAR	experiment series with parallel blowdown pipes
PC	polycarbonate
POOLEX	condensation pool experiments project
PPOOLEX	pressurized condensation pool experiments project
PWR	pressurized water reactor
SAFIR	Safety of Nuclear Power Plants - Finnish National Research Programme
SD	secure digital
SLR	steam line rupture
SRV	safety/relief valve
SS	stainless steel
TVO	Teollisuuden Voima Oyj
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 dry well to the condensation pool through the blowdown pipes in the Olkiluoto type BWR, see Figure 1. The wet well pool serves as the major heat sink for condensation of steam.

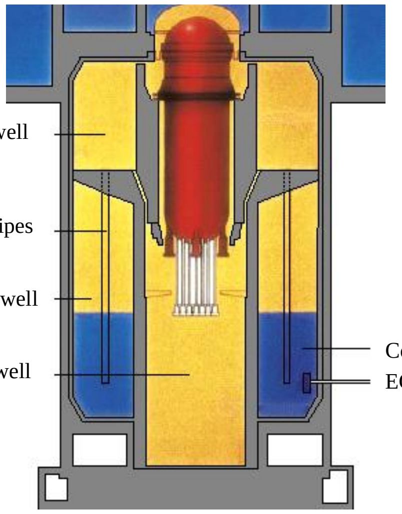

Figure 1. Schematic of the Olkiluoto type BWR containment.

The main objective of the CONDEX project is to improve understanding and increase fidelity in quantification of different phenomena inside the dry and wet well compartments of BWR containment during steam discharge. These phenomena could be connected, for example, to bubble dynamics issues, thermal stratification and mixing, wall condensation, direct contact condensation (DCC) 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 can occur frequently.

To achieve the project objectives, a combined experimental/analytical/computational study programme is being carried out. Experimental part at LUT is responsible for the development of a database on condensation pool dynamics and heat transfer at well controlled conditions. Analytical/computational part at VTT, KTH and LUT use the developed experimental database for the improvement and validation of models and numerical methods including CFD and system codes. Also analytical support is provided for the experimental part by pre- and post-calculations of the 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. 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/V213 reactor system, or in case of a submerged steam generator pipe break.

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 started in 2007 by running characterizing tests [1]. They focused on observing the general behaviour of the facility, on testing instrumentation and the proper operation of the automation, control and safety systems. The next five experiments (SLR series) focused on the initial phase of a postulated MSLB accident inside the containment [2]. Air was used as the flowing substance in these experiments. The research program continued in 2008 with a series of thermal stratification and mixing experiments [3]. Stratification in the water volume of the wet well during small steam discharge was of special interest. In December 2008 and January 2009 a test series focusing on steam condensation in the dry well compartment was carried out [4]. In April and May 2009 experiments were carried out to study the effect of the Forsmark type blowdown pipe outlet collar design on loads caused by chugging phenomena [5]. In the second half of 2009, the research programme continued with eleven experiments (TRA and PAR series) studying the effect of the number of blowdown pipes (one or two) on loads caused by chugging phenomenon [6]. In January 2010, experiments focusing on dynamic loading (DYN series) during steam discharge were carried out [7].

In November – December 2010, the interaction of parallel blowdown pipes was investigated further (continuation of the PAR series). The experiments with two transparent blowdown pipes with the PPOOLEX facility in 2009 gave contradictory results. In order to exclude the possible effect of the pipe material (polycarbonate) used in 2009 on the results an experiment series with steel pipes was decided to be carried out. Furthermore, previous Japanese studies with seven full scale vent pipes indicated that even a very small de-synchronization among the vent pipe pressure oscillations can reduce the magnitudes of the pool loads [8]. In this report, the results of the PAR experiments with the steel blowdown pipes 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 is introduced in chapter three. The test results are presented and shortly discussed in chapter four. Chapter five summarizes the findings of the experiments.

2 PPOOLEX TEST FACILITY

Condensation studies at LUT started with an open pool test facility (POOLEX) modelling 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 [9]. 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. It is constructed from three plate cylinder segments and two dome segments.

The test facility is able to withstand considerable structural loads caused by rapid condensation of steam. The dry and wet well sections are volumetrically scaled according to the compartment volumes of the Olkiluoto containment (ratio approximately1:320). Inlet plenum for injection of steam penetrates through the side wall of the dry well compartment. The inlet plenum is 2.0 m long and its inner diameter is 214.1 mm. There are several windows for visual observation in both compartments. A DN100 (∅ 114.3 x 2.5 mm) drain pipe with a manual valve is connected to the vessel bottom. A relief valve connection is mounted on the vessel head. The 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. The dry well is thermally insulated. A sketch of the test vessel is shown in Figure 2. Table 1 lists the main dimensions of the test facility compared to the conditions in the Olkiluoto plant.

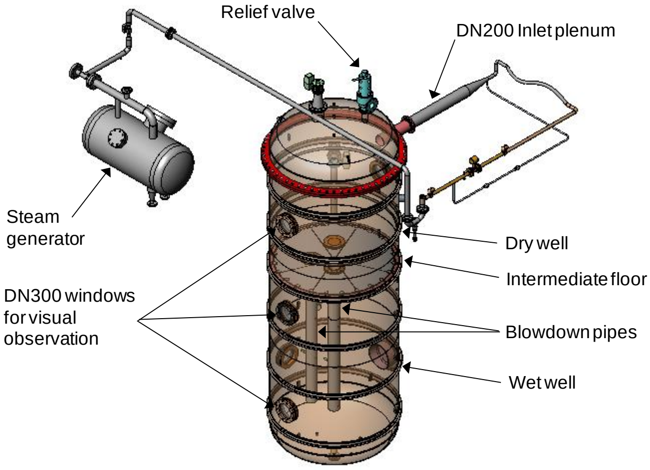

Figure 2. PPOOLEX test vessel.

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

	PPOOLEX test facility	Olkiluoto 1 and 2
Number of blowdown pipes	2	16
Inner diameter of the 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 the suppression pool [m^3]	8.38*	2700
Nominal water level in the suppression pool [m]	2.14*	9.5
Pipes submerged [m]	1.05	6.5
A_{pipes}/A_{pool}x100%	0.8 / 1.6**	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 / two blowdown pipes.

2.2 PIPING

In the plant, there are vacuum breakers between the dry and wet well compartments in order to keep the pressure in wet well in all possible accident situations less than 0.05 MPa above the dry well pressure. In the PPOOLEX facility, the pressure difference between the compartments is controlled via a connection line (Ø 114.3 x 2.5 mm) from the wet well gas space to the dry well. A remotely operated valve in the line can be programmed to open with a desired pressure difference according to test specifications. However, the pressure difference across the 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 [10] test facility, which has a core section of 1 MW heating power and three horizontal steam generators. Steam is led through a thermally insulated steam line, made of sections of standard DN80 (Ø88.9x3.2) and DN50 (Ø60.3x3.9) 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 lab can be used for providing non-condensable gas injection. A schematic illustration of the air and steam line piping is presented in Figure 3.

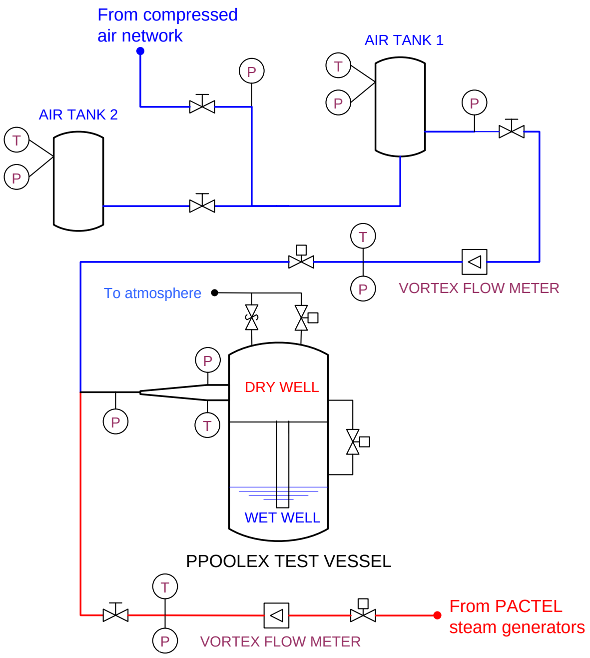

Figure 3. Arrangement of air and steam supply in the PPOOLEX facility.

2.3 BLOWDOWN PIPES

Two DN200 blowdown pipes are positioned inside the pool in a non-axisymmetric location, i.e. pipe 1 is 300 mm and pipe 2 500 mm away from the centre of the condensation pool. The total length of both pipes is 3209 mm. The pipes are made from austenitic stainless steel AISI 304L (Ø219.1x2.5). In the 2009 experiment series with two blowdown pipes, the lower ends of the pipes were made of polycarbonate. There is a huge difference between the two materials, for example, in thermal conductivity. Table 2 compares the properties of Esalux® polycarbonate (PC) and stainless steel (SS) AISI 304L.

Table 2. Physical, mechanical and thermal properties of PC and SS AISI 304L [11, 12, 13].

Physical properties	PC	SS AISI 304L
Density, ρ [kg/m^3]	1 200	7 900
Mechanical properties		
Surface roughness (average), R_a [µm]	0.3[1]	1.4[1]
Thermal properties		
Linear thermal expansion coefficient, α [1/K]	$68{\cdot}10^{-6}$	$16{\cdot}10^{-6}$
Specific heat capacity, c_p [kJ/kg/K]	1.2	0.50
Thermal conductivity, k [W/mK]	0.20	50
Melting temperature, T_m [°C]	166	1 450

[1] Measured by Mitutoyo SJ-201 surface roughness tester.

2.4 MEASUREMENT INSTRUMENTATION

Investigation of the steam/gas injection phenomenon requires high-grade measuring techniques. For example, to estimate the loads on pool structures by condensation pressure oscillations the frequency and amplitude of the oscillations have to be measured. Experience on the use of suitable instrumentation and visualization equipment was achieved already during the preceding research projects dealing with condensation pool issues.

The applied instrumentation depends on the experiments in question. Normally, the test facility is equipped with several thermocouples (T) for measuring steam, pool water and structure temperatures and with pressure transducers (P) for observing pressures in the dry well, inside the blowdown pipes, at the condensation pool bottom and in the gas phase of the wet well. Steam flow rate is measured with a vortex flow meter (F) in the steam line. Additional instrumentation includes, for example, strain gauges (S) on the pool outer wall and valve position sensors.

A list of different types of measurements of the PPOOLEX facility during the PAR experiments is presented in Table 3. The figures in Appendix 1 show the exact locations of the measurements and the table in Appendix 1 lists their identification codes and error estimations. The error estimations are calculated on the basis of variance analysis. The results agree with normal distributed data with 95 % confidence interval.

Table 3. Instrumentation of the PPOOLEX test facility.

Quantity measured		No.	Range	Accuracy
Pressure	Dry well	1	0–6 bar	0.06 bar
	Wet well	3	0–10/0–20 bar	0.5/0.7 bar
	Blowdown pipe 1	3	0–20 bar	0.7 bar
	Blowdown pipe 2	1	0-10 bar	0.5 bar
	Inlet plenum	1	0–6 bar	0.06 bar
	Steam line	1	1–51 bar	0.5 bar
Temperature	Dry well	5	-40–200 °C	±3.2 °C
	Wet well gas space	3	0–250 °C	±2.0 °C
	Wet well water volume	31	0–250 °C	±2.0 °C
	Blowdown pipe 1	10	0–250 °C	±2.0 °C
	Blowdown pipe 2	6	0–250 °C	±2.0 °C
	Inlet plenum	1	-40–200 °C	±3.2 °C
	Steam line	2	0–400 °C	±3.6 °C
	Structures	7	0–200 °C	±2.6 °C
Mass flow rate	Steam line	1	0–285 l/s	±4.9 l/s
Steam fraction in the dry well		1	0-100 %	N/A
Water level in the 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 bottom		1	N/A	N/A
Vertical acceleration of the pool bottom		1	N/A	N/A
Sonic speed		2	N/A	N/A

2.5 CCTV SYSTEM

In the PAR experiment series, standard video cameras, digital videocassette recorders and a quad processor were used for visual observation of the test vessel interior. With a digital colour quad processor it is possible to divide the TV screen into four parts and look at the view of four cameras on the same screen.

For more accurate observation of air/steam bubbles at the blowdown pipe outlet, a Casio Exilim EX-F1 digital camera [14] was used. The camera is capable of recording high-speed videos. The high-speed recordings are at first stored to the Secure Digital (SD) memory card in the camera in the QuickTime (.MOV) file format. From there they can be transferred to the PC hard disk via USB-cable. The camera is furnished with 2 GB SD memory card. The camera can achieve 1 200 frames/second (fps) recording speed with available 336x96 pixels resolution. During the experiments a recording speed of 300 fps with available resolution of 512x384 was used.

2.6 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 gauge measurements. The maximum recording capacity depends on the number of measurements and is in the region of three hundred thousand samples per second. Measurement software is LabView 8.6, Figure 4. The data acquisition system is discussed in more detail in reference [15].

Self-made software running in the National Instruments FieldPoint measurement system 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 with conversion software.

The used measurement frequency of LabView was 2 kHz. For the temperature measurements the recording frequency was 20 Hz. The temperature measurements are therefore averaged over 100 measured points. The rest of the measurements (for example temperature, pressure and flow rate in the steam line) were recorded by the self-made software with the frequency of 0.67 Hz.

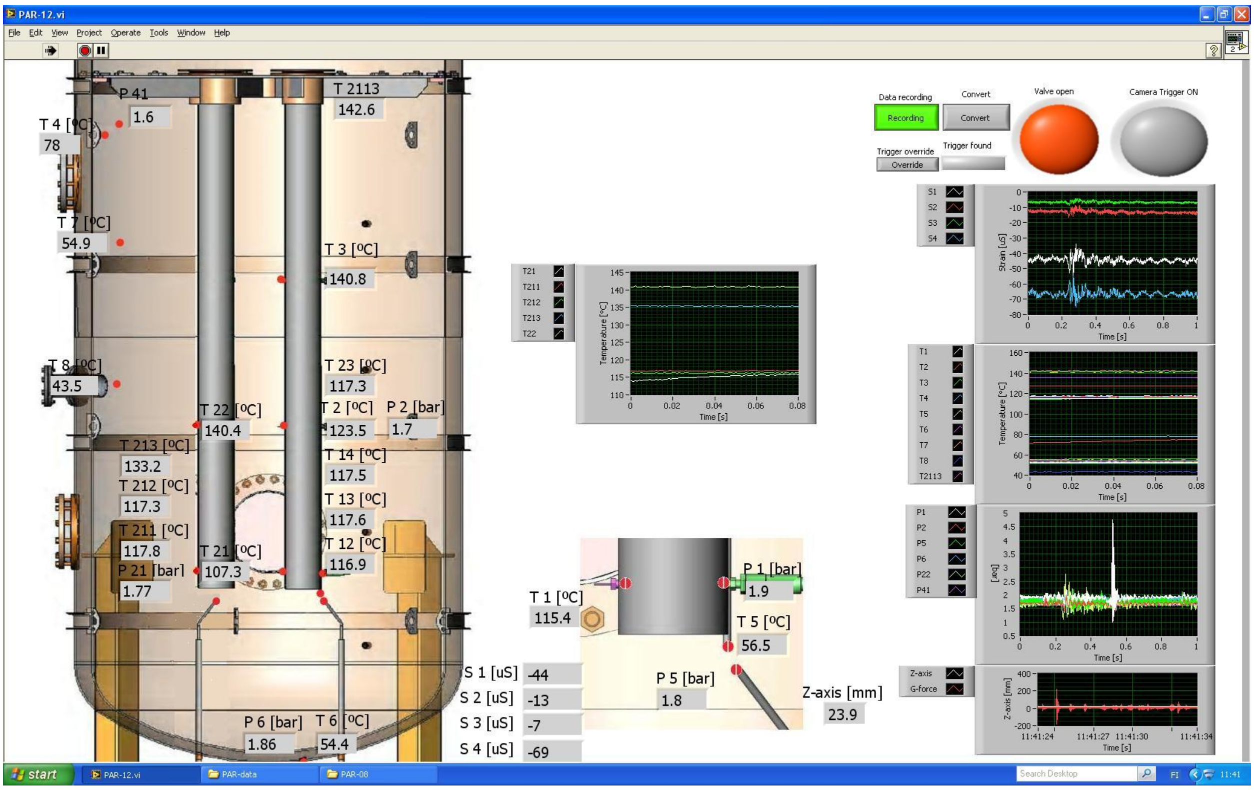

Figure 4. Monitoring of PAR experiment with LabView 8.6 software.

3 TEST PROGRAM FOR TWO PIPE EXPERIMENTS

The test program in November – December 2010 consisted of seven experiments (labeled from PAR-07 to PAR-13) with two steel blowdown pipes. The main purpose of the PAR test series was to study chugging phenomena while steam is discharged into the condensation pool filled with sub-cooled water through two parallel DN200 blowdown pipes.

Before the experiments the condensation pool was filled with isothermal water at 20 °C to the level of ~ 2.14 m i.e. the blowdown pipe outlets were submerged by 1.05 m except in PAR-08 where the initial pool water temperature and level were 50 °C and 2.22 m, respectively. The used initial air/water distribution of the test facility corresponds roughly to the scaled gas and liquid volumes in the containment of the reference plant.

Steam generators of the nearby PACTEL facility acted as a steam source. Considerably high pressure levels were used in order to utilize the heat stored in the structures of the steam generators for the production of extra steam. The initial pressure of the steam source varied from 0.6 MPa to 2.5 MPa.

All the experiments except PAR-08 were started with unheated dry well structures. In PAR-08, the structures were warm because that experiment was done after the PAR-07 experiment on the same day. Only a short ventilation of the test vessel with compressed air to dry the wall surfaces and to clear the viewing windows was done between the experiments.

Control of the steam flow rate was done remotely from the control room of the laboratory with the help of the valve guide system installed before the experiment series. Fully-automatic control using pre-set values was tested in a couple of experiments but due to too heavy flow rate oscillations semi-automatic control was used during the rest of the series.

Initially, the dry well compartment of the test vessel was filled with air at atmospheric pressure. After the correct initial pressure level in the steam generators had been reached the remote-controlled shut-off valve in the steam line was opened. As a result, the dry well compartment was filled with steam that mixed there with the initial air content. Pressure build-up in the dry well then pushed water in the two blowdown pipes downwards and after a while the pipes cleared and flow into the wet well compartment began. First, the flow was almost pure air and condensation at the pipe outlet was very light. As the fraction of steam among the flow increased the condensation phenomenon intensified. Chugging region of the condensation mode map was reached when the flow had decreased enough to let the steam/water interface periodically enter the blowdown pipe.

Typically the experiments with two blowdown pipes lasted for 800-1100 seconds. After that the pool water temperature had risen so much that continuation of the steam discharge would have threatened the durability of the measurement instrumentation.

Table 4 shows the main parameters of the PAR-07 – PAR-13 experiments. In PAR-07, PAR-08 and PAR-09 some problems with the desired recording frequency of measurement data was encountered and therefore the results of those three experiments are partly inadequate. They are used in the analysis presented in the next chapter only in a limited way.

Table 4. Initial parameter values of the PAR experiments in 2010.

Experiment	Steam source pressure [MPa]	Initial pool water level [m]	Initial pool water temperature [°C]	Comment
PAR-07	0.6	2.14	20	Reduced data recording frequency
PAR-08	2.0	2.22	50	Reduced data recording frequency Pre-heated dry well structures
PAR-09	1.5	2.14	20	Reduced data recording frequency Error on P1 signal, T5 came loose
PAR-10	1.5	2.14	20	
PAR-11	1.5	2.14	20	
PAR-12	2.0	2.14	20	
PAR-13	2.5	2.15	20	

4 ANALYSIS OF THE EXPERIMENTS

The following chapters give a more detailed description of the experiment program with the two blowdown pipes, present the observed phenomena and evaluate the loads experienced by the pool structures.

Table 5 summarizes the values of the main measured parameters of the PAR experiments in 2010.

Table 5. Main parameters during PAR experiments.

Test	Steam flow[2] [g/s]	Steam temperature[3] [°C]	Initial pool level [m]	Δp_{max} in blowdown pipe 1[4] [kPa]	Δp_{max} in blowdown pipe 2[5] [kPa]	Δp_{max} in pool[6] [kPa]	Δp_{max} at pool bottom[7] [kPa]	$\Delta \varepsilon_{max}$[8] [µS]	Pool vertical $a_{max.}$ [m/s^2]	Pool vertical Δs_{max} [mm]
PAR-07[9]	580…230	148…160	2.14	990 (P1) 190 (P2)	420	240 (P5)	70	60	370	5.0
PAR-08[9]	1320…350	204…193	2.22	390 70	200	210	50	40	170	1.7
PAR-09[9]	1450…400	185…165	2.14	1230 190	790	260	100	90	400	5.0
PAR-10	1220…250	185…170	2.14	2500 710	1620	570	150	80	400	4.8
PAR-11	1300…650	185…160	2.14	2600 770	1630	480	150	70	400	4.8
PAR-12	1800…360	200…175	2.14	2070 490	1040	770	140	80	310	3.8
PAR-13	2350…220	207…182	2.15	1900 900	1630	520	180	60	310	3.8

4.1 CHUGGING WITH TWO BLOWDOWN PIPES

The steam mass flow rate into the test vessel in these parallel blowdown pipe experiments ranged from 220 g/s to over 2350 g/s and the temperature of incoming steam from 148 °C to 207 °C.

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[2] Steam mass flow rate was calculated on the basis of volumetric flow rate (measured by F2100) and density of steam, which was determined on the basis of the steam pressure measurement (measured by P2100) by assuming saturated steam flow.
[3] Measured by thermocouple T2102 at the steam line flow meter.
[4] Measured by pressure transducers P1 and P2.
[5] Measured by pressure transducer P21 (the measurement range of the transducer exceeded in PAR10, PAR-11 and PAR-13).
[6] Measured by pressure transducer P5.
[7] Measured by pressure transducer P6.
[8] Measured by strain gauge S4.
[9] Due to the reduced recording frequency the measured pressures, strains, acceleration and movement are not directly comparable to those in the other experiments.

The highest measured flow rate values were instantaneous and registered right at the beginning of the blowdown. The maximum possible flow was limited by the critical flow criterion in the steam line valve. As the pressure of the steam source, the PACTEL steam generators, decreased, the flow rate dropped accordingly. Depending on the initial pressure level of the steam generators and on the position of the remotely controlled valve in the steam line the maximum constant flow rate that could be maintained for several minutes was in the range of 600-800 g/s (see Figure 5).

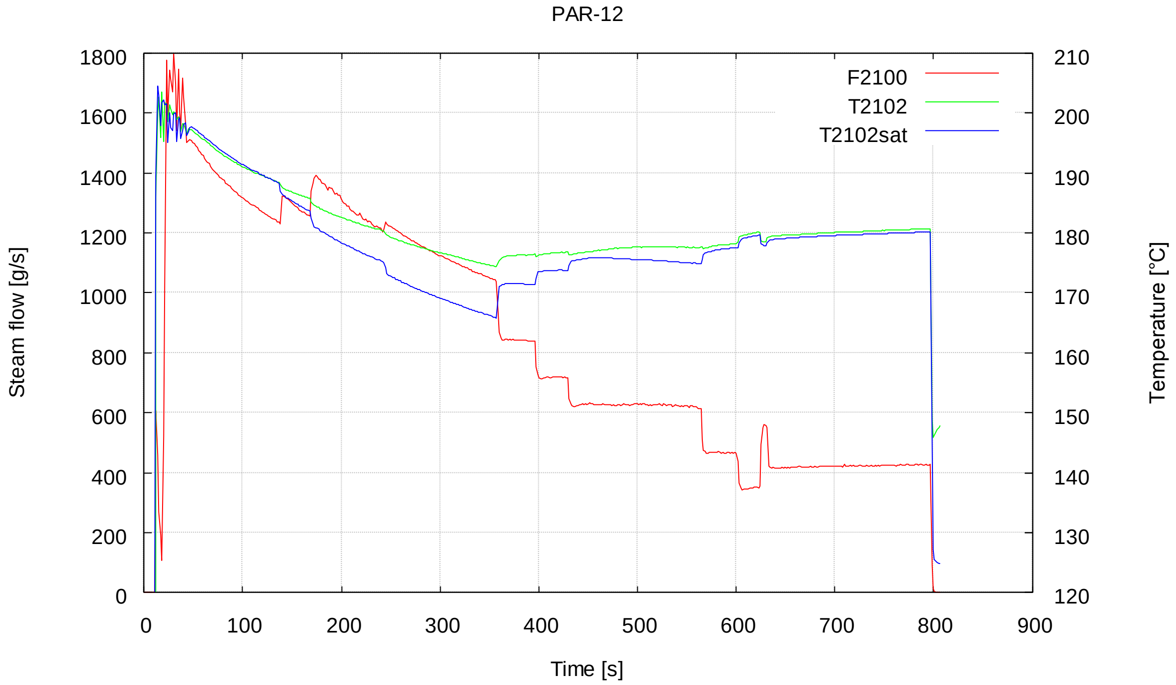

Figure 5. Flow rate (F2100) and temperature (T2102) of incoming steam in PAR-12. T2102sat is the saturated steam temperature at the flow meter.

In the beginning of the experiments the flow in the blowdown pipe was a mixture of non-condensable gas and steam because the dry well compartment was initially filled with air. Usually somewhere between 100 and 200 seconds into the experiments the steam fraction in the dry well reached 98-99 % according to the moisture meter installed there. From that moment on the flow through the blowdown pipe into the wet well pool was almost pure steam.

Assuming that the flow from the dry well to the wet well divided equally between the two blowdown pipes it can be concluded that the maximum achievable constant steam mass flux in each pipe was somewhere between 8 and 11 kg/m^{2}s (corresponding to 600-800 g/s). According to the condensation mode map of Lahey and Moody this mass flux is in the chugging region if the pool water temperature is above 30 °C. This was true in many of the experiments since the used high steam flow rates increased the pool water temperature considerably from the initial value of 20 °C already in a couple of hundred seconds so that when the pure steam discharge period began the flow mode was already on the chugging region of the map. The steam production capacity of the PACTEL facility was not, however, large enough for chugging to occur with two pipes in a pool water below 25 °C. The PAR-07 experiment, where the steam mass flux was only 5.5 kg/m^{2}s, belongs to the “steam condensation within vents or blowdown pipes” region on the map for the whole duration of the experiment. Most of the experiments clearly stretch to the overlapping “transition” region as the pool water temperature exceeds 45-50 °C. Figure 6 presents the PAR-07 – PAR-13 experiments placed on the condensation mode map of Lahey and Moody on the basis of the steam mass flux in each pipe and the pool bulk temperature.

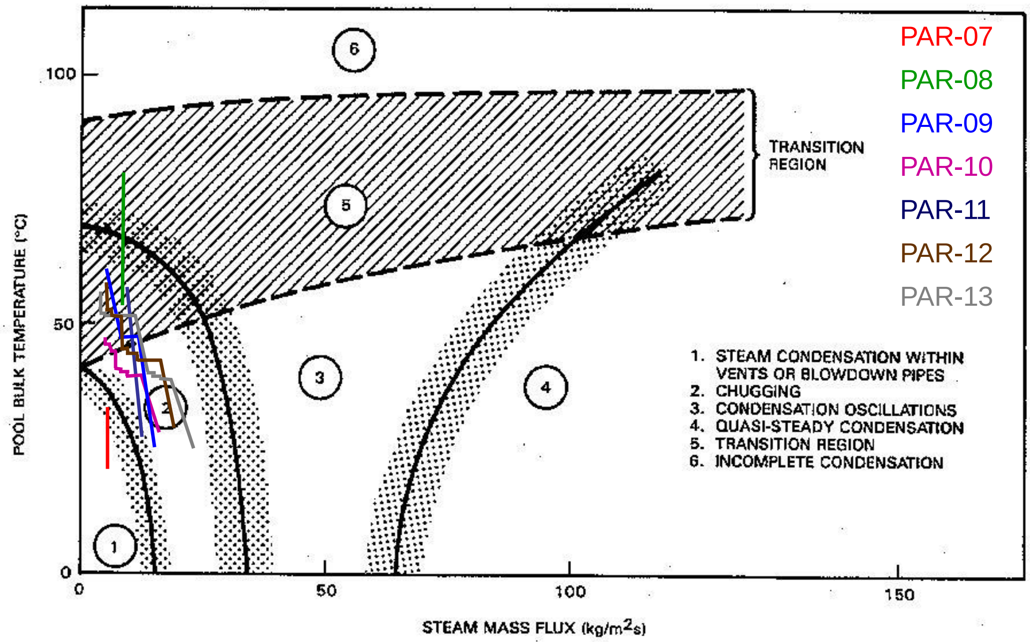

Figure 6. Experiments from PAR-07 to PAR-13 represented as lines of decreasing steam mass flux and increasing pool temperature on the condensation mode map of Lahey and Moody.

Figure 7 and Figure 8 present a few measured temperatures inside the two blowdown pipes in PAR-12. One can see that the strong oscillating behavior of the steam/water interface indicating chugging starts soon after the hundred second mark has passed. As the steam flow rate decreases and the pool water temperature rises towards the end of the experiment the chugging phenomenon calms down and more and more of the condensation happens inside the blowdown pipe without large steam bubbles forming at the pipe outlet. The movement of the steam/water interface is also less intense and the measurements further up inside the pipes register temperature oscillations every now and then.

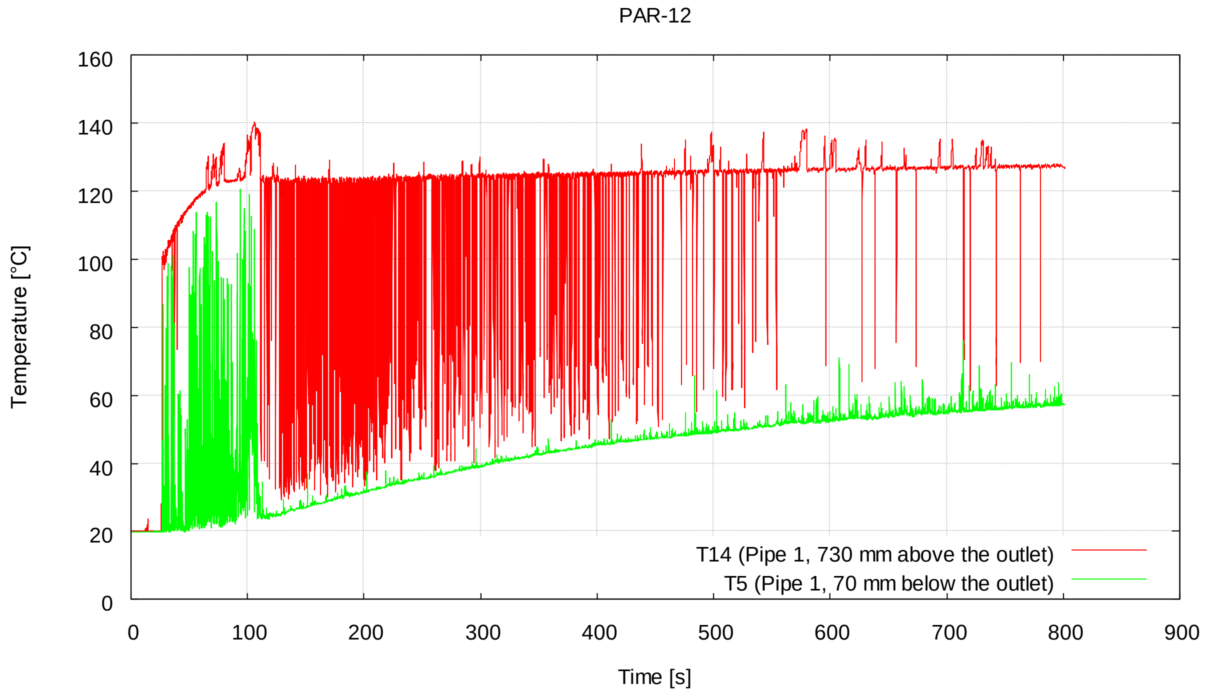

Figure 7. Temperatures inside (T14) and below the outlet (T5) of blowdown pipe 1 in PAR-12.

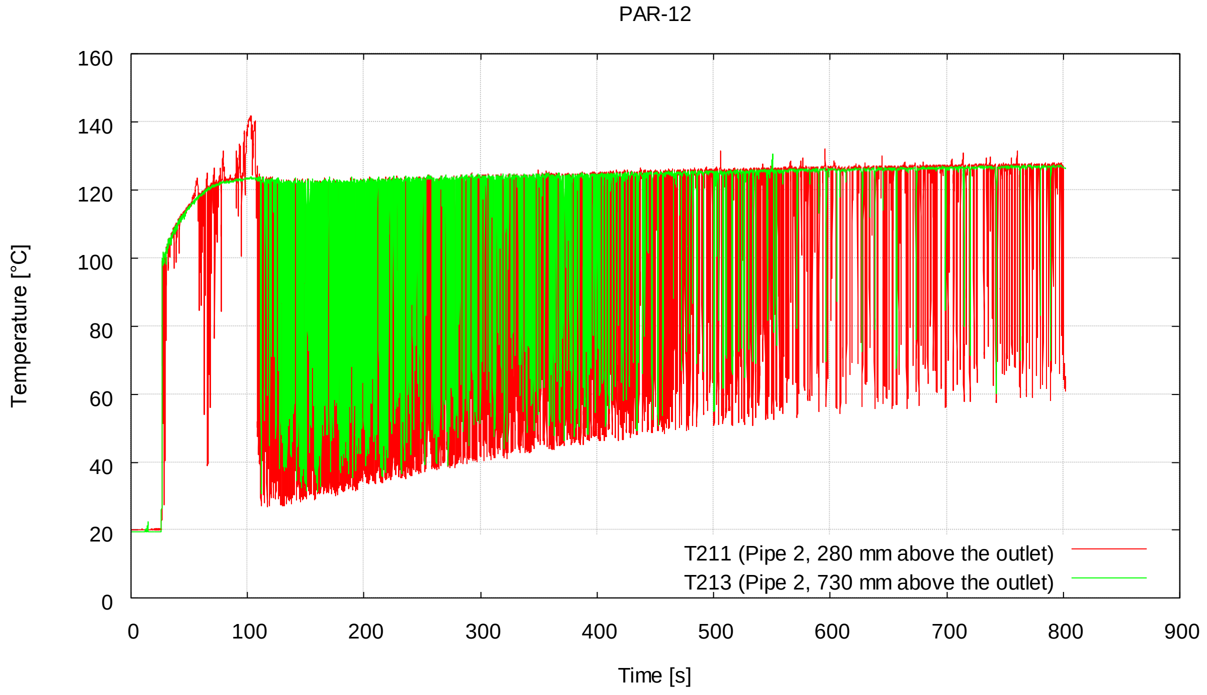

Figure 8. Temperatures inside blowdown pipe 2 at two different elevations in PAR-12.

During the most intensified chugging periods of the experiments underpressure sucked water high into the pipes after the collapse of large steam bubbles at the outlets of the pipes. From Figure 9 it can be seen that water ingress back into the blowdown pipes, for example in PAR-11, occasionally reached even thermocouple T23 in pipe 1 on the elevation of 1180 mm above the pipe outlet. There was no indication of steam/water interface movement on the highest measured elevation of pipe 1 (T3 at 1855 mm). Figure 10 presents the same time period from PAR-11 for blowdown pipe 2. The highest temperature measurement in pipe 2 is on the elevation of 955 mm

(T22). It indicates that the steam/water interface reached that far during the same cycles as in pipe 1. Temperature measurement T5, 70 mm below blowdown pipe 1, showed pool bulk temperature throughout the intense chugging period.

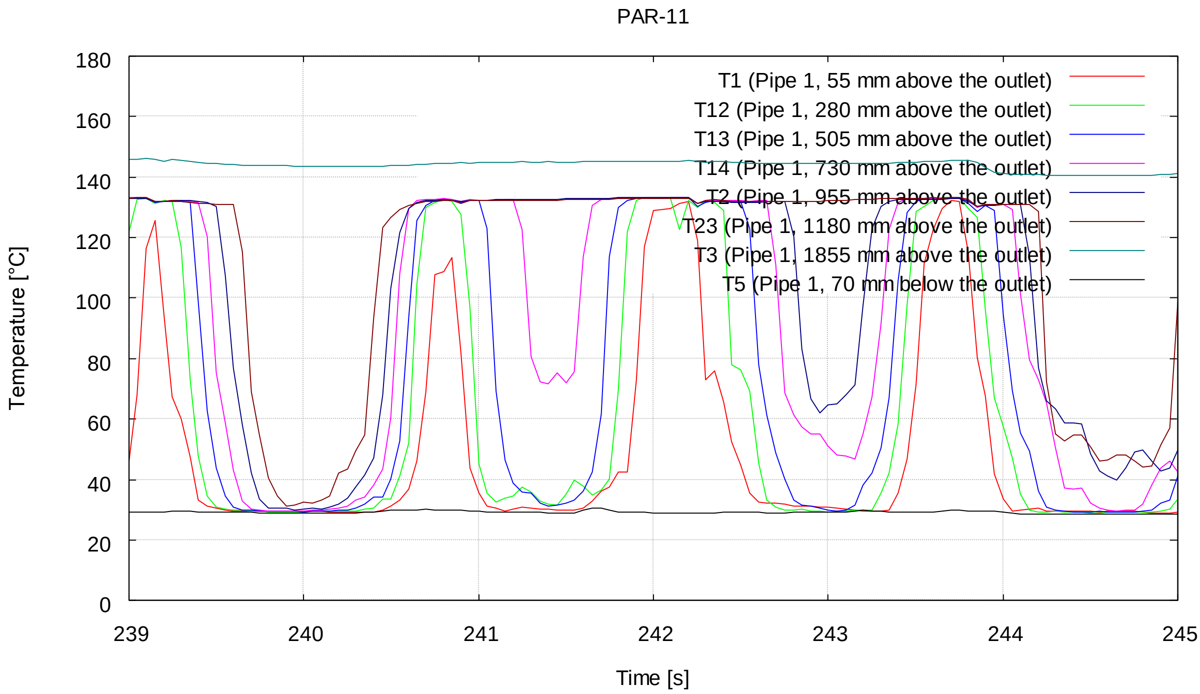

Figure 9. Temperatures inside (T1, T12, T13, T14, T2, T23, T3) and at the outlet (T5) of blowdown pipe 1 in PAR-11 during the most intensified chugging period.

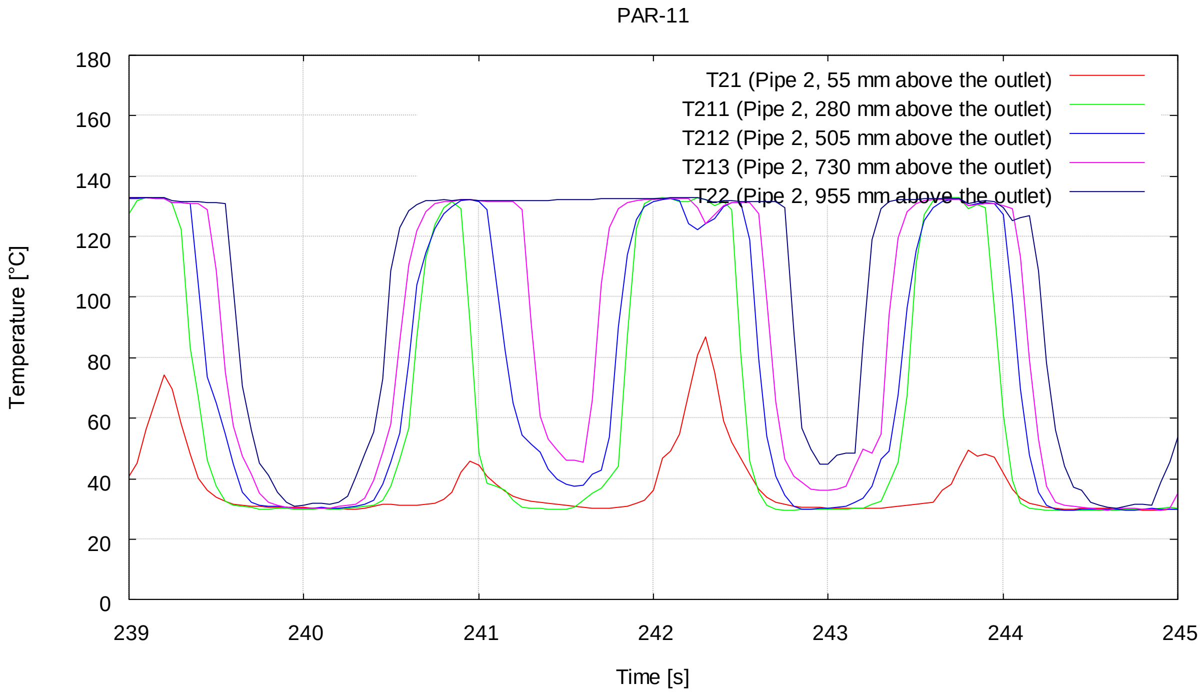

Figure 10. Temperatures inside (T21, T211, T212, T213, T22) blowdown pipe 2 in PAR-11 during the most intensified chugging period.

4.2 LOADS CAUSED BY PRESSURE OSCILLATIONS

Chugging caused dynamic loads to the pool structures in the PAR experiment series. High pressure pulses were measured inside the blowdown pipes and in the pool during the most intensified chugging period.

The highest pressure spikes inside blowdown pipe 1 were found from PAR-10 and PAR-11 and they were in the range of 2.5-2.6 MPa. The spikes were registered by P1, which is 55 mm upwards from the pipe outlet. Transducer P2, 955 mm above the pipe outlet, registered pressure spikes in the range of 710-770 kPa at maximum in PAR-10 and PAR-11. The highest spikes on the elevation of P2 did not always occur at the same time as those on the elevation of P1.

In blowdown pipe 2, the highest pressure pulses exceeded the measuring range of the transducer (P21) and therefore no definitive comparison between pipe 1 and 2 regarding the maximum measured pressures inside the pipes can be done. In those cases, where the measured pressure spikes were below the upper limit of the transducer, it seems however that in pipe 2 the spikes were lower than in pipe 1.

The highest pressure loads below blowdown pipe 1, measured by transducer P5, were between 480-770 kPa. The highest value was found from PAR-12 in the beginning of the pure steam discharge phase when the pool water was still quite cold.

When the pressure waves reached the pool bottom they had damped considerably. Spikes registered by transducer P6 were only in the range of 140-180 kPa, almost an order of magnitude lower than those measured below blowdown pipe 1. Figure 11 presents the measured pressures in the pool (P5 and P6) from PAR-12.

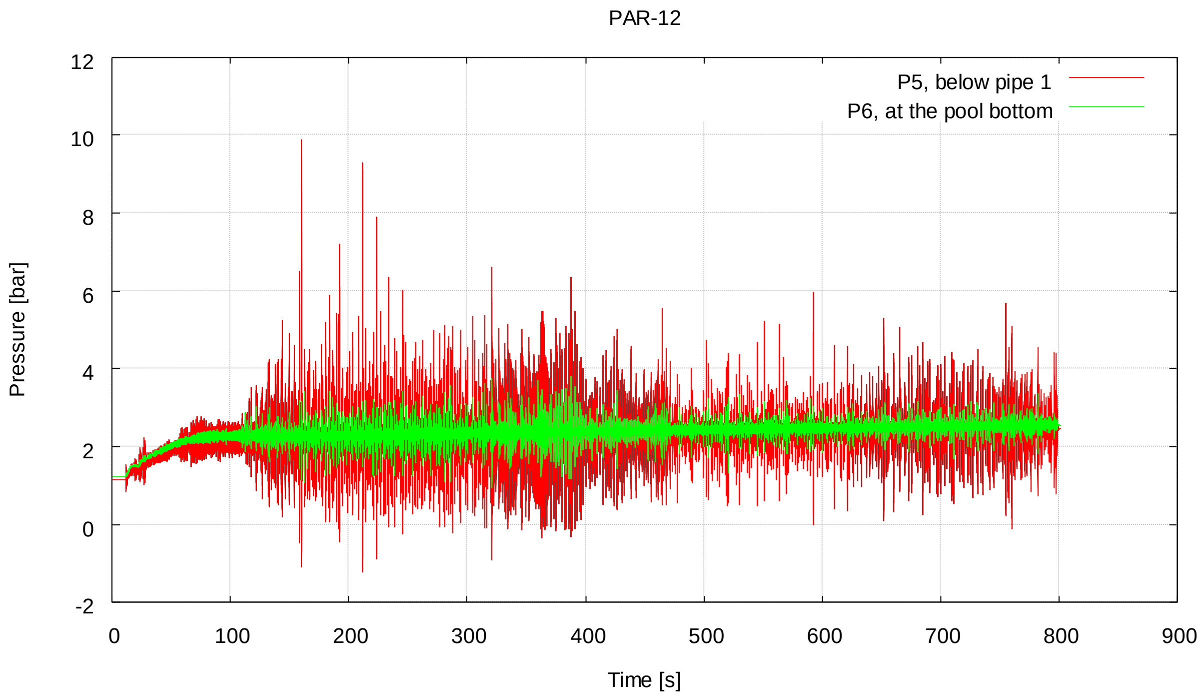

Figure 11. Pressure below blowdown pipe 1 (P5) and at the pool bottom (P6) in PAR-12.

The highest amplitude of sudden changes in the measured strains due to rapid condensation processes was below 100 µS. This is less than the overall change in the measured strains caused by the increase of the test vessel pressure during the whole duration of the experiments.

The maximum instantaneous vertical acceleration and movement of the test vessel were about 400 m/s^2 and 5 mm, respectively. The highest values were usually measured when the experiments had proceeded to the overlapping chugging and transition region.

4.3 SYNCHRONISM OF TWO PARALLEL BLOWDOWN PIPES

The upper ends of the two parallel blowdown pipes of the PPOOLEX facility are only 581 mm from each other in the dry well. There are no internal structures in the dry well to prevent the pressure differences between the pipes from balancing out. The blowdown pipes are therefore very much coupled and the conditions should be ideal for the two pipes to be synchronal.

Pressure increase in the dry well compartment pushes the steam/water interface downwards in both blowdown pipes and a steam bubble is formed at the outlet of each pipe. After the bubbles collapse, water surges back into the pipes and a new cycle starts. From Figure 9 and Figure 10 one can see that during these cycles the steam/water interface moves up and down at the same time in both pipes.

However, by examining the high speed video recording from the outlet elevation of the pipes in detail one can see that the formation, and particularly the collapse, of the parallel bubbles does not always happen synchronously. This can be verified with the help of the recorded pressure measurements close to the lower ends of the pipes. By plotting the curves in a millisecond scale one can first see the development of an underpressure due to rapid condensation and then the individual pressure pulses (and their periodic oscillations) associated with the collapse of the parallel steam bubbles (Figure 12).

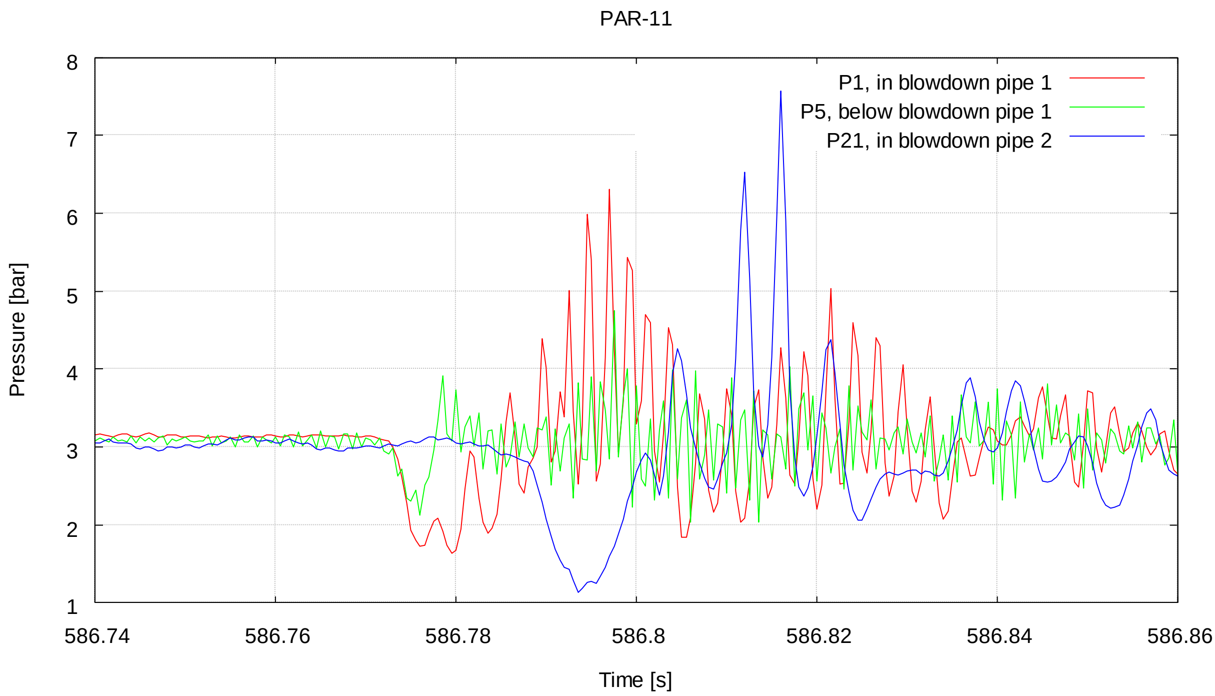

Figure 12. Pressure pulses caused by the non-synchronous collapse of parallel steam bubbles at the outlets of the two blowdown pipes in PAR-11.

Figure 13 shows a photograph series (captured from the high speed recording of the Casio Exilim EX-F1 digital camera) from PAR-11 of the development and collapse of parallel steam bubbles at the outlets of the two blowdown pipes. The photo series is of the bubbles causing the pressure pulses in the curves of Figure 12.

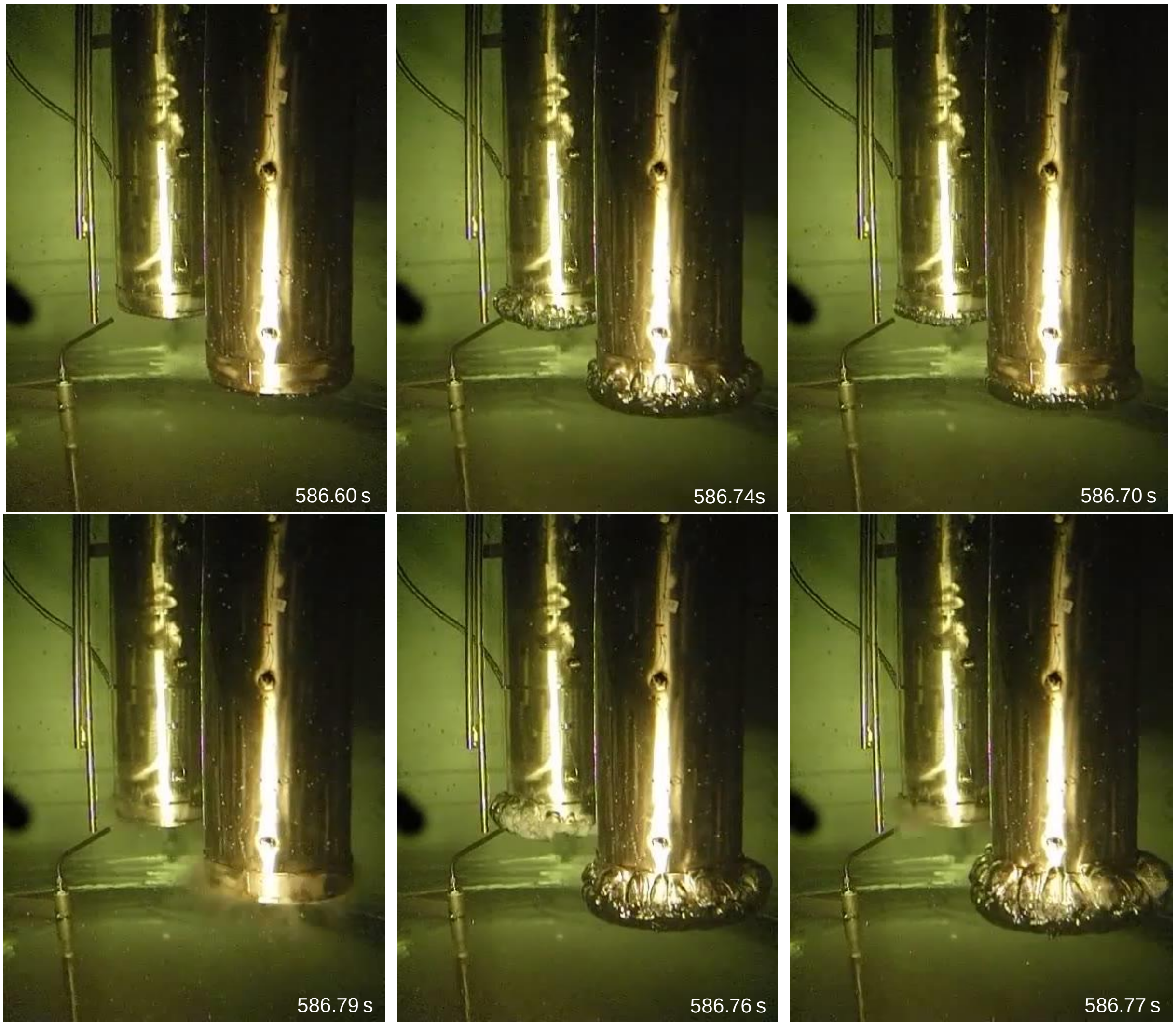

Figure 13. Non-synchronous collapse of steam bubbles at the outlets of the two blowdown pipes in PAR-11.

There is no clear pattern in which pipe the steam bubble first starts to collapse. Several successive bubbles can collapse first, for example, in pipe 1 but then the order can change for a single or several cycles. The time difference between the first pressure spikes of the parallel collapsing bubbles can range from 10 to even 70 milliseconds. This means that there can be over ten periodic oscillation spikes in one pipe before the first spike appears in the other pipe. The oscillations can even die away in the first pipe before they appear in the other as is the case in Figure 14.

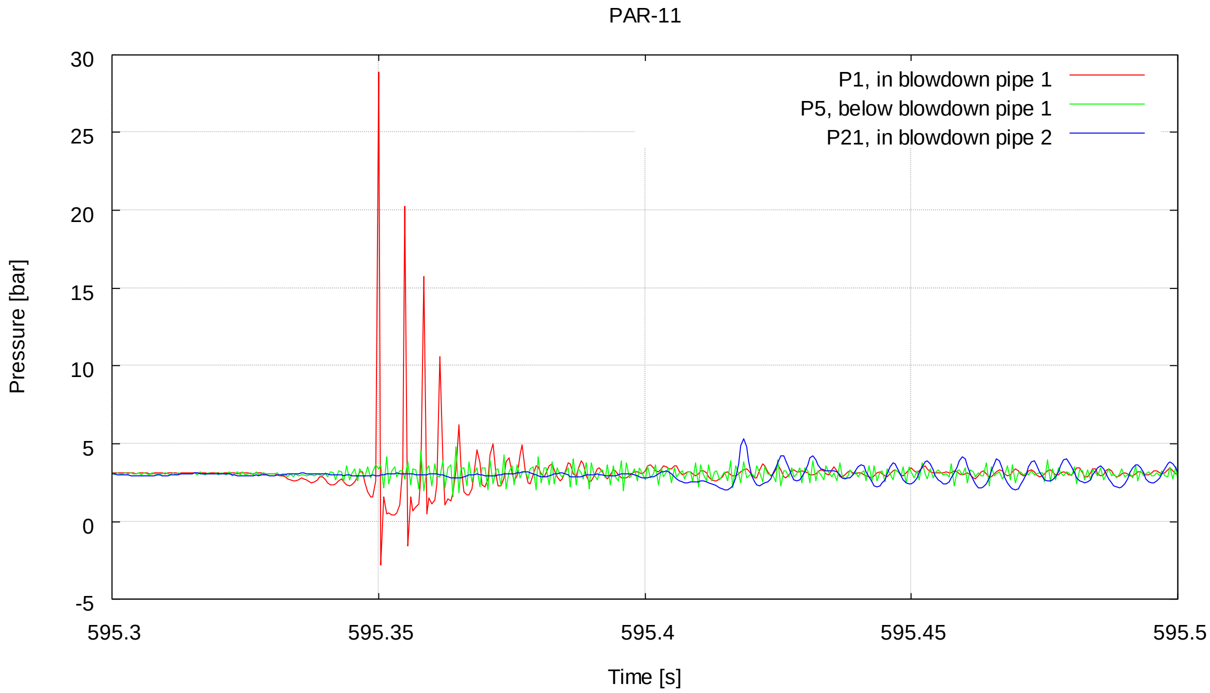

Figure 14. Pressure spikes and their periodic oscillations caused by a non-synchronous collapse of parallel steam bubbles at the outlets of the two blowdown pipes in PAR-10.

4.4 COMPARISON TO EXPERIMENTS WITH TWO TRANSPARENT BLOWDOWN PIPES

Regarding the comparability of the PAR series in 2009 (PAR-01 – PAR-06) with the transparent PC blowdown pipes to the PAR series in 2010 (PAR-07 – PAR-13) with the steel pipes one can find few time periods from the experiments where the test parameters and conditions were close to each other. The most suitable pair for comparison is probably the pair of PAR-04 and PAR-11. The steam flow rate into the test vessel, steam temperature, pool water temperature and test vessel pressure are almost equal if one selects a time interval around 415 seconds from PAR-4 and around 665 seconds from PAR-11. The decreasing trend of steam mass flow rate is slightly faster in PAR-04 than in PAR-11.

Figure 15 and Figure 16 present the steam mass flow rate, steam temperature and pool water temperature from the selected period in PAR-04 and PAR-11, respectively. The test vessel pressure was about 0.3 MPa in both experiments during that time.

The steam mass flow rate of 650 g/s corresponds to a mass flux of about 9 kg/m^{2}s in one blowdown pipe if the flow is assumed to divide equally between the two pipes. Because the pool water temperature is about 50 ºC it means that the flow mode in question is just on the overlapping chugging and transition region.

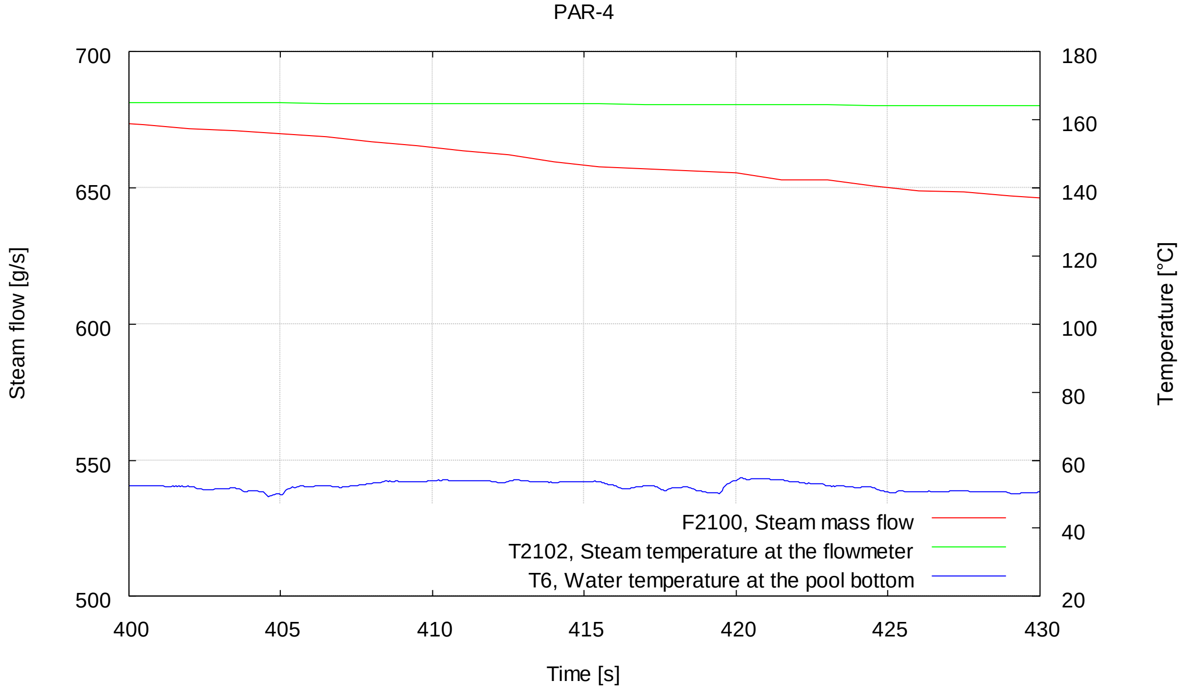

Figure 15. Steam flow rate, steam temperature and pool water temperature in PAR-04 in the selected time period for comparison between the experiments with PC and steel blowdown pipes.

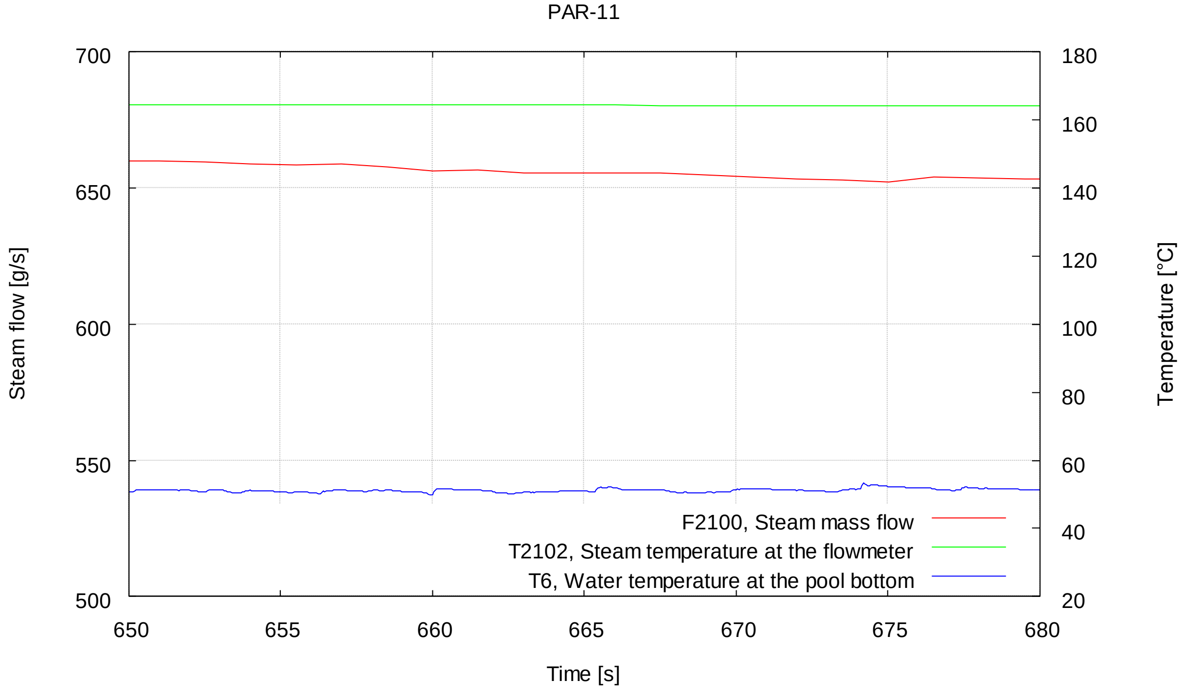

Figure 16. Steam flow rate, steam temperature and pool water temperature in PAR-11 in the selected time period for comparison between the experiments with PC and steel blowdown pipes.

Figure 17 and Figure 18 show the measured pressure curves inside and at the outlet of the blowdown pipes plotted with the same scale on the y-axis from the middle of the selected comparison periods in PAR-04 and PAR-11, respectively. One can see the huge difference between the measured pressure curves in PAR-04 and PAR-11. The amplitude of the pressure pulses caused by water hammer after a rapid condensation and collapse of steam bubbles at the pipe outlet (or a steam volume inside the pipe) is considerably larger in PAR-11 than in PAR-04.

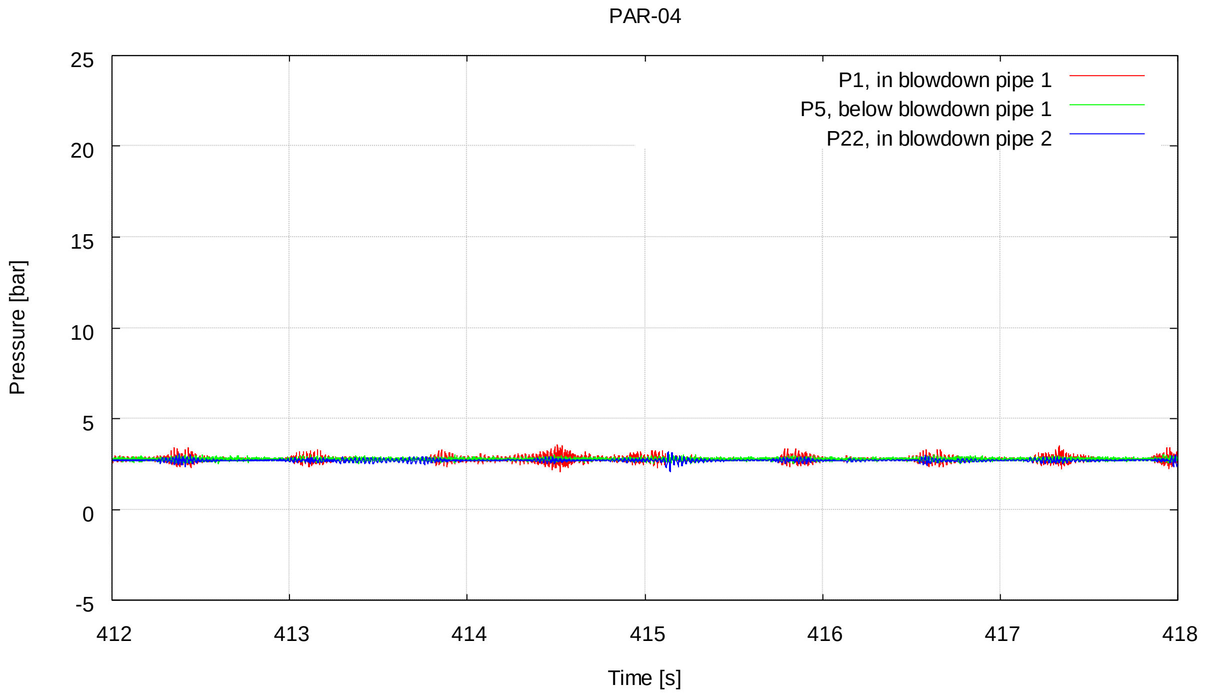

Figure 17. Pressure inside blowdown pipe 1 and 2 and at the outlet of pipe 1 during a six seconds interval in the middle of the comparison period in PAR-04.

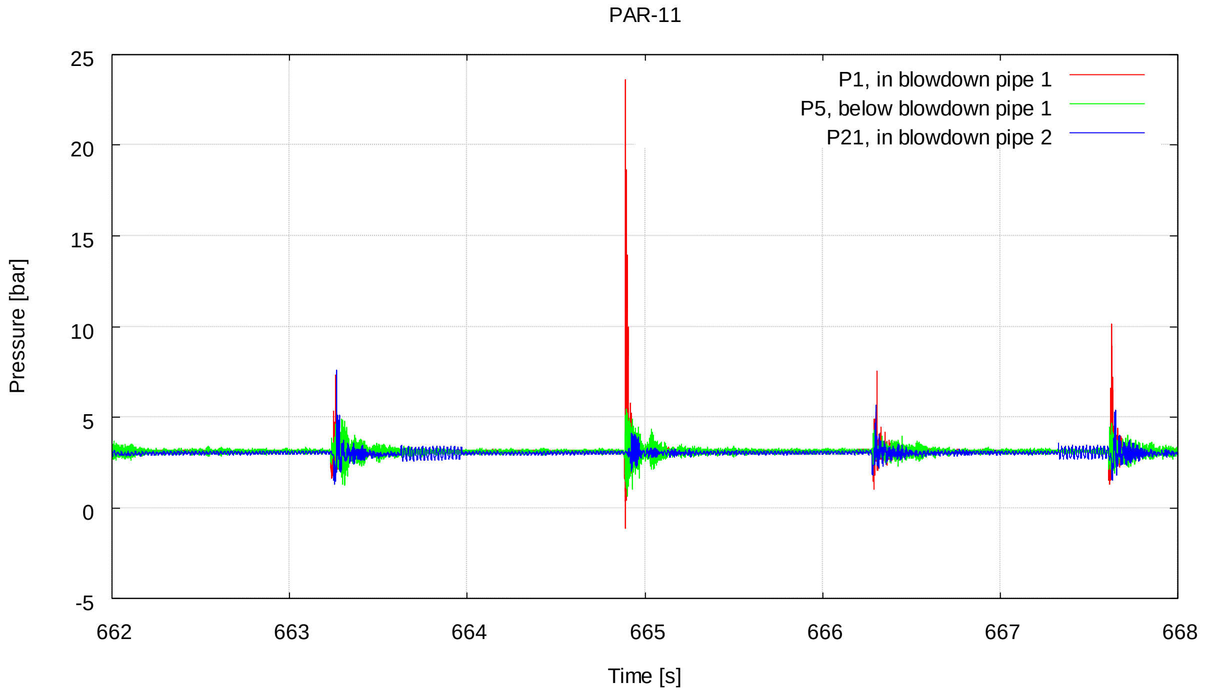

Figure 18. Pressure inside blowdown pipe 1 and 2 and at the outlet of pipe 1 during a six seconds interval in the middle of the comparison period in PAR-11.

Although the test conditions are almost equal it seems like the flow modes are different in these two cases. This could be actually true. In PAR-04, the frequency of the events that induce the oscillation surges is almost double but the amplitude of the highest oscillation peaks only a fraction of that in PAR-11. The high peaks present inside (and at the outlet of) the blowdown pipes in PAR-11 are totally missing in PAR-04. The high pressure spikes in PAR-11 are caused by rapid condensation and collapse of the steam volume inside the pipe and related to water hammer effects. In PAR-04, condensation occurs more or less at the pipe outlet and each condensation event involves a smaller steam volume than in PAR-11. The reason why there is not much condensation happening inside the pipes in PAR-04 could be found from the pipe material. Polycarbonate, used in the series with the transparent blowdown pipes, has over an order of magnitude smaller heat conductivity (see Table 2) than stainless steel. Due to minimal heat conduction through the polycarbonate pipe wall condensation tends to happen at the pipe outlet and therefore the flow mode changes from that experienced in PAR-11.

By comparing the peak values of the pressure loads inside the pipes from the whole duration of the experiment (listed in Table 5) to the peak values registered during the series with the transparent pipes [6] one can see that they are about four times higher. This further supports the assumption that the pipe material has had an effect on the condensation phenomena inside the blowdown pipes during the whole PAR series with the polycarbonate pipes in 2009.

On the other hand there is no big difference between the measured maximum pressure loads on the pool bottom, strains on the outer wall and vertical acceleration and movement of the test vessel in PAR-04 and PAR-11. The peak values are all in the same range. The used blowdown pipe material does not have much effect on phenomena occurring in the wet well pool. Those phenomena depend more on the test conditions in the water pool itself (coolant temperature and level, pressure, fraction of non-condensables). The events inside the blowdown pipe are in some respect local and their influence is not so strong in the water pool.

4.5 COMPARISON TO EARLIER SINGLE PIPE EXPERIMENTS

Several experiment series concentrating on different aspects of condensation related phenomena in a suppression pool have been carried out with a single DN200 steel blowdown pipe during the CONDEX and preceding POOLEX research projects. On many occasions high pressure loads have been measured inside and at the outlet of the blowdown pipe. Many of these cases have been with cold pool water, 20 ºC and even below that. With a single pipe a larger area of the condensation mode map regarding the achievable steam mass flux can be covered in the experiments with the PPOOLEX facility. Furthermore, the pool water temperature does not increase as fast with one pipe as it does with two pipes since the desired flow mode is achieved with a smaller flow rate in one pipe. High initial flow rates used in the two pipe experiments increase the pool water temperature considerably even before the pure steam discharge period starts. Comparison at pool water temperature levels of 20-35 ºC between the one and two pipe experiments is therefore impossible due to the lack of two pipe data in that temperature range. However, some recorded data from the single pipe experiments covers also those pool water temperatures that were dominant in the PAR series in 2010. For example, the reference experiment COL-02 with a straight steel pipe from the series, where the effect of a collar outlet design of the blowdown pipe was investigated, partly covers the same pool temperature and steam mass flux range as PAR-12. The temperature of incoming steam is higher and the test vessel pressure slightly smaller in PAR-12. These differences in the conditions should not affect the results too much. The data recording frequency was 10 kHz in COL-02 and 2 kHz in PAR-12.

Figure 19 and Figure 20 show the measured pressure curves inside and at the outlet of the single blowdown pipe in COL-02 and inside the two pipes and at the outlet of pipe 1 in PAR-12 from a six second interval plotted with the same scale on the y-axis. The steam mass flux per one pipe (assuming equal division between the two pipes in PAR-12) is about 16.5 kg/m^{2}s during the examined period. According to the condensation mode map of Lahey and Moody chugging should be the prevailing mode in this flux range (and with 35-40 ºC pool water).

The curves reveal that the amplitudes of the highest pressure pulses inside the pipes are in the range of 0.4-0-5 MPa in both experiments. The behavior of pressure below the blowdown pipe outlet is, however, somewhat different in COL-02 from that in PAR-12. It looks like the formation of bubbles happens quite continuously in COL-02 while in PAR-12 the bubbles form more periodically and grow bigger before collapsing. As a result the transducer P5 below the pipe registers higher pressure loads in PAR-12. This observation was verified with the help of the high speed video recordings. Those showed almost a continuous pulsating steam bubble at the pipe outlet in COL02 but only now and then appearing larger bubble and water ingress into the pipe in PAR-12. This kind of result would indicate that a two blowdown pipe system tends to change the flow behavior compared to a single pipe system although the used steam mass flux per pipe is the same.

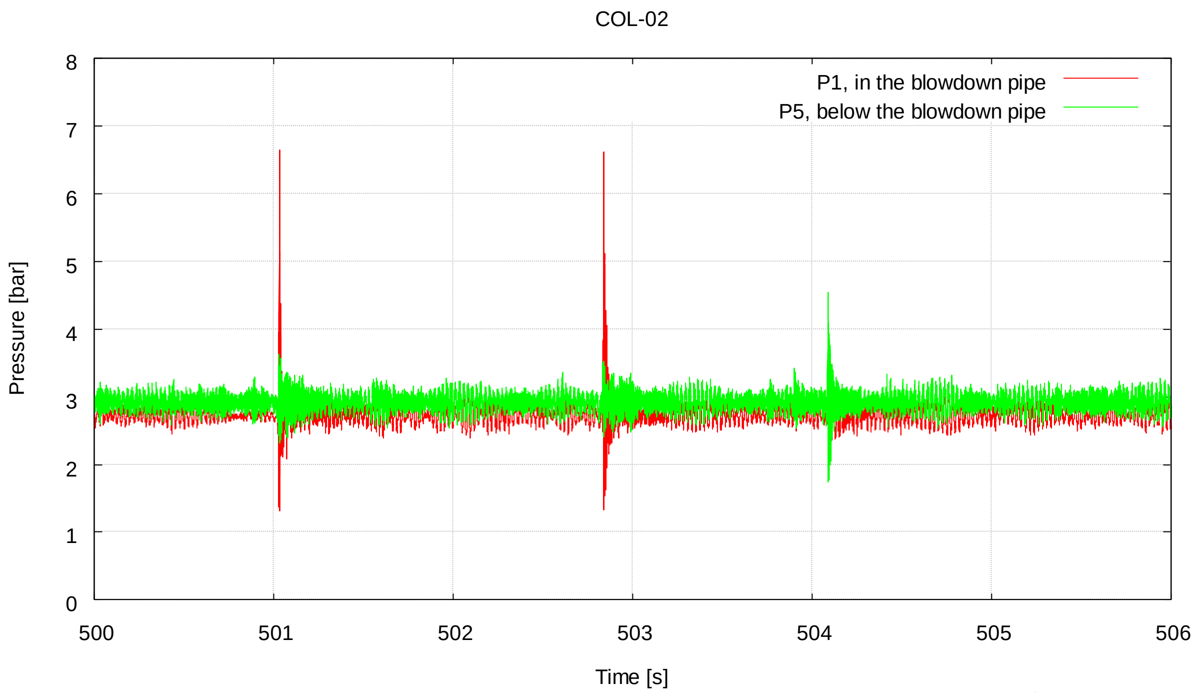

Figure 19. Pressure inside and at the outlet of the blowdown pipe with a 16.5 kg/m^{2}s mass flux in COL-02.

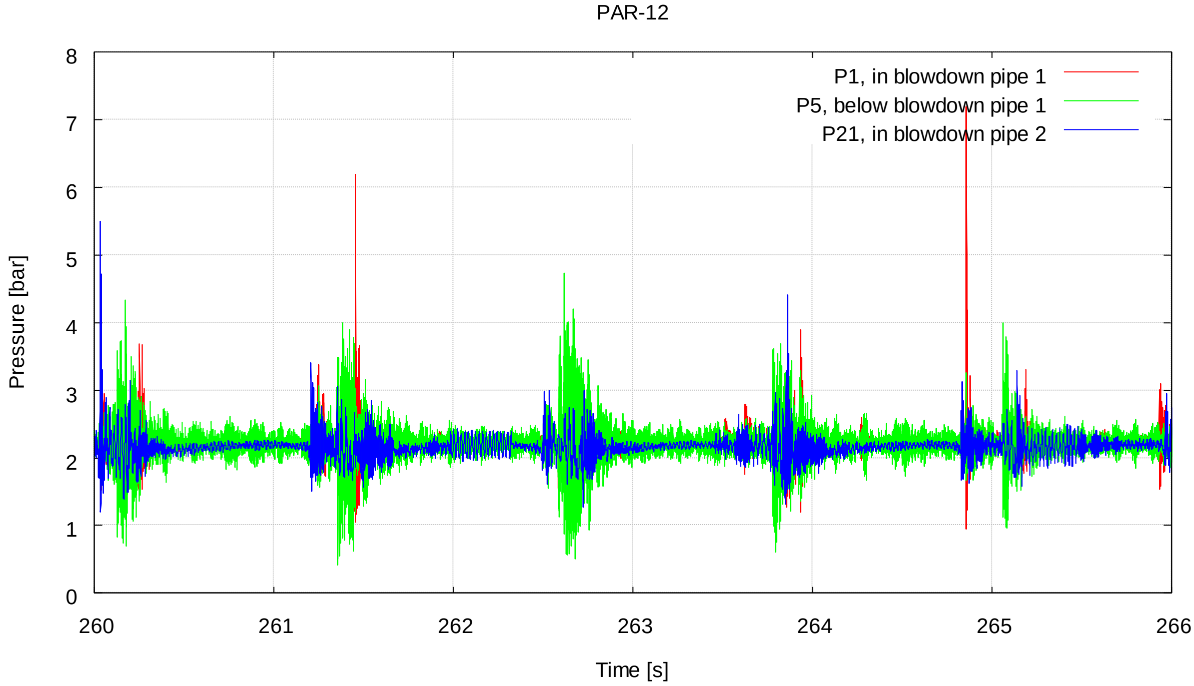

Figure 20. Pressure inside the two blowdown pipes and at the outlet of pipe 1 with a 16.5 kg/m²s mass flux in PAR-12.

5 SUMMARY AND CONCLUSIONS

This report summarizes the results of the experiments with two blowdown pipes carried out with the scaled down PPOOLEX test facility designed and constructed at Lappeenranta University of Technology. Steam was blown into the dry well compartment and from there through two vertical blowdown pipes to the condensation pool. Seven experiments (labelled from PAR-07 to PAR-13) with the two parallel blowdown pipes were carried out in 2010.

The PPOOLEX test facility is a closed stainless steel vessel divided into two compartments, dry well and wet well. The DN200 blowdown pipes (Ø219.1x2.5) were made of stainless steel and equipped with temperature and pressure measurements. During the experiments the initial temperature of the condensation pool water was 20 °C except in PAR-08 50 °C. The steam flow rate ranged from 220 g/s to 2 350 g/s and the temperature of incoming steam from 148 °C to 207 °C. The data acquisition system recorded data with a frequency of 2 kHz. A digital high-speed video camera was used for accurate observation of steam bubbles at the outlets of the blowdown pipes.

The main purpose of the experiment series was to study chugging phenomena (rapid condensation) while steam is discharged through two parallel blowdown pipes into the condensation pool filled with sub-cooled water. Particularly, the aim was to study if the pipe material (polycarbonate) used in the earlier experiment series with two blowdown pipes has had an effect on the general chugging behavior and measured loads. Structural loads due to pressure oscillations were also compared to a single pipe situation. In previous studies, loads in case of a single blowdown pipe have been found to be higher than with several pipes.

On the condensation mode map of Lahey and Moody the experiments belong to the "chugging" and "transition" regions except PAR-07 which belongs to the "steam condensation within vents or blowdown pipes " region. Due to quite high initial flow rates the temperature of the pool water rose several degrees already during the discharge period of air/steam mixture. Therefore the lowest temperature region of the condensation mode map could not be covered in these two pipe experiments as it has been done in the single pipe experiments with smaller initial flow rates.

In the experiments, steam flow pushed the steam/water interface downwards inside the blowdown pipes and steam bubbles formed at the pipe outlets. After rapid condensation, underpressure sucked water back into the pipes. The direction of the flow in the pipes changed very soon again as the steam pressure in the dry well remained high and forced the flow downwards again. These cycles were repeated hundreds of times during the experiments. Chugging caused dynamic loads to the pipes and pool structures.

The formation and collapse of steam bubbles and the movement of the steam/water interface inside the pipes seemed to be synchronous on the basis of visual observation during the experiments and temperature measurements inside the pipes. A more detailed analysis with the help of the high speed video and high frequency pressure measurements revealed however, that there can be even a 70 ms time difference between the occurrences of steam bubble collapses at the outlets of the two pipes. There is no clear pattern in which pipe the steam bubble first starts to collapse. Several successive bubbles can collapse first, for example, in pipe 1 but then the order can change for a single or several cycles.

High pressure loads were measured inside the blowdown pipes due to rapid condensation of the steam volumes in the pipes and resulting water hammer effects. The loads seemed to be higher in pipe 1 than in pipe 2. An explanation for this could be a possible unequal distribution of steam flow between the two pipes.

The pipe material has an effect on the condensation phenomena inside the blowdown pipes. When the experiments done in 2009 with the polycarbonate blowdown pipes are compared with the steel pipe experiments a huge difference between the measured pressure curves inside the pipes can be observed. With the same test conditions the amplitude of the pressure pulses caused by water hammer is considerably larger in the steel pipe experiments. It seems like the flow mode is different with the polycarbonate pipes from that with the steel pipes. Due to minimal heat conduction through the polycarbonate pipe wall condensation tends to happen at the pipe outlet and therefore no high pressure loads due to water hammer are experienced inside the pipe.

The used blowdown pipe material does not have much effect on phenomena occurring in the wet well pool. The measured maximum pressure loads on the pool bottom, strains on the outer wall and vertical acceleration and movement of the test vessel are all in the same range in both experiment series. Phenomena in the pool depend more on the conditions in the water pool itself (coolant temperature and level, pressure, fraction of non-condensables) while the events inside the blowdown pipes are in some respect local and do not influence on the pool behavior very much.

Some results indicated also that a two blowdown pipe system tends change the flow behavior compared to a single pipe system although the used steam mass flux per pipe is the same. It looks like the formation of bubbles happens quite continuously in the single pipe case while the bubbles form more periodically and grow bigger before collapsing in the two pipe case. The high speed video reveals that there is an almost continuous pulsating steam bubble at the outlet of the single pipe but only now and then appearing larger bubbles and water ingress back into the pipes in the two pipe experiment. A contributing factor to this could be the smaller dry well volume per blowdown pipe ratio in the two pipe case than in the single pipe case.

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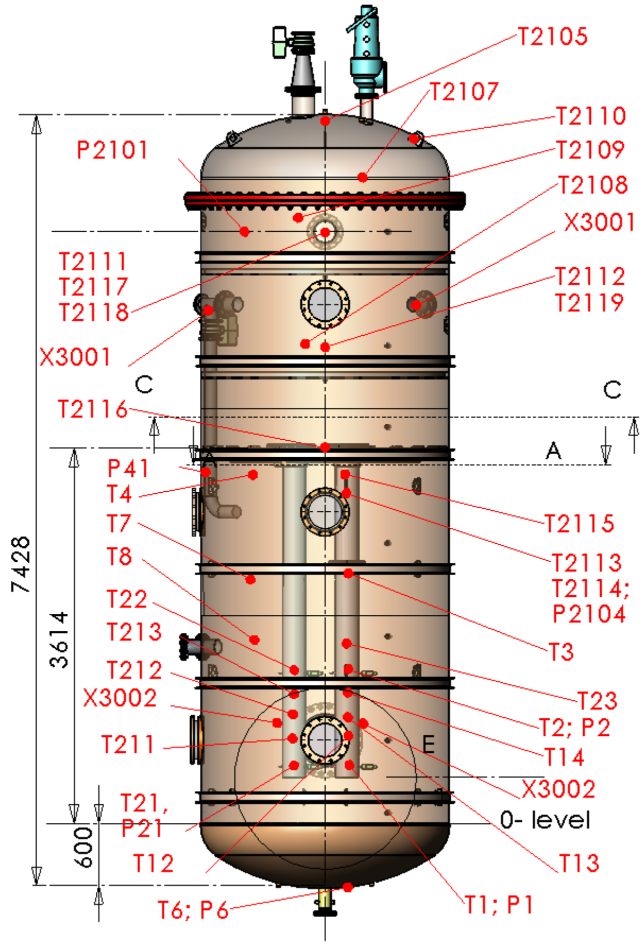
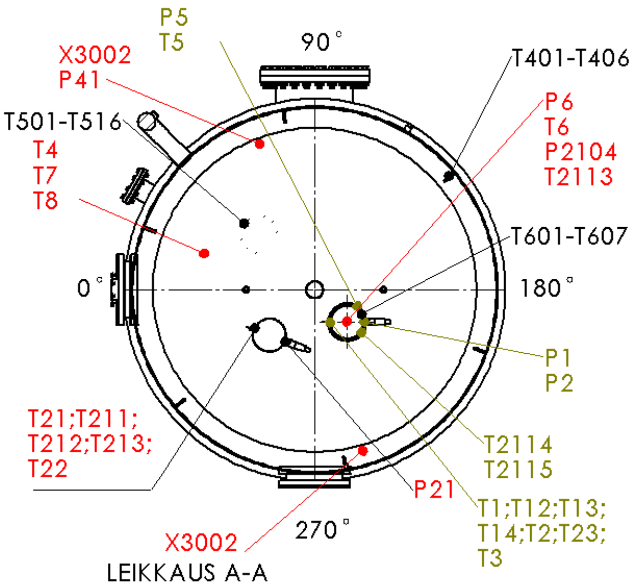
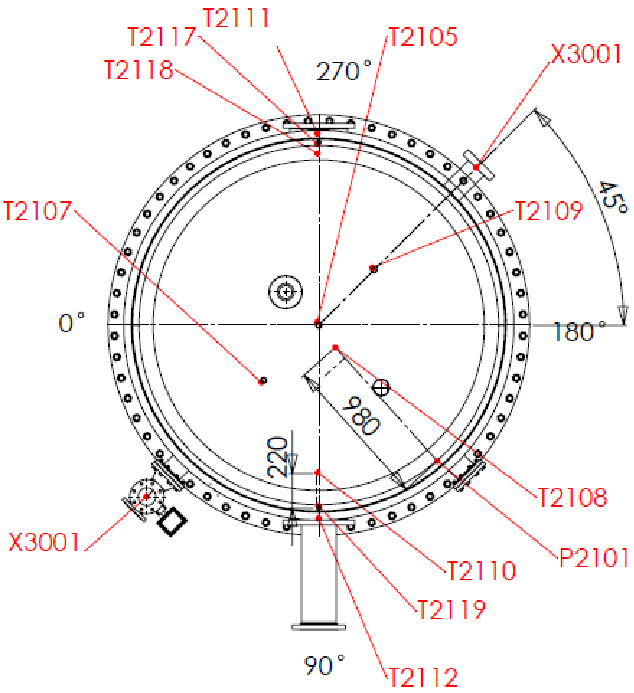
APPENDIX 1: PPOOLEX INSTRUMENTATION



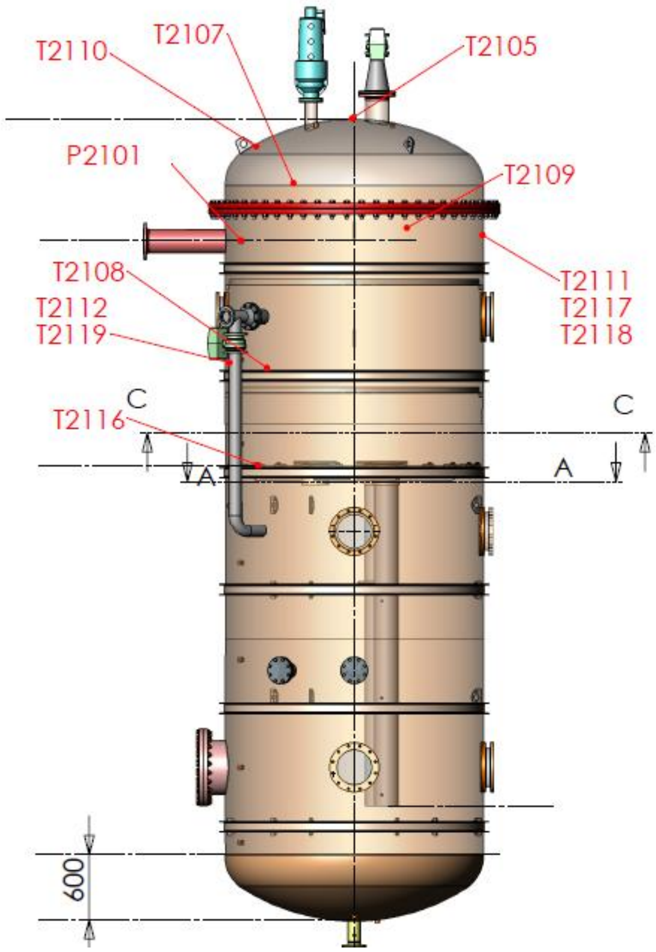
Test vessel measurements.



Cross-section A-A.



Cross-section C-C.



Dry well measurements.

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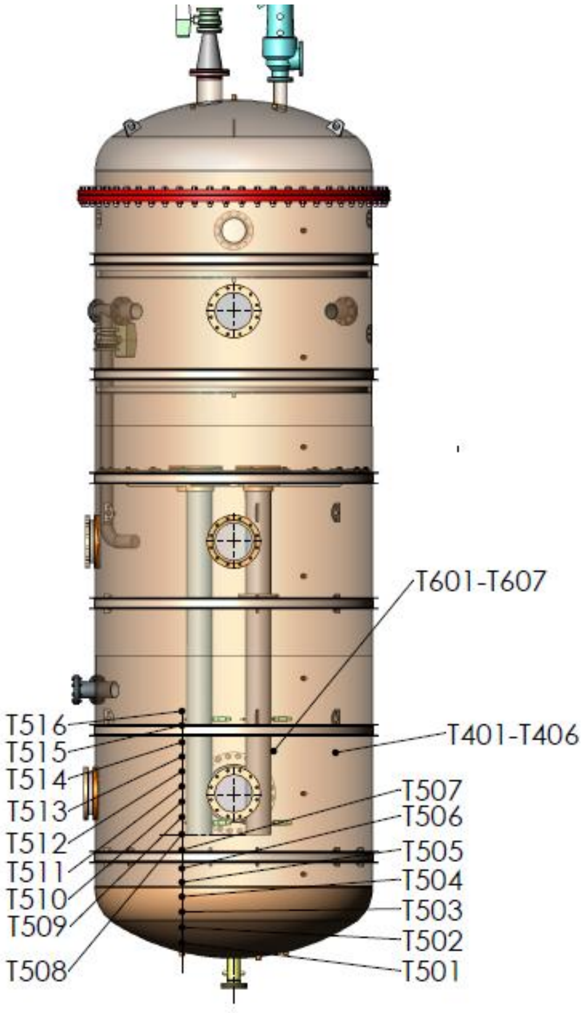
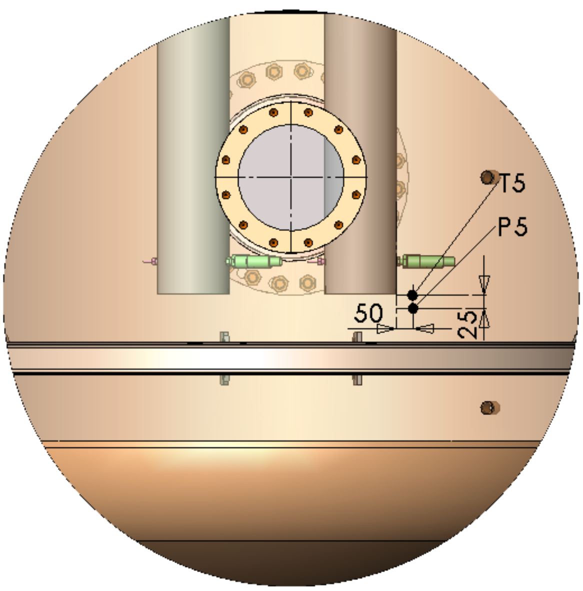
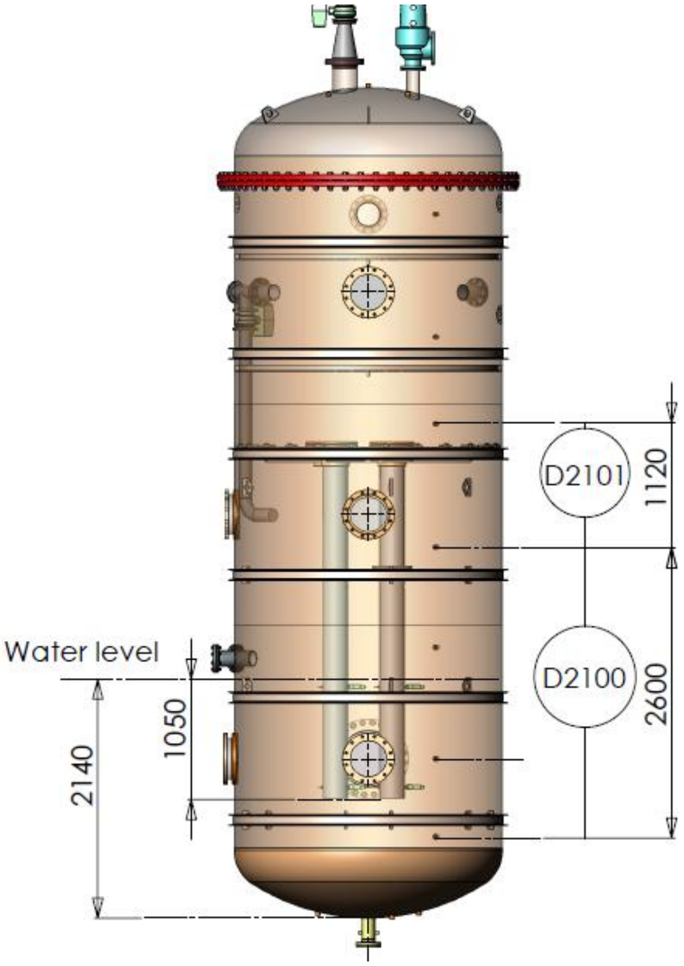


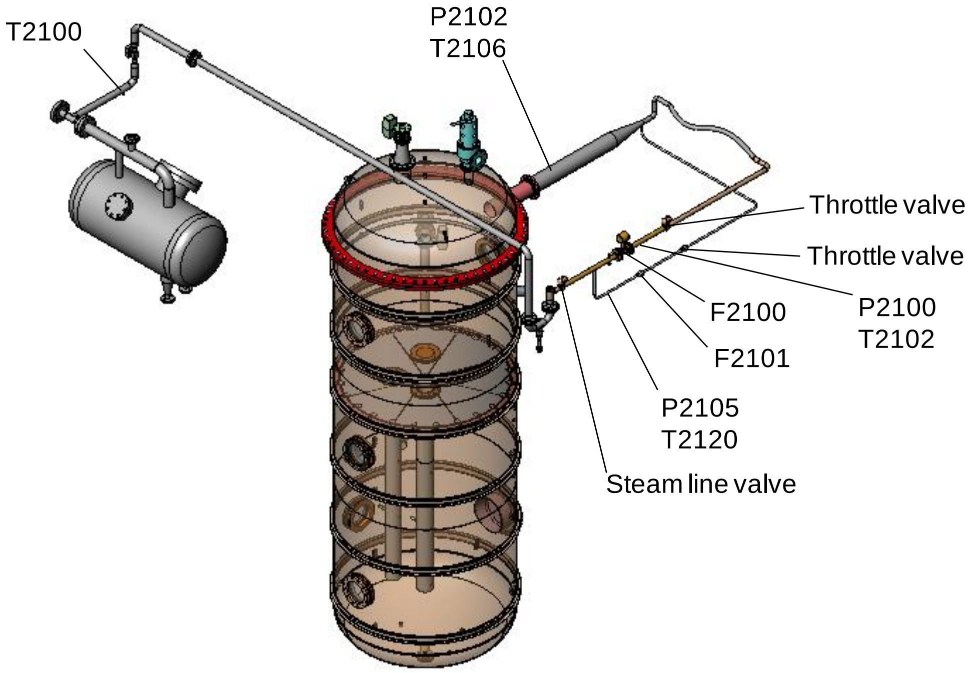
Additional temperature measurements in the wet well pool.



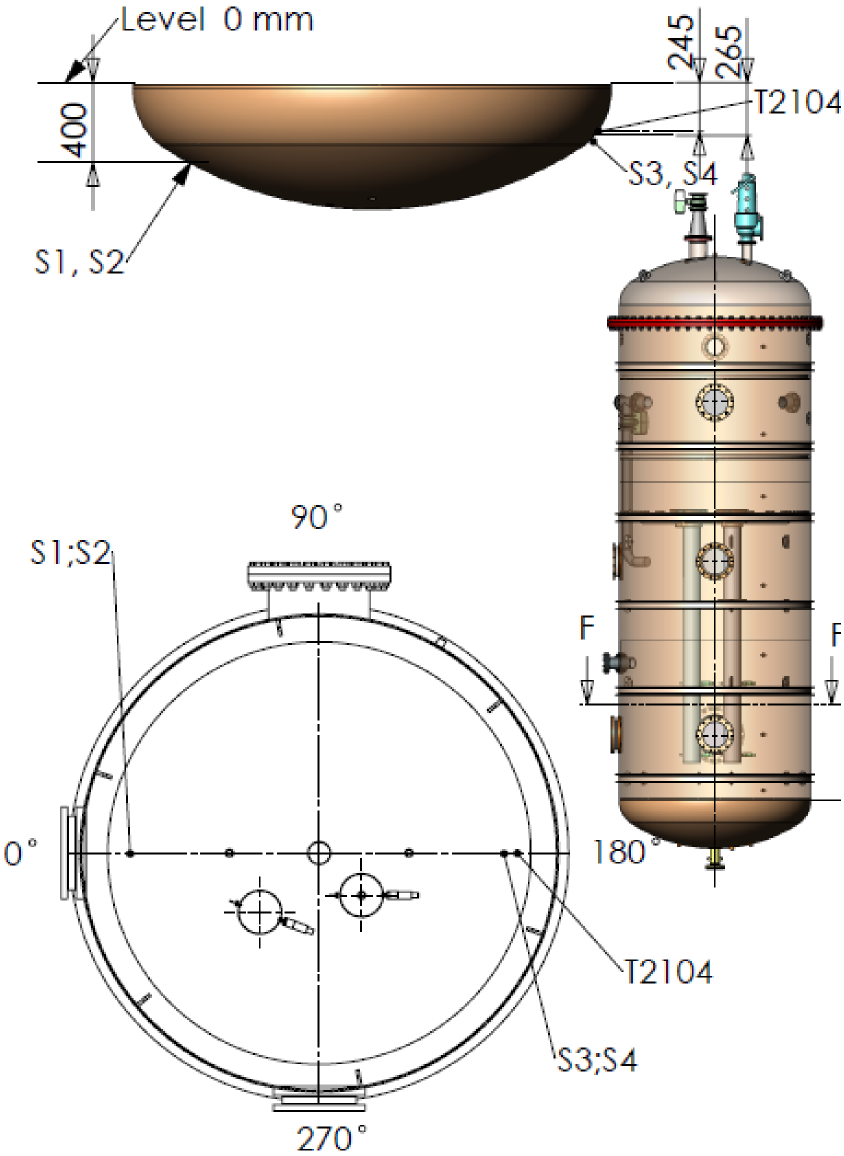
Pressure and temperature measurements at the outlet of blowdown pipe 1.



Pressure difference measurements. Nominal water level is 2.14 m.



Measurements in the steam line.



Strain gauges and thermocouple T2104 on the outer wall of the pool bottom.

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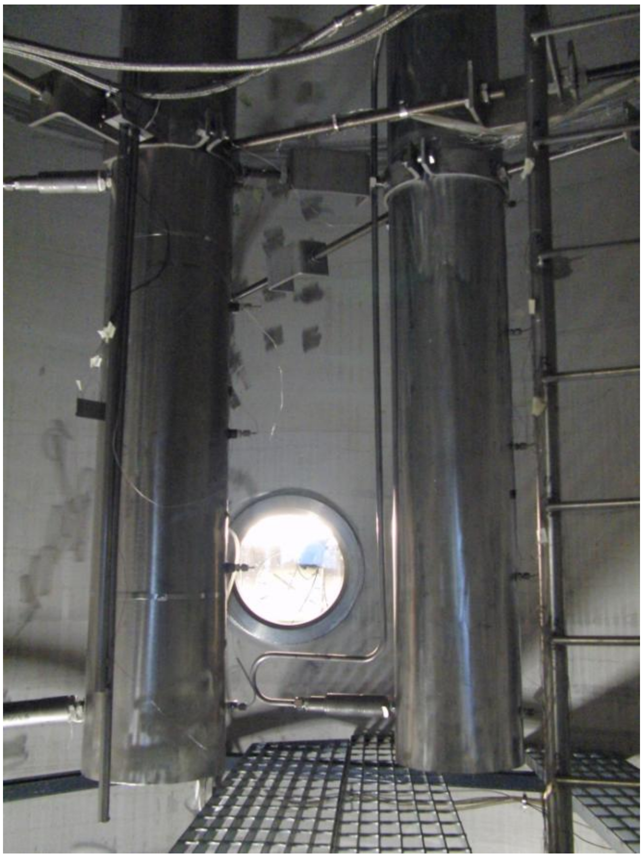
Measurement	Code	Elevation	Angle	Location	Error estimation
Pressure	P1	545	214	Blowdown pipe 1	±0.7 bar
Temperature	T1	545	245	Blowdown pipe 1	±1.8 °C
Pressure	P2	1445	214	Blowdown pipe 1	±0.7 bar
Temperature	T2	1445	245	Blowdown pipe 1	±1.8 °C
Temperature	T4	3410	20	Wet well gas space	±1.8 °C
Pressure	P5	395	198	Blowdown pipe 1 outlet	±0.7 bar
Temperature	T5	420	198	Blowdown pipe 1 outlet	±1.8 °C
Pressure	P6	-615	225	Wet well bottom	±0.5 bar
Temperature	T6	-615	225	Wet well bottom	±1.8 °C
Temperature	T7	2585	20	Wet well gas space	±1.8 °C
Temperature	T8	1760	20	Wet well gas space	±1.8 °C
Temperature	T12	770	245	Blowdown pipe 1	±1.8 °C
Temperature	T13	995	245	Blowdown pipe 1	±1.8 °C
Temperature	T14	1220	245	Blowdown pipe 1	±1.8 °C
Temperature	T23	1670	245	Blowdown pipe 1	±1.8 °C
Temperature	T21	545	305	Blowdown pipe 2	±1.8 °C
Pressure	P21	545	323	Blowdown pipe 2	±0.7 bar
Temperature	T211	770	305	Blowdown pipe 2	±1.8 °C
Temperature	T212	995	305	Blowdown pipe 2	±1.8 °C
Temperature	T213	1220	305	Blowdown pipe 2	±1.8 °C
Temperature	T22	1445	305	Blowdown pipe 2	±1.8 °C
Pressure	P41	3600	45	Wet well gas space	±0.1 bar
Temperature	T401	1000	140	Wet well	±1.8 °C
Temperature	T402	1000	140	Wet well	±1.8 °C
Temperature	T403	1000	140	Wet well	±1.8 °C
Temperature	T404	1000	140	Wet well	±1.8 °C
Temperature	T405	1000	140	Wet well	±1.8 °C
Temperature	T406	1000	140	Wet well	±1.8 °C
Temperature	T501	-530	45	Wet well	±1.8 °C
Temperature	T502	-390	45	Wet well	±1.8 °C
Temperature	T503	-260	45	Wet well	±1.8 °C
Temperature	T504	-125	45	Wet well	±1.8 °C
Temperature	T505	10	45	Wet well	±1.8 °C
Temperature	T506	150	45	Wet well	±1.8 °C
Temperature	T507	287	45	Wet well	±1.8 °C
Temperature	T508	427	45	Wet well	±1.8 °C
Temperature	T509	560	45	Wet well	±1.8 °C
Temperature	T510	695	45	Wet well	±1.8 °C
Temperature	T511	830	45	Wet well	±1.8 °C
Temperature	T512	965	45	Wet well	±1.8 °C
Temperature	T513	1103	45	Wet well	±1.8 °C
Temperature	T514	1236	45	Wet well	±1.8 °C
Temperature	T515	1369	45	Wet well	±1.8 °C
Temperature	T516	1505	45	Wet well	±1.8 °C
Temperature	T601	1000	202	Wet well	±1.8 °C
Temperature	T602	1000	202	Wet well	±1.8 °C
Temperature	T603	1000	202	Wet well	±1.8 °C
Temperature	T604	1000	202	Wet well	±1.8 °C
Temperature	T605	1000	202	Wet well	±1.8 °C

Temperature	T606	1000	202	Wet well	±1.8 °C
Temperature	T607	1000	202	Wet well	±1.8 °C
Flow rate	F2100	-	-	Steam line	±4.9 l/s
Pressure	P2100	-	-	Steam line	±0.5 bar
Temperature	T2100	-	-	Steam line beginning	±3.5 °C
Pressure	P2101	5700	90	Dry well	±0.06 bar
Pressure	P2102	-	-	Inlet plenum	±0.06 bar
Temperature	T2102	-	-	Steam line	±3.5 °C
Pressure	P2104	3400	202	Blowdown pipe 1	±0.06 bar
Temperature	T2104	-245	180	Wet well outer wall	±1.8 °C
Temperature	T2105	6780	-	Dry well top	±1.8 °C
Temperature	T2106	-	-	Inlet plenum	±1.8 °C
Temperature	T2107	6085	45	Dry well middle	±1.8 °C
Temperature	T2108	4600	120	Dry well bottom	±1.8 °C
Temperature	T2109	5790	225	Dry well lower middle	±1.8 °C
Temperature	T2110	6550	90	Dry well outer wall	±1.8 °C
Temperature	T2111	5700	270	Dry well outer wall	±1.8 °C
Temperature	T2112	4600	90	Dry well outer wall	±1.8 °C
Temperature	T2113	3400	225	Blowdown pipe 1	±1.8 °C
Temperature	T2114	3400	212	Blowdown pipe 1	±1.8 °C
Temperature	T2115	3250	212	Blowdown pipe 1	±1.8 °C
Temperature	T2116	3600	135	Dry well floor	±1.8 °C
Temperature	T2117	5700	270	Dry well inner wall	±1.8 °C
Temperature	T2118	5700	270	Dry well, 10 mm from the wall	±1.8 °C
Temperature	T2119	4600	90	Dry well inner wall	±1.8 °C
Pressure difference	D2100	100–2700	120	Wet well	±0.06 m
Pressure difference	D2101	2700–3820	120	Across the floor	±0.09 bar
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	892	180	Below pool bottom	Not defined
Pool bottom acceleration	G-force	892	180	Pool bottom	Not defined
Valve position	X1100	-	-	Steam line	Not defined
Steam partial pressure	X2102	4600	120	Dry well	Not defined
Sonic speed	X3001	5000	45 225	Dry well	Not defined
Sonic speed	X3002	940 (640)	70 255	Wet well	Not defined
Valve position	V1	-	-	Steam line	Not defined
Camera trigger	Camera trigger	-	-	Wet well	Not defined

Measurements in the PPOOLEX facility for the PAR-07- PAR-13 experiment.

APPENDIX 2: PPOOLEX TEST FACILITY PHOTOGRAPHS

Thermally insulated dry well compartment and steam line.



Two parallel steel blowdown pipes. Pipe 1 is on the left and pipe 2 on the right.

Title	MULTIPLE BLOWDOWN PIPE EXPERIMENTS WITH THE PPOOLEX FACILITY
Author(s)	Markku Puustinen, Jani Laine, Antti Räsänen
Affiliation(s)	Lappeenranta University of Technology, Nuclear Safety Research Unit
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Project	NKS-R / POOL
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No. of tables	5 + 1
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No. of references	15

Abstract

This report summarizes the results of the experiments with two steel blowdown pipes carried out with the scaled down PPOOLEX test facility designed and constructed at Lappeenranta University of Technology. Steam was blown into the dry well compartment and from there through the blowdown pipes to the condensation pool.

The main purpose of the experiment series was to study chugging phenomena (rapid condensation) while steam is discharged through two parallel blowdown pipes into the condensation pool filled with sub-cooled water. Particularly, the aim was to study if the pipe material (polycarbonate) used in the earlier experiment series with two blowdown pipes has had an effect on the general chugging behaviour and measured loads.

In the experiments the initial temperature of the pool water was 20 ºC. The steam flow rate ranged from 220 g/s to 2 350 g/s and the temperature of incoming steam from 148 ºC to 207 ºC.

The formation and collapse of steam bubbles and the movement of the steam/water interface inside the pipes was non-synchronous. There could be even a 70 ms time difference between the occurrences of steam bubble collapses at the outlets of the two pipes. There was no clear pattern in which pipe the steam bubble first starts to collapse. Several successive bubbles could collapse first in either pipe but then the order changed for a single or several cycles.

High pressure loads were measured inside the blowdown pipes due to rapid condensation of the steam volumes in the pipes and resulting water hammer effects. The loads seemed to be higher in pipe 1 than in pipe 2. An explanation for this could be a possible unequal distribution of steam flow between the two pipes.

The pipe material has an effect on the condensation phenomena inside the blowdown pipes. A huge difference in the measured pressure curves inside the pipes could be observed compared to the experiments with the polycarbonate pipes. With the same test conditions the amplitude of the pressure pulses caused by water hammer was considerably larger in the steel pipe experiments. It seemed like the flow mode was different with the polycarbonate pipes from that with the steel pipes. Due to minimal heat conduction through the polycarbonate pipe wall condensation tended to happen at the pipe outlet and therefore no high pressure loads due to water hammer were experienced inside the pipe.

Key words: condensation pool, steam/air blowdown, chugging, dynamic loading

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