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PPOOLEX Experiments with Two Parallel Blowdown Pipes

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Abstract

This report summarizes the results of the experiments with two transparent 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 either one or two vertical transparent blowdown pipes to the condensation pool. Five experiments with one pipe and six with two parallel pipes were carried out. The main purpose of the experiments was to study loads caused by chugging (rapid condensation) while steam is discharged into the condensation pool filled with sub-cooled water.

The PPOOLEX test facility is a closed stainless steel vessel divided into two compartments, dry well and wet well. In the experiments the initial temperature of the condensation pool water varied from 12 ºC to 55 ºC, the steam flow rate from 40 g/s to 1 300 g/s and the temperature of incoming steam from 120 ºC to 185 ºC.

In the experiments with only one transparent blowdown pipe chugging phenomenon didn't occur as intensified as in the preceding experiments carried out with a DN200 stainless steel pipe. With the steel blowdown pipe even 10 times higher pressure pulses were registered inside the pipe. Meanwhile, loads registered in the pool didn't indicate significant differences between the steel and polycarbonate pipe experiments.

In the experiments with two transparent blowdown pipes, the steam-water interface moved almost synchronously up and down inside both pipes. Chugging was stronger than in the one pipe experiments and even two times higher loads were measured inside the pipes. The loads at the blowdown pipe outlet were approximately the same as in the one pipe cases. Other registered loads around the pool were about 50–100 % higher than with one pipe.

The experiments with two parallel blowdown pipes gave contradictory results compared to the earlier studies dealing with chugging loads in case of multiple pipes. Contributing factors to this may be the smaller dry well volume per blowdown pipe ratio and the lack of dry well internal structures in the PPOOLEX facility. Furthermore, the pipe material seemed to have an effect on the condensation process inside the pipe. Polycarbonate has two orders of magnitude smaller thermal conductivity than steel.

Key words

condensation pool, steam/air blowdown, chugging, parallel blowdown pipes

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The main purpose of the experiments was to study loads caused by chugging (rapid condensation) while steam is discharged into the condensation pool filled with sub-cooled water through one or two blowdown pipes.

The PPOOLEX test facility is a closed stainless steel vessel divided into two compartments, dry well and wet well. The lower parts of the DN200 blowdown pipes were machined from transparent polycarbonate. In the experiments the initial temperature of the condensation pool water varied from 12 °C to 55 °C, the steam flow rate from 40 g/s to 1 300 g/s and the temperature of incoming steam from 120 °C to 185 °C.

In the experiments with only one transparent blowdown pipe chugging phenomenon didn't occur as intensified as in the preceding experiments carried out with a DN200 stainless steel pipe. With the steel blowdown pipe even 10 times higher pressure pulses were registered inside the pipe. Meanwhile, loads registered in the pool didn't indicate significant differences between the steel and polycarbonate pipe experiments.

In the experiments with two transparent blowdown pipes, the steam-water interface moved almost synchronously up and down inside both pipes. Chugging was stronger than in the one pipe experiments and even two times higher loads were measured inside the pipes. The loads at the blowdown pipe outlet were approximately the same as in the one pipe cases. Other registered loads around the pool were about 50–100 % higher than with one pipe.

The experiments with two parallel blowdown pipes gave contradictory results compared to the earlier studies dealing with chugging loads in case of multiple pipes. Contributing factors to this may be the smaller dry well volume per blowdown pipe ratio and the lack of dry well internal structures in the PPOOLEX facility. Furthermore, the pipe material seemed to have an effect on the condensation process inside the pipe. Polycarbonate has two orders of magnitude smaller thermal conductivity than steel. Heat transfer from steam to pool water through the blowdown pipe wall is much smaller and therefore condensation process inside the pipe weaker.

Polycarbonate proved to be durable enough material against the dynamic loads caused by chugging phenomenon.

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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).

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
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
TRA	experiment series with transparent blowdown pipe
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.

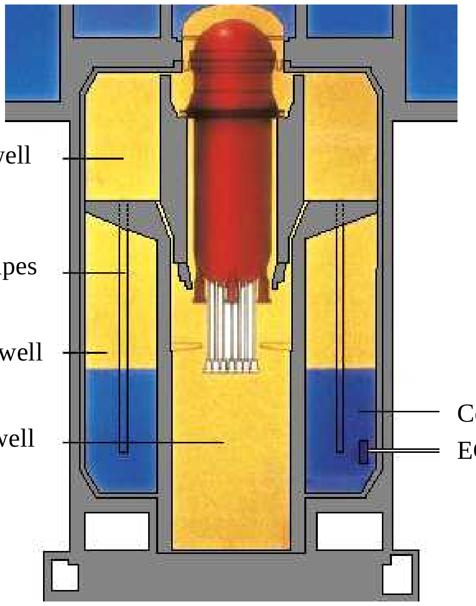

Figure 1. Schematic of the Olkiluoto type BWR containment.

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 a series of 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].

The research programme continued in June, July September, and November 2009 with eleven experiments (TRA and PAR series) studying the effect of the number of blowdown pipes (one or two) on loads caused by chugging phenomena. In the previous Japanese studies with seven full scale vent pipes a significant influence of the number of the vent pipes on the condensation loads was observed [6]. It was noticed that even very small de-synchronization among the vent pipe pressure oscillations can reduce the magnitudes of the pool loads. In this report, the results of the TRA and PAR experiments with the PPOLEX facility are presented. First, chapter two gives a short description of the test facility and its measurements as well as of the data acquisition system used. The test programme of the TRA and PAR experiment series is introduced in chapter three. The test results are presented and shortly discussed in chapter four. Chapter five summarizes the findings of the experiment series.

2 PPOOLEX TEST FACILITY

Condensation studies at LUT started with an open 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 [7]. However, the main features of the facility and its instrumentation are introduced below. Some test facility photographs are shown in Appendix 3.

2.1 TEST VESSEL

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

The main component of the facility is the ~31 m^3 cylindrical test vessel, 7.45 m in height and 2.4 m in diameter. The vessel is constructed from three separate plate cylinder segments and from two dome segments. The test facility is able to withstand considerable structural loads caused by rapid condensation of steam. The vessel sections modelling dry well and wet well are volumetrically scaled according to the compartment volumes of the Olkiluoto containment buildings (ratio approximately 1:320). 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 the inner diameter 214.1 mm. There are several windows for visual observation in the walls of both compartments. A DN100 (∅ 114.3 x 2.5 mm) drain pipe with a manual valve is connected to the bottom of the vessel. A relief valve connection is mounted on the vessel head. The large removable vessel head and a man hole (DN500) in the wet well compartment wall provide access to the interior of the vessel for maintenance and modifications of internals and instrumentation. The test vessel is not thermally insulated. A sketch of the test vessel is presented in Figure 2. Table 1 lists the main dimensions of the test facility compared to the conditions in the Olkiluoto plant.

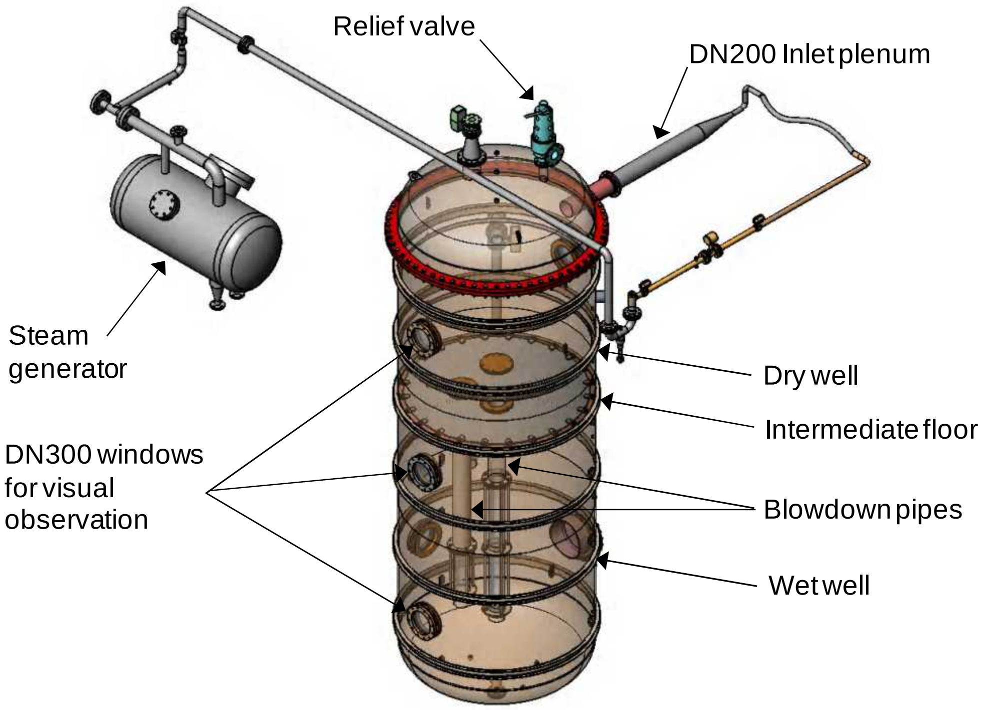

Figure 2. PPOOLEX test vessel.

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

	PPOOLEX test facility	Olkiluoto 1 and 2
Number of blowdown pipes	1	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 [8] 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.

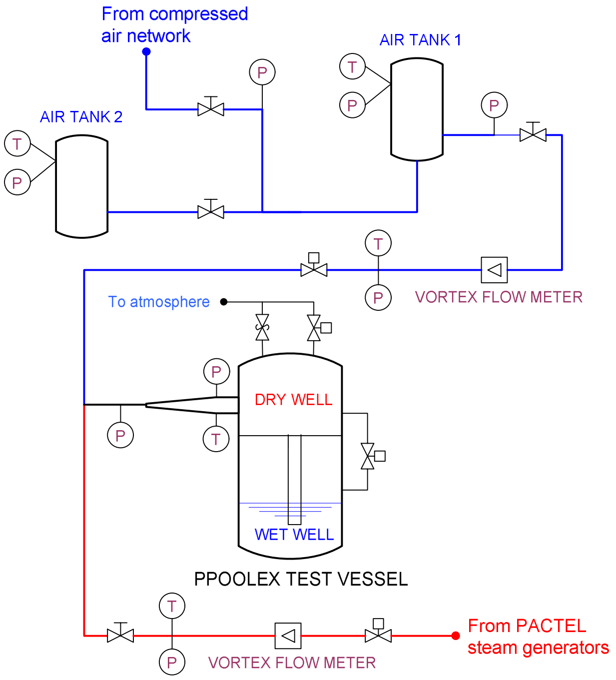

Figure 3. Arrangement of air and steam supply in the PPOOLEX facility.

2.3 BLOWDOWN PIPES

Two DN200 blowdown pipes are positioned inside the pool in a non-axisymmetric location, i.e. pipe 1 300 mm and pipe 2 500 mm away from the centre of the condensation pool. The total length of the both blowdown pipes is 3 209 mm. The upper parts of the pipes are made from austenitic stainless steel AISI 304L (Ø219.1x2.5) and the lower parts from transparent Esalux® polycarbonate (Ø200x5.0), Figure 4. The pipes are not identical. The lengths of the transparent parts of the pipes 1 and 2 are 2 050 mm and 858 mm, correspondingly.

Detailed drawings of the blowdown pipes are shown in Appendix 1. Table 2 compares properties of Esalux® polycarbonate (PC) and stainless steel (SS) AISI 304L.

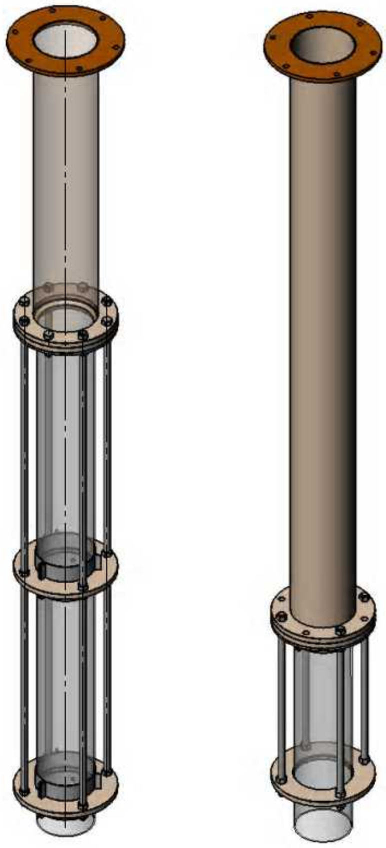

Figure 4. Blowdown pipes used in TRA and PAR experiment series. Pipe 1 is on the left and pipe 2 on the right.

Table 2. Physical, mechanical and thermal properties of PC and SS AISI 304L [9, 10, 11].

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

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.

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

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 behaviour in the dry well compartment, inside the blowdown pipe, at the condensation pool bottom and in the gas phase of the wet well compartment. Steam and air flow rates are measured with vortex flow meters (F) in the steam and air lines. Additional instrumentation includes, for example, strain gauges (S) on the pool outer wall and valve position sensors. Strains are measured both in circumferential and axial direction.

A list of different types of measurements of the PPOOLEX facility during the TRA and 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 the identification codes and error estimations of the measurements. 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	5	0–6/0–10 bar	0.4/0.5 bar
	Blowdown pipe	3	0–10 bar	0.7 bar
	Inlet plenum	1	0–6 bar	0.06 bar
	Steam line	1	1–51	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	5	-40–200 °C	±3.2 °C
	Wet well gas space	3	0–250 °C	±2.0 °C
	Wet well water volume	2	0–250 °C	±2.0 °C
	Blowdown pipe	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
	Air line	1	-20–100 °C	±2.8 °C
	Air tanks 1&2	2	-20–100/200 °C	±2.8/3.1 °C
	Structures	7	0–200 °C	±2.6 °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
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

2.5 CCTV SYSTEM

In the TRA and 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, Figure 5.

For more accurate observation of air/steam bubbles at the blowdown pipe outlet, a Casio Exilim EX-F1 digital camera [12] 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. Table 4 shows resolution/speed/recording time combinations that can be attained with the camera.

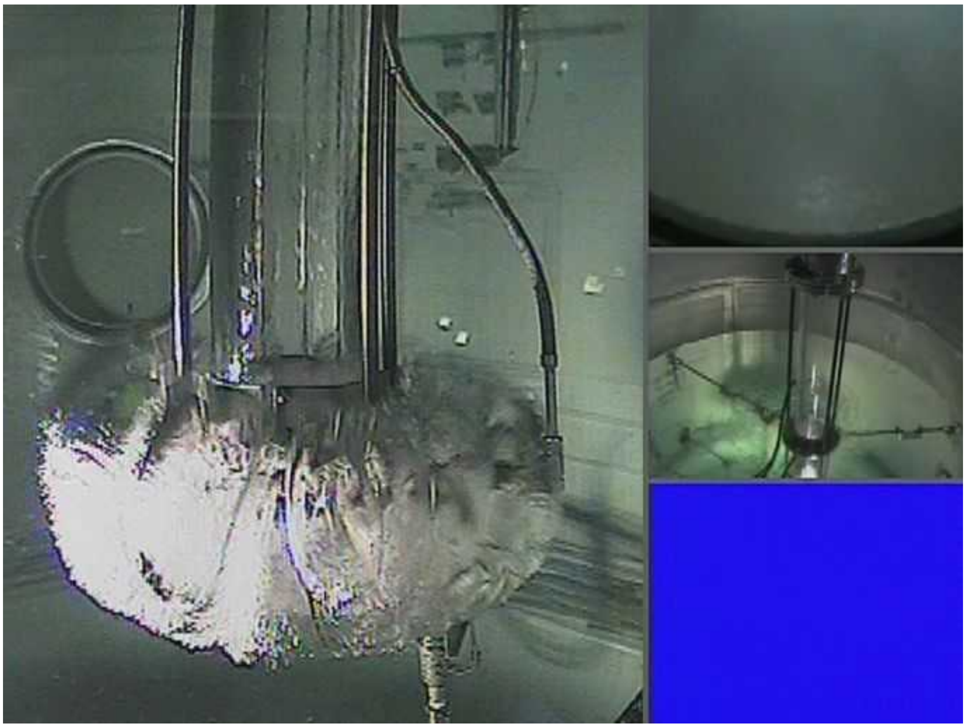

Figure 5. Typical camera views from the beginning of the TRA experiments.

Table 4. Available resolution, recording speed and time combinations of the Casio Exilim EX-F1 digital camera.

Resolution [pixels]	Recording speed [fps]	Max recording time with 2 GB SD memory card [min, s]
336x96	1 200	14 min 36 s
432x192	600	14 min 38 s
512x384	300	14 min 38 s

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 speed 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 6. The data acquisition system is discussed in more detail in reference [13].

A 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 data recording frequency of LabView was 1 kHz. For the temperature measurements the data recording frequency was 20 Hz. The temperature measurements are therefore averaged over 50 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.

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

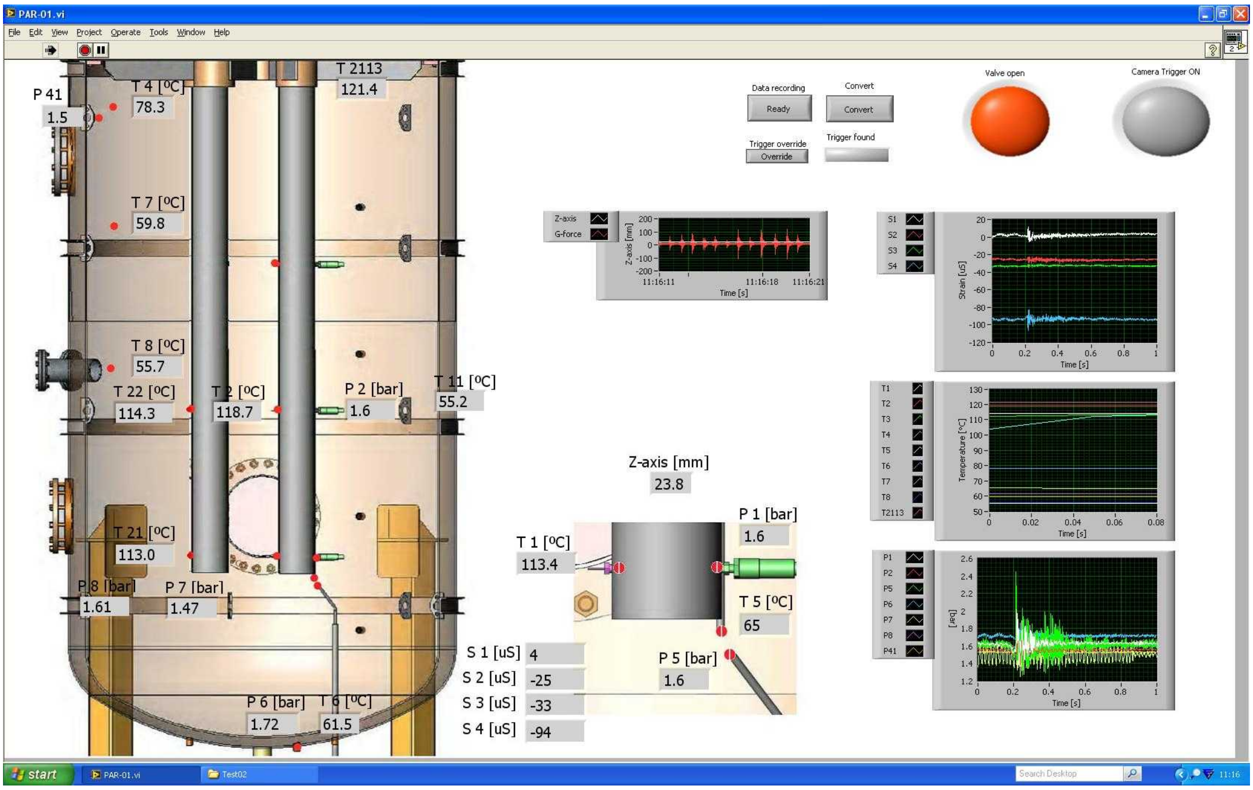

Figure 6. Monitoring of PAR experiment with LabView 8.6 software.

3 TEST PROGRAM

The test program in June, July, September and November 2009 consisted of eleven experiments with transparent blowdown pipes. Five of the experiments were carried out with one transparent blowdown pipe (labeled from TRA-01 to TRA-05) and six experiments with two transparent blowdown pipes (labeled from PAR-01 to PAR-06). The main purpose of the TRA and PAR test series was to study chugging phenomena while steam is discharged into the condensation pool filled with sub-cooled water through one or two transparent blowdown pipes. The experiments were carried out by using one or two DN200 blowdown pipes whose lower parts were machined from transparent polycarbonate. Steam generators of the nearby PACTEL facility acted as a steam source.

Before most of the experiments the condensation pool was filled with isothermal water (temperature 12–55 °C) to the level of 2.14 m i.e. the blowdown pipe outlets were submerged by 1.05 m. This air/water distribution corresponds roughly to the scaled gas and liquid volumes in the containment of the reference plant. However, with this water level 0.19 m of the stainless steel part of the blowdown pipe 2 was submerged too. To find out if this causes significant differences to the steam condensation phenomenon between the blowdown pipes, initial pool water level was lowered to the level of 1.80 m in TRA-05-2 and PAR-02. With this pool water level the blowdown pipe outlets were submerged by 0.71 m i.e. only transparent parts of the both pipes were submerged.

The steam source initial pressure varied from 0.25 MPa to 1.5 MPa. Between individual tests the test vessel was shortly ventilated with compressed air to dry the wall surfaces and to clear the viewing windows.

Initially, the dry well compartment 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 blowdown pipe(s) downwards and after a while the pipe(s) 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.

In TRA-01…04 only the blowdown pipe 1 was used and in TRA-05 the pipe 2. In PAR experiment series steam was blown into the pool through both blowdown pipes. Table 5 shows the main parameters of the TRA and PAR experiments.

Table 5. Initial parameter values of the TRA and PAR experiments.

Experiment	Steam source pressure [MPa]	Initial pool water level [m]	Initial pool water temperature [°C]	Blowdown pipe [1 and/or 2]
TRA-01	0.25, 0.4	2.14	25, 28	1
TRA-02	0.55	2.14	12	1
TRA-03	0.55	2.14	20	1
TRA-04	1.0	2.14	45	1
TRA-05	0.5	2.14, 1.80	25, 45	2
PAR-01	0.35, 0.55, 0.75	2.14	25, 31, 45	1 and 2
PAR-02	0.55, 0.75	1.80	25, 40	1 and 2
PAR-03	0.55	2.14	20	1 and 2
PAR-04	1.5	2.14	33	1 and 2
PAR-05	0.55	2.14	50	1 and 2
PAR-06	1.5	2.14	55	1 and 2

4 ANALYSIS OF THE EXPERIMENTS

The following chapters give a more detailed description of the experiment program and present the observed phenomena from selected, most representative cases. Table 6 and Table 7 summarize the values of the main parameters during the TRA and PAR experiment series, correspondingly.

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Table 6. Main parameters during TRA experiments.

Test	Initial pressure of steam generator [MPa]	Steam flow rate[2] [g/s]	Initial T_{pool} [°C]	Temperature of steam[3] [°C]	Initial pool water level [m]	Δp_{max} in the DN200 pipe[4] [kPa]	Δp_{max} in the pool[5] [kPa]	Δp_{max} at the pool bottom[6] [kPa]	$\Delta \varepsilon_{max}$[7] [µS]	Pool bottom vertical $a_{max.}$ [m/s^2]	Pool bottom vertical Δs_{max} [mm]
TRA-01-1	0.25	80…250	25	118…136	2.14	140 (P1) 70 (P2)	50 (P5) 20 (P7) 15 (P8)	20	15	80	0.3
TRA-01-2	0.4	340…40	28	137…129	2.15	100 50	100 50 40	30	20	130	0.4
TRA-02	0.65	540…190	12	152…141	2.14	180 100	210 50 40	50	35	210	2.5
TRA-03	0.55	380…150	20	147…136	2.14	160 100	360 50 50	60	30	210	1.5
TRA-04	1.0	700…230	45	171…146	2.14	170 80	240 70 60	50	30	210	1.6
TRA-05-1	0.5	380…160	25	144…131	2.14	50 (P22)	210 (P25) 40 (P7)	60	35	200	1.1
TRA-05-2	0.5	360…170	45	141…133	1.80	50	240 60	60	35	190	1.1

[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.
[4] Measured by pressure transducer P1 and P2 (P22 in TRA-05).
[5] Measured by pressure transducers P5, P7 and P8 (P25 and P7 in TRA-05).
[6] Measured by pressure transducer P6.
[7] Measured by strain gauge S4.

Table 7. Main parameters during PAR experiments.

Test	Initial pressure of steam generator [MPa]	Steam flow rate[8] [g/s]	Initial T_{pool} [°C]	Temperature of steam[9] [°C]	Initial pool water level [m]	Δp_{max} in the DN200 pipe[10] [kPa]	Δp_{max} in the pool[11] [kPa]	Δp_{max} at the pool bottom[12] [kPa]	$\Delta \varepsilon_{max}$[13] [µS]	Pool bottom vertical $a_{max.}$ [m/s^2]	Pool bottom vertical Δs_{max} [mm]
PAR-01-1	0.35	340…220	25	127…135	2.14	140 (P1) 130 (P2)	130 (P5) 50 (P7) 50 (P8)	50	30	200	0.9
PAR-01-2	0.55	500…220	31	143…136	2.16	710 140	260 120 70	70	50	260	2.8
PAR-01-3	0.75	690…280	45	155…142	2.22	500 110	240 100 70	100	70	320 (400)	4.2
PAR-02-1	0.55	510…380	25	143…138	1.80	400 120	290 130 80	100	50	320 (350)	4.1
PAR-02-2	0.75	670…340	40	154…142	1.85	550 120	240 70 80	60	40	200	3.0
PAR-03	0.55	520…350	20	145…140	2.14	400 (P1) 200 (P22)	220 (P5) 210 (P25) 100 (P7)	90	50	290	3.3
PAR-04	1.5	1330…410	33	184…156	2.20	490 100	310 470 130	120	80	370	4.9
PAR-05	0.55	520…390	50	145…140	2.14	620 70	230 310 140	70	40	300	2.5
PAR-06	1.5	1340…320	55	184…155	2.18	100 40	50 60 30	20	10	70	0.4

[8] 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.
[9] Measured by thermocouple T2102.
[10] Measured by pressure transducer P1 and P2 (P1 and P22 in PAR-03…06).
[11] Measured by pressure transducers P5, P7 and P8 (P5, P25 and P7 in PAR-03…06).
[12] Measured by pressure transducer P6.
[13] Measured by strain gauge S4.

4.1 TRA-03

In TRA-03 only the blowdown pipe 1 was used. Initial pressure of the steam source was 0.55 MPa and the initial level and temperature of pool water were 2.14 m and 20 °C, correspondingly. With this pool water level the blowdown pipe was submerged 1.05 m i.e. only the transparent part of the blowdown pipe was submerged. During the steam discharge, which lasted for 1 335 seconds, the steam flow rate decreased from 380 g/s to 150 g/s and the temperature of incoming steam from 147 °C to 136 °C, Figure 7.

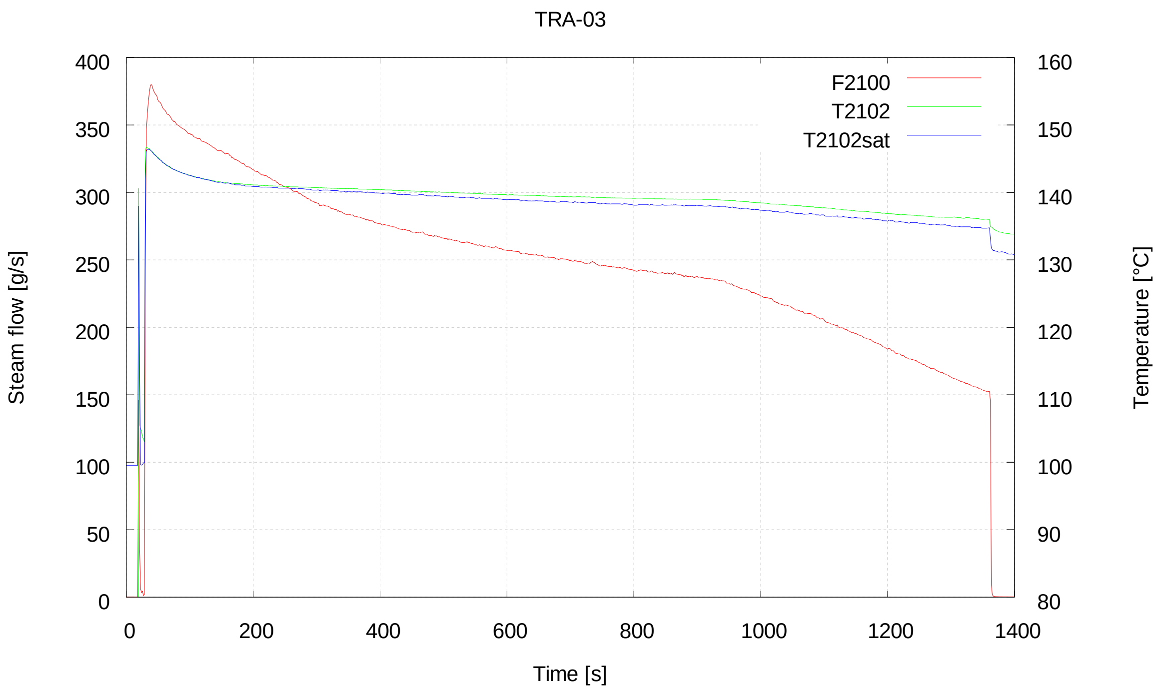

Figure 7. Flow rate (F2100) and temperature (T2102) of incoming steam in TRA-03. T2102sat is the saturated steam temperature at the flow meter.

Initially, the dry well compartment was filled with air at atmospheric pressure. After the remote-controlled shut-off valve in the steam line was opened 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 blowdown pipe downwards and after a while the pipe cleared and flow into the wet well compartment began.

First, the flow was almost pure air and condensation at the pipe outlet was very weak. As the test continued the fraction of steam in the dry well compartment increased. At 650 seconds the dry well was totally filled with steam i.e. partial pressure of steam was approximately the same as the absolute pressure in the dry well, Figure 8. Unexpectedly, the chugging condensation mode didn’t occur as intense, regular and continuous as in the preceding experiment series carried out with the DN200 stainless steel blowdown pipe, see chapter 4.4. However, in the time period from 730 to 1060 seconds one could see every now and then how steam flow pushed steam-water interface downwards in the transparent part of the blowdown pipe and steam bubbles formed at the pipe outlet. After rapid condensation, underpressure sucked water back into the pipe as it does in the characteristic cases of chugging phenomenon. Chugging occurred most intensified during the time periods from 730 to 740 (Figure 9) and from 1 014 to 1 020 seconds. From Figure 9 it can also be seen that water ingress back into the blowdown pipe after the collapse of the steam bubbles didn't reach thermocouple T2 although this was initially 50 mm below the pool water level.

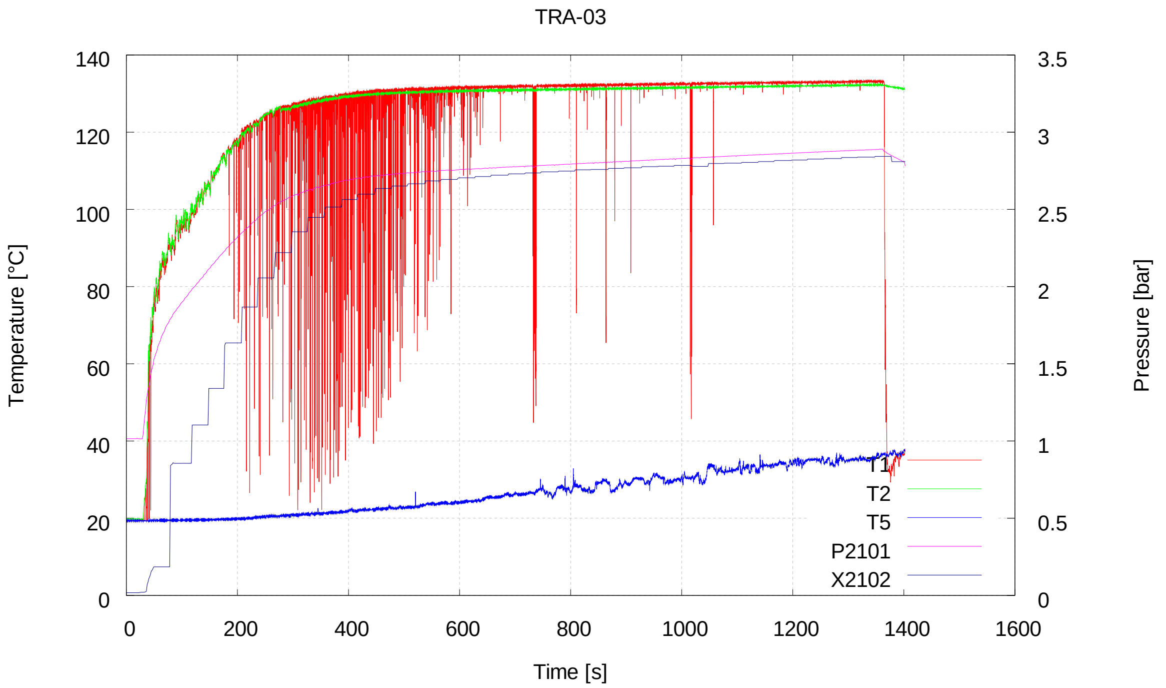

Figure 8. Temperatures inside (T1 and T2) and at the outlet (T5) of blowdown pipe 1, dry well pressure (P2101) and steam fraction pressure (X2102) in TRA-03.

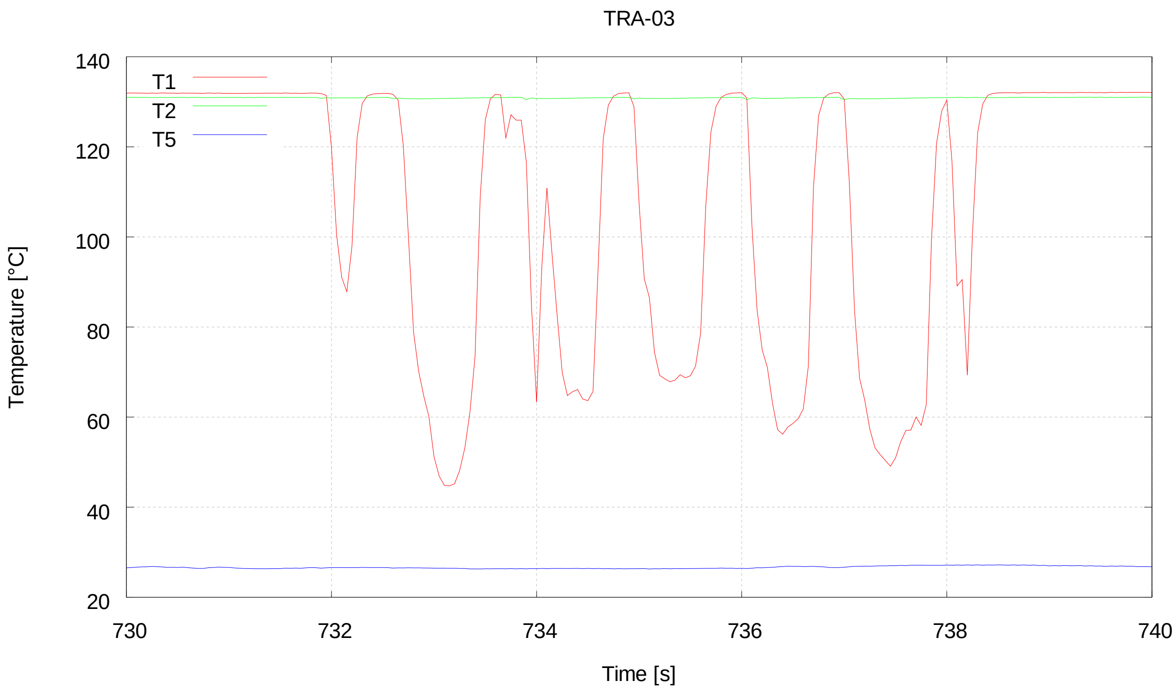

Figure 9. Temperatures inside (T1 and T2) and at the outlet (T5) of blowdown pipe 1 in TRA-03 in the time period of 730…740 seconds.

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Chugging caused dynamic loads to the pool structures. The corresponding pressure loads are registered also by the middle elevation pressure sensor (P2) inside the blowdown pipe, Figure 10. The highest pressure load is, however, measured by P5 below the blowdown pipe, Figure 11. Figure 12 shows the vertical movement of the test vessel. Also strain gauges registered loads, Figure 13.

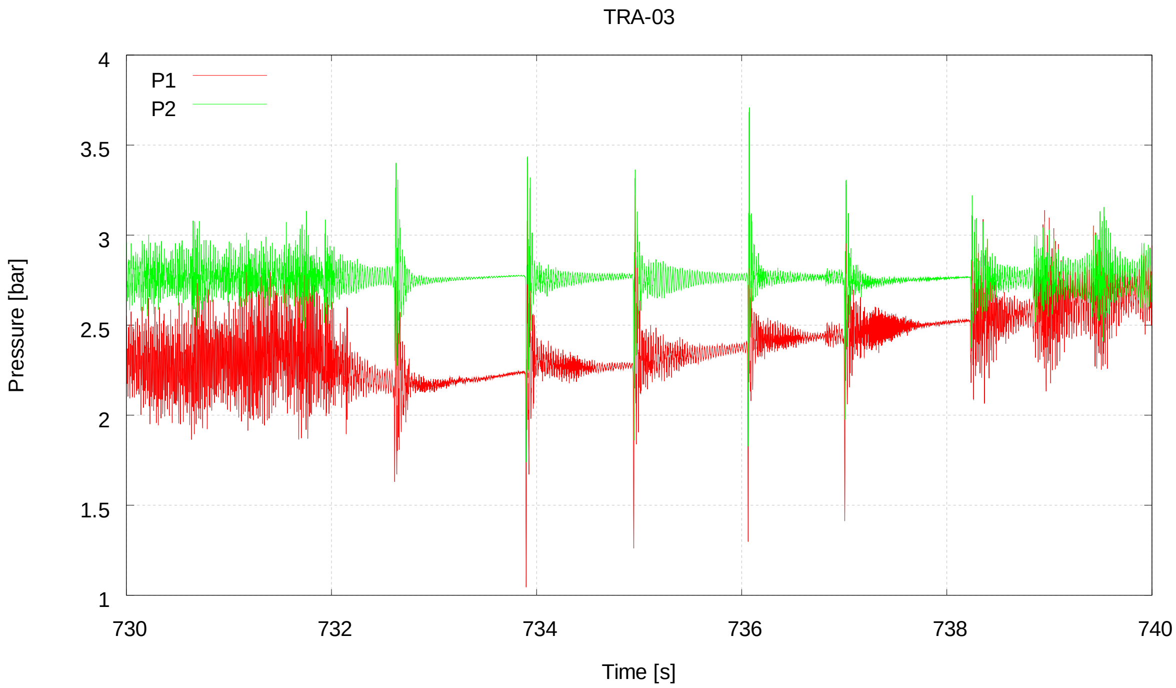


Figure 10. Pressures inside blowdown pipe 1 in TRA-03 in the time period of 730…740 seconds.

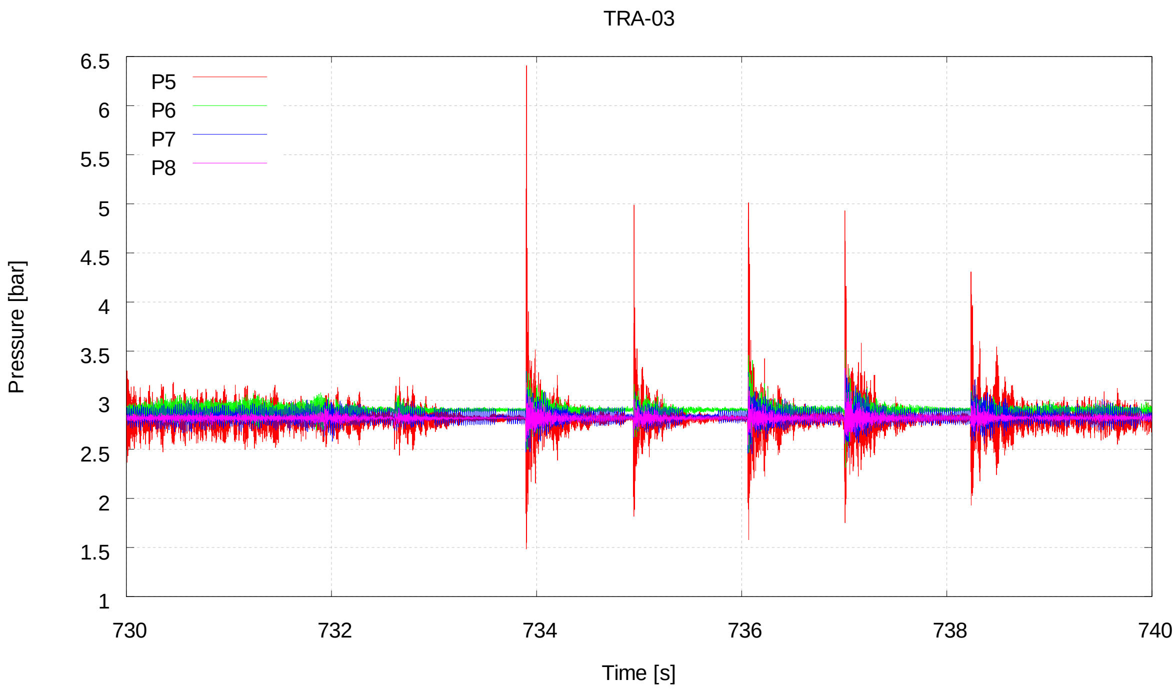


Figure 11. Pressures in the wet well pool in TRA-03 in the time period of 730…740 seconds.

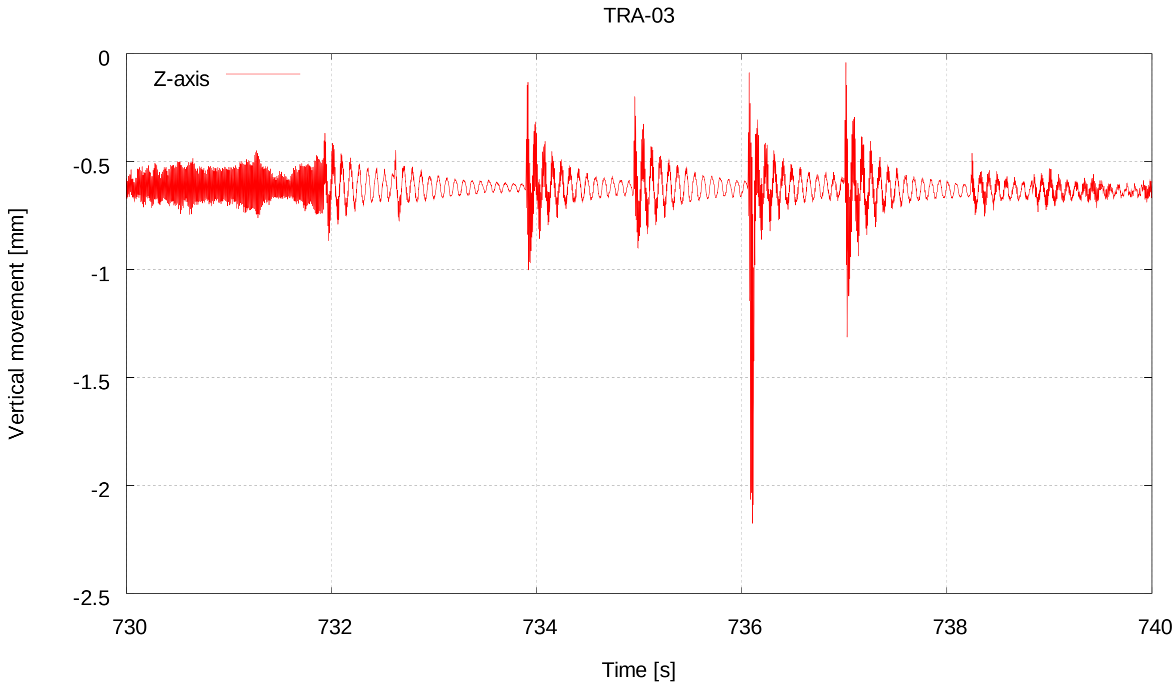


Figure 12.Vertical movement of the test vessel in TRA-03 in the time period of 730…740 seconds.

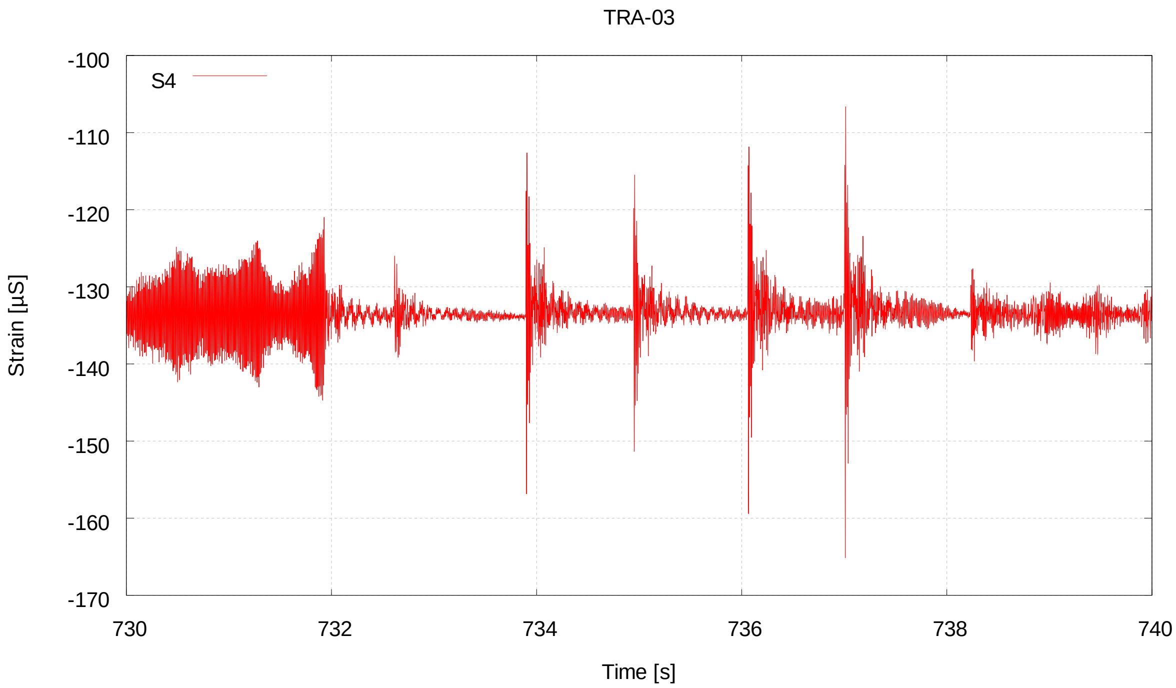


Figure 13. Strain S4 in TRA-03 in the time period of 730…740 seconds.

Figure 14 shows all six separate steam bubbles that formed at the blowdown pipe outlet in the time period from 730 to 740 seconds. The bubbles are not evenly distributed along the whole ten second period but are occurring on about a six second span.

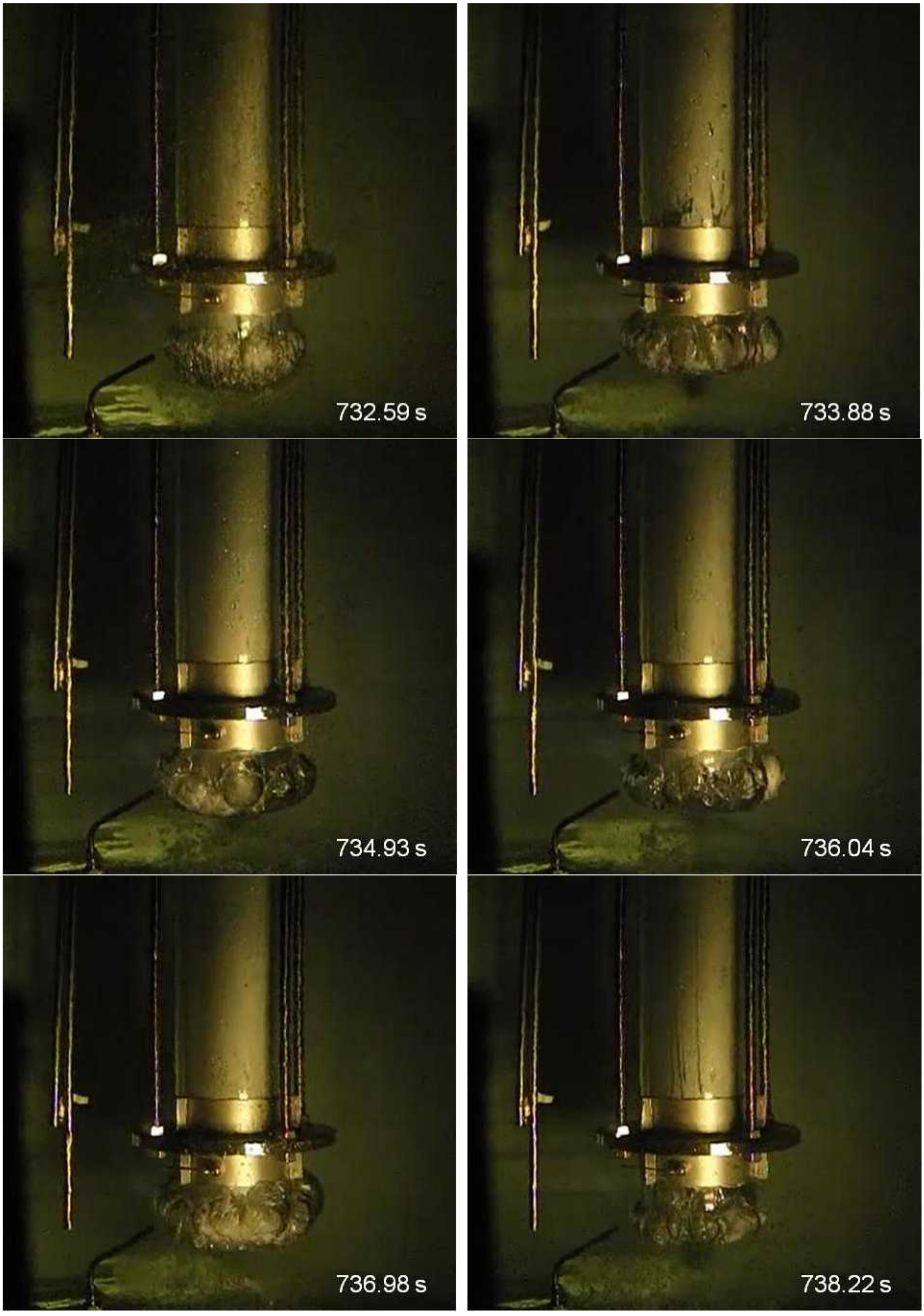


Figure 14. Steam bubbles at the blowdown pipe outlet in TRA-03 in the time period of 730…740 seconds.

4.2 TRA-05-1

In TRA-05-1, only blowdown pipe 2 was used. The experiment was carried out to find out if the blowdown pipe 2 gives significantly different test results than the blowdown pipe 1. Therefore, the initial parameters were approximately the same as in TRA-03; the pressure of the steam source was 0.5 MPa and the level and temperature of pool water 2.14 m and 25 °C, correspondingly. With this nominal pool water level the transparent part of the pipe (length 858 mm) was submerged totally and approximately 0.190 m (1.05 – 0.86 m) of the stainless steel part of the pipe was submerged too. During the steam discharge, lasting for 1 172 seconds, the steam flow rate decreased from 380 g/s to 160 g/s and the temperature of incoming steam from 144 °C to 131 °C, Figure 15.

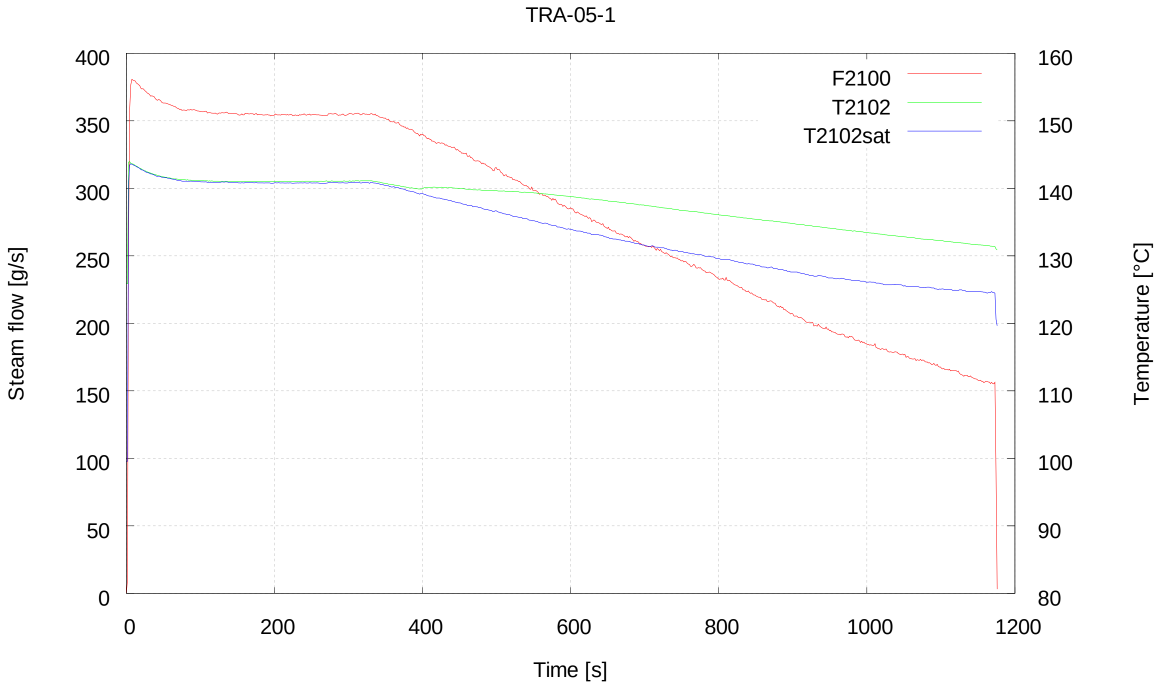


Figure 15. Flow rate (F2100) and temperature (T2102) of incoming steam in TRA-05-1. T2102sat is the saturated steam temperature at the flow meter.

The intensity of the chugging phenomenon was similar as in TRA-03, Figure 16 and Figure 17. Also, loads registered in the pool (pressure pulses, strains and vertical movement of the pool bottom) don't indicate significant differences between the tests TRA-03 and TRA-05-1, Figure 18 and Figure 19, Table 6 and Table 7. Thus, it can be concluded that the two blowdown pipes give uniform test results despite of the slightly non-identical construction.

As in TRA-03 there are periods of regular bubble formation (chugging) between the periods of no bubble formation. Figure 20 shows a 1.10 seconds interval photograph series (captured from the high speed recording of the Casio Exilim EX-F1 digital camera) from TRA-05-1 of the development and collapse of a single steam bubble at the blowdown pipe outlet.

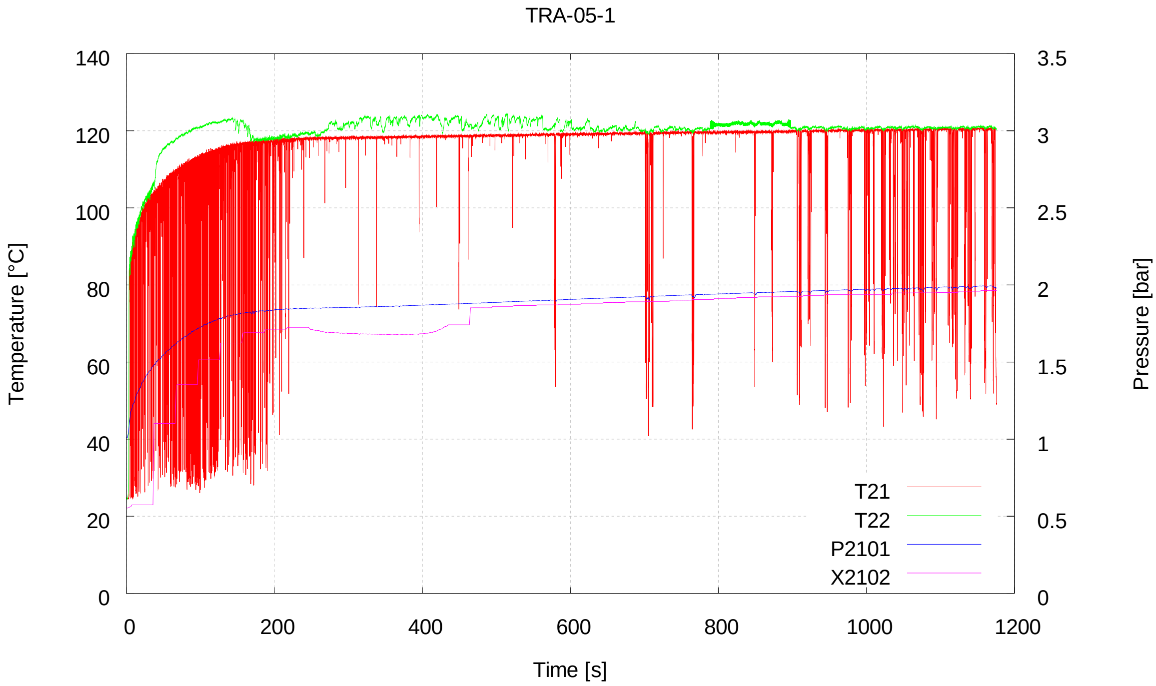


Figure 16. Temperatures inside blowdown pipe 2 (T21 and T22), dry well pressure (P2101) and steam fraction pressure (X2102) in TRA-05-1.

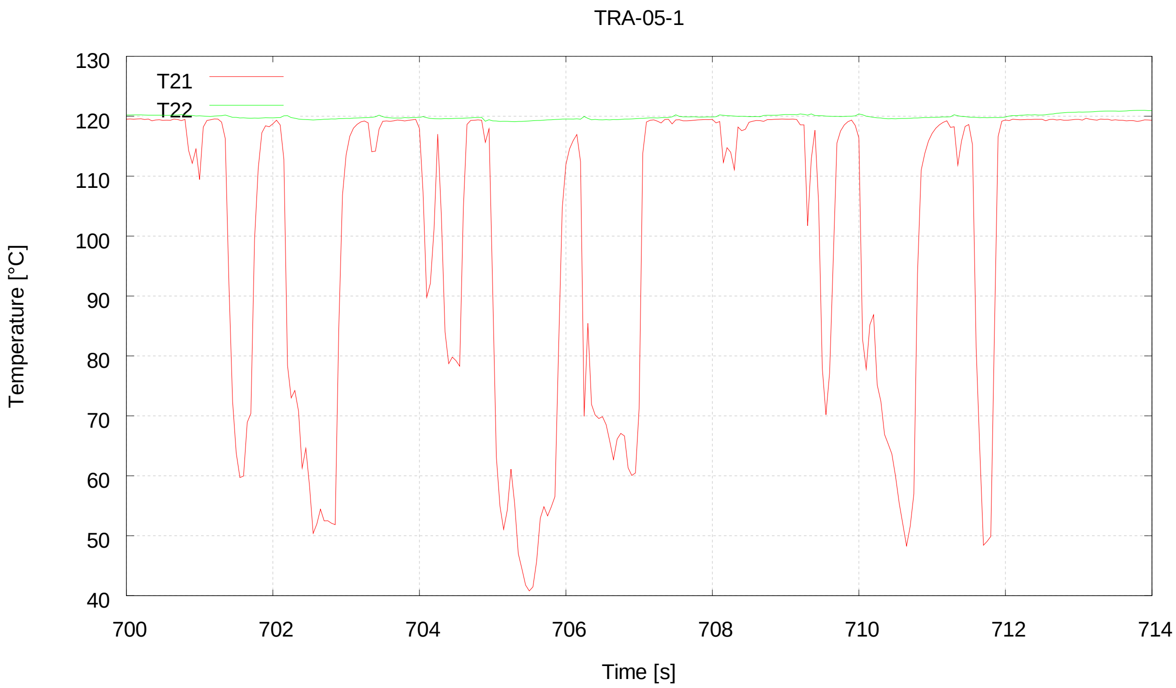


Figure 17. Temperatures inside blowdown pipe 2 in TRA-05-1 in the time period of 700…714 seconds.

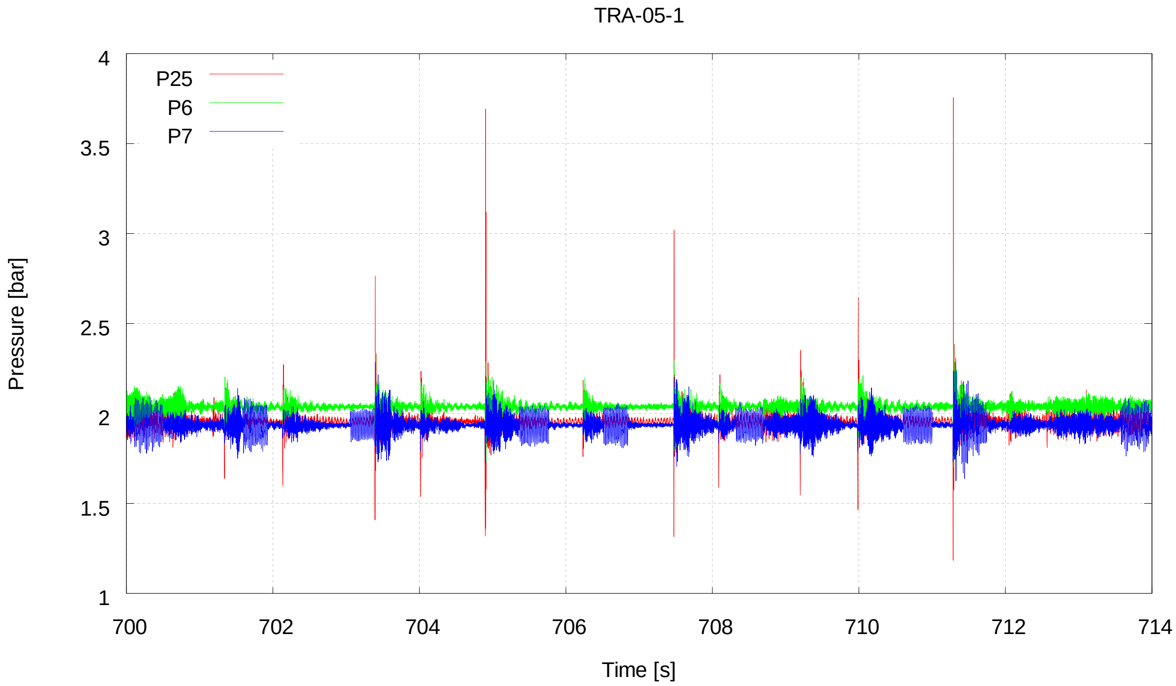


Figure 18. Pressures in the wet well pool in TRA-05-1 in the time period of 700…714 seconds.

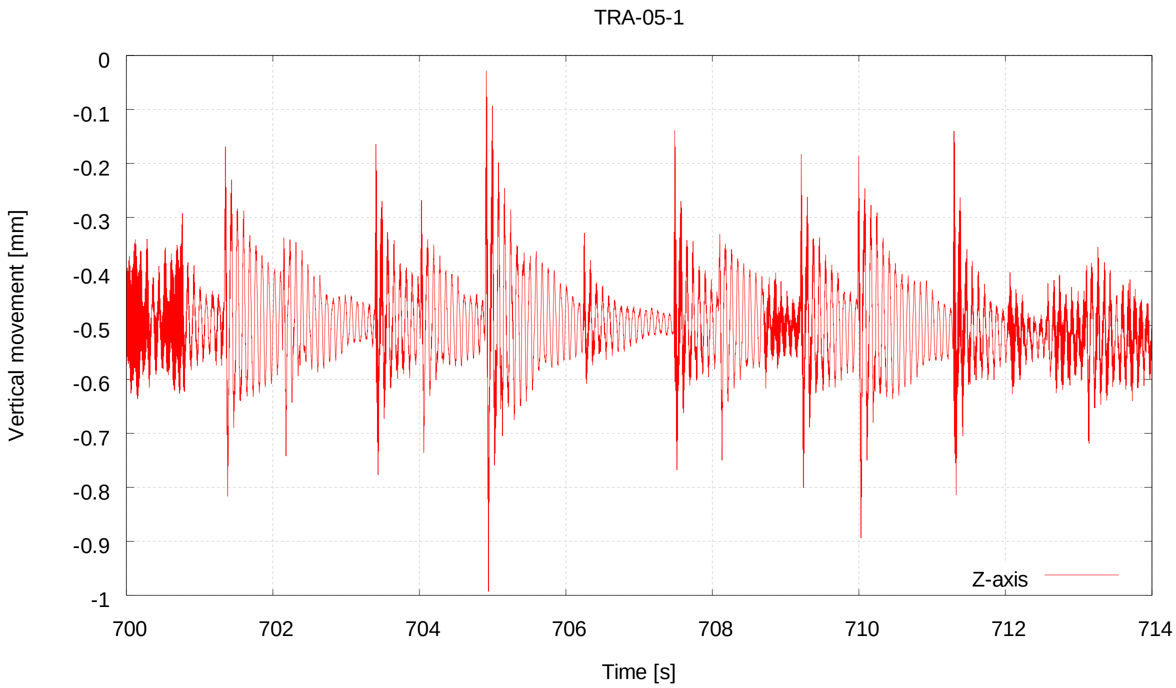
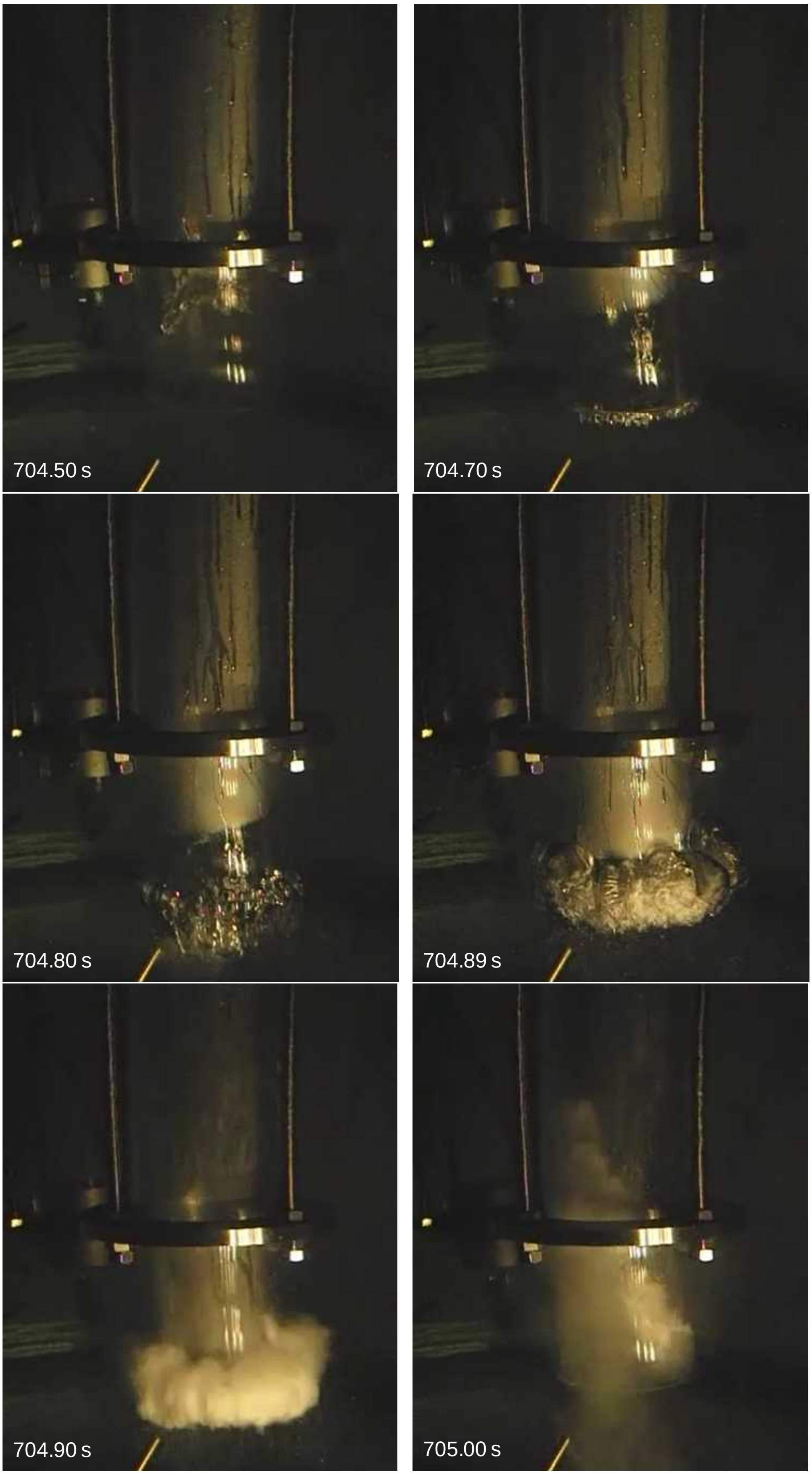


Figure 19.Vertical movement of the test vessel in TRA-05-1 in the time period of 700…714 seconds.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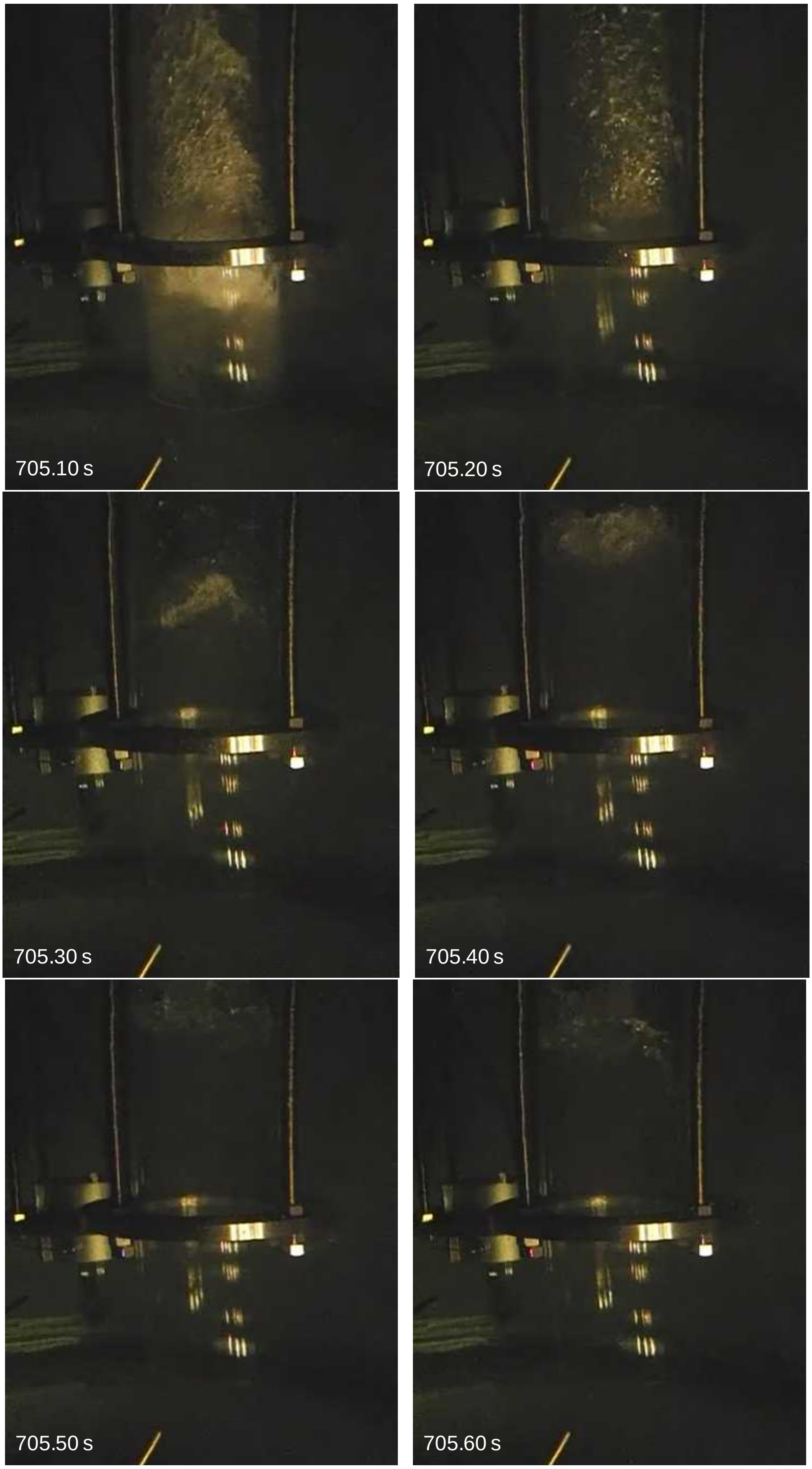

Figure 20. Development and collapse of a steam bubble at blowdown pipe 2 outlet in TRA-05-1.

4.3 PAR-03

In PAR-03 both blowdown pipes were used. The initial pressure of the steam source was 0.55 MPa and level and temperature of the pool water 2.14 m and 20 °C, correspondingly. With this pool water level the blowdown pipes were submerged 1.05 m. From blowdown pipe 1 only the lower end of the transparent part was under water. The transparent part of pipe 2 was submerged totally and approximately 0.19 m of the stainless steel part was submerged too. During the steam discharge, lasting for 691 seconds, the steam flow rate decreased from 520 g/s to 350 g/s and the temperature of incoming steam from 145 °C to 140 °C, Figure 21.

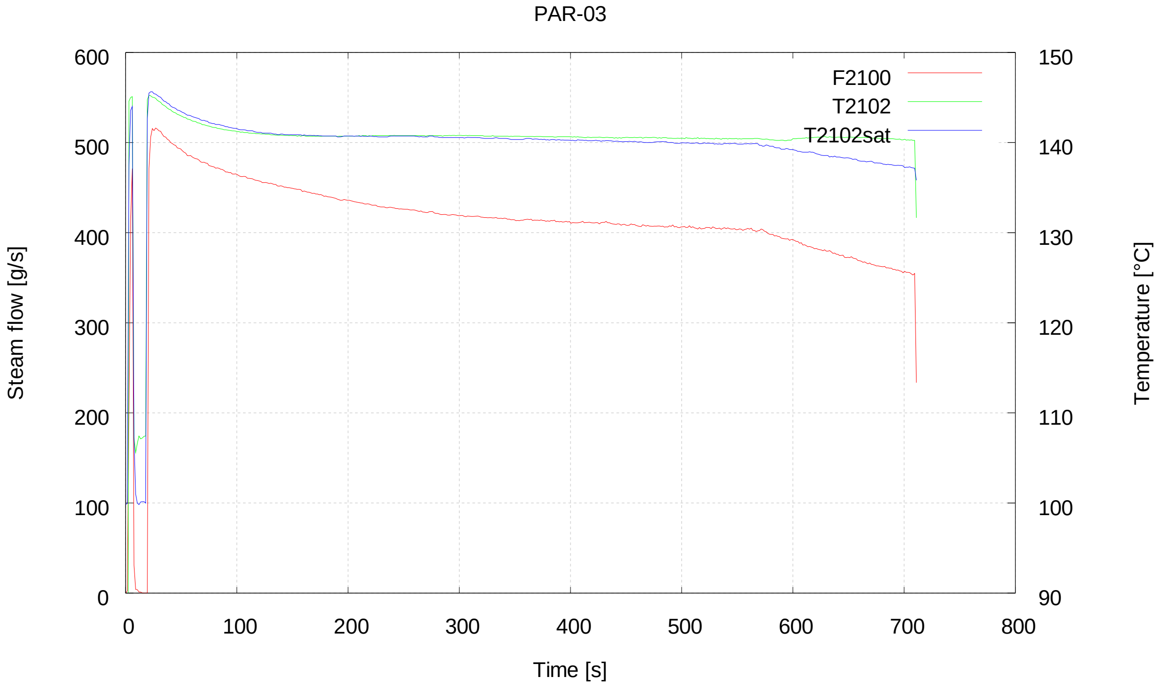

Figure 21. Flow rate (F2100) and temperature (T2102) of incoming steam in PAR-03. T2102sat is the saturated steam temperature at the flow meter.

During the PAR-03 experiment chugging phenomenon occurred more intensified than in the experiments with only one transparent blowdown pipe, Figure 22 and Figure 23. Also water ingress back into the pipe after the collapse of steam bubbles was registered few times by thermocouples T2 and T22. The steam-water interface moved up and down almost synchronously inside both pipes, Figure 24. From Figure 24 it can also be seen that temperatures were at the same level in both pipes in the corresponding measurement points (T1 vs. T21 and T2 vs. T22) despite of the slight differences in the pipe constructions. More than two times higher pressure pulses were measured inside the blowdown pipes than during the TRA experiment series, Figure 25. Meanwhile, registered pressure loads at the blowdown pipe outlet were approximately in the same range as during the TRA series, Figure 26. Other registered loads in the pool were approximately 50–100 % higher than during the TRA series.

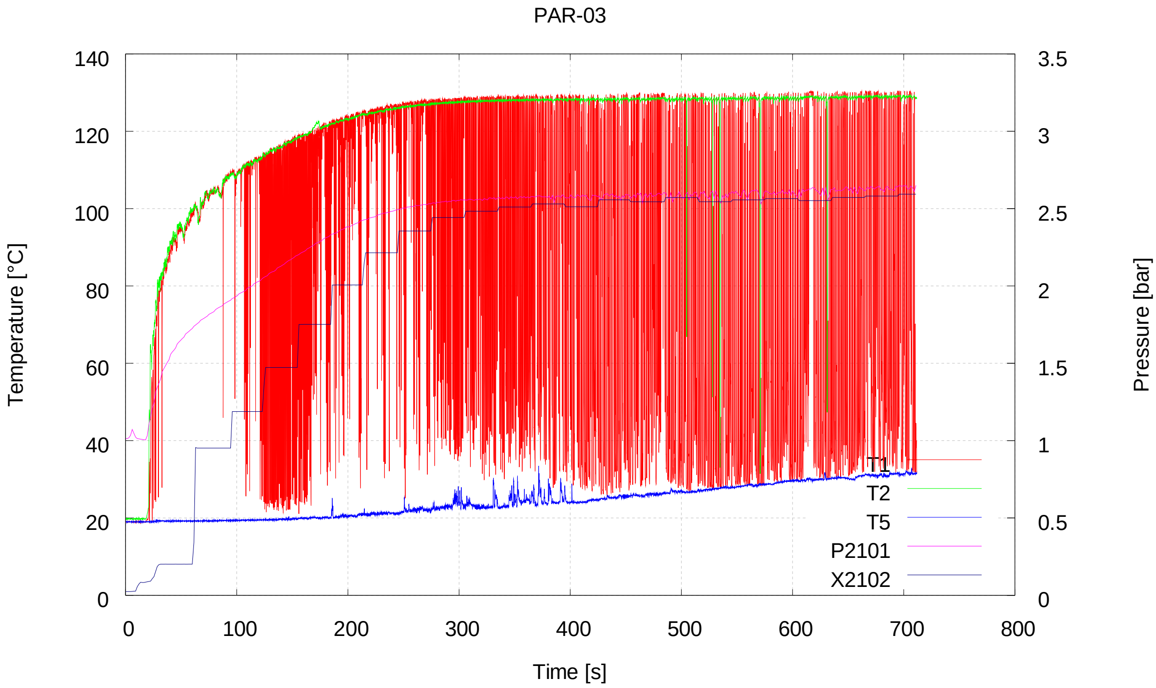

Figure 22. Temperatures inside (T1 and T2) and at the outlet (T5) of blowdown pipe 1, dry well pressure (P2101) and steam fraction pressure (X2102) in PAR-03.

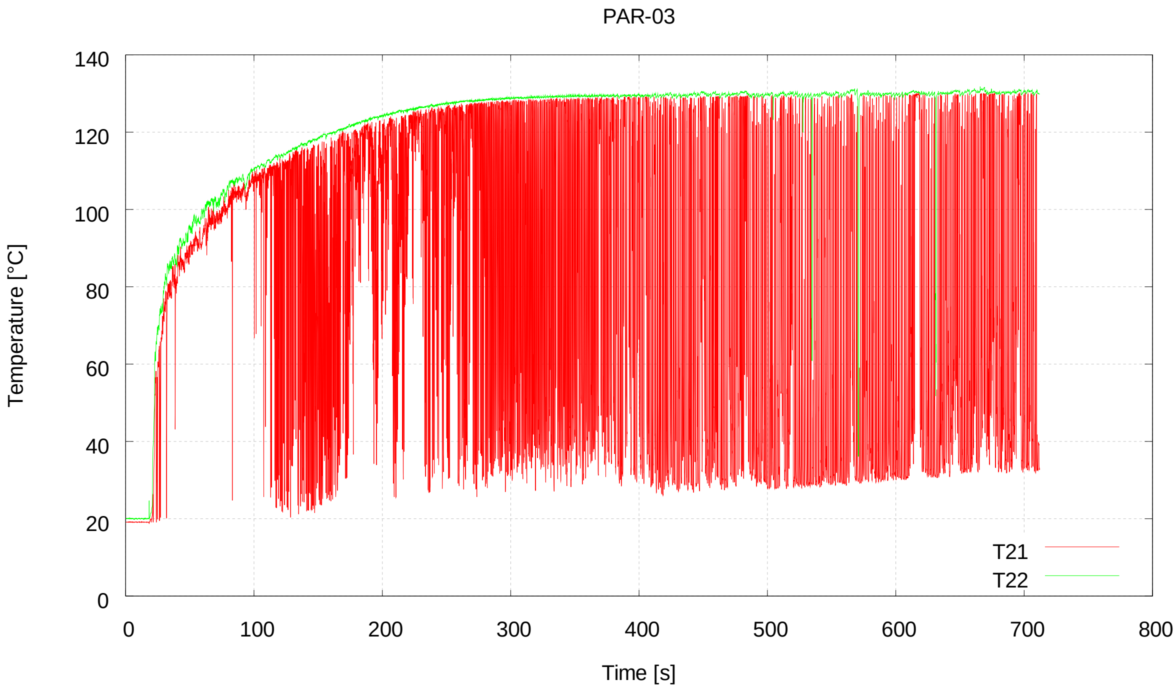

Figure 23. Temperatures inside blowdown pipe 2 (T21 and T22) in PAR-03.

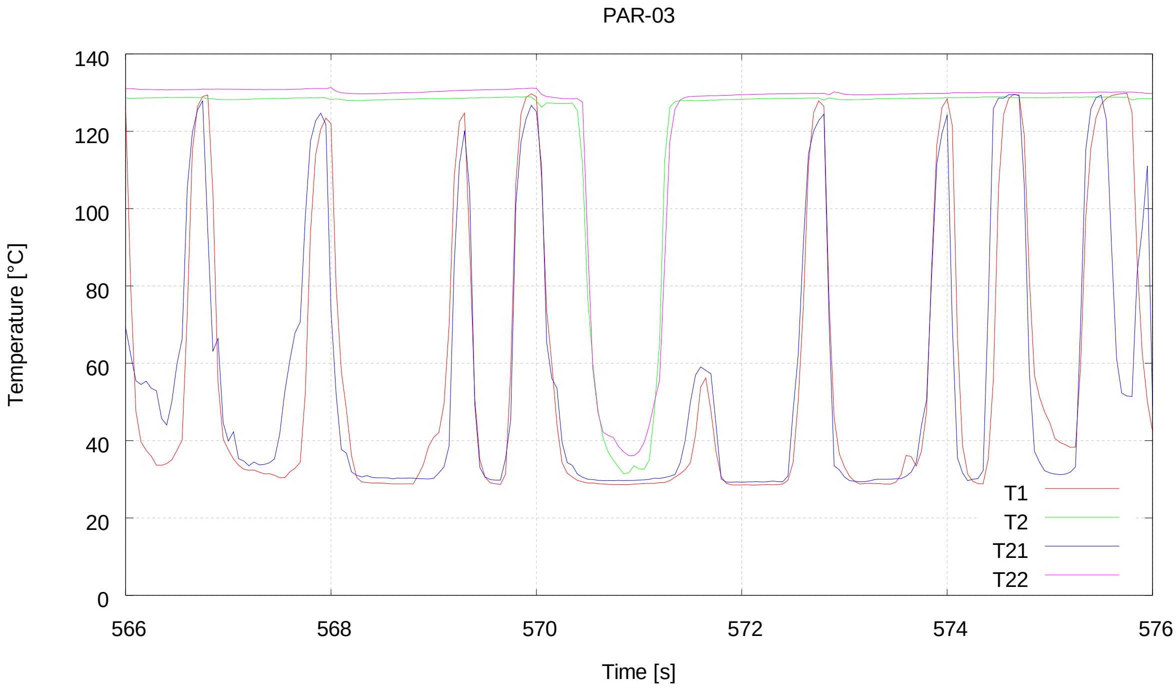

Figure 24. Temperatures in blowdown pipe 1 (T1 and T2) and 2 (T21 and T22) in the time period of 566…576 seconds in PAR-03.

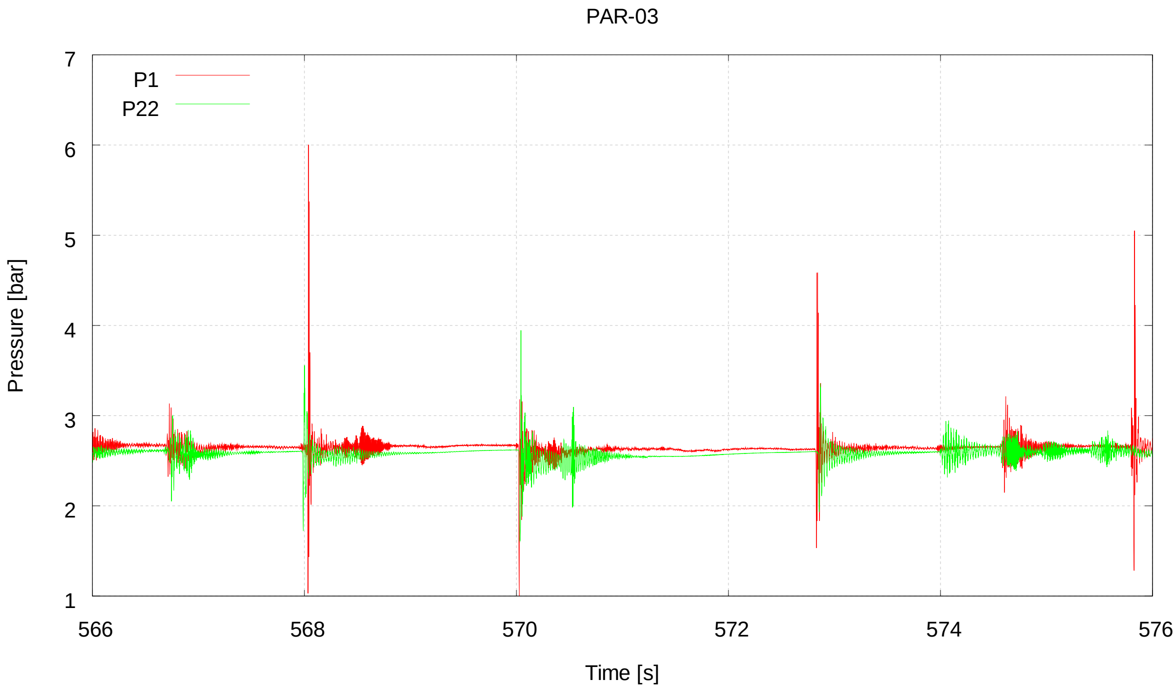

Figure 25. Pressure in blowdown pipe 1 (P1) and 2 (P22) in the time period of 566…576 seconds in PAR-03.

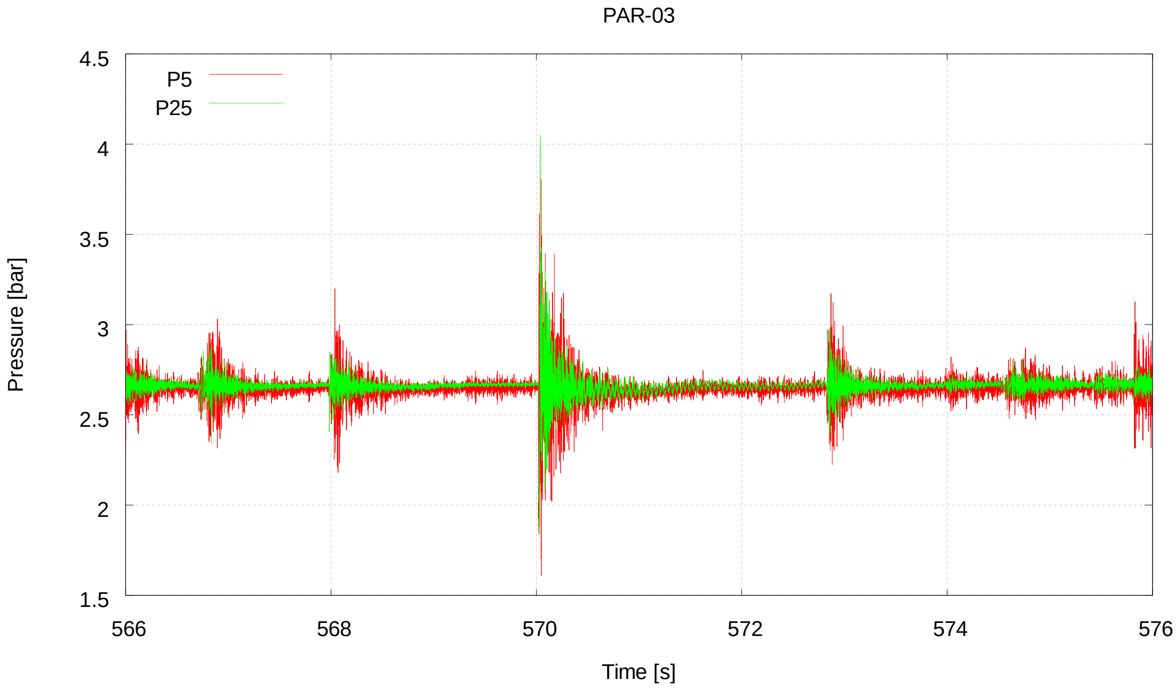

Figure 26. Pressure in blowdown pipe 1 outlet (P5) and pipe 2 outlet (P25) in the time period of 566…576 seconds in PAR-03.

4.4 COMPARISON TO THE PREVIOUS PPOOLEX EXPERIMENTS

During the TRA and PAR experiments chugging phenomenon didn't occur as intensified as in the several preceding experiment series carried out with the PPOOLEX facility using a DN200 stainless steel blowdown pipe. 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 (COL experiment series) [5]. During that experiment series four reference experiments with a straight DN200 stainless steel pipe were carried out (labeled from COL-01 to COL-04), Table 8. These experiments are also the most suitable to be used as reference cases when comparing the behavior between the single polycarbonate and steel blowdown pipes. Some differences in the test parameters between the compared experiments do exist, mainly concerning the steam mass flow rate, but the deviations is considered to be acceptable.

Table 8. Main parameters during COL-01…04 experiments [5].

Test	Initial pressure of steam generator [MPa]	Steam flow rate[14] [g/s]	Temperature of incoming steam[15] [°C]	Collar in use [Yes/No]	Δp_{max} in the DN200 pipe[16] [kPa]	Δp_{max} in the pool[17] [kPa]	Δp_{max} at the pool bottom[18] [kPa]	$\Delta \varepsilon_{max}$[19] [µS]	Pool bottom vertical $\lvert a \rvert_{max.}$ [m/s²]	Pool bottom vertical Δs_{max} [mm]
COL-01	0.55	440…430	144	No	1600 (P1) 200 (P2)	270 (P5) 110 (P7) 80 (P8)	100	50	250	2.9
COL-02	1.5	600…560	161…159	No	390 90	>300[20] 80 60	70	35	180	0.8
COL-03	0.55	430…420	143	No	100 50	70 30 20	20	15	60	0.3
COL-04	1.5	630…540	163…160	No	50 20	40 20 10	20	5	20	0.5

In COL-01 the initial pressure of the steam source was 0.55 MPa and the initial level and temperature of the pool water 2.14 m and 20 °C, correspondingly. During the experiment the used recording frequency of the data acquisition system was 10 kHz and therefore only a short interval of the chugging period was recorded with the LabView measurement system to avoid too excessive amount of data. In that period steam flow rate was 440…430 g/s.

It seems that during the recorded interval of the reference experiment chugging phenomenon occurred more intensified than in the TRA experiment series. The movement of the steam/water interface inside the blowdown pipe, particularly at the lower end, was dynamic and unceasing, Figure 27. With the single transparent pipe such continuous period of intense movement of the interface and repeated formation of steam bubbles at the pipe outlet (chugging) does not exist during the pure steam discharge, see for example Figure 8. In COL-01 the maximum registered pressure pulse inside the blowdown pipe was even 1 600 kPa which is approximately 10 times higher than during the TRA series, Figure 28. A logical explanation for this could found from the pipe material. The material of the transparent pipe, polycarbonate, has two orders of magnitude smaller thermal conductivity than steel. Heat transfer from steam to pool water through the blowdown pipe wall is much smaller and therefore condensation process inside the pipe weaker.

Meanwhile, loads registered in the water pool do not indicate significant differences between the TRA and COL experiment series, Figure 29….Figure 31. The highest pressure pulses as well as strains are of the same order of magnitude in both experiment series. Furthermore, the vertical movement and acceleration of the pool bottom do not differ from each other in the TRA and COL series. 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 (rapid condensation of steam) are in some respect local and their influence is not

[14] 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.
[15] Measured by thermocouple T2102.
[16] Measured by pressure transducers P1 and P2.
[17] Measured by pressure transducers P5, P7 and P8.
[18] Measured by pressure transducer P6.
[19] Measured by strain gauge S4.
[20] Measurement range of pressure transducer P5 was exceeded.

so strong in the water pool. They do have a connection to the pool behavior through the steam bubbles forming and collapsing at the pipe outlet but the blowdown pipe itself acts as a shielding and suppressing structure.

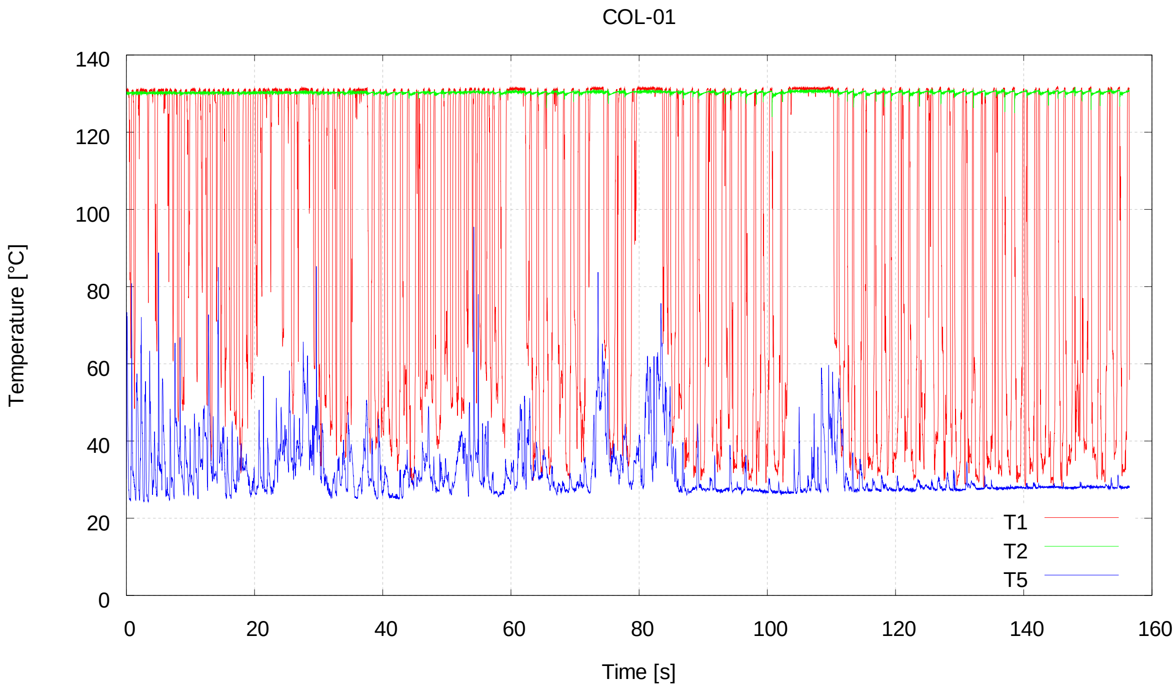

Figure 27. Temperatures inside (T1 and T2) and at the outlet (T5) of the blowdown pipe in COL-01.

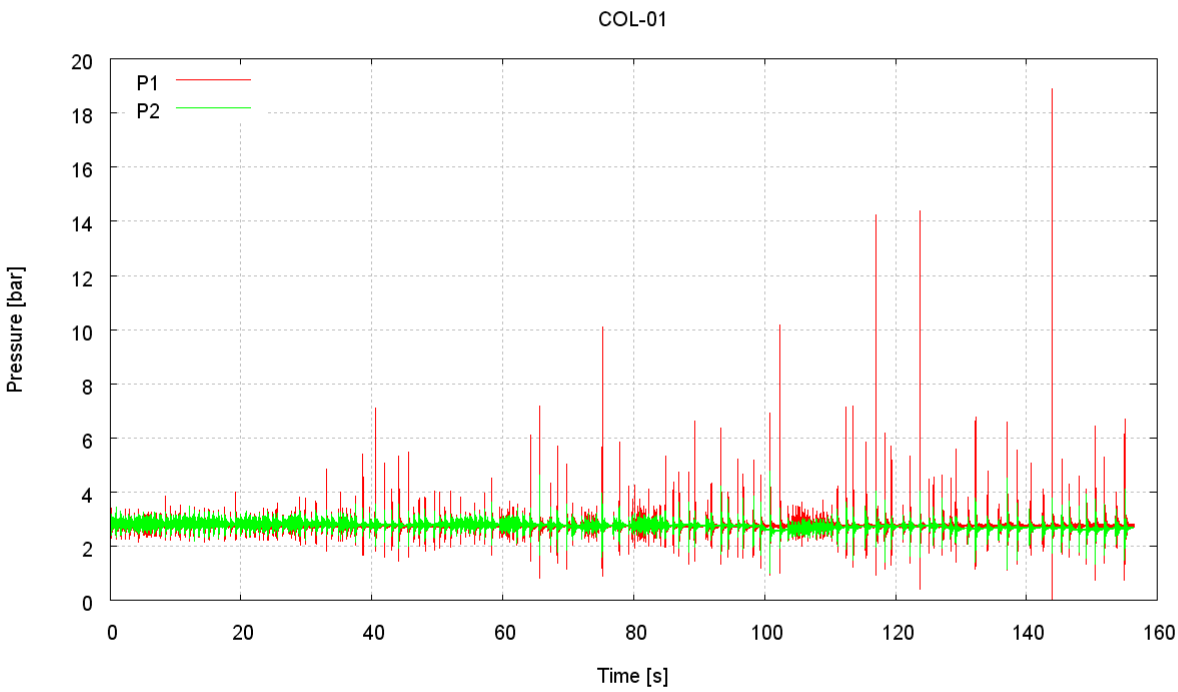

Figure 28. Pressures in the blowdown pipe in COL-01.

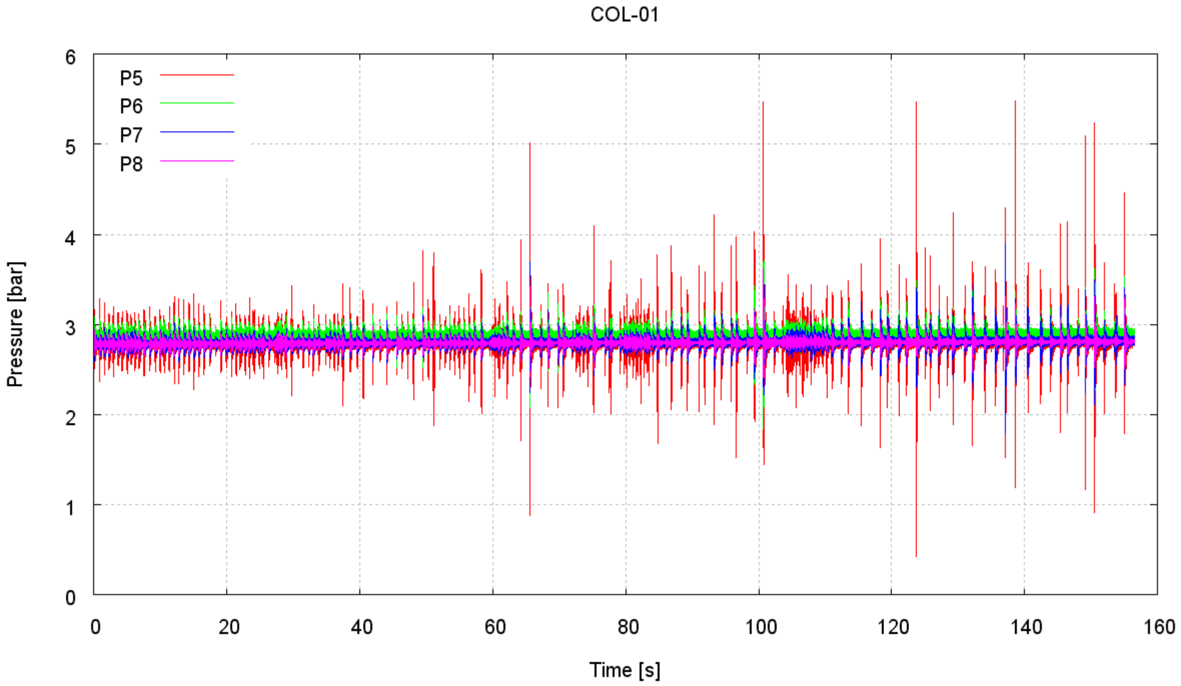

Figure 29. Pressures in the wet well compartment in COL-01.

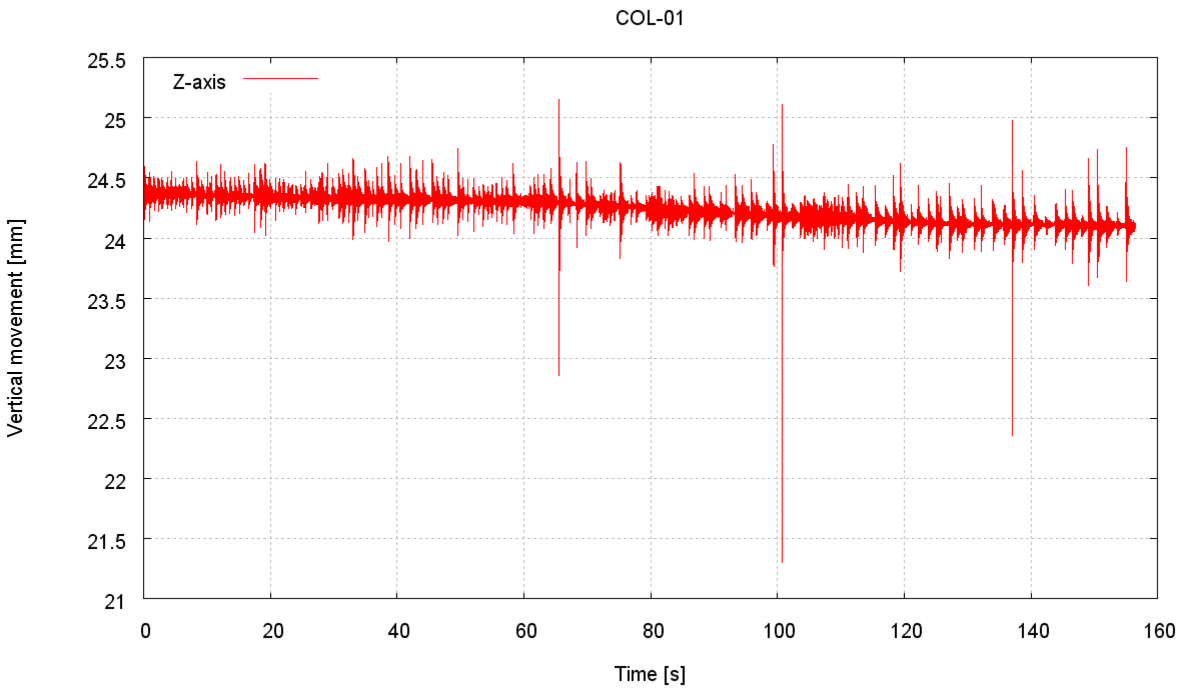

Figure 30.Vertical movement of the test vessel in COL-01.

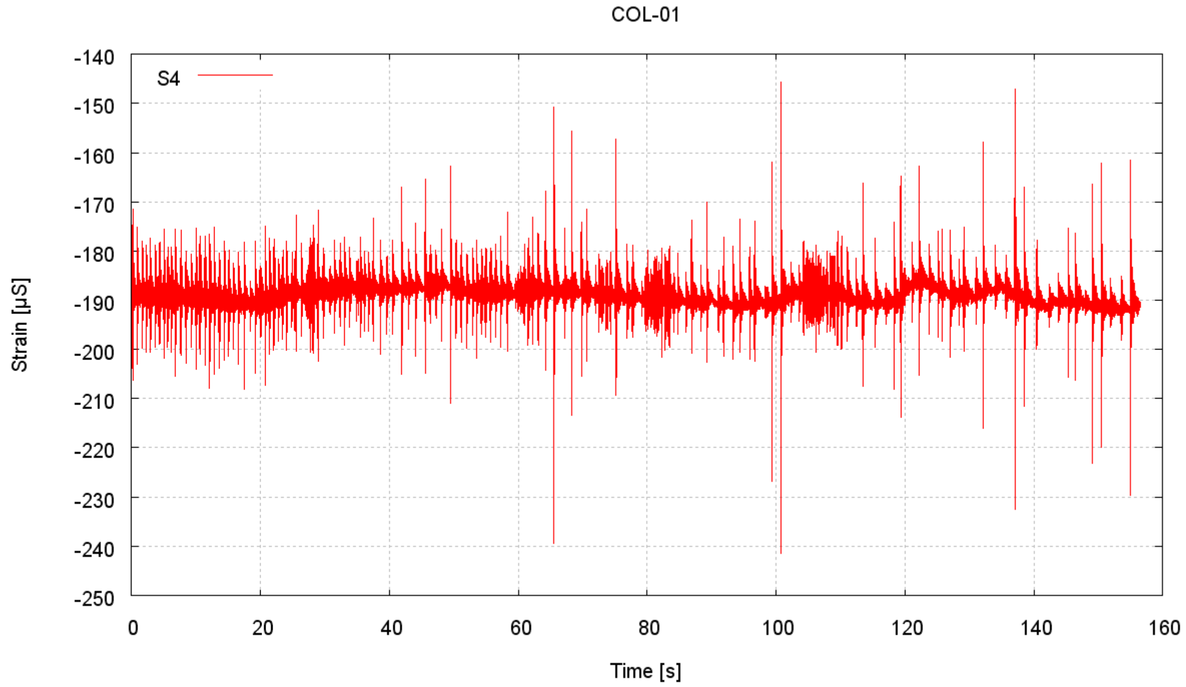

Figure 31. Strain S4 in COL-01.

5 SUMMARY AND CONCLUSIONS

This report summarizes the results of the experiments with two transparent 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 either one or two vertical transparent blowdown pipes to the condensation pool. Five experiments with one blowdown pipe and six experiments with two parallel blowdown pipes were carried out.

The PPOOLEX test facility is a closed stainless steel vessel divided into two compartments, dry well and wet well. The lower parts of the DN200 blowdown pipes (Ø219.1x2.5) were machined from a transparent polycarbonate pipes (Ø200x5.0) and equipped with temperature and pressure measurements. During the experiments the initial temperature of the condensation pool water varied from 12 °C to 55 °C, the steam flow rate from 40 g/s to 1 300 g/s and the temperature of incoming steam from 120 °C to 185 °C. During the experiments the data acquisition system recorded data with a frequency of 1 kHz. A digital high-speed video camera was used for accurate observation of steam bubbles at the blowdown pipe outlet and steam-water interface inside the transparent blowdown pipes. A system for sound velocity measurement, to determine the void fraction of the pool volume, was supposed to be used in these experiments but it was not delivered in time by the manufacture.

The main purpose of the experiment series was to study chugging phenomena (rapid condensation) while steam is discharged through two blowdown pipes into the condensation pool filled with sub-cooled water. Particularly, the aim was to study how structural loads due to pressure oscillations induced by chugging differ in a multiple pipe case from 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.

When the chugging condensation mode was dominating, steam flow pushed the steam-water interface downwards inside the transparent blowdown pipes and steam bubbles formed at the pipe outlets. After rapid condensation, underpressure sucked water back into the pipes. Chugging caused dynamic loads to the pipe and pool structures. Polycarbonate proved to be durable enough material against the dynamic loads caused by chugging phenomenon in this kind of experimental arrangement.

In the experiments with two transparent blowdown pipes, the steam-water interface moved almost synchronously up and down inside both pipes. Chugging phenomenon was stronger than in the one pipe experiments and even two times higher loads were measured inside the pipes. Meanwhile, registered pressure loads at the blowdown pipe outlet were approximately the same as in the one pipe cases. Other registered loads around the pool were approximately 50–100 % higher than with one pipe. The synchronization of the pressure oscillations in the blowdown pipes probably resulted from a strong coupling between the two pipes and between the pipes and the dry well. This strong coupling in the PPOOLEX facility is due to the reduced dry well volume per blowdown pipe if compared to the full scale experimental arrangements. Furthermore, there are no any internal structures or walls in the dry well to decrease the coupling between the pipes.

During the experiments with only one transparent blowdown pipe chugging phenomenon didn’t occur as intensified as in the preceding experiment series carried out with a DN200 stainless steel blowdown pipe. With the steel pipe even 10 times higher individual pressure pulses were registered inside the blowdown pipe. Meanwhile, loads registered in the pool (pressure pulses, strains and vertical movement of the pool bottom) didn’t indicate significant differences between the test series with the steel and transparent pipe. The pipe material seemed to have an effect on the condensation process inside the pipe. The material of the transparent pipe, polycarbonate, has two orders of magnitude smaller thermal conductivity than steel. Heat transfer from steam to pool water through the blowdown pipe wall is much smaller and therefore condensation process inside the pipe weaker.

In summary it can be said that the experiments with two parallel blowdown pipes gave contradictory results compared to the previous studies dealing with chugging loads in case of multiple pipes. It was expected that loads with two pipes would be smaller than with a single pipe. However, the results from the PPOOLEX experiments indicate that loads inside the pipe are higher with two pipes than with one pipe. On the other hand, loads at the pipe outlet are on the same level in both cases. Elsewhere in the pool loads are again higher with two pipes. Contributing factors to the contradictory results compared to the earlier studies may be the smaller dry well volume per blowdown pipe ratio and the lack of dry well internal structures in the PPOOLEX facility. To exclude the possible effect of the used pipe material, polycarbonate, on the results a new experiment series with multiple steel blowdown pipes have been planned for 2010.

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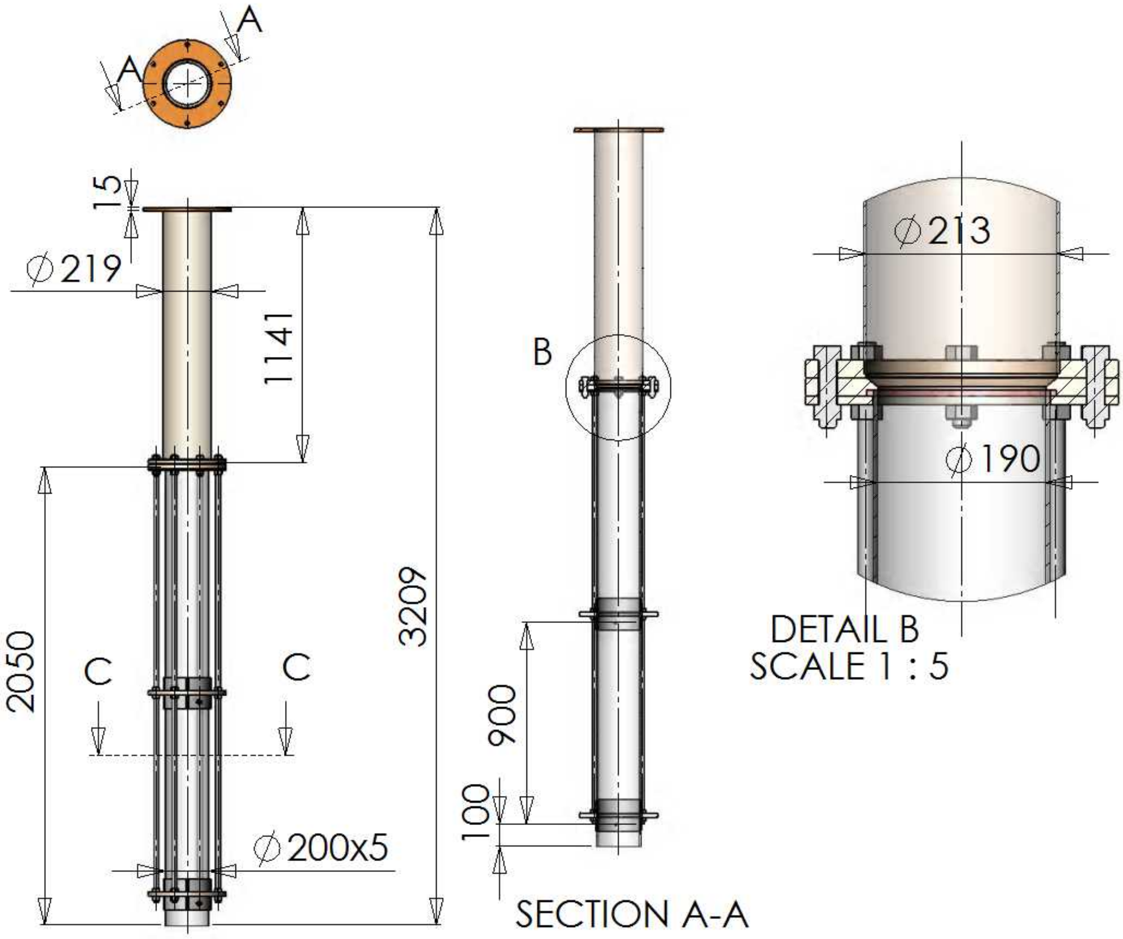
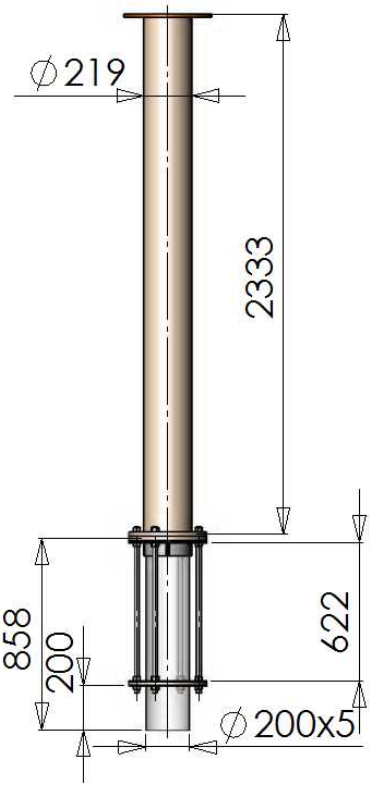
APPENDIX 1: DRAWINGS OF THE BLOWDOWN PIPES

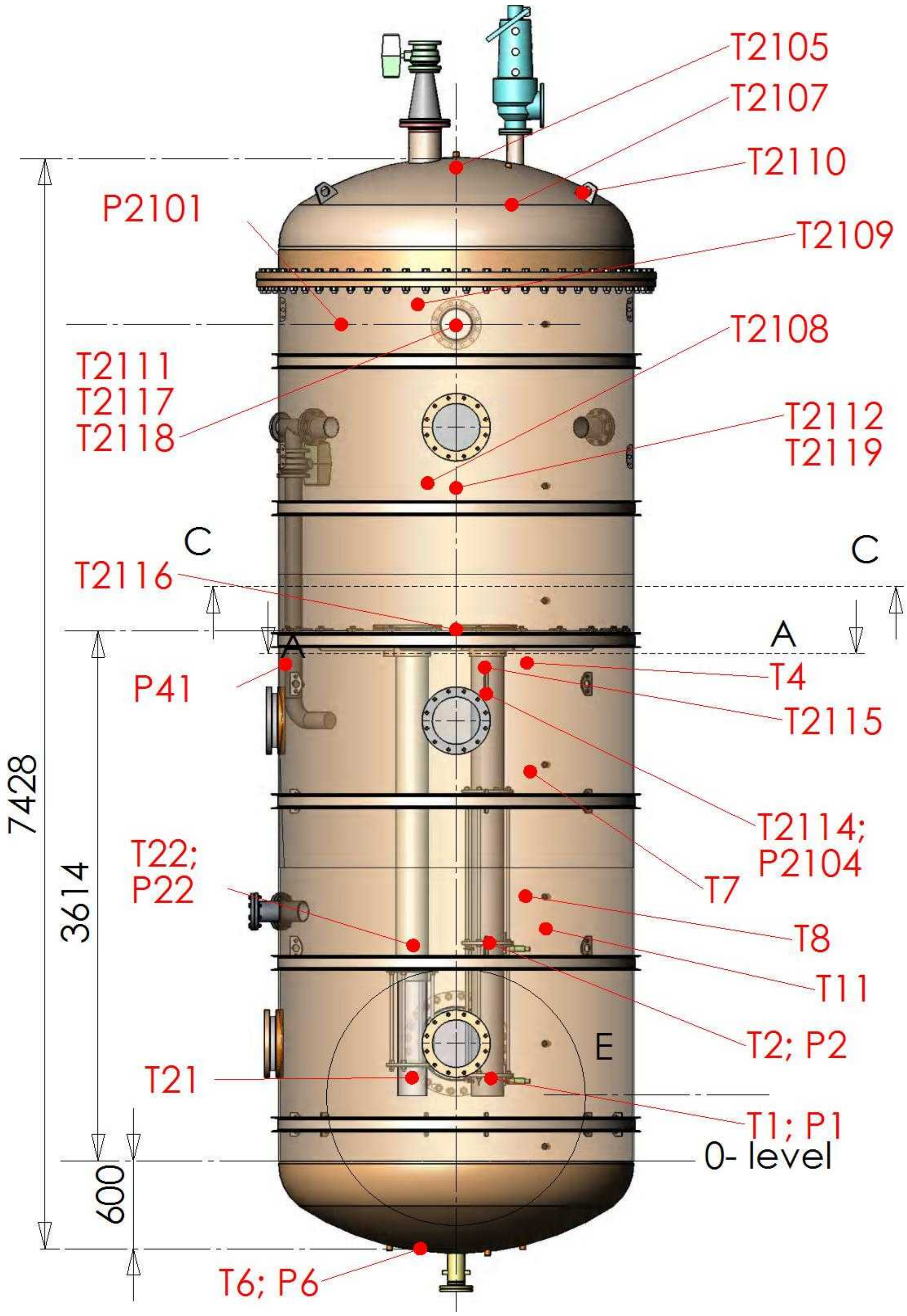


Dimensioning of the blowdown pipe 1.

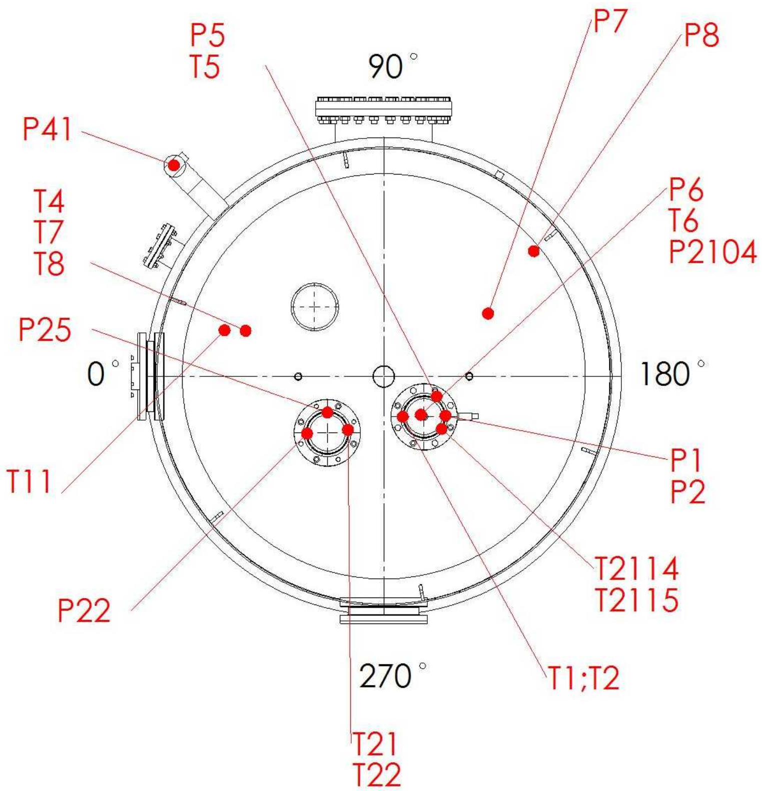


Dimensioning of the blowdown pipe 2.

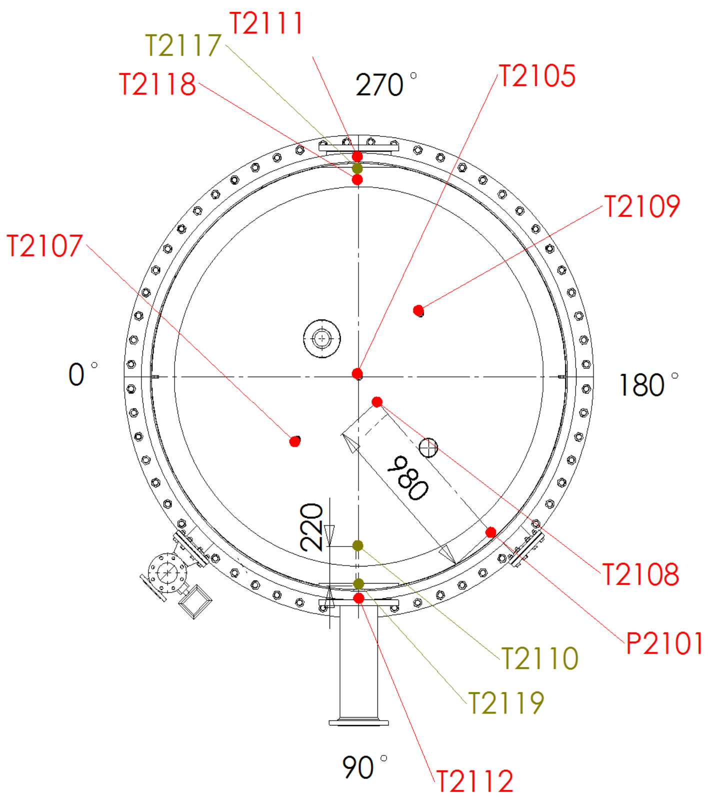
APPENDIX 2: INSTRUMENTATION OF THE PPOOLEX TEST FACILITY



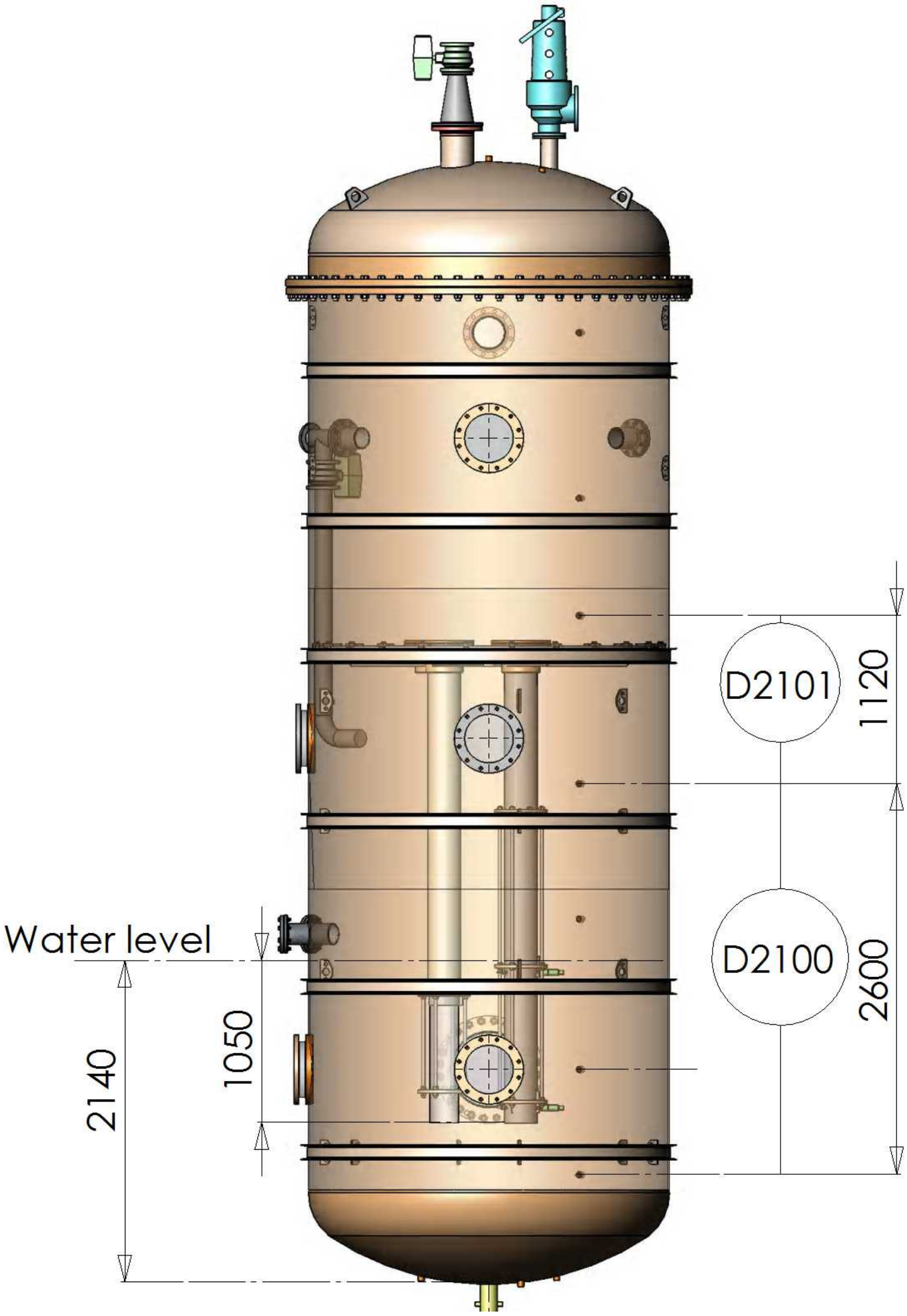
Test vessel measurements.



Cross-section A-A.



Cross-section C-C.



Pressure difference measurements. Water level is at the nominal value of 2.14 m.

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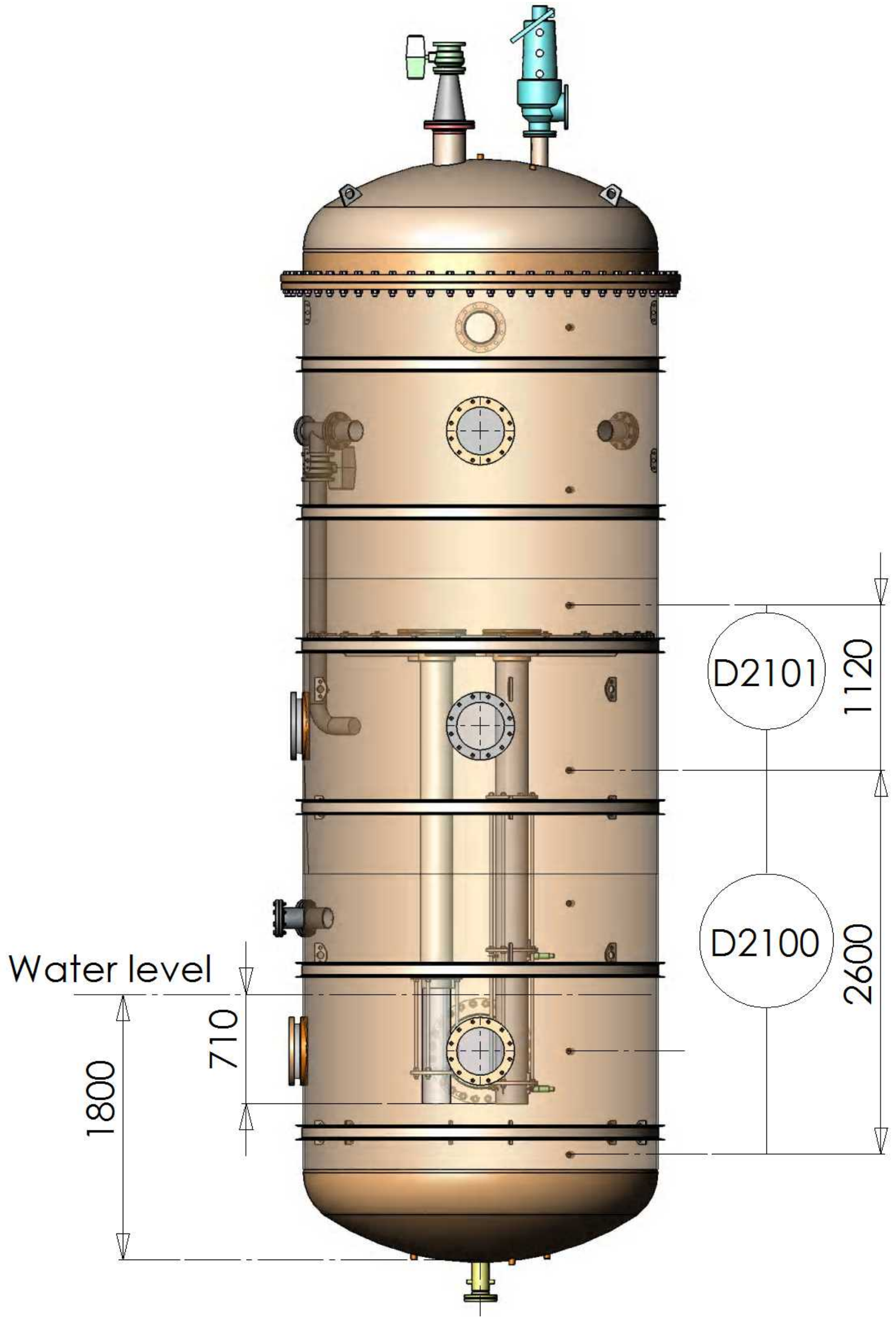
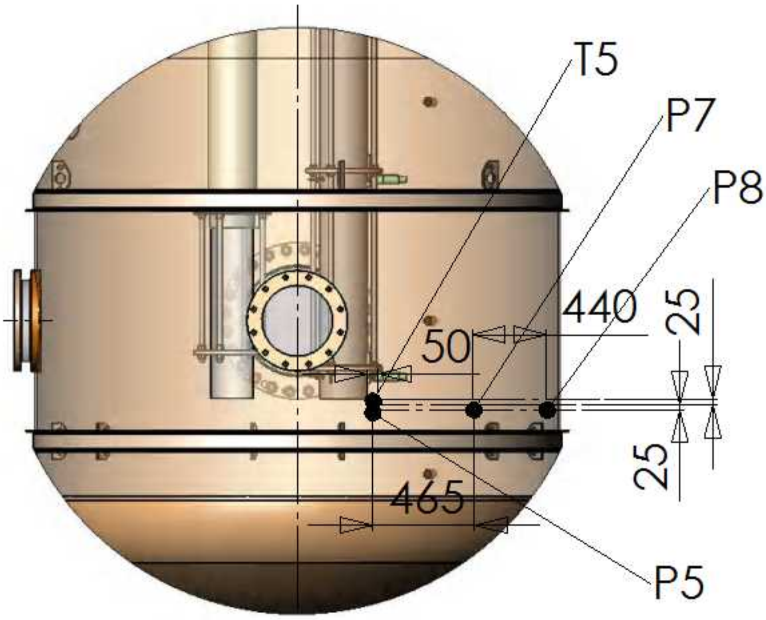
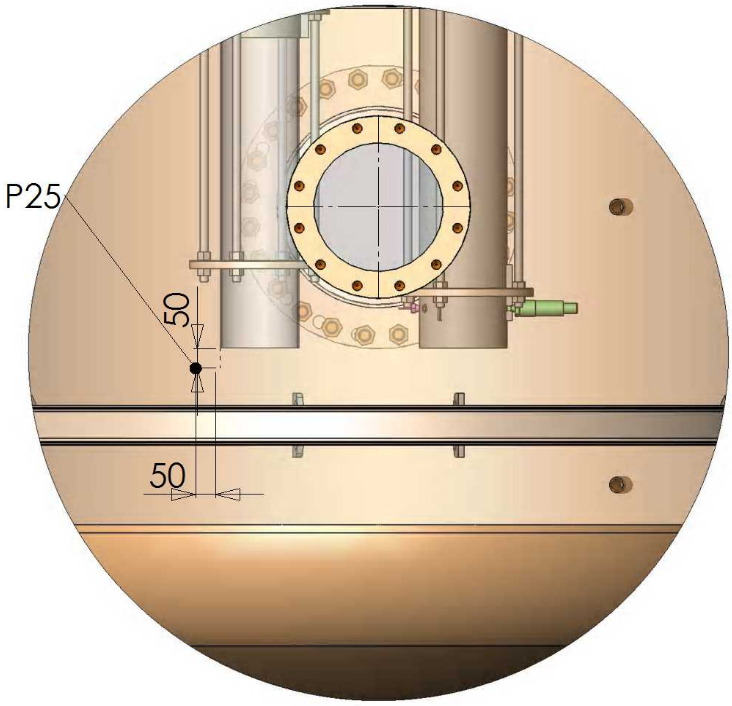


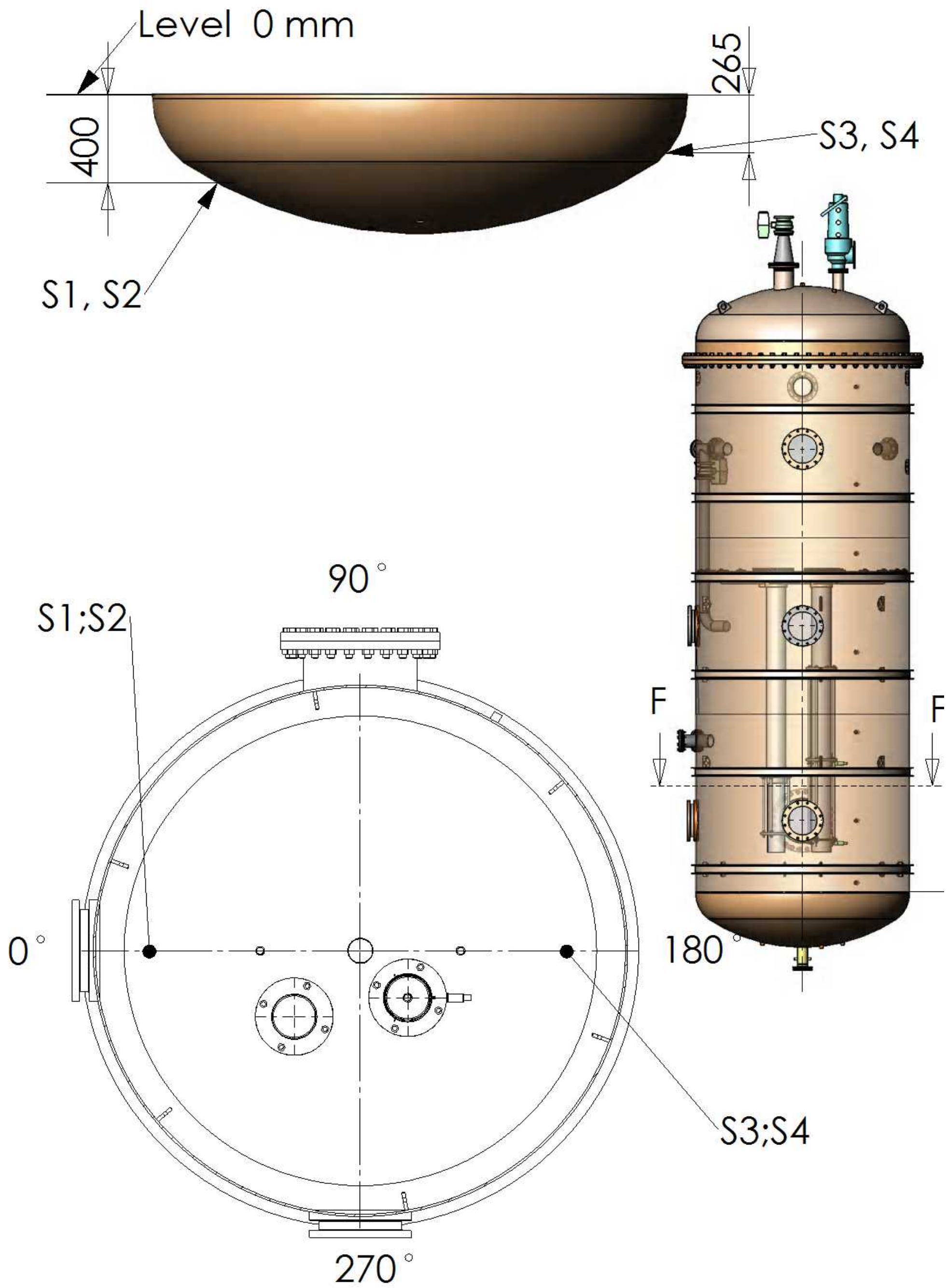
Pressure difference measurements. Water level is at 1.80 m.



Pressure and temperature measurements at the blowdown pipe 1 outlet.



Pressure measurement P25 at the blowdown pipe 2 outlet.



Strain gauges on the outer wall of the pool.

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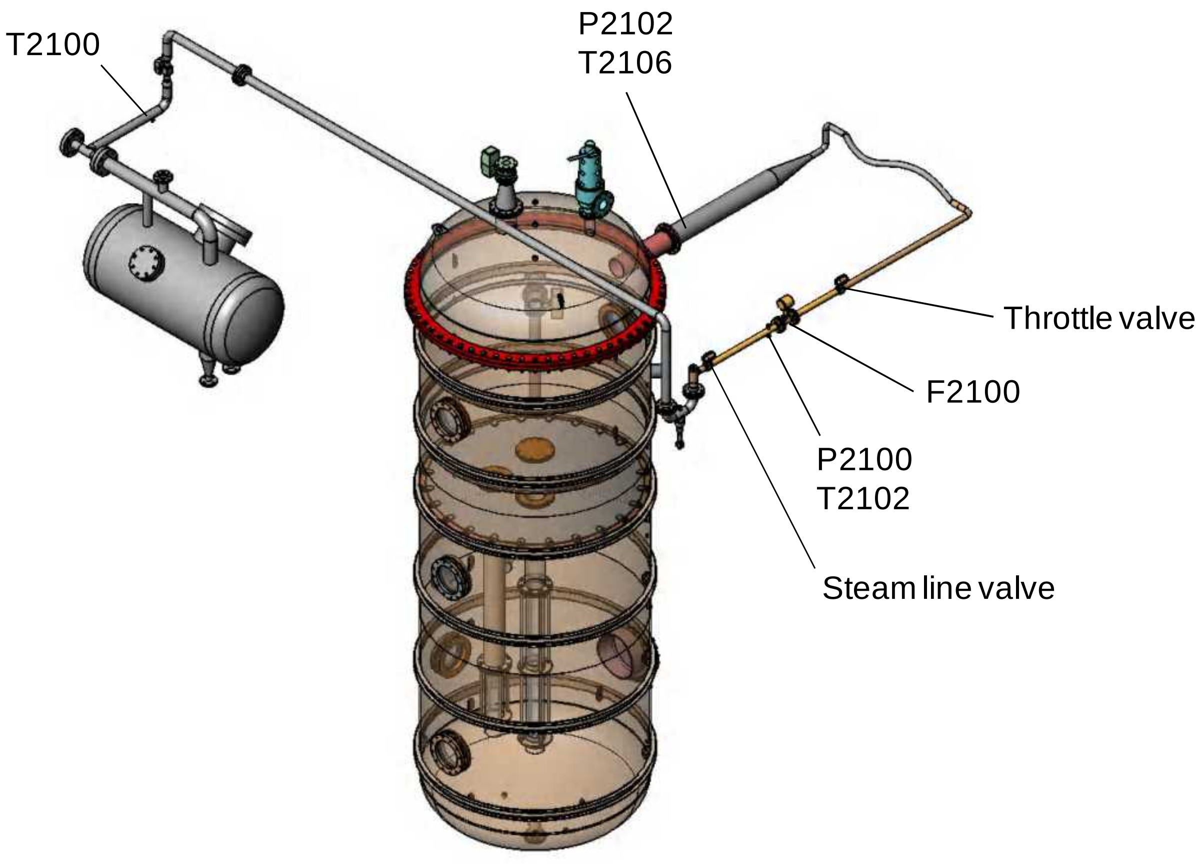

Measurements in the steam line.

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	-1060	225	Wet well bottom	±0.5 bar
Temperature	T6	-1060	225	Wet well bottom	±1.8 °C
Pressure	P7	395	135	Wet well	±0.4 bar
Temperature	T7	2585	20	Wet well	±1.8 °C
Pressure	P8	395	135	Wet well	±0.4 bar
Temperature	T8	1760	20	Wet well	±1.8 °C
Temperature	T11	1545	20	Wet well	±1.8 °C
Temperature	T21	545	305	Blowdown pipe 2	±1.8 °C
Pressure	P22	1445	323	Blowdown pipe 2 (TRA-05 only)	±0.7 bar
Temperature	T22	1445	305	Blowdown pipe 2	±1.8 °C
Pressure	P25	395	327	Blowdown pipe 2 outlet (TRA-05 only)	±0.7 bar
Pressure	P41	3600	45	Wet well gas space	±0.1 bar
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	225	Blowdown pipe	±0.06 bar
Temperature	T2104	-245	180	Wet well outer wall	±2.9 °C
Temperature	T2105	6780	-	Dry well top	±3.1 °C
Temperature	T2106	-	-	Inlet plenum	±3.1 °C
Temperature	T2107	6085	45	Dry well middle	±1.9 °C
Temperature	T2108	4600	120	Dry well bottom	±3.1 °C
Temperature	T2109	5790	225	Dry well lower middle	±9.9 °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	T2114	3400	220	Blowdown pipe	±1.8 °C
Temperature	T2115	3250	220	Blowdown pipe	±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
Valve position	V1	-	-	Steam line	Not defined
Camera trigger	Camera trigger	-	-	Wet well	Not defined

Measurements in the PPOOLEX facility for the PAR and TRA experiments.

APPENDIX 3: TEST FACILITY PHOTOGRAPHS

Dry well compartment, relief valves and inlet plenum.

Inlet plenum.

Blowdown pipes and intermediate floor. Pipe 1 is on the left and pipe 2 on the right.

Lower parts of the blowdown pipes. Pipe 1 is on the left and pipe 2 on the right.

Title	PPOOLEX Experiments with Two Parallel Blowdown Pipes
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Affiliation(s)	Lappeenranta University of Technology, Nuclear Safety Research Unit
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Abstract

This report summarizes the results of the experiments with two transparent 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 either one or two vertical transparent blowdown pipes to the condensation pool. Five experiments with one pipe and six with two parallel pipes were carried out. The main purpose of the experiments was to study loads caused by chugging (rapid condensation) while steam is discharged into the condensation pool filled with sub-cooled water.

The PPOOLEX test facility is a closed stainless steel vessel divided into two compartments, dry well and wet well. In the experiments the initial temperature of the condensation pool water varied from 12 ºC to 55 ºC, the steam flow rate from 40 g/s to 1 300 g/s and the temperature of incoming steam from 120 ºC to 185 ºC.

In the experiments with only one transparent blowdown pipe chugging phenomenon didn't occur as intensified as in the preceding experiments carried out with a DN200 stainless steel pipe. With the steel blowdown pipe even 10 times higher pressure pulses were registered inside the pipe. Meanwhile, loads registered in the pool didn't indicate significant differences between the steel and polycarbonate pipe experiments.

In the experiments with two transparent blowdown pipes, the steam-water interface moved almost synchronously up and down inside both pipes. Chugging was stronger than in the one pipe experiments and even two times higher loads were measured inside the pipes. The loads at the blowdown pipe outlet were approximately the same as in the one pipe cases. Other registered loads around the pool were about 50–100 % higher than with one pipe.

The experiments with two parallel blowdown pipes gave contradictory results compared to the earlier studies dealing with chugging loads in case of multiple pipes. Contributing factors to this may be the smaller dry well volume per blowdown pipe ratio and the lack of dry well internal structures in the PPOOLEX facility. Furthermore, the pipe material seemed to have an effect on the condensation process inside the pipe. Polycarbonate has two orders of magnitude smaller thermal conductivity than steel.

Key words condensation pool, steam/air blowdown, chugging, parallel blowdown pipes