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PPOOLEX Experiments on Dynamic Loading with Pressure Feedback

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Abstract

This report summarizes the results of the dynamic loading experiments (DYN series) carried out with the scaled down, two compartment PPOOLEX test facility designed and constructed at LUT. Steam was blown into the dry well compartment and from there through the DN200 vertical blowdown pipe to the condensation pool filled with sub-cooled water. The main purpose of the experiments was to study dynamic loads caused by different condensation modes. Particularly, the effect of counterpressure on loads due to pressure oscillations induced by chugging was of interest.

Before the experiments the condensation pool was filled with isothermal water so that the blowdown pipe outlet was submerged by 1.03-1.11 m. The initial temperature of the pool water varied from 11 ºC to 63 ºC, the steam flow rate from 290 g/s to 1220 g/s and the temperature of incoming steam from 132 ºC to 182 ºC. Non-condensables were pushed from the dry well into the gas space of the wet well with a short discharge of steam before the recorded period of the experiments. As a result of this procedure, the system pressure was at an elevated level in the beginning of the actual experiments. An increased counterpressure was used in the last experiment of the series.

The diminishing effect of increased system pressure on chugging intensity and on measured loads is evident from the results of the last experiment. The highest pressure pulses both inside the blowdown pipe and in the condensation pool were about half of those measured with a lower system pressure but otherwise with similar test parameters.

The experiments on dynamic loading gave expected results. The loads experienced by pool structures depended strongly on the steam mass flow rate, pool water temperature and system pressure. The DYN experiments indicated that chugging and condensation within the blowdown pipe cause significant dynamic loads in case of strongly sub-cooled pool water. The level of pool water temperature is decisive. High individual pressure pulses (and loads) were missing with increased temperature and the oscillations were continuous in nature and their amplitude was almost constant. With an increased steam mass flow rate the highest loads were found from the condensation pool and not from inside the blowdown pipe.

Key words

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

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PPOOLEX EXPERIMENTS ON DYNAMIC LOADING WITH PRESSURE FEEDBACK

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Before the experiments the condensation pool was filled with isothermal water so that the blowdown pipe outlet was submerged by 1.03-1.11 m. The initial temperature of the pool water varied from 11 °C to 63 °C, the steam flow rate from 290 g/s to 1220 g/s and the temperature of incoming steam from 132 °C to 182 °C. Non-condensables were pushed from the dry well into the gas space of the wet well with a short discharge of steam before the recorded period of the experiments. As a result of this procedure, the system pressure was at an elevated level in the beginning of the actual experiments. This differentiates the DYN series from the previous PPOOLEX experiments where no removal of non-condensables or elevated initial system pressures has been used. An increased counterpressure was used in the last experiment of the series.

The diminishing effect of increased system pressure on chugging intensity and on measured loads is evident from the results of the last experiment. The highest pressure pulses both inside the blowdown pipe and in the condensation pool were about half of those measured with a lower system pressure but otherwise with similar test parameters.

The experiments on dynamic loading gave expected results. The loads experienced by condensation pool structures depended strongly on the steam mass flow rate, pool water temperature and system pressure. The DYN experiments indicated that chugging and condensation within the blowdown pipe cause significant dynamic loads in case of strongly sub-cooled pool water. The level of pool water temperature is decisive. High individual pressure pulses (and loads) were missing with increased temperature and the oscillations were continuous in nature and their amplitude was almost constant. With an increased steam mass flow rate the highest loads were found from the condensation pool and not from inside the blowdown pipe.

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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

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NOMENCLATURE

a	acceleration
A	area
p	pressure
Q	volumetric flow rate
q_m	mass flow rate
T	temperature

Greek symbol

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
NORTHNET	Nordic Nuclear Reactor Thermal-Hydraulics Network
PAR	experiment series with parallel blowdown pipes
PACTEL	parallel channel test loop
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
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.

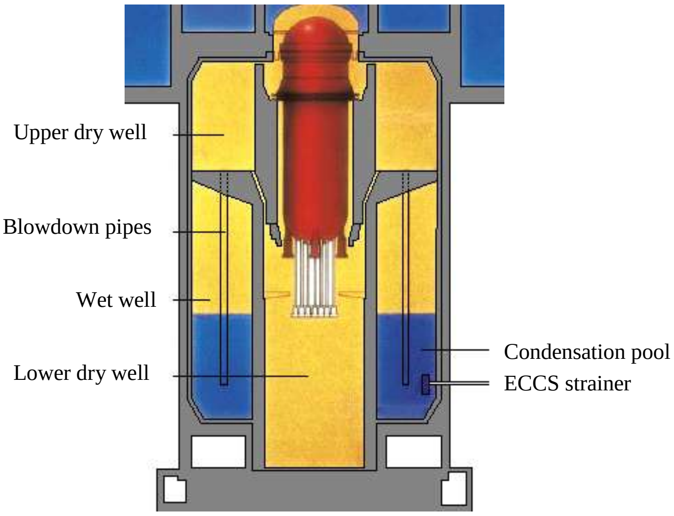

Figure 1. Schematic of the Olkiluoto type BWR containment.

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 the instrumentation and 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 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. The main purpose of the experiments was to study dynamic loads caused by different condensation modes. Particularly, the effect of counterpressure on loads caused by chugging was of interest. In this report, the results of the DYN experiments are presented. First, chapter two presents the different condensation modes in a BWR suppression pool during steam discharge. Chapter three gives a short description of the test facility and its measurements as well as of the data acquisition system used. The test programme of the DYN experiment series is introduced in chapter four. The test results are presented and shortly discussed in chapter five. Chapter six summarizes the findings of the experiment series.

2 CONDENSATION MODES

In the handbook of thermal hydraulics of BWRs, Lahey and Moody present a map of condensation modes that have been observed during either LOCA or safety/relief valve (SRV) steam discharge, see Figure 2.

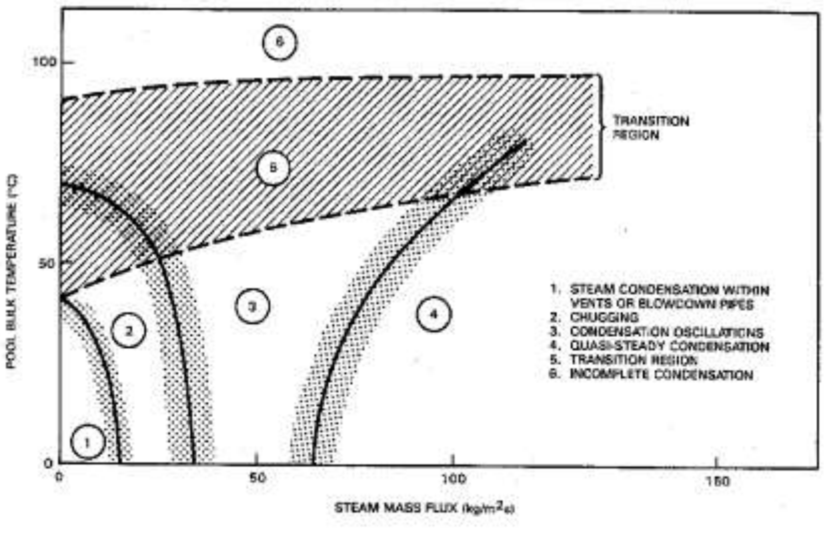

Figure 2. Condensation mode map for pure steam discharge [7].

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

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

Increasing the steam mass flux further leads to condensation oscillations. The steam-water interface undergoes a condensation event entirely in the pool. Steam bubble forms at the pipe outlet and begins to collapse. However, the high steam flow rate prevents water re-entry into the blowdown pipe. Condensation oscillations cause unsteady loads on submerged structures [7].

3 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 [8]. However, the main features of the facility and its instrumentation are introduced below. Some test facility photographs are shown in Appendix 2.

3.1 TEST VESSEL

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

The main component of the facility is the ~31 m^3 cylindrical test vessel, 7.45 m in height and 2.4 m in diameter. The vessel is 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 3. Table 1 lists the main dimensions of the test facility compared to the conditions in the Olkiluoto plant.

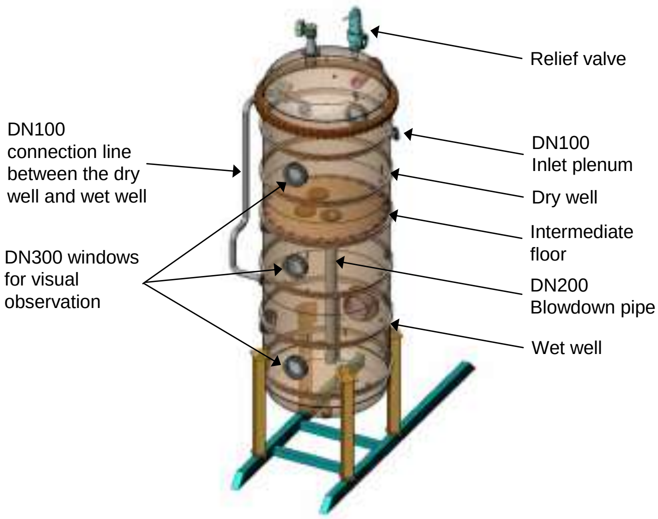

Figure 3. PPOOLEX test vessel.

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

* 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.

3.2 PIPING

In the plant, there are vacuum breakers between the dry and wet well compartments in order to keep the pressure in the 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 [9] 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 4.

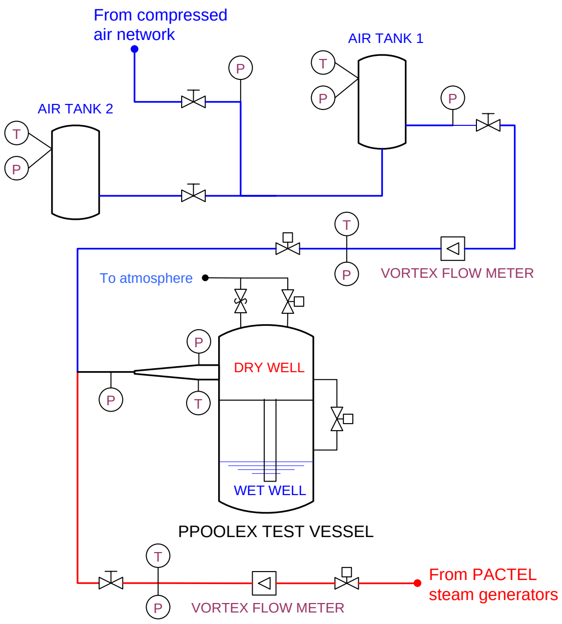

Figure 4. Arrangement of air and steam supply in the PPOOLEX facility.

3.3 BLOWDOWN PIPE

The DN200 (Ø219.1x2.5) stainless steel blowdown pipe is positioned inside the pool in a non-axisymmetric location, i.e. 300 mm away from the centre of the condensation pool, Figure 5. The total length of the blowdown pipe is 3 169 mm.

Figure 5. Blowdown pipe.

3.4 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.

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. 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 DYN experiments is presented in Table 2. The figures in Appendix 1 show the exact locations of the measurements and the table in Appendix 1 lists the identification codes and error estimations of the measurements. The error estimations are calculated on the basis of variance analysis. The results agree with normal distributed data with 95 % confidence interval.

Table 2. Instrumentation of the PPOOLEX test facility.

Quantity measured		No.	Range	Accuracy
Pressure	Dry well	1	0–6 bar	0.06 bar
	Wet well	4	0–6/0–10 bar	0.4/0.5 bar
	Blowdown pipe	2	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

3.5 CCTV SYSTEM

In the DYN 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 [10] 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.

3.6 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 [11].

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 5 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.

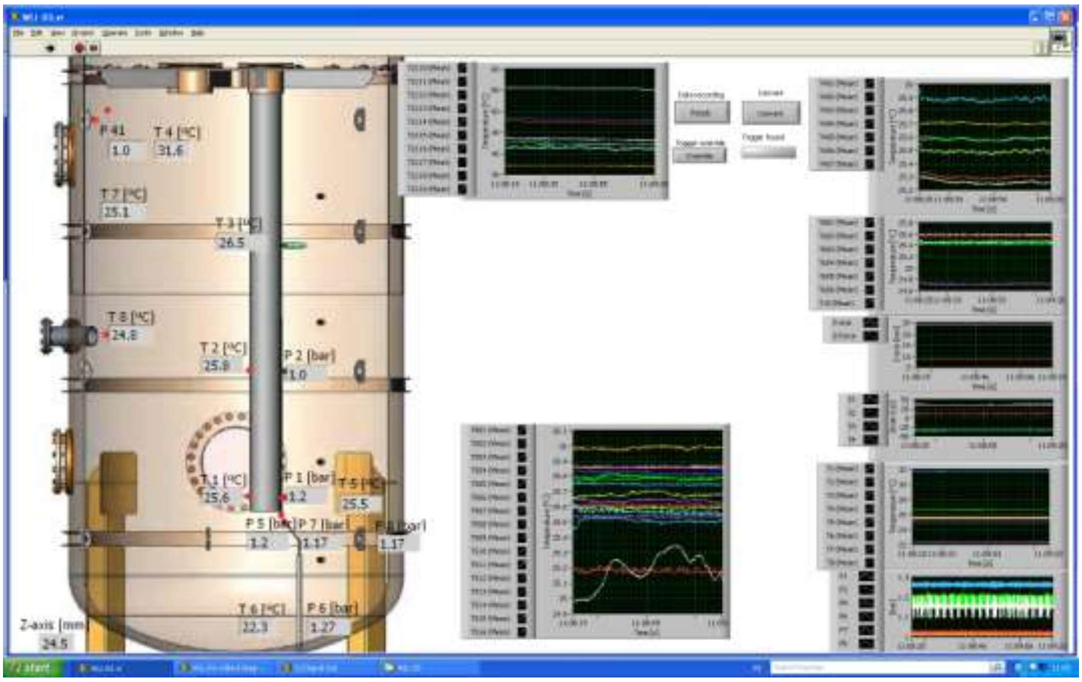

Figure 6. Monitoring of experiments with LabView 8.6 software.

4 TEST PROGRAM

The test program consisted of eight experiments labeled from DYN-01 to DYN-08. The main purpose of the experiments was to study dynamic loads caused by different condensation modes while steam is discharged through one steel blowdown pipe into the condensation pool filled with sub-cooled water. Steam generators of the nearby PACTEL facility acted as a steam source.

Before the experiments the condensation pool was filled with isothermal water (temperature 11–63 °C) to the level of 2.12-2.20 m i.e. the blowdown pipe outlet was submerged by 1.03-1.11 m. This air/water distribution corresponds roughly to the scaled gas and liquid volumes in the containment of the reference plant. The steam source initial pressure varied from 0.35 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.

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 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 light. As the fraction of steam among the flow increased the condensation phenomenon intensified. Now, the steam discharge into the dry well compartment was stopped and the conditions in the test facility were let to settle down. The valve in the connection line between the compartments and in the relief line on the top of the vessel head were not opened and therefore the system pressure remained at an elevated level. The idea of this kind of procedure was to push the non-condensables from the dry well into the gas space of the wet well as completely as possible so that the actual recorded discharge period of the experiment would consist of nearly pure vapour. This should help the simulation partners to better define the initial/boundary conditions for the calculation exercises. After waiting for a couple of minutes the steam discharge was continued and the actual experiment period began. The recording of the high-speed video and high frequency measurements were started accordingly.

The removal of non-condensables and the elevated initial system pressure differentiates the DYN series from the previous PPOOLEX experiments. In DYN-08, even an increased counterpressure was used by injecting compressed air (0.15 MPa) into the closed test vessel. The removal of non-condensables from the dry well was not always completely successful. Some amount of non-condensables could have been left in the dry well in the beginning of the actual experiments. In some experiments it therefore took for a while before the desired condensation mode with pure enough steam began. Table 3 shows the main parameters of the DYN experiments.

Table 3. Initial parameter values of the DYN experiments.

Experiment	Steam source pressure [MPa]	Initial pool water level [m]	Initial pool water temperature [°C]	Initial test vessel pressure [MPa]
DYN-01	0.35	2.13	21	0.10
DYN-02	0.55	2.15	27	0.10
DYN-03	1.5	2.20	41	0.10
DYN-04	0.55	2.12	55	0.10
DYN-05	1.5	2.16	63	0.10
DYN-06	0.55	2.14	11	0.10
DYN-07	0.55	2.19	23	0.10
DYN-08	0.55	2.14	25	0.15

5 ANALYSIS OF THE EXPERIMENTS

The following chapters give a more detailed description of the experiment program and present the observed phenomena from selected, the most representative cases. Table 4 summarizes the values of the main parameters during the DYN experiment series.

5.1 DYNAMIC LOADS IN SMALL FLOW RATE CASES

Experiments DYN-04 and DYN-06 are selected from the test series for a more detailed study of pressure loads in case of a small steam flow rate. The test parameters of those experiments belong to the region of condensation mode map of Lahey and Moody where condensation within blowdown pipes, chugging and condensation oscillations should occur. Furthermore, those two experiments represent the cases where the fraction of steam in the discharge flow was the highest according to the steam partial pressure measurement.

The initial pressure of the steam source was 0.55 MPa in both experiments. The initial level and temperature of pool water was 2.12 m and 55 °C in DYN-04 and 2.14 m and 11 °C in DYN-06. In DYN-04, the recorded steam discharge period lasted for about 200 s and in DYN-06 for about 270 s. The flow rate was initially 460 g/s in both experiments and decreased to 410 g/s in DYN-04 and to 390 g/s in DYN-06. The temperature of incoming steam decreased from 144 °C to 142 °C in DYN-04 and to 141 °C in DYN-06. The fraction of steam in the dry well did not reach 100 % in either experiment but was anyway very close to that in the latter part of the experiments. The measured temperature and flow rate of incoming steam and the steam fraction in the dry well in DYN-04 are presented in Figure 7. The corresponding curves for DYN-06 are practically the same.

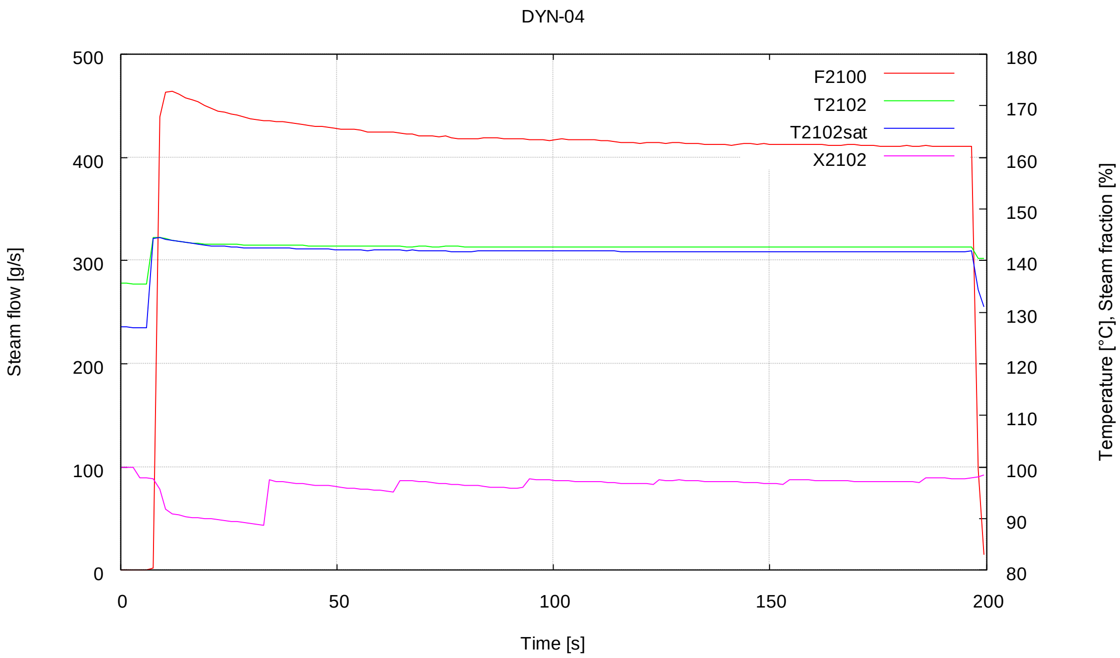

Figure 7. Flow rate (F2100) and temperature (T2102) of incoming steam in DYN-04. T2102sat is the saturated steam temperature at the flow meter and X2102 the steam fraction in the dry well.

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Table 4. Main parameters during DYN experiments.

Test	Initial pressure of steam generator [MPa]	Steam flow rate[1] [g/s]	T_{pool} [°C]	Temperature of steam[2] [°C]	Initial water level [m]	Δp_{max} in the DN200 pipe[3] [kPa]	Δp_{max} in the pool[4] [kPa]	Δp_{max} at the pool bottom[5][kPa]	$\Delta \varepsilon_{max}$[6] [µS]	Pool bottom vertical $\|a\|_{max.}$ [m/s^2]	Pool bottom vertical Δs_{max} [mm]
DYN-01	0.35	290…250	21	132…134	2.13	90 60	40 20 20	30	20	100	0.3
DYN-02	0.55	470…430	27	143…142	2.15	1140 190	450 70 100	110	60	320	3.2
DYN-03	1.5	1220…830	41	182…171	2.20	120 70	400 30 20	30	20	150	0.4
DYN-04	0.55	460…410	55	144…142	2.12	50 40	40 40 15	15	10	70	0.2
DYN-05	1.5	1180…890	63	181…172	2.16	30 25	160 30 15	20	10	60	0.4
DYN-06	0.55	460…390	11	144…141	2.14	1760 200	390 70 90	80	40	230	3.0
DYN-07	0.55	460…430	23	144…142	2.19	2010 310	500 70 120	80	50	280	3.5
DYN-08	0.55	440…320	25	144…142	2.14	1000 130	230 34 62	46	25	150	0.9

[1] 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.
[2] Measured by thermocouple T2102.
[3] Measured by pressure transducer P1 and P2.
[4] Measured by pressure transducers P5, P7 and P25.
[5] Measured by pressure transducer P6.
[6] Measured by strain gauge S4.

In the beginning of the recorded period (after the procedure of removing non-condensables) the pressure level in the dry well compartment was about 0.25 MPa in the both experiment. The dry well was mostly filled with steam, but as said earlier a small fraction of air remained there despite of the preliminary steam discharge procedure. Steam and air probably stratified during the settle down period so that the steam partial pressure sensor (at the elevation of 4600 mm) was surrounded by steam since it indicated figures of 100 % before the restart of the discharge.

After the remote-controlled shut-off valve in the steam line was opened to initiate the actual experiment steam and the small amount of air left in the dry well mixed and therefore the fraction of steam, as indicated by the steam partial pressure sensor, decreased to about 90 %. It then began to increase and reached the 95 % mark in less than 40 seconds. Pressure build-up in the dry well pushed water in the blowdown pipe downwards and after a while the pipe cleared and flow into the wet well compartment began. Due to the large steam content of the flow condensation at the pipe outlet was strong already in the beginning of the recorded period.

Typical chugging phenomenon (steam bubble formation at the outlet of the blowdown pipe and movement of steam/water interface inside the pipe) was observed in DYN-06 after the steam fraction in the dry well had increased to 96-97 % i.e. from about 75 seconds forward. In DYN-04, the chugging condensation mode didn't occur as intense as in DYN-06. The behaviour appeared to belong more to the condensation oscillations mode or to the transition region. The reason for this is the higher pool water temperature of DYN-04, which calms the condensation process.

In DYN-06, the transition from the chugging mode to the condensation within blowdown pipes mode due to decreasing flow rate occurred at about 225 s into the experiment, see Table 1 and Figure 8. This mode prevailed until the end of the experiment. The strongest pressure loads were measured during that period. Water ingress back into the blowdown pipe reached thermocouple T2 at the middle elevation of the pipe several times, Figure 8. In DYN-04, water ingress back into the blowdown pipe didn't reach T2 at all.

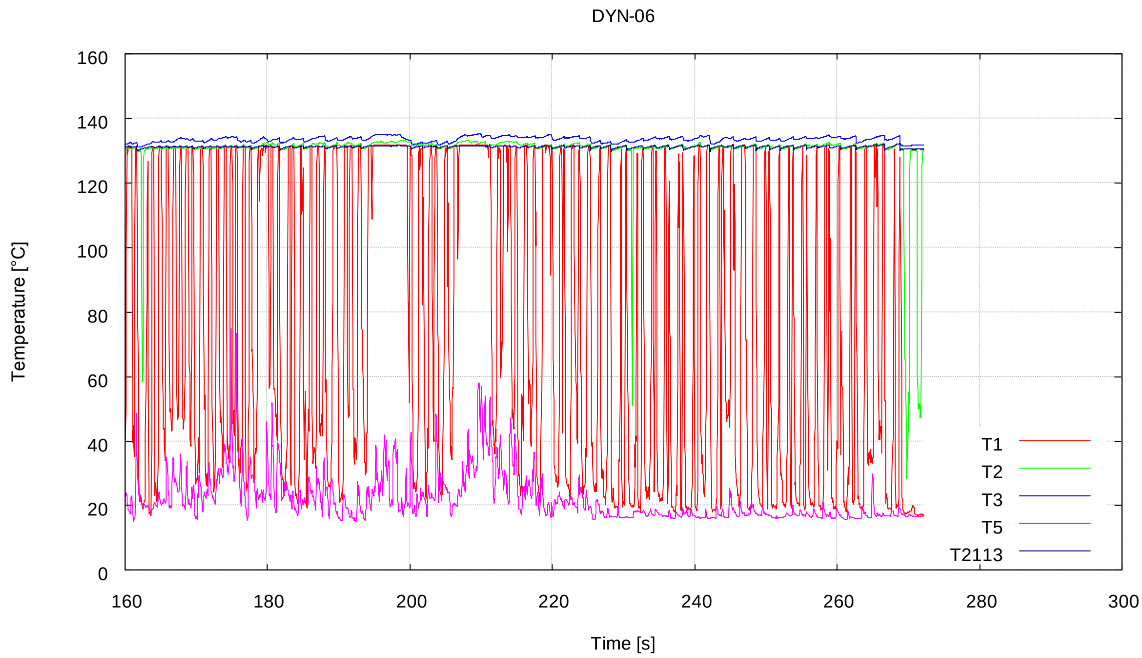

Figure 8. Temperatures inside (T1, T2, T3 and T2113) and at the outlet (T5) of the blowdown pipe during the latter part of the DYN-06 experiment. Transition from chugging mode to condensation within blowdown pipes mode occurs at about 225 seconds.

In DYN-06, chugging and condensation within the blowdown pipe caused strong dynamic loads to the pool structures. The largest pressure loads were registered by pressure sensor P1, which is located inside the blowdown pipe close to its lower end. P2 at the middle elevation of the pipe indicated almost one order of magnitude smaller loads, Figure 9. Considerable loads were measured also with the pressure sensors in the condensation pool. The highest individual value was registered by P5 below the blowdown pipe, Figure 10. However, the largest registered single pressure pulses inside the blowdown pipe and in the pool did not occur simultaneously. Both can be anyway found from a 15 second interval close to the end of the experiment.

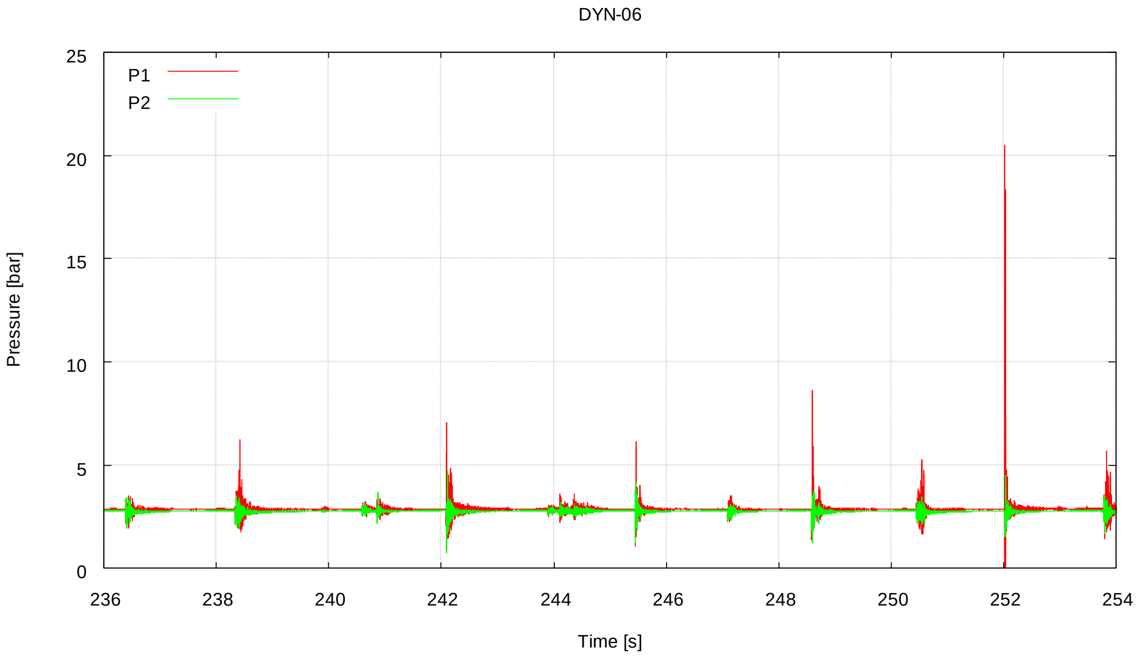

Figure 9. Pressures inside the blowdown pipe in DYN-06 in the time period of 236…254 seconds.

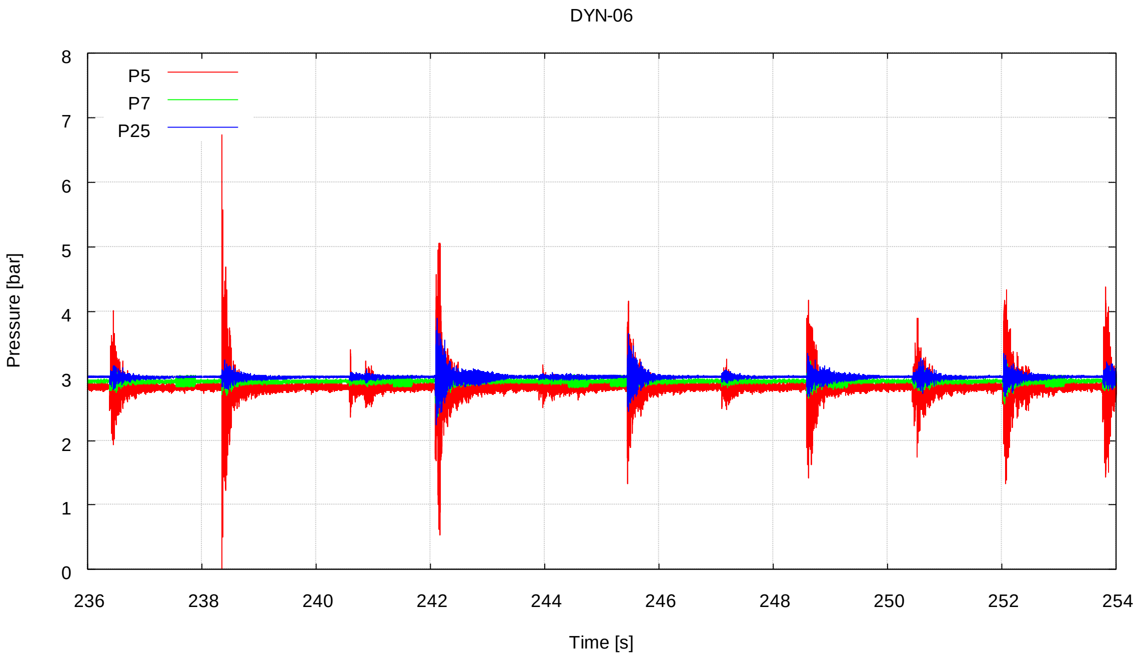

Figure 10. Pressures in the condensation pool in DYN-06 in the time period of 236…254 seconds.

Figure 11 shows the vertical movement of the test vessel. The largest movement was recorded at the same time as the largest load in the condensation pool. Loads registered by the strain gauges are presented in Figure 12.

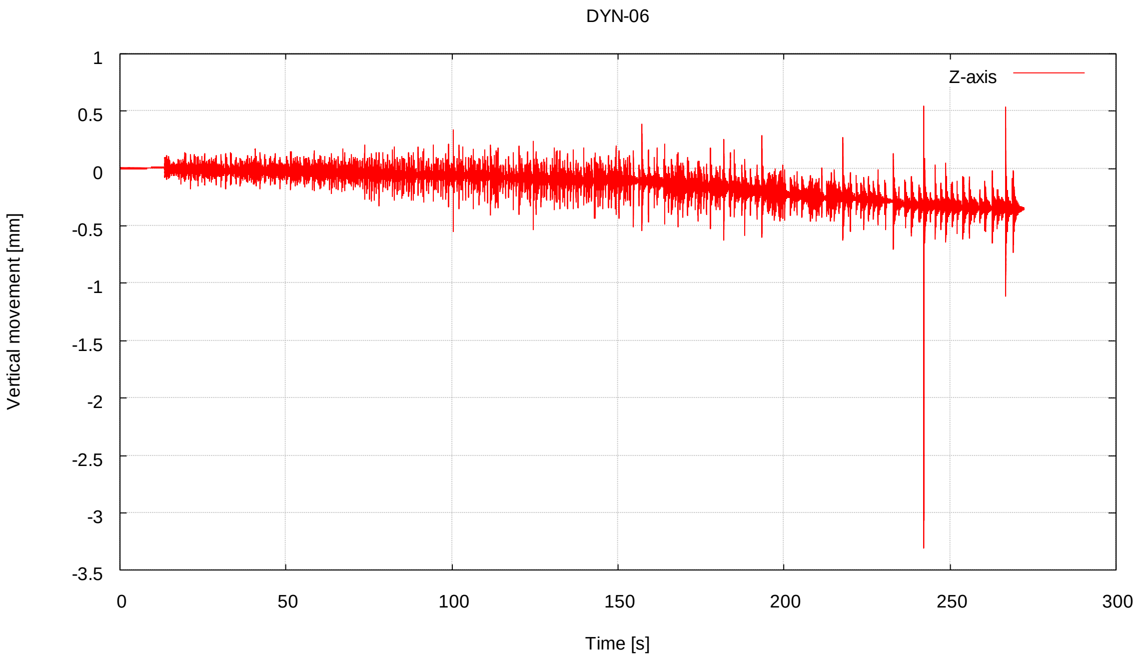

Figure 11.Vertical movement of the test vessel in DYN-06.

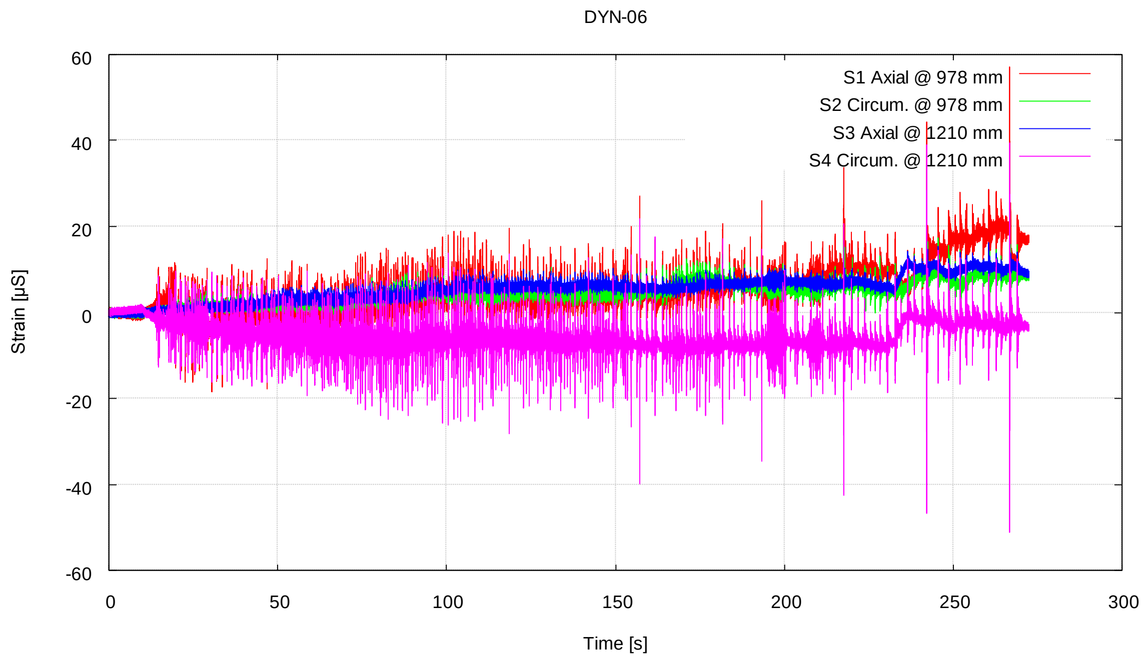

Figure 12. Measured strains in DYN-06.

Figure 13 shows a photograph series (captured from the high speed recording of the Casio Exilim EX-F1 digital camera) from the time period of 238,0 - 238.5 seconds of the development and collapse of the steam bubble related to the largest measured loads in the condensation pool in DYN-06.

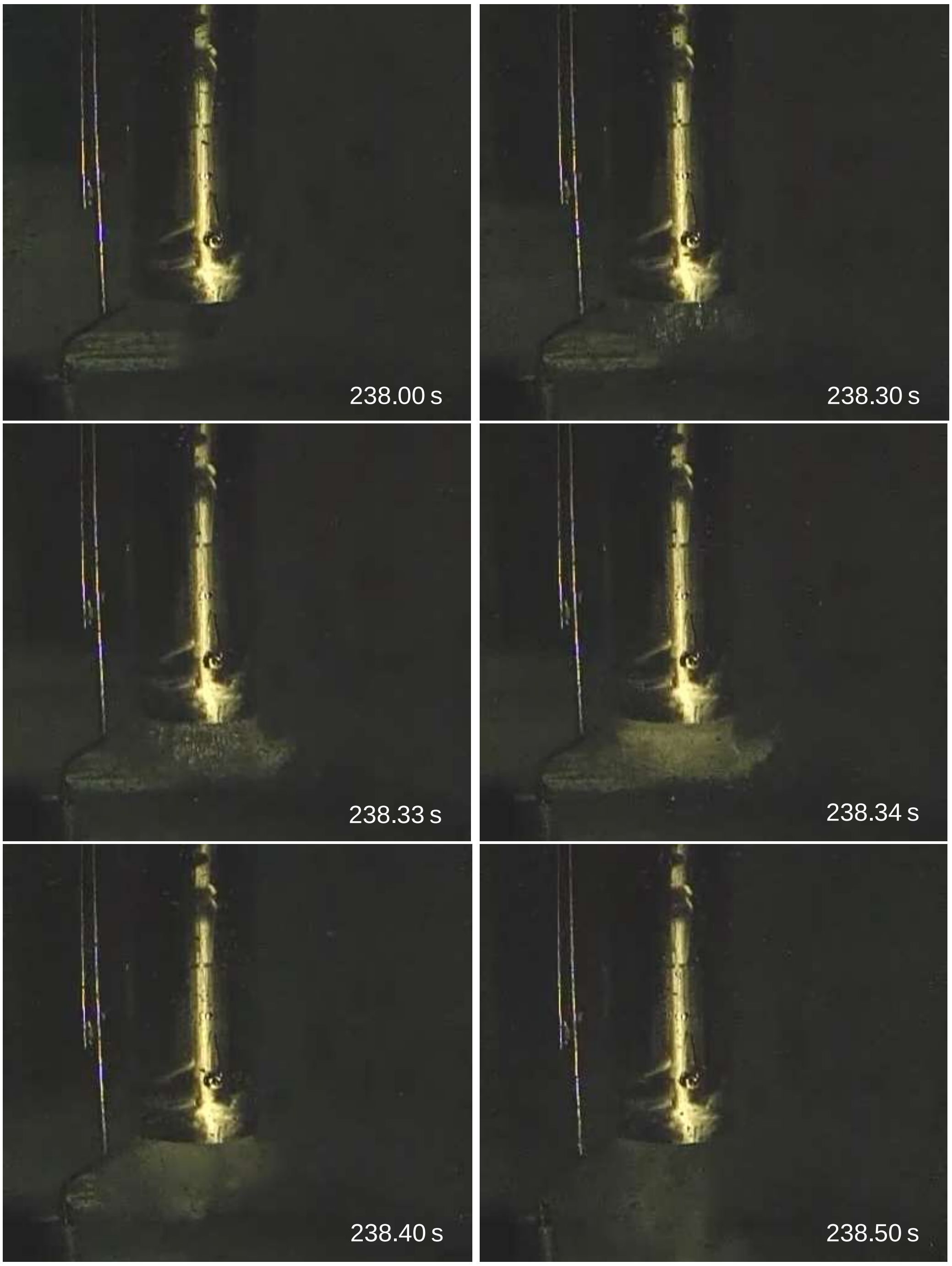

Figure 13. Formation and collapse of a steam bubble causing the largest load in the condensation pool in DYN-06.

In DYN-04, the largest measured pressure loads inside the blowdown pipe and in the condensation pool were about one order of magnitude smaller than in DYN-06 despite of the similar steam mass flow rate, Figure 14 and Figure 15. The higher pool water temperature in DYN-04 had an effect on the condensation process and prevented the chugging phenomenon and related high pressure spikes from occurring. Instead, the much milder condensation oscillations mode and transition region were prevailing during the experiment. The oscillations were continuous in nature and their amplitude was almost constant throughout the experiment. Water ingress back into the blowdown pipe reached only the measurement T1 that is located close to the pipe outlet, Figure 16. The vertical movement of the test vessel as well as the strains of the vessel walls was also considerably smaller in DYN-04 than in DYN-06.

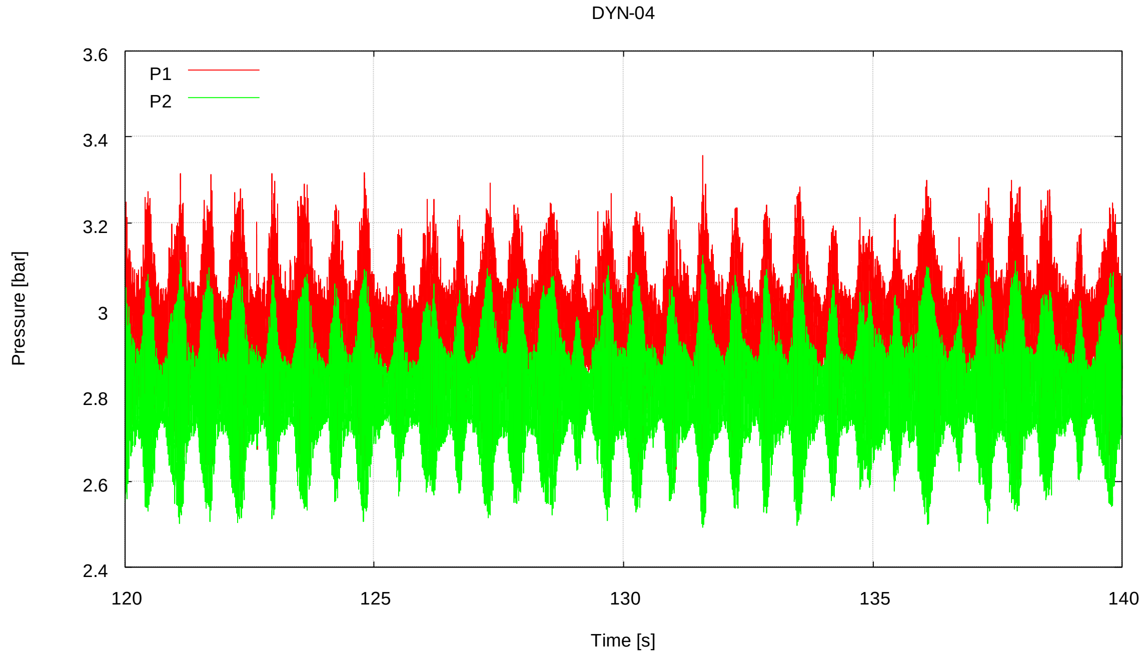

Figure 14. Pressures inside the blowdown pipe in DYN-04 in the time period of 120…140 seconds.

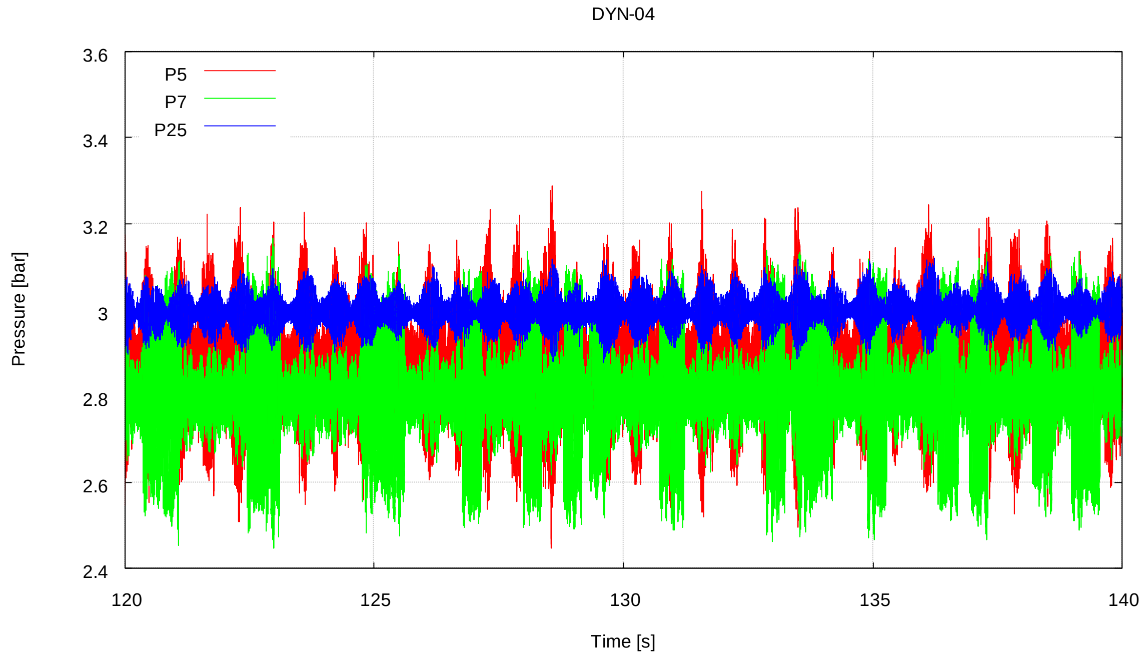

Figure 15. Pressures in the condensation pool in DYN-04 in the time period of 120…140 seconds.

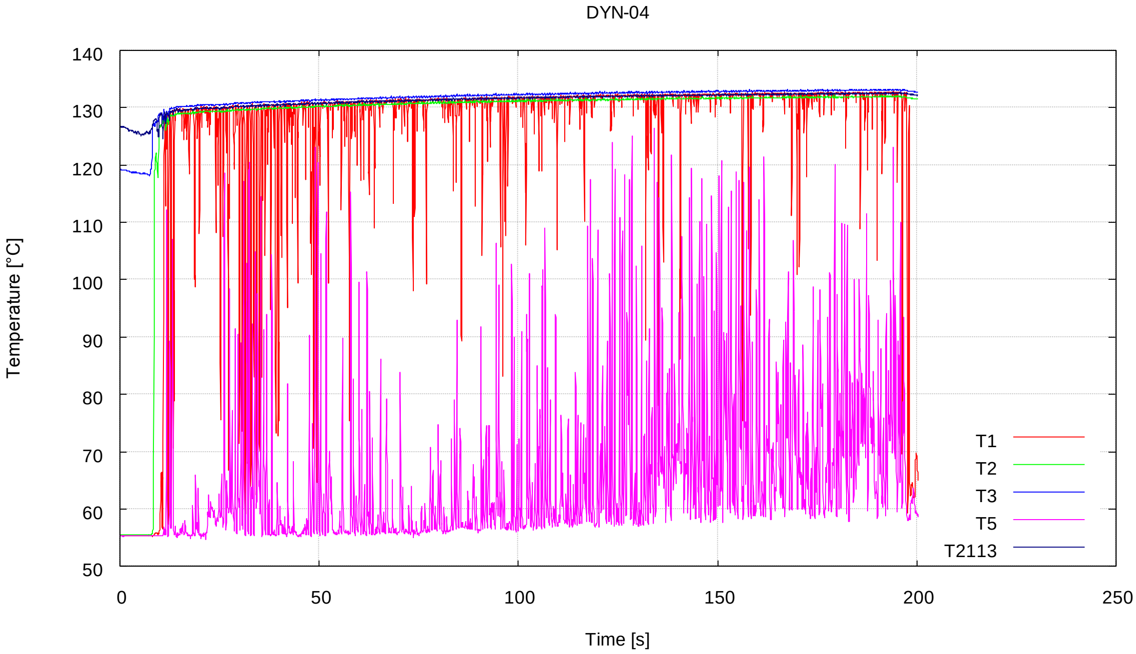

Figure 16. Temperatures inside (T1, T2, T3 and T2113) and at the outlet (T5) of the blowdown pipe in DYN-04.

5.2 DYNAMIC LOADS IN HIGH FLOW RATE CASES

In DYN-03 and DYN-05, clearly larger steam flow rates were used. The initial pressure of the steam source was 0.55 MPa and the level and temperature of pool water 2.20 m and 41 °C in DYN-03 and 2.16 m and 63 °C in DYN-05. In DYN-03, the recorded steam discharge period lasted for about 230 seconds. The flow rate was initially 1220 g/s and decreased to 830 g/s during the experiment. In DYN-05, the steam discharge period lasted for about 160 seconds. The flow rate decreased from 1180 g/s to 890 g/s. The temperature of incoming steam varied between 171 °C and 182 °C. The fraction of steam in the dry well compartment levelled off to about 75 % in the both experiment. This is a considerably lower value than in the small flow rate cases. Possible explanations for this could be a more extensive release of dissolved non-condensable gas (air) from the steam generator water due to larger pressure drop or stronger local condensation in the dry well compartment causing the steam fraction measurement device to indicate faulty values. In the beginning of the recorded period (after the procedure of removing non-condensables) the pressure level in the dry well compartment in DYN-03 was about 0.23 MPa and in DYN-05 about 0.21 MPa. The measured temperature and flow rate of incoming steam and the steam fraction in the dry well in DYN-03 are presented in Figure 17.

According to the condensation mode map of Lahey and Moody the condensation oscillations mode should first prevail in DYN-03 and then transition to the chugging mode should occur as the steam flow rate decreases along the experiment. The condensation within blowdown pipes mode should not be present at all in this experiment. The total lack of pressure spikes inside the blowdown pipe seems to prove this. Instead, the highest pressure loads were found from the condensation pool. The P5 measurement close to the blowdown pipe outlet registered a maximum load of 0.4 MPa and several other pressure spikes in the same category throughout the experiment, Figure 18. Other pressure measurements in the pool indicated continuous and almost constant amplitude load typical for the condensation oscillations mode. The vertical movement of the test vessel as well as the strains of the vessel walls was small in DYN-03.

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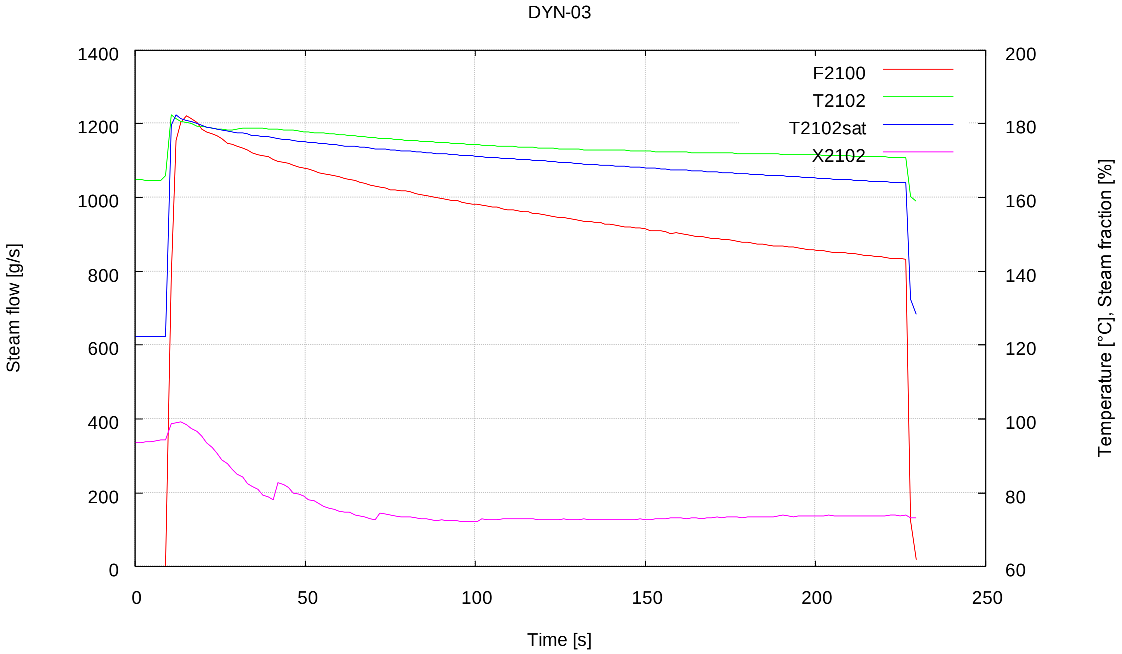

Figure 17. Flow rate (F2100) and temperature (T2102) of incoming steam in DYN-03. T2102sat is the saturated steam temperature at the flow meter and X2102 the steam fraction in the dry well.

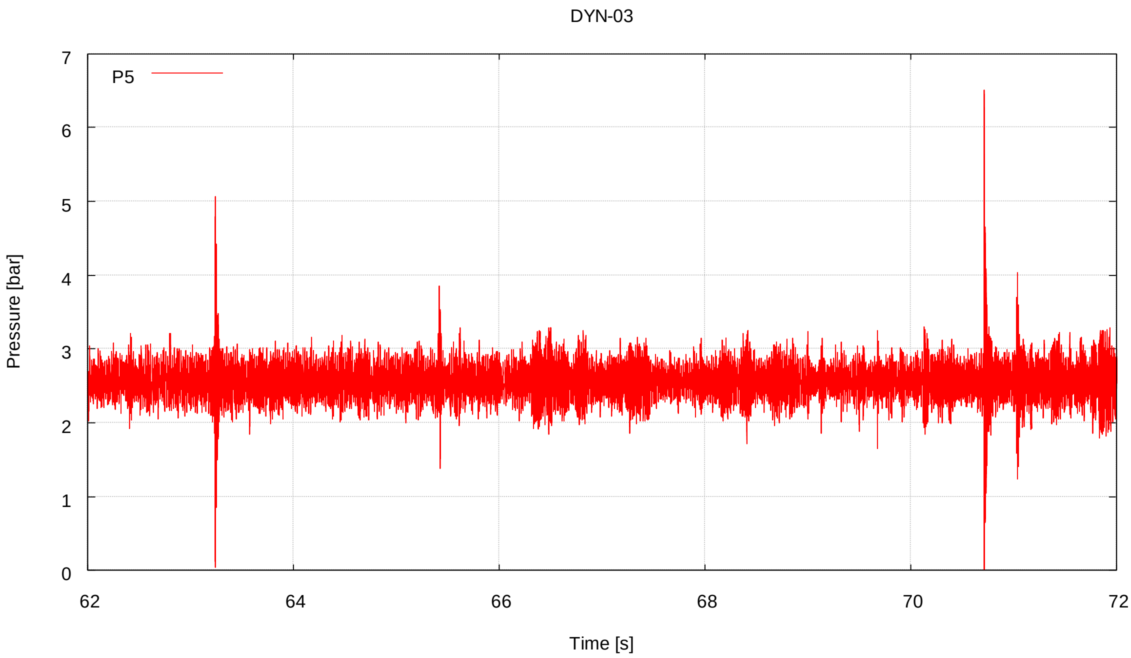

Figure 18. Pressure loads at the blowdown pipe outlet (P5) in the time period of 62…72 seconds in DYN-03.

There was no water ingress back into the blowdown pipe at all during the whole experiment. This is an additional proof of the fact that the condensation within blowdown pipes mode was not encountered in this experiment.

In DYN-05, the largest measured pressure loads inside the blowdown pipe (P1) and in the condensation pool (P5) were roughly half of those measured in DYN-03 despite of the almost similar steam mass flow rate. The reason for this was again the higher pool water temperature in DYN-05. It shifted the condensation process to the transition region in the condensation mode map and therefore high pressure loads related to the modes of chugging and condensation within blowdown pipes are missing. The other pressure measurements, the sensor of vertical movement and the strain gauges showed also slightly smaller values than in DYN-03. Again, there was no water ingress into the blowdown pipe at all. Instead, the temperature measurement closest to the blowdown pipe outlet (T5) experienced a constant change of surrounding medium from water to steam and vice versa, Figure 19.

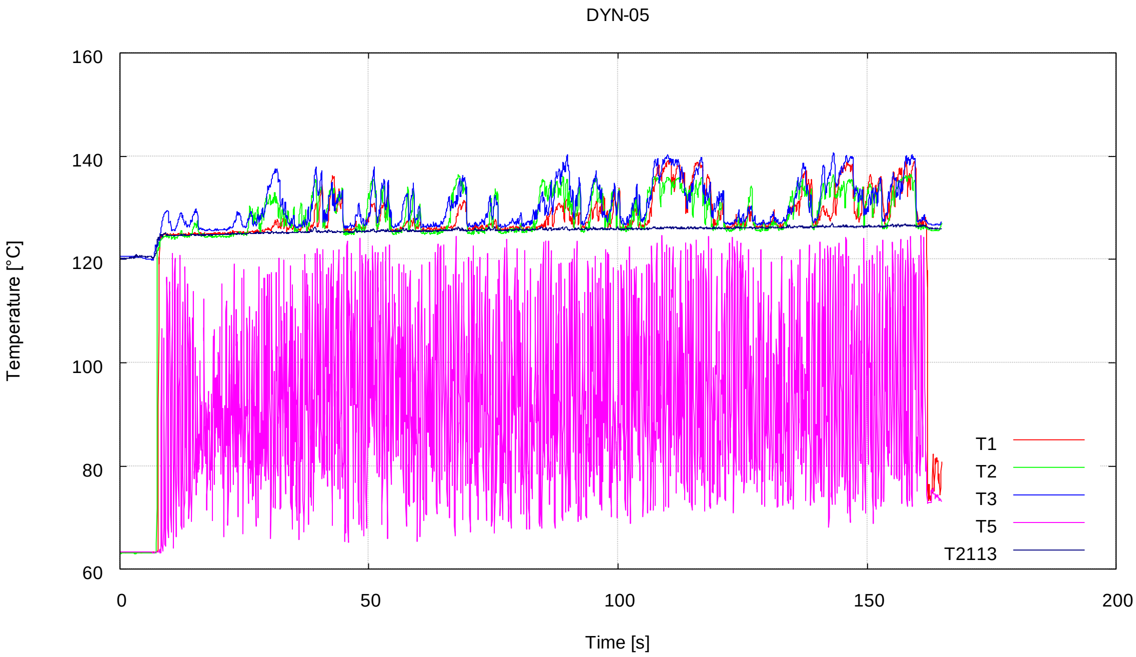

Figure 19. Temperatures inside (T1, T2, T3 and T2113) and at the outlet (T5) of the blowdown pipe in DYN-05.

5.3 EFFECT OF COUNTERPRESSURE

In DYN-08, a small initial counterpressure (0.15 MPa) in the test vessel was used. The aim was to study how the loads induced by condensation change due to increased system pressure. A reference case for DYN-08 can be found from DYN-07, where the main test parameters were almost similar. In both experiments, the initial pressure of the steam source was 0.55 MPa and the temperature of the incoming steam 142-144 °C. In DYN-08, the initial pool water temperature was two degrees higher (25 °C) than in DYN-07 (23 °C). The pool water level was 2.19 m in DYN-07 and 2.14 m in DYN-08. In DYN-07, the recorded steam discharge period lasted for about 160 seconds. The flow rate was initially 460 g/s and decreased to 430 g/s during the experiment. In DYN-08, the steam discharge period lasted for about 310 seconds and the flow rate decreased from 440 g/s to 320 g/s.

For some reason the removal of non-condensables from the dry well was not as successful as expected in either experiment. According to the sensor the steam fraction in the dry well compartment had a decreasing trend throughout the experiments and it finally ended to a level of about 80 % in DYN-07 and 50 % in DYN-08. Since the steam fraction measurement is based on a local sensor in the dry well, the actual steam/non-condensable gas content of the flow in the blowdown pipe cannot be estimated reliably. It is assumed that the fraction of steam in the blowdown pipe flow was much higher than the value indicated by the sensor in the dry well. This is evidenced by the vigorous condensation behavior during the last third of the DYN-08 experiment. With high non-condensable gas contents of the flow such behavior would not probably be possible. In DYN-08, the removal period of non-condensables was about 40 seconds shorter than in DYN-07. This could contribute to some extend to the different steam fraction measurement values between these two experiments. Despite of this it is believed that the test conditions in the blowdown pipe and in the condensation pool were identical enough for the comparison between the experiments to be allowable.

The diminishing effect of increased system pressure on measured loads is evident. Highest pressure pulses both inside the blowdown pipe and in the condensation pool are about twice as high in DYN-07 as in DYN-08, see Table 4 and Figure 20. Also the vertical movement and acceleration of the test vessel as well as the strains are doubled in DYN-07. Furthermore, a direct comparison of the experiments reveals a reduced chugging intensity due to counterpressure in DYN-08 and even a bigger difference between the loads during the chugging period can be assumed. The highest pressure pulses in DYN-08 are measured during the last 60 seconds of the experiment when chugging was no more present but the steam condensation within blowdown pipes mode existed. In DYN-07, this mode was missing completely and chugging prevailed throughout the experiment. This was evidenced by the dynamic, intense and unceasing movement of the steam/water interface inside the blowdown pipe and repeated formation of steam bubbles at the pipe outlet.

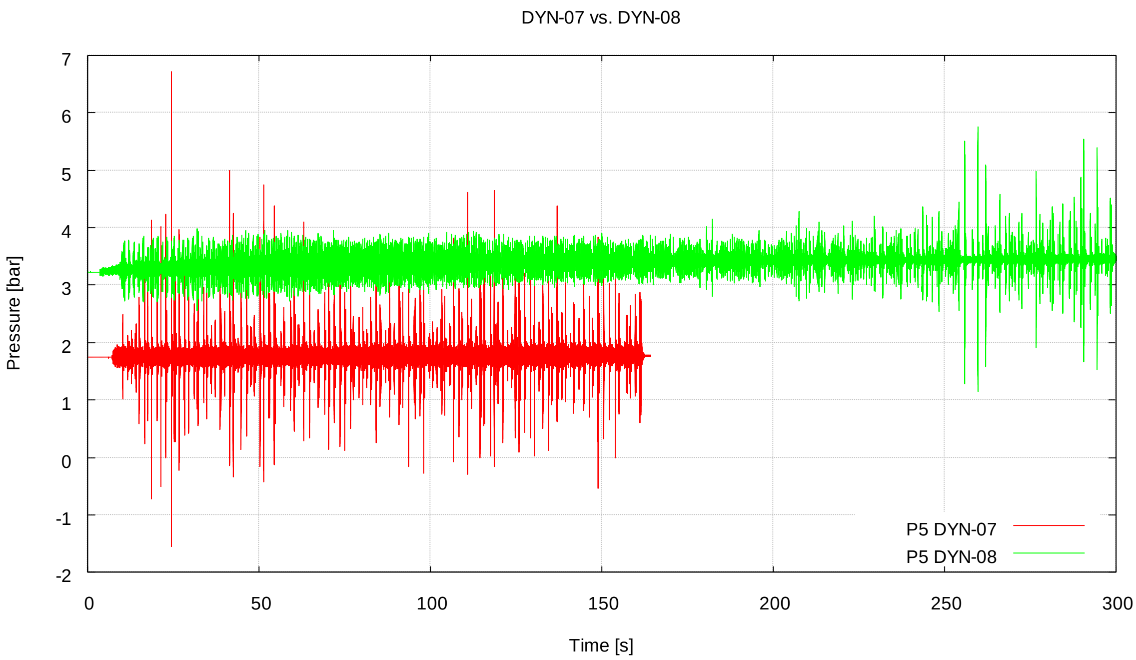

Figure 20. Pressure loads during chugging at the blowdown pipe outlet (P5) with normal (DYN-07) and increased counterpressure (DYN-08). The last 60 seconds of DYN-08 belong to the condensation within blowdown pipes mode.

6 SUMMARY AND CONCLUSIONS

This report summarizes the results of the dynamic loading experiments (DYN series) carried out with the scaled down, two compartment PPOOLEX test facility designed and constructed at LUT. Steam was blown into the dry well compartment and from there through the DN200 vertical blowdown pipe to the condensation pool filled with sub-cooled water. The experiment series consisted of eight individual tests. The main purpose of the experiments was to study dynamic loads caused by different condensation modes. Particularly, the effect of counterpressure on loads due to pressure oscillations induced by chugging was of interest.

Before the experiments the condensation pool was filled with isothermal water so that the blowdown pipe outlet was submerged by 1.03-1.11 m. The initial temperature of the pool water varied from 11 °C to 63 °C, the steam flow rate from 290 g/s to 1220 g/s and the temperature of incoming steam from 132 °C to 182 °C. The steam source initial pressure was between 0.35-1.5 MPa. Non-condensables were pushed from the dry well into the gas space of the wet well with a short discharge of steam before the recorded period of the experiments. The idea was to increase the steam fraction of the actual discharge period and so to help the simulation partners to better define the initial/boundary conditions for the calculation exercises. As a result of this procedure, the system pressure was at an elevated level in the beginning of the actual experiments. This differentiates the DYN series from the previous PPOOLEX experiments where no removal of non-condensables or an elevated initial system pressure has been used. In DYN-08, even an increased counterpressure was used by injecting compressed air into the closed test vessel before starting the recorded steam discharge. During the experiments the data acquisition system recorded with a frequency of 5 kHz. A digital high-speed video camera was used for the observation of steam bubbles at the blowdown pipe outlet.

In the small steam flow rate cases, the diminishing effect of increased pool water temperature on condensation loads was evidenced once again. With strongly sub-cooled pool water chugging and condensation within the blowdown pipe caused strong dynamic loads to the pool structures. The largest pressure loads were registered inside the blowdown pipe close to its lower end. Considerable loads were measured also by the pressure sensors in the condensation pool. However, the largest registered individual pressure pulses inside the blowdown pipe and in the pool did not occur simultaneously. This indicates that the condensation mode in question (chugging or condensation within blowdown pipes) dictates very strongly where the maximum structural loads occur. With increased pool water temperature the largest measured pressure loads inside the blowdown pipe and in the condensation pool were about one order of magnitude smaller than in the cold water experiments despite of the similar steam mass flow rate. The higher pool water temperature prevented the chugging phenomenon and related high pressure pulses from occurring. Instead, the much milder condensation oscillations mode and transition region were prevailing during the experiment. The oscillations were continuous in nature and their amplitude was almost constant throughout the experiment.

In the high steam flow rate cases, the strongest pressure loads were found from the condensation pool. The prevailing condensation modes were condensation oscillations and chugging. The condensation within blowdown pipes mode was not encountered in these experiments. Practically, no pressure pulses were measured inside the blowdown pipe and there was no water ingress back into the pipe at all. Increased pool water temperature had an effect on the condensation process also in the high flow rate cases. It shifted the condensation phenomenon to the transition region in the condensation mode map and therefore high pressure loads related to the modes of chugging and condensation within blowdown pipes were missing.

The diminishing effect of increased system pressure on chugging intensity and measured loads is evident from the results of the last experiment where a small initial pressure in the test vessel was used. The highest pressure pulses inside the blowdown pipe and in the condensation pool were about half of those measured with a lower system pressure but otherwise with similar parameters. Also the vertical movement and acceleration of the vessel as well as the strains were smaller.

In summary it can be said that the experiments on dynamic loading gave expected results. The loads experienced by condensation pool structures depended strongly on the steam mass flow rate, pool water temperature and system pressure. The DYN experiments indicated that chugging and condensation within the blowdown pipe cause significant dynamic loads in case of strongly sub-cooled pool water. The level of pool water temperature is decisive. High individual pressure pulses (and loads) were missing with increased temperature and the oscillations were continuous in nature and their amplitude was almost constant. With an increased steam mass flow rate the highest loads were found from the condensation pool and not from inside the blowdown pipe.

Some uncertainties related to the amount of non-condensables among the steam flow prevent definitive conclusions of their effect on the condensation process and measured loads. The general trend of reduced loads due to increased amount of non-condensables can, however, be seen from the results of the experiment series.

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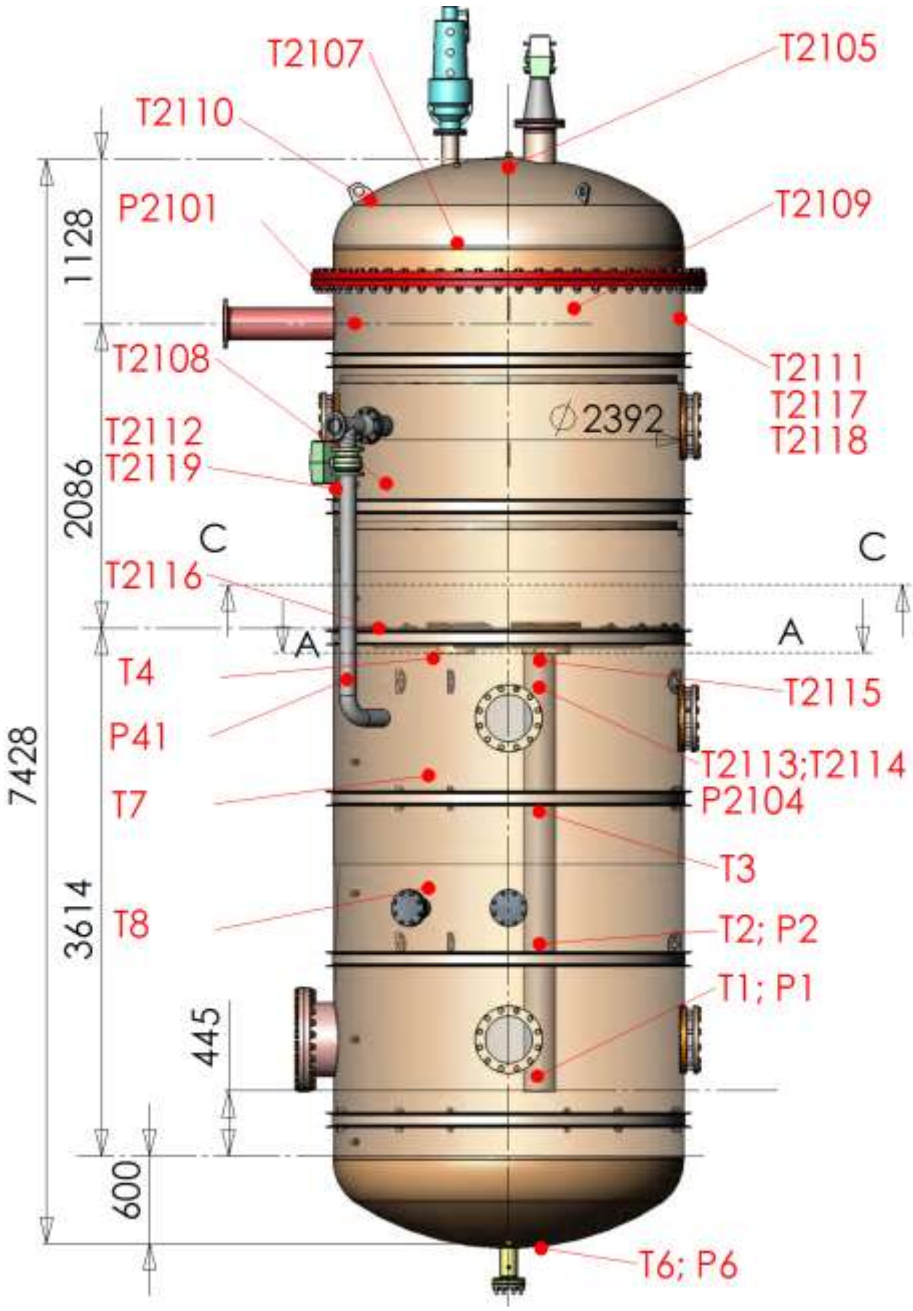
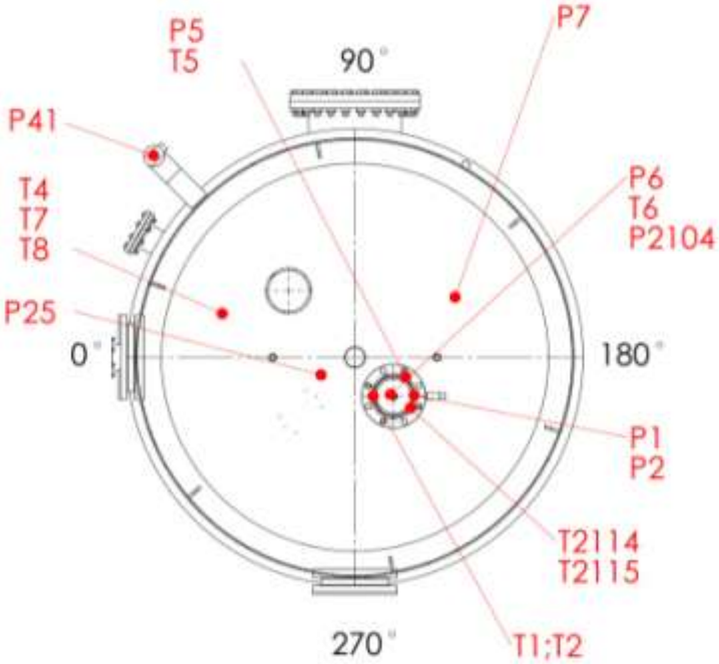
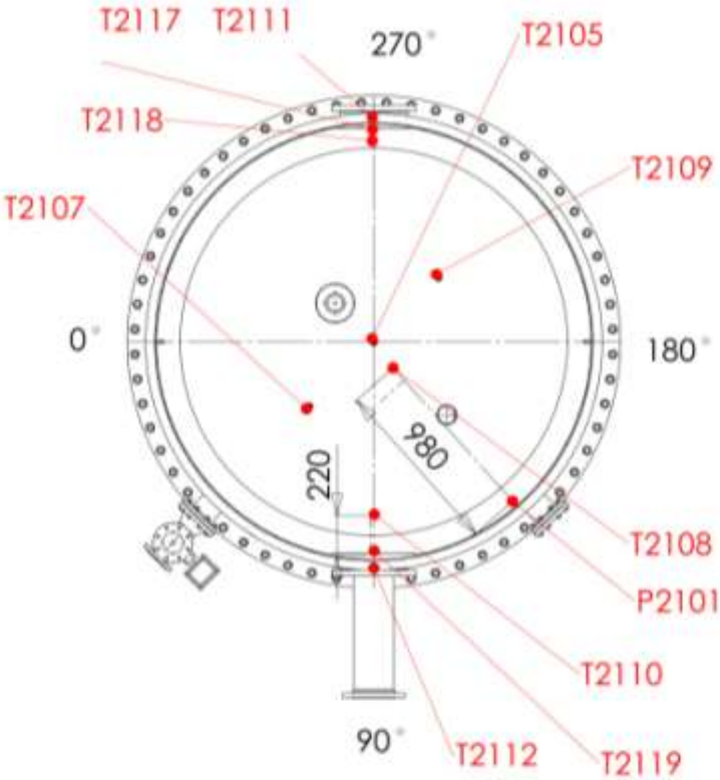
APPENDIX 1: INSTRUMENTATION OF THE PPOOLEX TEST FACILITY



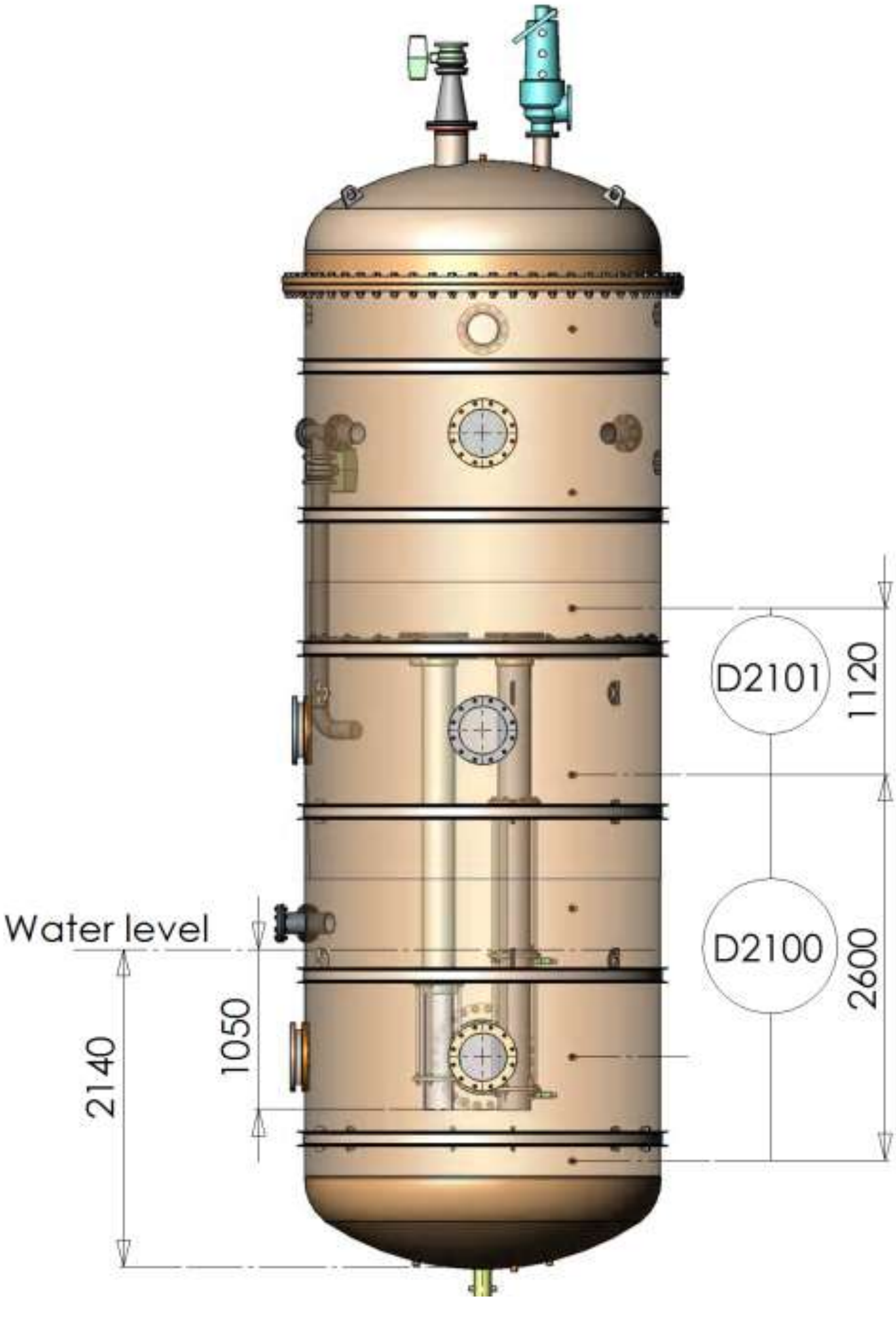
Test vessel measurements.



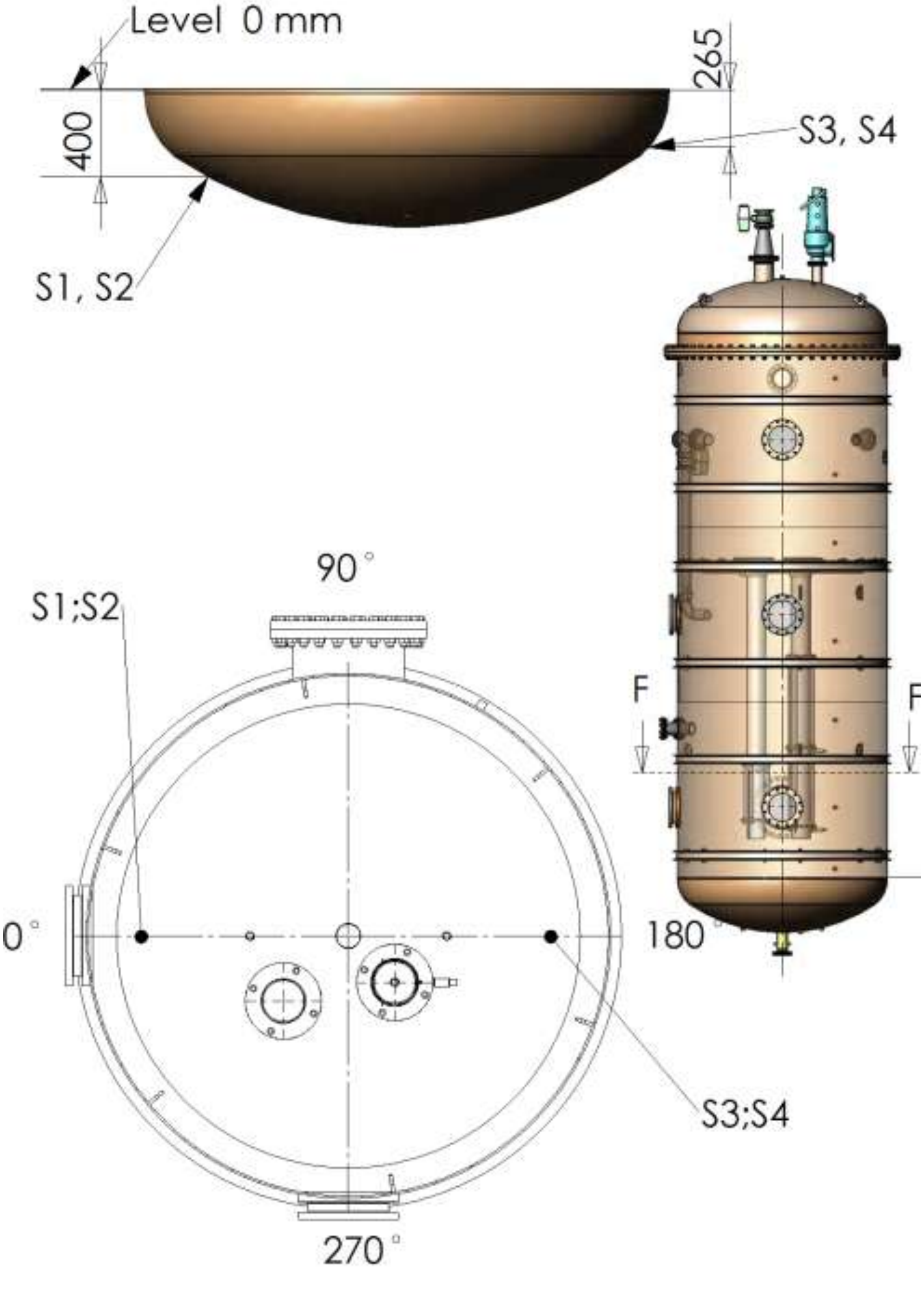
Cross-section A-A.



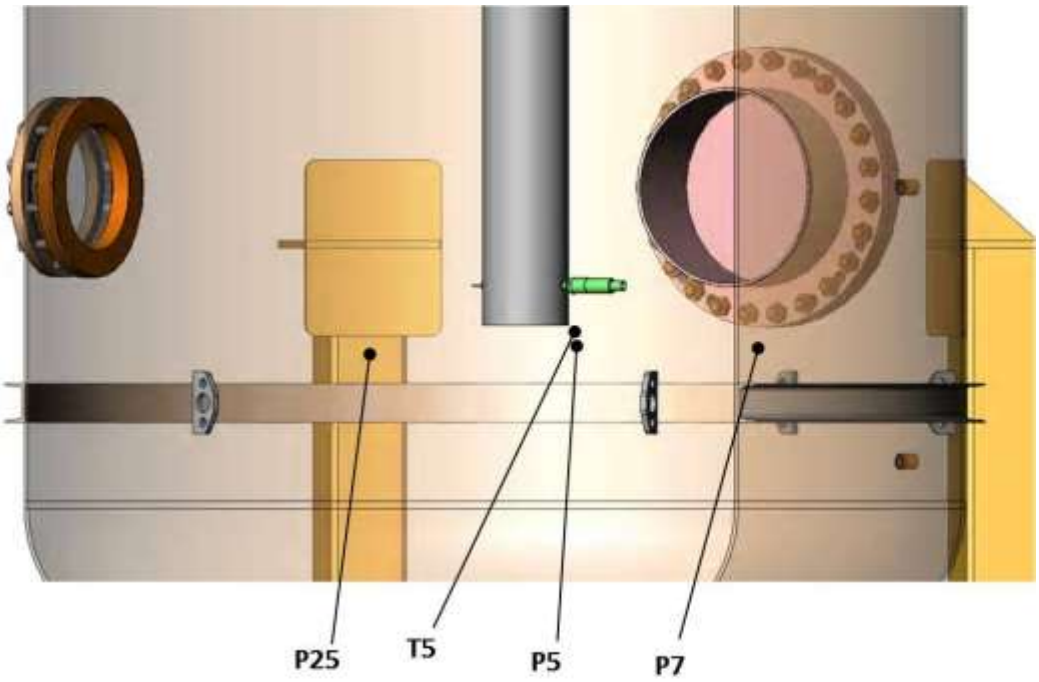
Cross-section C-C.



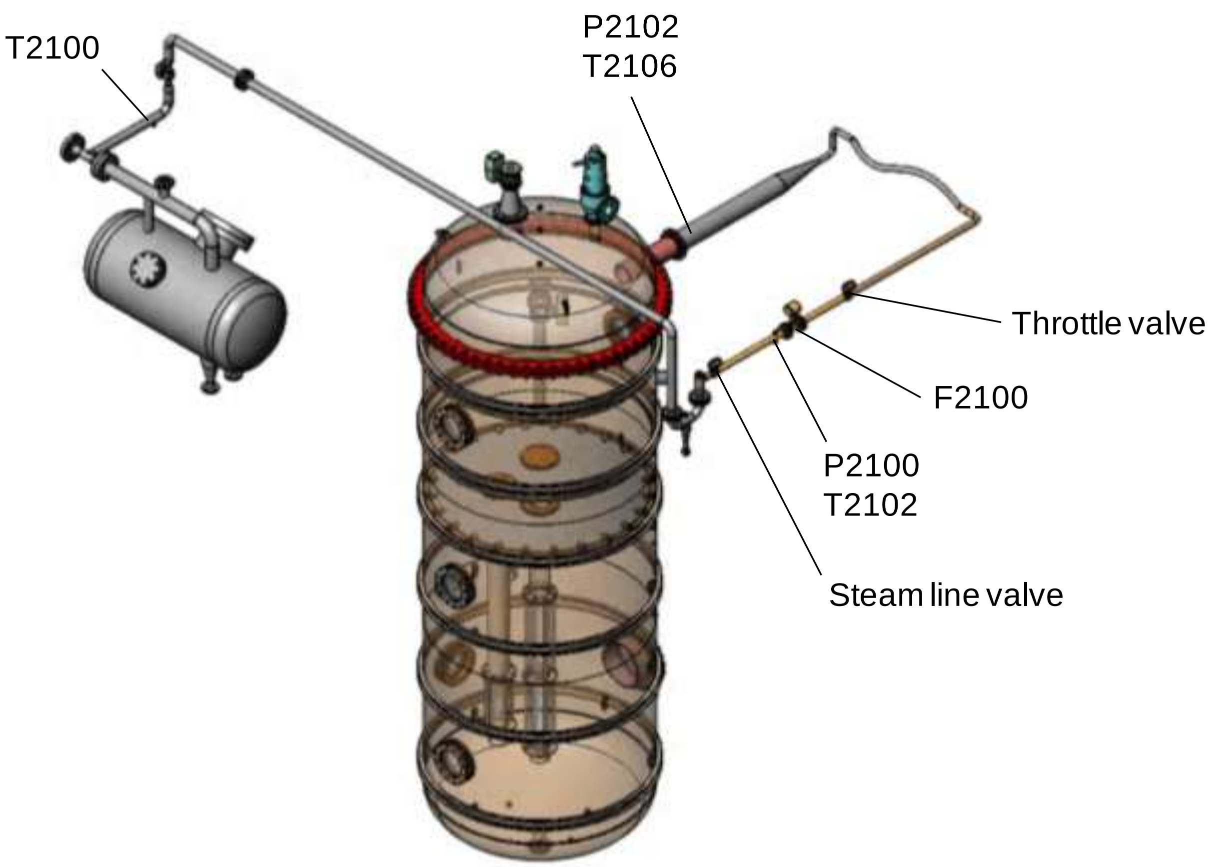
Pressure difference measurements. Water level is at the nominal value of 2.14 m.



Strain gauges on the outer wall of the pool.



Pressure and temperature measurements at the blowdown pipe outlet.



Measurements in the steam line.

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Measurement	Code	Elevation	Angle	Location	Error estimation
Pressure	P1	545	214	Blowdown pipe	±0.7 bar
Temperature	T1	545	245	Blowdown pipe	±1.8 °C
Pressure	P2	1445	214	Blowdown pipe	±0.7 bar
Temperature	T2	1445	245	Blowdown pipe	±1.8 °C
Temperature	T3	2345	245	Blowdown pipe	±1.8 °C
Temperature	T4	3410	20	Wet well gas space	±1.8 °C
Pressure	P5	395	198	Blowdown pipe outlet	±0.7 bar
Temperature	T5	420	198	Blowdown pipe outlet	±1.8 °C
Pressure	P6	-1060	225	Wet well bottom	±0.5 bar
Temperature	T6	-1060	225	Wet well bottom	±1.8 °C
Pressure	P7	395	135	Wet well	±0.4 bar
Temperature	T7	2585	20	Wet well	±1.8 °C
Temperature	T8	1760	20	Wet well	±1.8 °C
Pressure	P25	395	305	Wet well	±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	120	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	T2113	3400	225	Blowdown pipe	±1.8 °C
Temperature	T2114	3400	220	Blowdown pipe	±1.8 °C
Temperature	T2115	3550	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	X2100	-	-	Steam line	Not defined
Steam partial	X2102	4600	120	Dry well	Not defined

pressure					
Valve position	V1	-	-	Steam line	Not defined
Camera trigger	Camera trigger	-	-	Wet well	Not defined

Measurements in the PPOOLEX facility for the DYN experiments.

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APPENDIX 2: PPOOLEX TEST FACILITY PHOTOGRAPHS

Dry well compartment, relief valves and inlet plenum.

Pressure (P1, P5 and P7) and temperature (T1 and T5) measurements at the blowdown pipe outlet.

Title	PPOOLEX Experiments on Dynamic Loading with Pressure Feedback
Author(s)	Markku Puustinen, Jani Laine, Antti Räsänen
Affiliation(s)	Lappeenranta University of Technology, Nuclear Safety Research Unit
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Abstract

This report summarizes the results of the dynamic loading experiments (DYN series) carried out with the scaled down, two compartment PPOOLEX test facility designed and constructed at LUT. Steam was blown into the dry well compartment and from there through the DN200 vertical blowdown pipe to the condensation pool filled with sub-cooled water. The main purpose of the experiments was to study dynamic loads caused by different condensation modes. Particularly, the effect of counterpressure on loads due to pressure oscillations induced by chugging was of interest.

Before the experiments the condensation pool was filled with isothermal water so that the blowdown pipe outlet was submerged by 1.03-1.11 m. The initial temperature of the pool water varied from 11 ºC to 63 ºC, the steam flow rate from 290 g/s to 1220 g/s and the temperature of incoming steam from 132 ºC to 182 ºC. Non-condensables were pushed from the dry well into the gas space of the wet well with a short discharge of steam before the recorded period of the experiments. As a result of this procedure, the system pressure was at an elevated level in the beginning of the actual experiments. An increased counterpressure was used in the last experiment of the series.

The diminishing effect of increased system pressure on chugging intensity and on measured loads is evident from the results of the last experiment. The highest pressure pulses both inside the blowdown pipe and in the condensation pool were about half of those measured with a lower system pressure but otherwise with similar test parameters.

The experiments on dynamic loading gave expected results. The loads experienced by pool structures depended strongly on the steam mass flow rate, pool water temperature and system pressure. The DYN experiments indicated that chugging and condensation within the blowdown pipe cause significant dynamic loads in case of strongly sub-cooled pool water. The level of pool water temperature is decisive. High individual pressure pulses (and loads) were missing with increased temperature and the oscillations were continuous in nature and their amplitude was almost constant. With an increased steam mass flow rate the highest loads were found from the condensation pool and not from inside the blowdown pipe.

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

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