NKS-310
ISBN 978-87-7893-388-1

Chugging Test with DN100 Blowdown Pipe in the PPOOLEX Facility

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June 2014

Abstract

This report summarizes the results of the DCC-05 direct contact condensation experiment in 2013 with the scaled down PPOOLEX test facility designed and constructed at Lappeenranta University of Technology. The main purpose of the DCC-05 experiment was to obtain high quality measurement data from the chugging condensation mode for the validation of DCC models used in CFD codes and to make 3D high speed video recordings to be used in the development work of pattern recognition algorithms. During the experiment the DN100 blowdown pipe was equipped with extra temperature measurements for capturing different aspects of the investigated phenomena.

The general trend of the measured parameters in the DCC-05 experiment was similar with those of the corresponding chugging experiments carried out with the DN200 blowdown pipe. Temperatures in the gas space of the wetwell rose due to compression by pressure build-up. As the gas space temperatures increased, they also stratified. During the DCC-05 experiment the pool water stratified, too. Temperatures at the pool bottom remained close to the initial value but increased from the blowdown pipe outlet elevation upwards so that water was warmest on the pool surface.

During the chugging mode high pressure loads were measured inside the blowdown pipe and at the pool bottom. However, the oscillating movement of the steam/water-interface inside the blowdown pipe during the chugging periods was not very wide. The interface reached the elevations of 200 mm (TC05) and 260 mm (TC06) above the pipe outlet few times. In the previous experiments with the DN200 blowdown pipe the up and down movement of the steam/water-interface has been much larger.

The high frequency measurement data of the DCC-05 experiment in PPOOLEX can be used in the validation of DCC models of CFD codes. Furthermore, the pattern recognition algorithms being developed and improved at LUT can be later used to assess the steam bubble surface area and volume as well as the chugging frequencies from the video material as a function of pool water temperature and steam mass flux.

Key words

chugging, steam blowdown

NKS-310
ISBN 978-87-7893-388-1
Electronic report, June 2014
NKS Secretariat
P.O. Box 49
DK - 4000 Roskilde, Denmark
Phone +45 4677 4041
www.nks.org
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Research Report
Lappeenranta University of Technology
Nuclear Safety Research Unit

EXCOP 2/2013

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Lappeenranta, 26.2.2014

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Research organization and address	Customer
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Project title and reference code SAFIR2014-EXCOP NKS-ENPOOL	**Report identification & Pages** EXCOP 2/2013 19 p. + app. 12 p. — **Date** 26.2.2014

Report title and author(s)

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Principal author or Project manager	Reviewed by
Markku Puustinen, Research Scientist	Vesa Riikonen, Senior Research Scientist
Approved by	**Availability statement**
Heikki Purhonen, Research Director	SAFIR2014 limitations

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Acknowledgement

NKS conveys its gratitude to all organisations and persons who by means of financial support or contributions in kind have made the work presented in this report possible.

Disclaimer

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 have been modelled with computational fluid dynamics (CFD), lumped parameter and structural analysis codes at VTT. Pattern recognition analysis and CFD simulations of some of these experiments have been carried out at LUT within the NURESIM and NURISP EU-projects.

A 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 focused on several containment issues and continued further the work done in this area within the FINNUS and SAFIR programs. For the new experiments, a closed test facility modelling the drywell and wetwell compartments of BWR containment was designed and constructed. The main objective of the CONDEX project was to increase the understanding of different phenomena inside the containment during a postulated main steam line break (MSLB) accident. The studies were funded by the VYR, NKS and Nordic Nuclear Reactor Thermal-Hydraulics Network (NORTHNET).

A new research project called Experimental Studies on Containment Phenomena (EXCOP) started in 2011 within the national nuclear power plant safety research programme SAFIR2014. The EXCOP project focuses on gathering an extensive experiment database on condensation dynamics, heat transfer and structural loads, which can be used for testing and developing computational methods used for nuclear safety analysis. To achieve the above mentioned goals sophisticated measuring solutions i.e. a Particle Image Velocimetry (PIV) system and modern high speed cameras have been installed to the PPOOLEX facility in 2011-2013. Networking among international research organizations is enhanced via participation in the NORTHNET framework and the NKS/ENPOOL project. Analytical and numerical work of Kungliga Tekniska Högskolan (KTH) is combined to the EXCOP, ELAINE, NUMPOOL, ESA and nuFoam projects of SAFIR2014. The studies are funded by the VYR, NKS and NORTHNET. The simulation work at LUT is also partially funded by the NURESAFE EU-project.

CONTENTS

NOMENCLATURE

Abbreviations

BWR	boiling water reactor
CCTV	closed circuit television
CFD	computational fluid dynamics
CONDEX	condensation experiments project
DCC	direct contact condensation
DYN	experiment series focusing on dynamic loading
ECCS	emergency core cooling system
EHS	effective heat source
ELAINE	enhancement of Lappeenranta instrumentation of nuclear safety experiments project
EMS	effective momentum source
ENPOOL	experimental and numerical studies on suppression pool issues project
ESA	enhancement of safety evaluation tools project
EXCOP	experimental studies on containment phenomena project
FINNUS	Finnish Research Programme on Nuclear Power Plant Safety
KTH	Kungliga Tekniska Högskolan
LUT	Lappeenranta University of Technology
MSLB	main steam line break
MIX	mixing experiment series
NKS	Nordic nuclear safety research
nuFoam	OpenFOAM CFD-solver for nuclear safety related flow simulations project
NUMPOOL	numerical modeling of condensation pool project
NURESAFE	NUclear REactor SAFEty Simulation Platform
NURESIM	Nuclear Reactor Simulations
NURISP	The Nuclear Reactor Integrated Simulation Project
PACTEL	parallel channel test loop
PAR	experiment series with parallel blowdown pipes
PIV	particle image velocimetry
POOLEX	condensation pool experiments project, test facility for condensation pool studies
PPOOLEX	test facility for containment studies
SAFIR	Safety of Nuclear Power Plants - Finnish National Research Programme
SAFIR2010	The Finnish Research Programme on Nuclear Power Plant Safety 2007–2010
SAFIR2014	The Finnish Research Programme on Nuclear Power Plant Safety 2011–2014
SLR	steam line rupture
TC	thermocouple
TRA	experiment series with transparent blowdown pipes
TVO	Teollisuuden Voima Oyj
VTT	Technical Research Centre of Finland
VYR	State Nuclear Waste Management Fund

1 INTRODUCTION

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

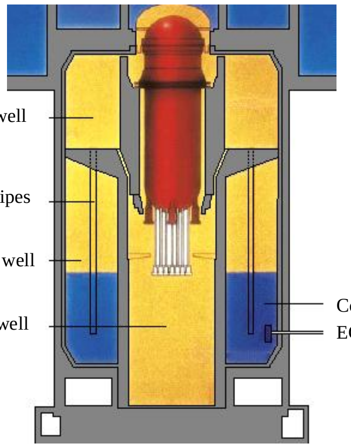

Figure 1. Schematic of the Olkiluoto type BWR containment.

The main objective of the EXCOP project is to improve understanding and increase fidelity in quantification of different phenomena inside the dry and wetwell 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 experiment 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.

In 2006, a new test facility, called PPOOLEX, suitable for BWR containment studies was designed and constructed by Nuclear Safety Research Unit at LUT. It models both the drywell and wetwell (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 PPOOLEX facility started in 2007 by running characterizing tests where the general behaviour of the facility was observed and instrumentation and the proper operation of automation, control and safety systems was tested [1]. The SLR series focused on the initial phase (air as flowing substance) of a postulated MSLB accident inside the containment [2]. The research program continued in 2008 with thermal stratification and mixing experiments [3]. Stratification in the water volume of the wetwell during small steam discharge was of special interest. In December 2008 and January 2009 a test series focusing on steam condensation in the drywell compartment was carried out [4]. Experiments to study the effect of the Forsmark type blowdown pipe outlet collar design on loads caused by chugging were also done in 2009 [5]. Then the research programme continued with the TRA and PAR series studying the effect of the number of blowdown pipes (one or two) on loads caused by chugging phenomenon [6]. In January 2010, experiments focusing on dynamic loading (DYN series) during steam discharge were carried out [7]. Stratification and mixing in the wetwell pool and the interaction of parallel blowdown pipes were investigated further in 2010 [8], [9]. In January – February 2011 a second series of the experiments with the Forsmark type blowdown pipe outlet collar was carried out [10]. First tests with the new PIV measurement system were executed at the end of 2011 [11].

In June–October 2012, a new series of thermal stratification and mixing experiments (labelled as MIX-01…06) was carried out [12]. For the test series additional thermocouples were installed inside the DN200 blowdown pipe to get accurate information of the movement of steam/water-interface inside the pipe during the mixing phase. The main purpose of the experiments was to generate data for the development of the Effective Momentum Source (EMS) and Effective Heat Source (EHS) models to be implemented in GOTHIC code by KTH [13]. The research program continued in November 2013 with a second series of of thermal stratification and mixing experiments (MIX-07…12) [14]. For the test series the blowdown pipe diameter was reduced to DN100 and the amount of thermocouples inside the pipe was further increased.

Studies on chugging were also continued in 2013. The new triple high speed camera system enables better observation of the direct contact condensation (DCC) phenomenon at the blowdown pipe outlet. The main objective of the experiments was to obtain high quality measurement data for the validation of DCC models used in CFD codes as well as to make 3D high speed recordings to be used in the development work of pattern recognition algorithms. In this report, the results of the DCC-05 experiment in 2013 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 DCC-05 experiment is introduced in chapter three. The test results are presented and discussed in chapter four. Chapter five summarizes the findings.

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

2.1 TEST VESSEL

The PPOOLEX facility consists of a wetwell compartment (condensation pool), drywell 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 drywell to the wetwell is created by a vertical blowdown pipe attached underneath the floor.

The main component of the facility is the ~31 m^3 cylindrical test vessel, 7.45 m in height and 2.4 m in diameter. It is constructed from three plate cylinder segments and two dome segments. The test facility is able to withstand considerable structural loads caused by rapid condensation of steam. The dry and wetwell sections are volumetrically scaled according to the compartment volumes of the Olkiluoto containment (ratio approximately1:320). Inlet plenum for injection of steam penetrates through the side wall of the drywell compartment. The inlet plenum is 2.0 m long and its inner diameter is 214.1 mm. To prevent steam hitting to the opposite wall of the drywell during the blowdowns, there is a cone shaped flow straightener installed inside the inlet plenum. There are several windows for visual observation in both compartments. A DN100 (∅ 114.3 x 2.5 mm) drain pipe with a manual valve is connected to the vessel bottom. A relief valve connection is mounted on the vessel head. The removable vessel head and a man hole (DN500) in the wetwell compartment wall provide access to the interior of the vessel for maintenance and modifications of internals and instrumentation. The drywell is thermally insulated. A sketch of the test vessel is shown in Figure 2. Table 1 lists the main dimensions of the test facility compared to the conditions in the Olkiluoto plant.

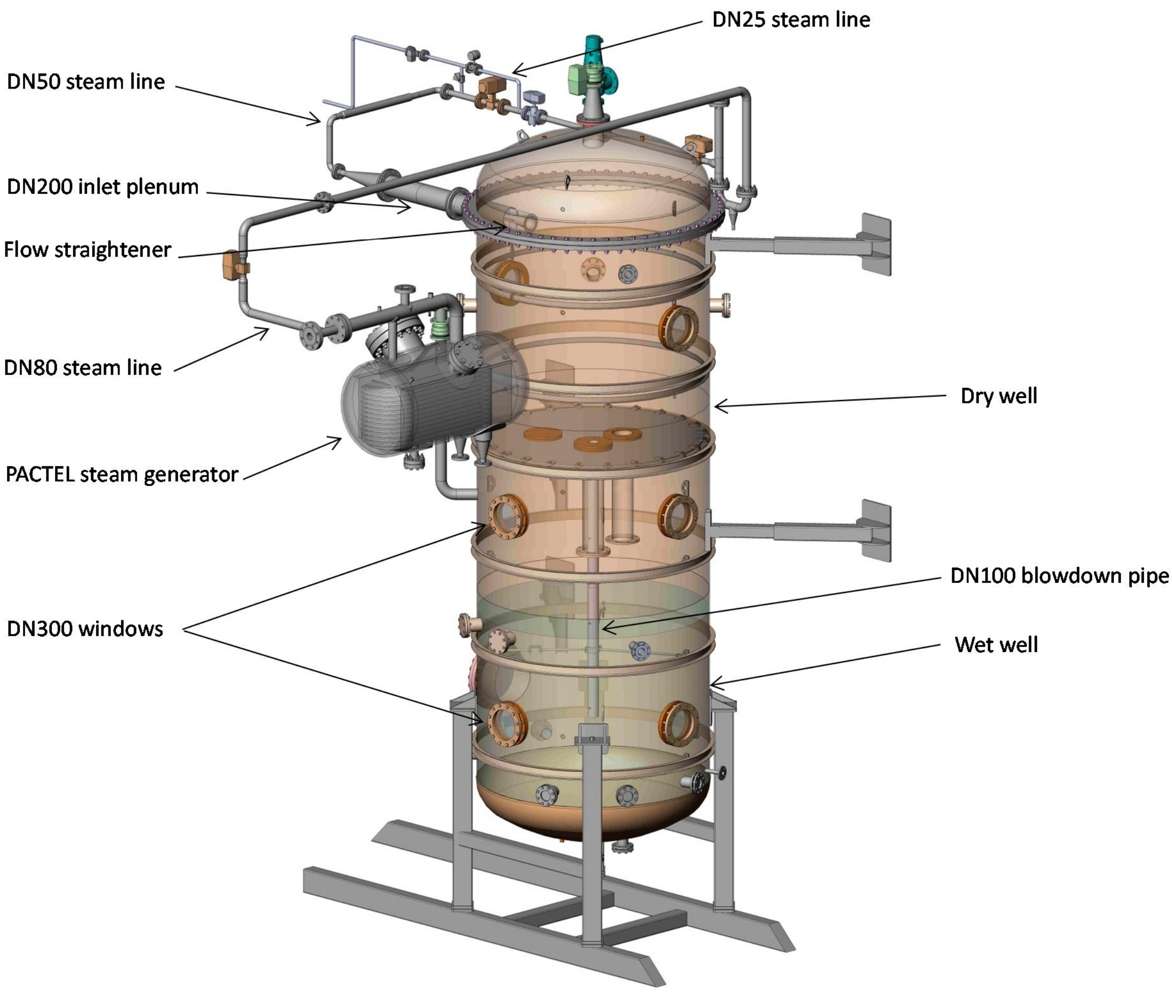

Figure 2. PPOOLEX test vessel.

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

	PPOOLEX test facility	Olkiluoto 1 and 2
Number of blowdown pipes	1–2	16
Inner diameter of the DN100 blowdown pipe [mm]	109.3	600
Suppression pool cross-sectional area [m^2]	4.45	287.5
Drywell volume [m^3]	13.3	4350
Wetwell 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%	0.2 / 0.4**	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 DN100 blowdown pipes.

2.2 PIPING

In the plant, there are vacuum breakers between the dry and wetwell compartments in order to keep the pressure in wetwell in all possible accident situations less than 0.05 MPa above the drywell 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 wetwell gas space to the drywell. 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 [16] 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. A section of a parallel DN25 pipe with a small range flow meter enables the measurement of steam flow during the stratification period.

2.3 BLOWDOWN PIPE

In the DCC-05 experiment in 2013 the DN100 (∅ 114.3 x 2.5 mm) blowdown pipe was used. The pipe was made from austenitic stainless steel EN 1.4301 (AISI 304) and was positioned inside the pool in a non-axisymmetric location, i.e. it was 300 mm away from the centre of the condensation pool. To enable better conditions for the triple camera system the total length of the DN100 blowdown pipe was decreased from 3209 mm to 2917 mm. Thus the outlet of the DN100 pipe was 292 mm higher than the outlet of the DN200 pipe, which had been used in the experiments earlier. The water level of the condensation pool was increased accordingly in order to keep the submergence depth of the blowdown pipes the same.

2.4 MEASUREMENT INSTRUMENTATION

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

For the MIX 2013 experiments an extensive net of temperature measurements (thermocouples TC1–TC145) were installed in the DN100 blowdown pipe to accurately record the frequency and amplitude of steam/water-interface oscillations inside the pipe. These measurements were in use also during the DCC-05 experiment with DN100 blowdown pipe. Figures in Appendix 1 show the locations of the PPOOLEX measurements during the DCC-05 experiment the table in Appendix 1 lists their identification codes and other details.

2.5 CCTV SYSTEM

Two standard video cameras, three high speed cameras and a digital videocassette recorder were used for visual observation of the test vessel interior during the test series. High speed cameras were used for capturing the chugging phenomenon at the blowdown pipe outlet from three different viewing angels.

2.6 DATA ACQUISITION

National Instruments PXIe PC-driven measurement system was used for data acquisition. The system enables high-speed multi-channel measurements. The maximum number of measurement channels is 64 with additional eight channels for strain gauge measurements. The maximum recording capacity depends on the number of measurements and is in the region of three hundred thousand samples per second. Measurement software was LabView 2011. The data acquisition system is discussed in more detail in reference [17].

Self-made software using the National Instruments FieldPoint measurement system was used for monitoring and recording the essential measurements of the PACTEL facility generating the steam. Both data acquisition systems measure signals as volts. After the experiments, the voltage readings are converted to engineering units with conversion software.

The used measurement frequency of LabView was 1 kHz for pressures and strains and 20 Hz for temperatures. 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.

3 DCC-05 EXPERIMENT

The test program of the DCC experiments in 2013 consisted of two tests with the DN200 blowdown pipe (labeled DCC-03 and DCC-04) and of a test with the DN100 pipe (labeled DCC-05). In the DCC-03 test, the purpose was to test the PIV measurement system with LIF particles. It was not an official experiment and it is therefore not reported in more detail. In the DCC-04 and DCC-05 tests, the new triple high speed camera system was used during the chugging phase. DCC-04 was the first trial with the new camera system and it was therefore also an unofficial test without any exact specification of the test parameters and course. It is left out of this report as well.

The main purpose of the DCC-05 experiment was to obtain high quality measurement data for the validation of DCC models used in CFD codes and to make 3D high speed video recordings to be used in the development work of pattern recognition algorithms. Originally, the PIV measurement system was thought to be used in the DCC-05 experiment as well in order to track flow fields below the collapsing steam bubbles during the chugging phase. Unfortunately, the system broke down during the preceding MIX experiment series and could not be repaired in time before the DCC-05 test.

Before the DCC-05 experiment, the wetwell pool was filled with almost isothermal water (25 °C) so that the blowdown pipe outlet was submerged by ~1.0 m. The drywell compartment of the test vessel was filled with air at atmospheric pressure. After the correct initial conditions had been reached in the PPOOLEX and PACTEL facilities, the remote-controlled cut-off valve in the steam line was opened. The steam discharge rate into the PPOOLEX vessel was controlled with the help of the pressure level of the steam source and a remote-operated control valve in the steam line. During the main part of the clearing phase the steam flow rate was between 320 and 340 g/s. As a result, the drywell compartment was soon filled with steam that mixed there with the initial air content. Part of the steam condensed on the drywell walls until the structures had heated up. Pressure build-up in the drywell then pushed water in the blowdown pipe downwards and after a while the pipe cleared and air/steam flow into the wetwell compartment started. Air was displaced from the drywell into the gas space of the wetwell at ~500 seconds into the experiment.

In DCC-05, the idea was to keep the pool water temperature as constant as possible but use a large range of different flow rates. To achieve this goal the steam flow rate was quickly adjusted to the correct value for the recorded periods, but between them (while data was being transferred from the camera memory) it was reduced to almost zero to prevent the unnecessary heat-up of pool water. However, the temperature of pool water at the blowdown pipe outlet elevation rose about 10 degrees during the investigated period. Steam flow rates between 75 and 200 g/s were used in the chugging blows of DCC-05.

The individual steam blows of the DCC-05 experiment defined by the steam mass flux and pool bulk temperature are marked on the condensation mode map of Lahey and Moody in Figure 3. The average value calculated from the readings of thermocouples T2510 and T2511 is used as a pool bulk temperature.

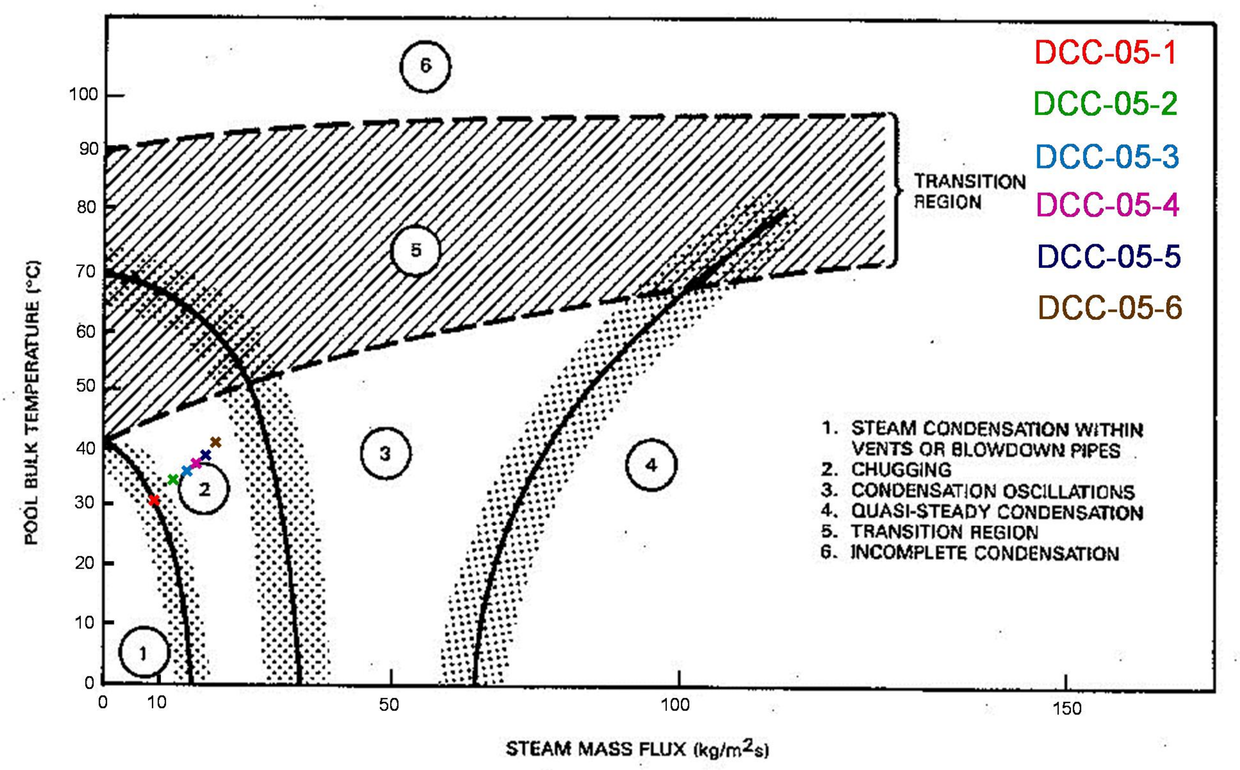

Figure 3. Steam blows of the DCC-05 experiment on the condensation mode map of Lahey and Moody [18].

4 EXPERIMENT RESULTS

The following chapters give a more detailed description of the experiments and present the observed phenomena.

4.1 GENERAL BEHAVIOUR IN DCC-05

The general trend of the measured parameters in the DCC-05 experiment is similar with those of the corresponding chugging experiments carried out with the DN200 blowdown pipe. Temperatures in the gas space of the wetwell rise due to compression by pressure build-up after the discharge is initiated. As the flow in the blowdown pipe changes from air/steam mixture to pure steam, the pressure build-up slows down. However, the heat-up process in the gas space remains quite strong. The main source of heat is now by conduction from the hot drywell compartment via the intermediate floor and test vessel walls and by convection from the upper layers of the hot pool water. As the gas space temperatures increase, they also stratify. Temperatures increase more on the uppermost measurement elevation (T2204) than on the lower elevations (T2207, T2208). Figure 4 shows the pressure build-up of the test vessel during the DCC-05 experiment and the corresponding temperature behavior of the wetwell gas space.

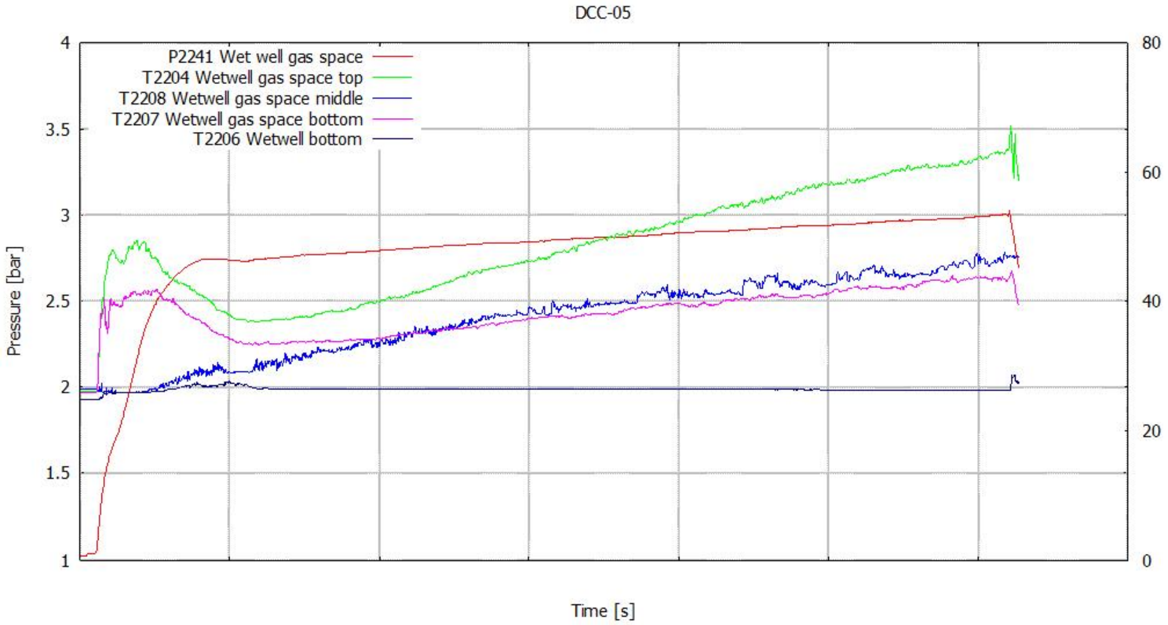

Figure 4. Pressure build-up and thermal stratification in the wetwell gas space in DCC-05.

During the DCC-05 experiment the pool water stratified. Temperatures at the pool bottom remained close to the initial value but increased from the blowdown pipe outlet elevation upwards so that water was warmest on the pool surface. Figure 5 presents the development of vertical temperature distribution of the pool. Measurement T2501 is at the pool bottom and T2518 close to the surface. The blowdown pipe outlet elevation is between measurements T2510 and T2511.

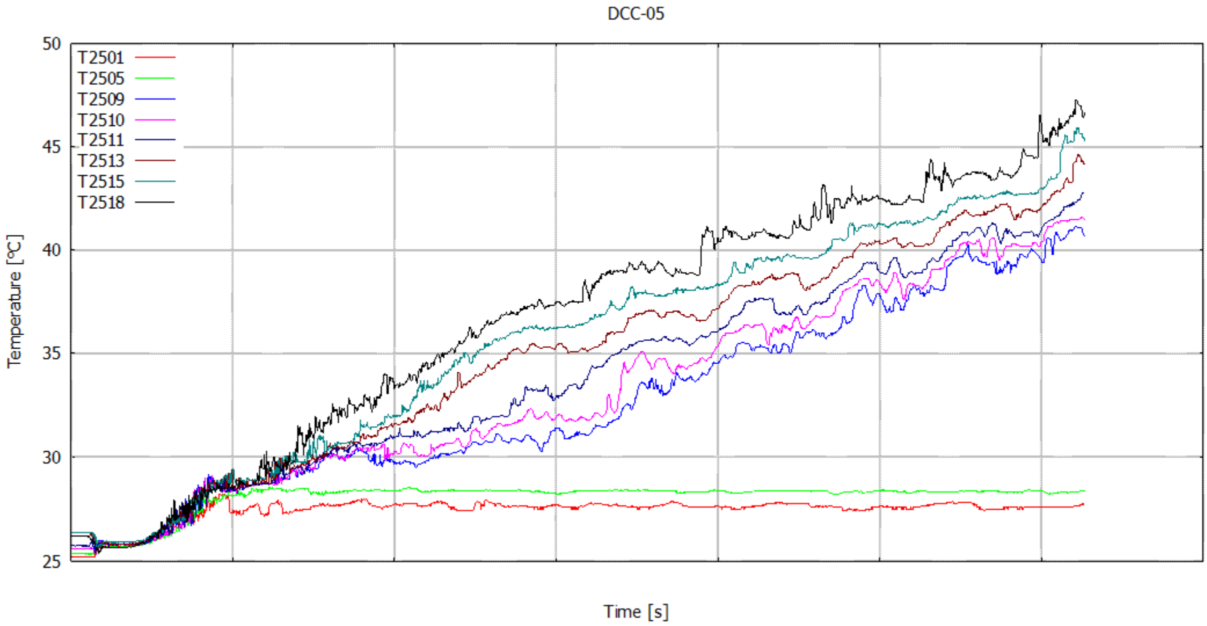

Figure 5. Development of vertical temperature distribution during DCC-05.

4.2 CHUGGING MODE

For the chugging phase measurements and video recordings the steam flow rate was quickly adjusted to the desired value but decreased to minimum between these periods in order to reduce the temperature increase of the pool water. In Figure 6 the steam mass and volumetric flow rates of the six different chugging blows (DCC-05-1 … DCC-05-6) are shown. The first 1000 seconds consists of the clearing/heat-up phase and some testing of the control valve in the steam line.

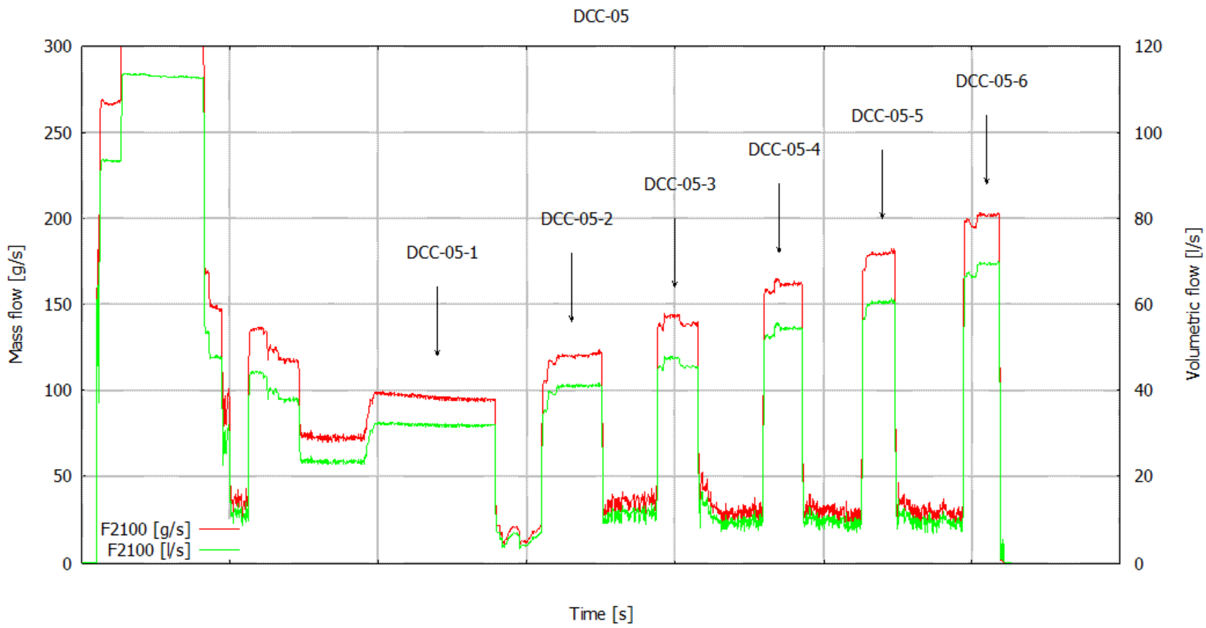

Figure 6. Six chugging blows of the DDC-05 experiment.

During the first recorded period (DCC-05-1) the chugging phenomenon was quite weak because the intersection of steam mass flux and pool bulk temperature was just on the edge of the chugging region (see Figure 3). Chugging intensified as the mass flux was increased and the pool bulk temperature slightly rose. During the last blow an opposite trend could be observed. Chugging was not so violent anymore because the right hand edge of the chugging region was being reached and the flow mode started to change to condensation oscillations. This behavior can be seen also in the pressure curves measured from inside the blowdown pipe (Figure 7). The highest pressure spikes were registered during the DCC-05-2 and DCC-05-3 blows and after that the loads inside the pipe had a decreasing trend. On the pool bottom the behavior was slightly different. The highest loads were registered during DCC-05-3, DCC-05-4 and DCC-05-5. Again, the loads were clearly smaller in DCC-05-6.

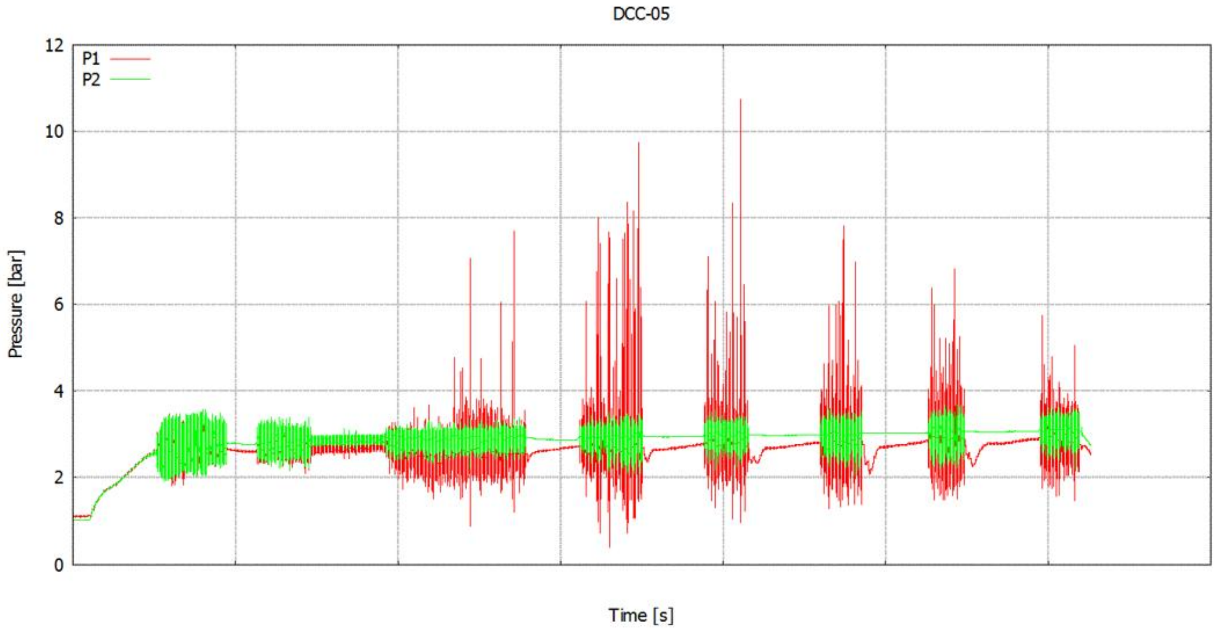

Figure 7. Pressure inside the blowdown pipe during the DCC-05 experiment.

Figure 8 shows frame captures taken from the triple camera high speed video material at the moment when the steam bubble causing the highest pressure spike (at 2054.8 s) inside the blowdown pipe during the DCC-05-3 blow starts to collapse. Pattern recognition algorithms are being developed and improved to help in assessing the steam bubble surface area and volume as well as chugging frequencies from the video material as a function of pool water temperature and steam mass flux [19]. With this information available the size distribution of the bubbles can be calculated. Work with the pattern recognition algorithms is still in progress and the analysis results will be reported later.

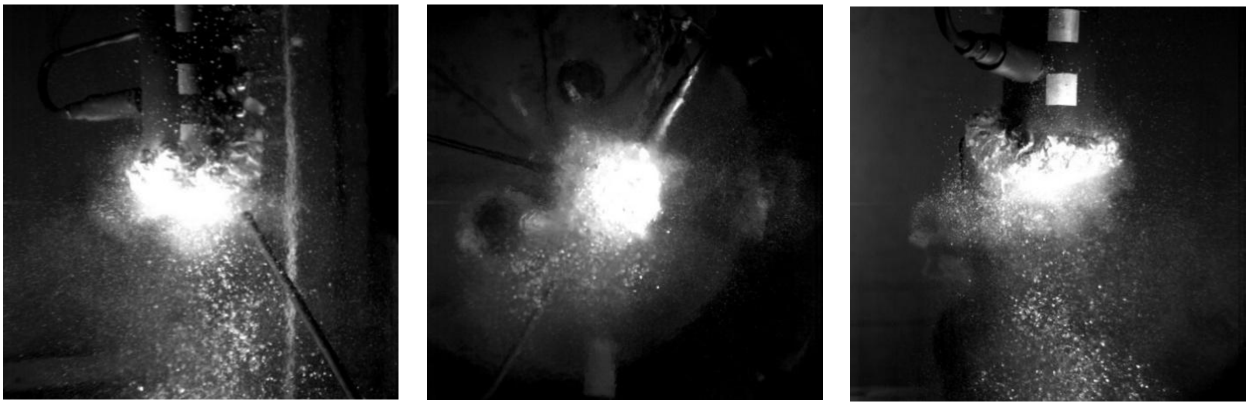

Figure 8. High speed video captures of a steam bubble starting to collapse from the right side, bottom and left side cameras in DCC-05-3.

Thermocouples (TC01–TC145) installed inside the lower part of the blowdown pipe enable accurate measurement of the oscillatory up and down motion of the steam/water-interface inside the pipe caused by the chugging condensation mode. The thermocouples inside the pipe are along a 1 330 mm section upwards from the pipe outlet, see Appendix 1. The distance between two thermocouples ranges from 16 to 110 mm.

The oscillating movement of the steam/water-interface inside the blowdown pipe during the chugging periods was not very wide. The up and down movement of the interface was registered few times by thermocouples TC05 and TC06, which are installed 200 mm and 260 mm above the blowdown pipe outlet. As a comparison in the MIX-01…06 tests with the DN200 blowdown pipe the up and down movement of the interface was much more intensified and was even registered in every test by thermocouple TC15 on the elevation of 999 mm above the blowdown pipe outlet [12]. The exit jet velocity in the DN100 blowdown pipe seems to be lower in the DCC-05 experiment than in the earlier experiments with the DN200 blowdown pipe. Figure 9 shows the movement of the interface during the DCC-05-3 blow.

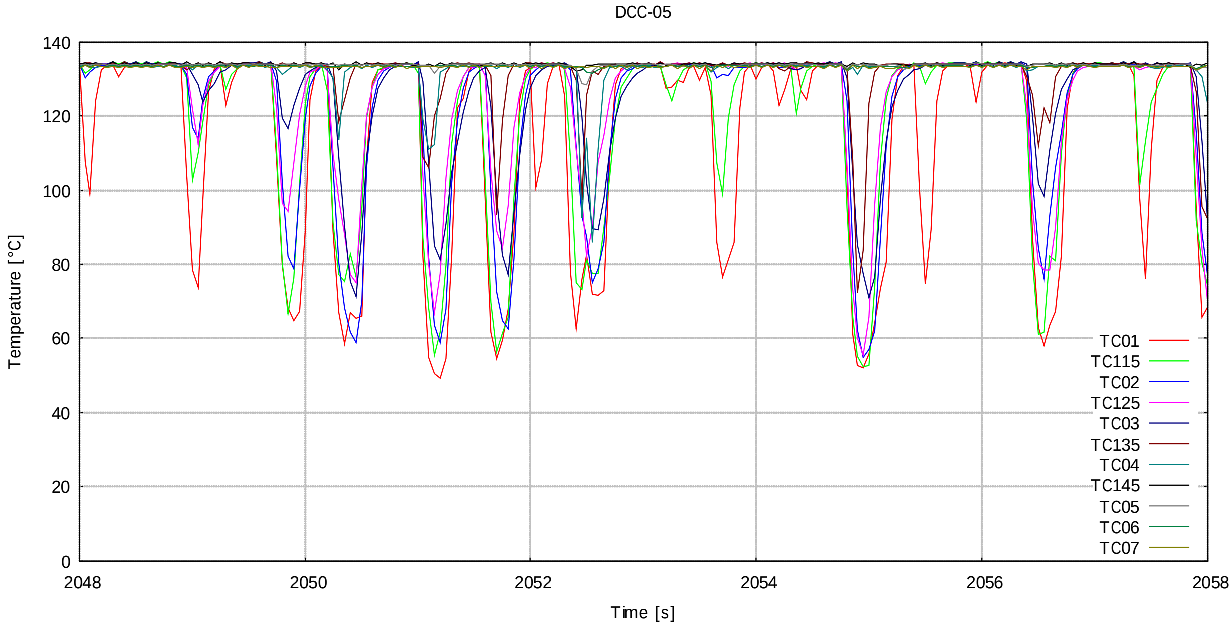

Figure 9. Movement of the steam/water-interface inside the blowdown pipe registered with the TCs during DCC-05-3.

Table 2 lists some oscillation related observations from the DCC-05 experiment. The presented 10 seconds time intervals were chosen so that they begin about 50 s after each chugging blow was initiated. The oscillation amplitude was determined from the readings of thermocouples TC01…TC06. As it could be expected on the basis of Figure 7 the oscillations were clearly stronger in DCC-05-2…DCC-05-5 than in the first and last chugging blow.

Table 2. Oscillation related observations in DCC-05.

Test	Time period [s]	Amplitude [mm]	Average amplitude [mm]	Average frequency [Hz]
DCC-05-1	1060–1070	33–150	48	1.6
DCC-05-2	1650–1660	33–200	82	1.7
DCC-05-3	2010–2020	50–200	91	1.6
DCC-05-4	2345–2355	33–200	117	1.8
DCC-05-5	2700–2710	50–260	102	2.0
DCC-05-6	3070–3080	33–125	53	1.6

5 SUMMARY AND CONCLUSIONS

This report summarizes the results of the DCC-05 direct contact condensation experiment in 2013 with the scaled down PPOOLEX test facility designed and constructed at Lappeenranta University of Technology. The test facility is a closed stainless steel vessel divided into two compartments, drywell and wetwell. During the experiment the DN100 blowdown pipe was equipped with extra temperature measurements for capturing different aspects of the investigated phenomena. The PACTEL facility was used as a steam source. The main purpose of the DCC-05 experiment was to obtain high quality measurement data from the chugging condensation mode for the validation of DCC models used in CFD codes and to make 3D high speed video recordings to be used in the development work of pattern recognition algorithms.

Before the DCC-05 experiment, the wetwell pool was filled with almost isothermal water (25 °C) so that the blowdown pipe outlet was submerged by ~1.0 m. The drywell compartment of the test vessel was filled with air at atmospheric pressure. During the clearing phase air was displaced from the drywell into the gas space of the wetwell and the drywell structures were heated up to prevent excessive steam condensation in the drywell during the chugging period. Steam flow rates between 75 and 200 g/s were used in the individual chugging blows.

The general trend of the measured parameters in the DCC-05 experiment was similar with those of the corresponding chugging experiments carried out with the DN200 blowdown pipe. Temperatures in the gas space of the wetwell rose due to compression by pressure build-up after the discharge was initiated. As the gas space temperatures increased, they also stratified. During the DCC-05 experiment the pool water also stratified. Temperatures at the pool bottom remained close to the initial value but increased from the blowdown pipe outlet elevation upwards so that water was warmest on the pool surface.

During the chugging mode high pressure loads were measured inside the blowdown pipe and at the pool bottom. The loads were smaller when the intersection of steam mass flux and pool bulk temperature on the condensation mode map was close to the edge of the chugging region (the first and last chugging blow of the DCC-05 test).

The oscillating movement of the steam/water-interface inside the blowdown pipe during the chugging periods was not very wide. The interface reached the elevations of 200 mm (TC05) and 260 mm (TC06) above the pipe outlet few times. In the experiments with the DN200 blowdown pipe the up and down movement of the steam/water-interface has been much larger. The exit jet velocity in the DN100 blowdown pipe seems to be lower than in the DN200 blowdown pipe.

The high frequency measurement data of the DCC-05 experiment in PPOOLEX can be used in the validation of DCC models of CFD codes. Furthermore, the pattern recognition algorithms being developed and improved at LUT can be later used to assess the steam bubble surface area and volume as well as the chugging frequencies from the video material as a function of pool water temperature and steam mass flux.

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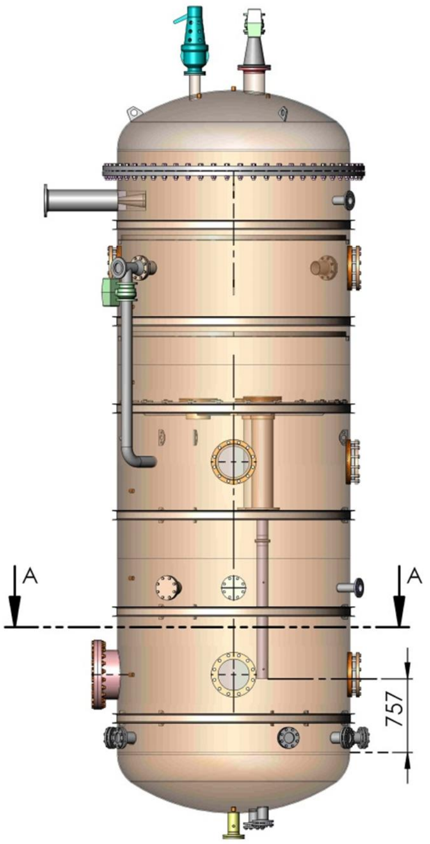
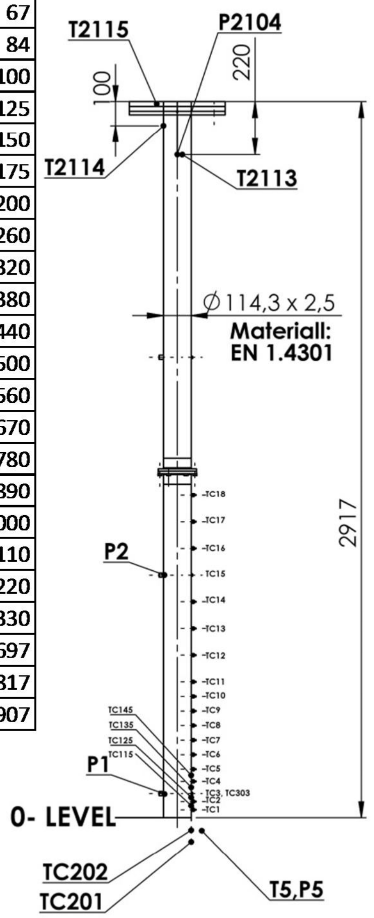
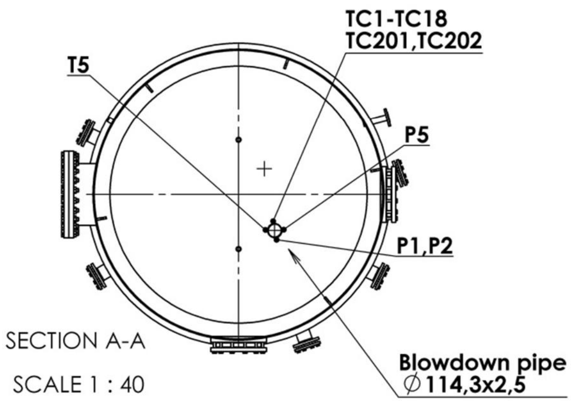
APPENDIX 1: PPOOLEX INSTRUMENTATION

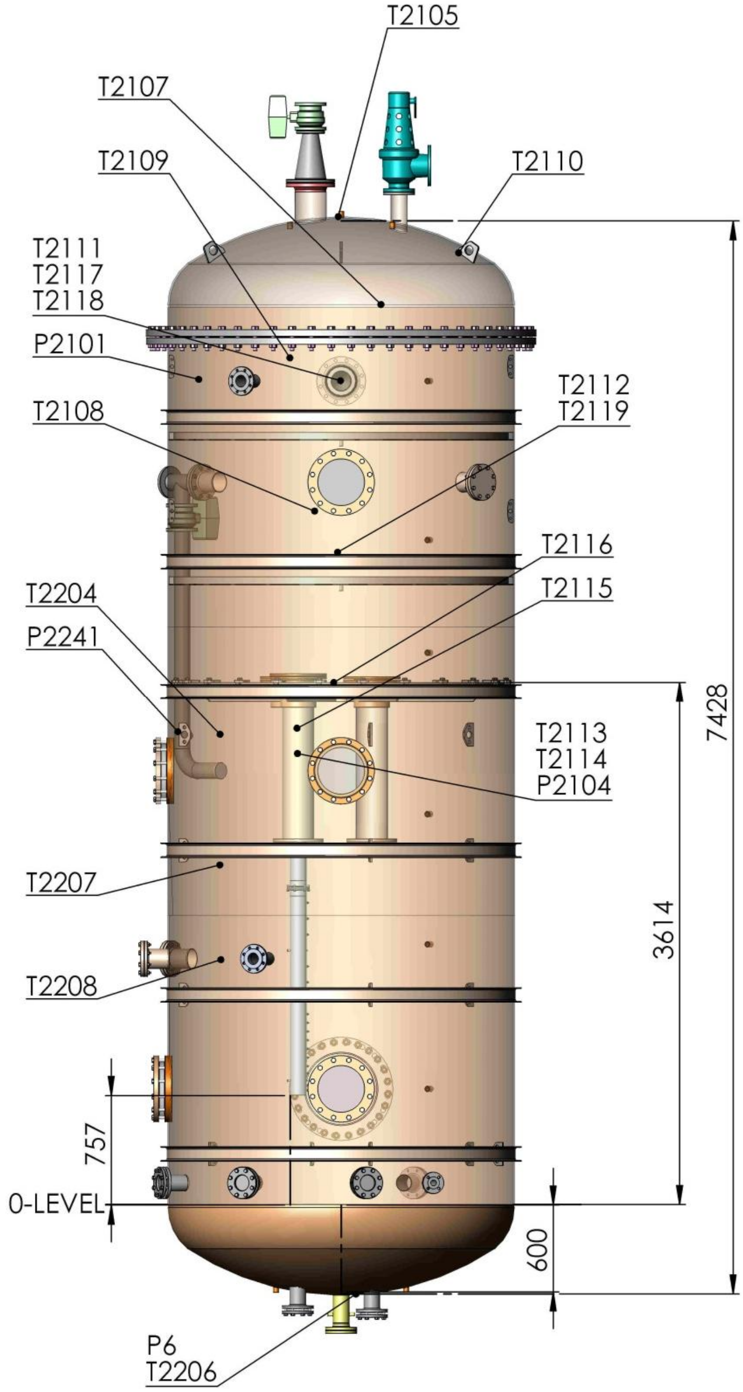


Code	Level
TC201	-100
TC202, T5, P5	-50
TC1	33
TC115	50
TC2	67
TC125	84
TC3, TC303, P1	100
TC135	125
TC4	150
TC 145	175
TC5	200
TC6	260
TC7	320
TC8	380
TC9	440
TC10	500
TC11	560
TC12	670
TC13	780
TC14	890
TC15, P2	1000
TC16	1110
TC17	1220
TC18	1330
T2113, P2104	2697
T2114	2817
T2115	2907

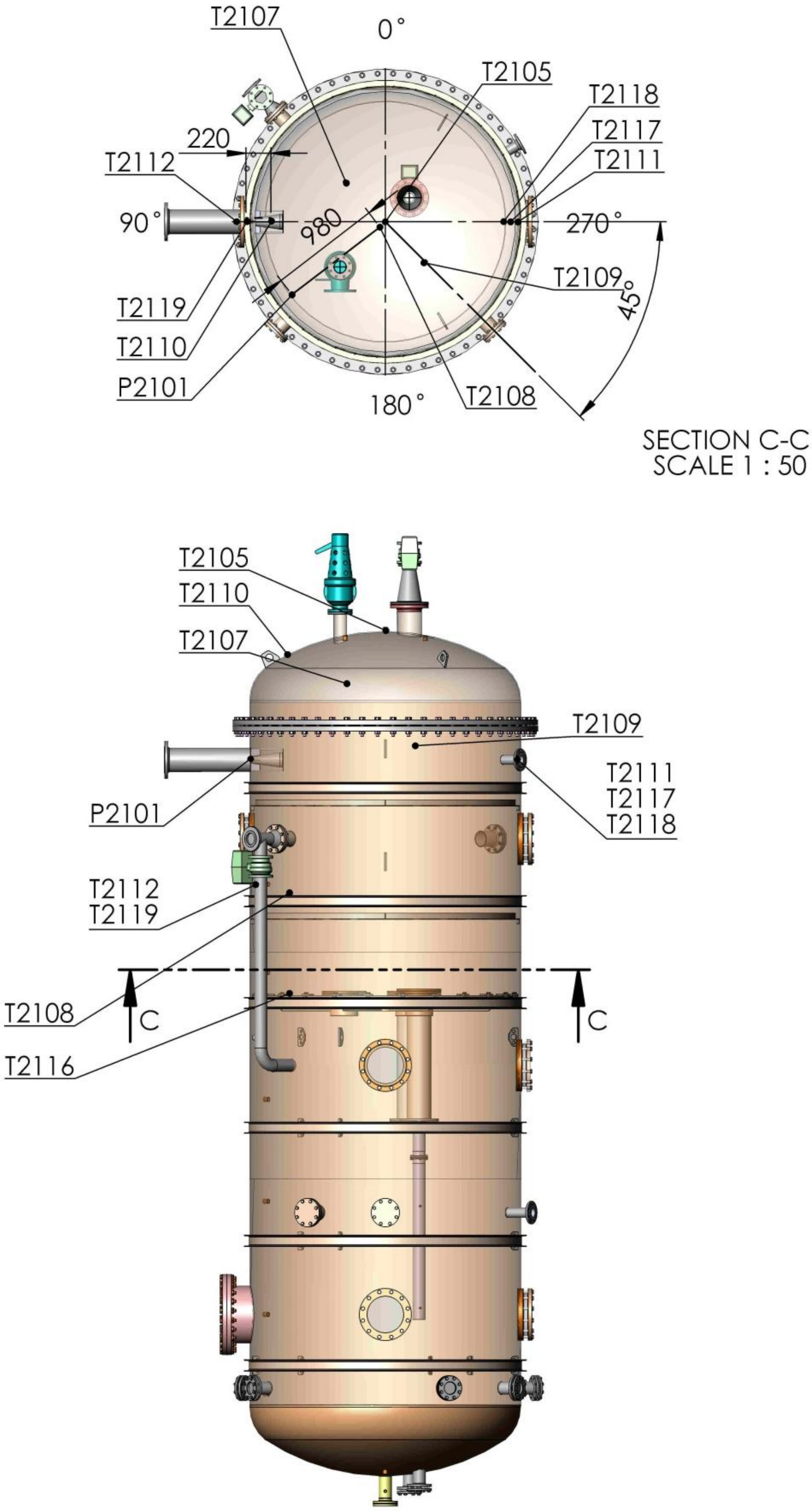




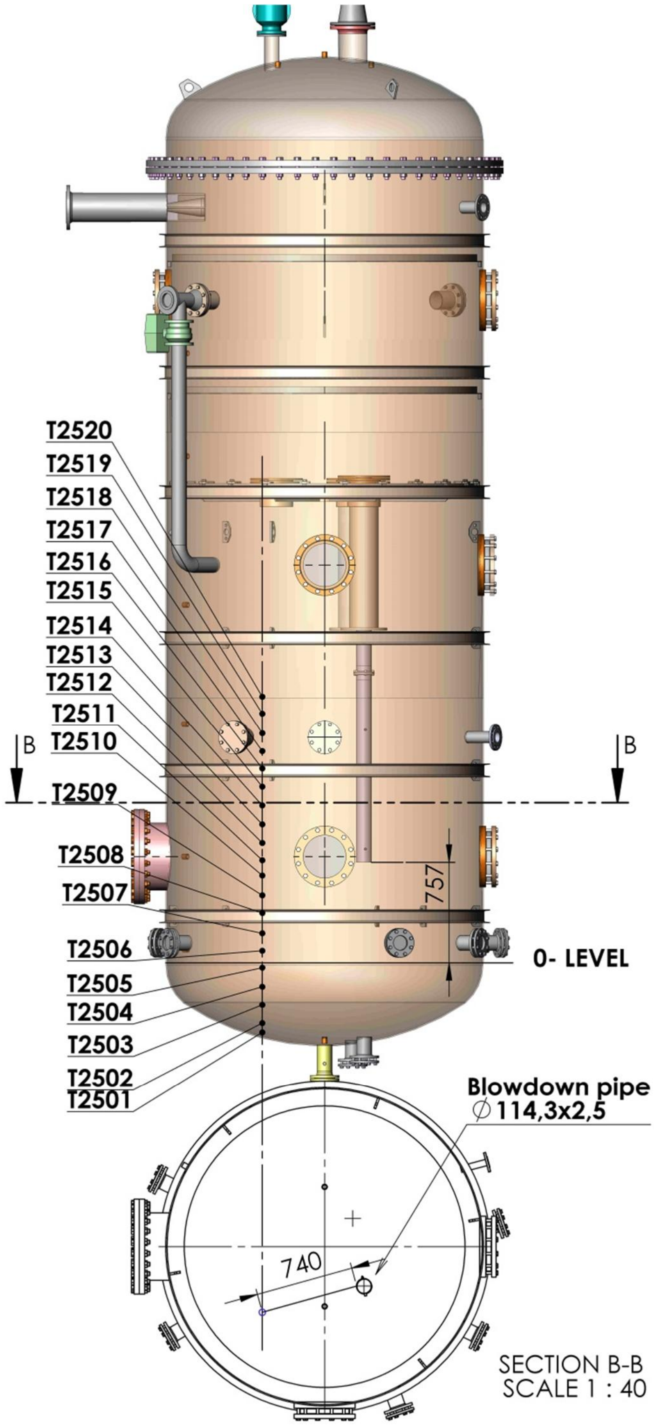
Blowdown pipe measurements in the DCC-05 experiment.



Test vessel measurements.

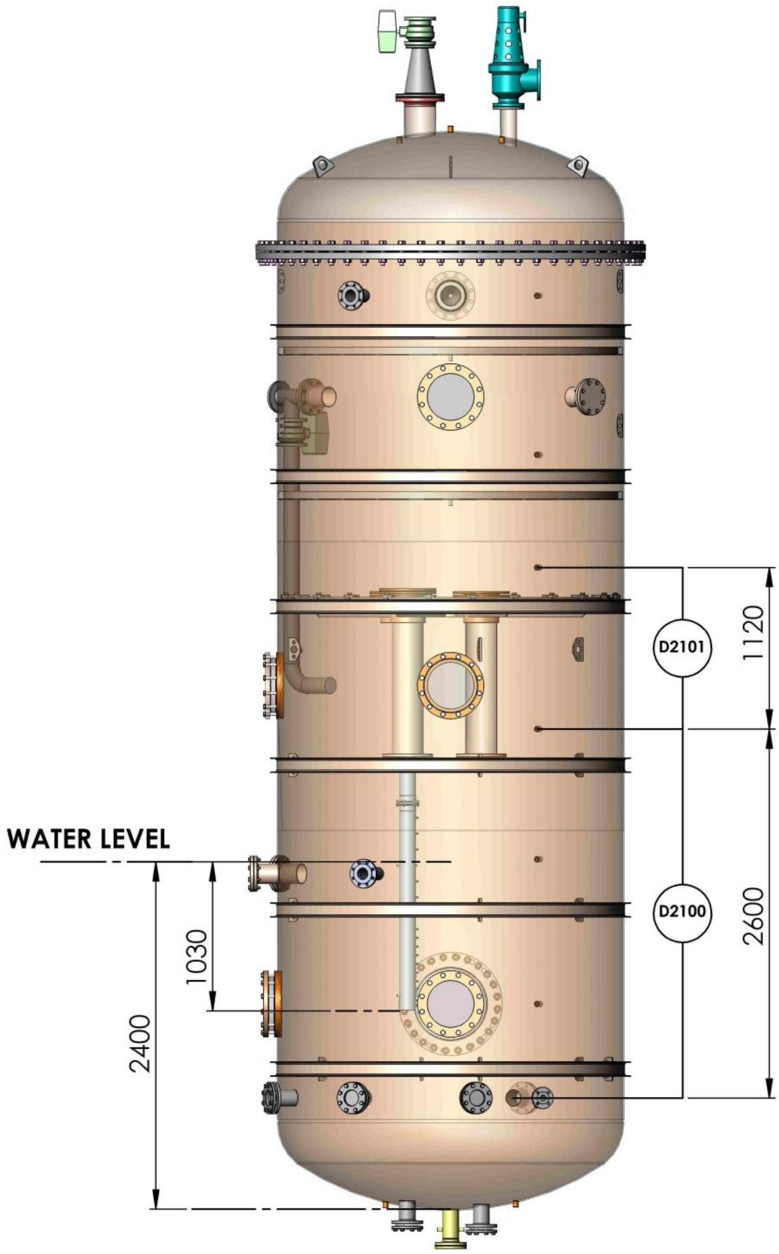


Drywell measurements.

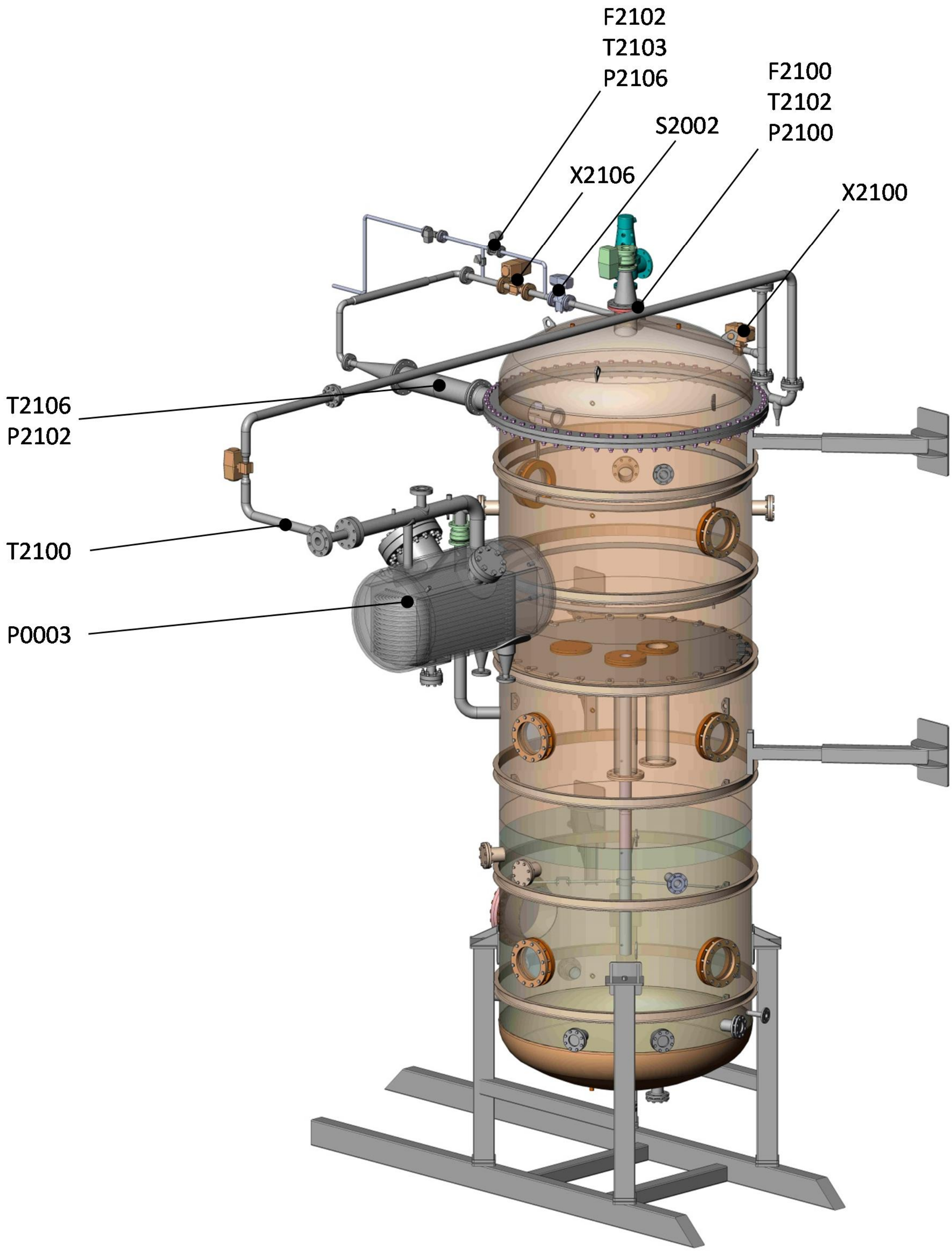


Code	Level
T2501	-530
T2502	-390
T2503	-260
T2504	-125
T2505	10
T2506	150
T2507	287
T2508	427
T2509	560
T2510	695
T2511	830
T2512	965
T2513	1103
T2514	1236
T2515	1369
T2516	1505
T2517	1640
T2518	1775
T2519	1910
T2520	2045

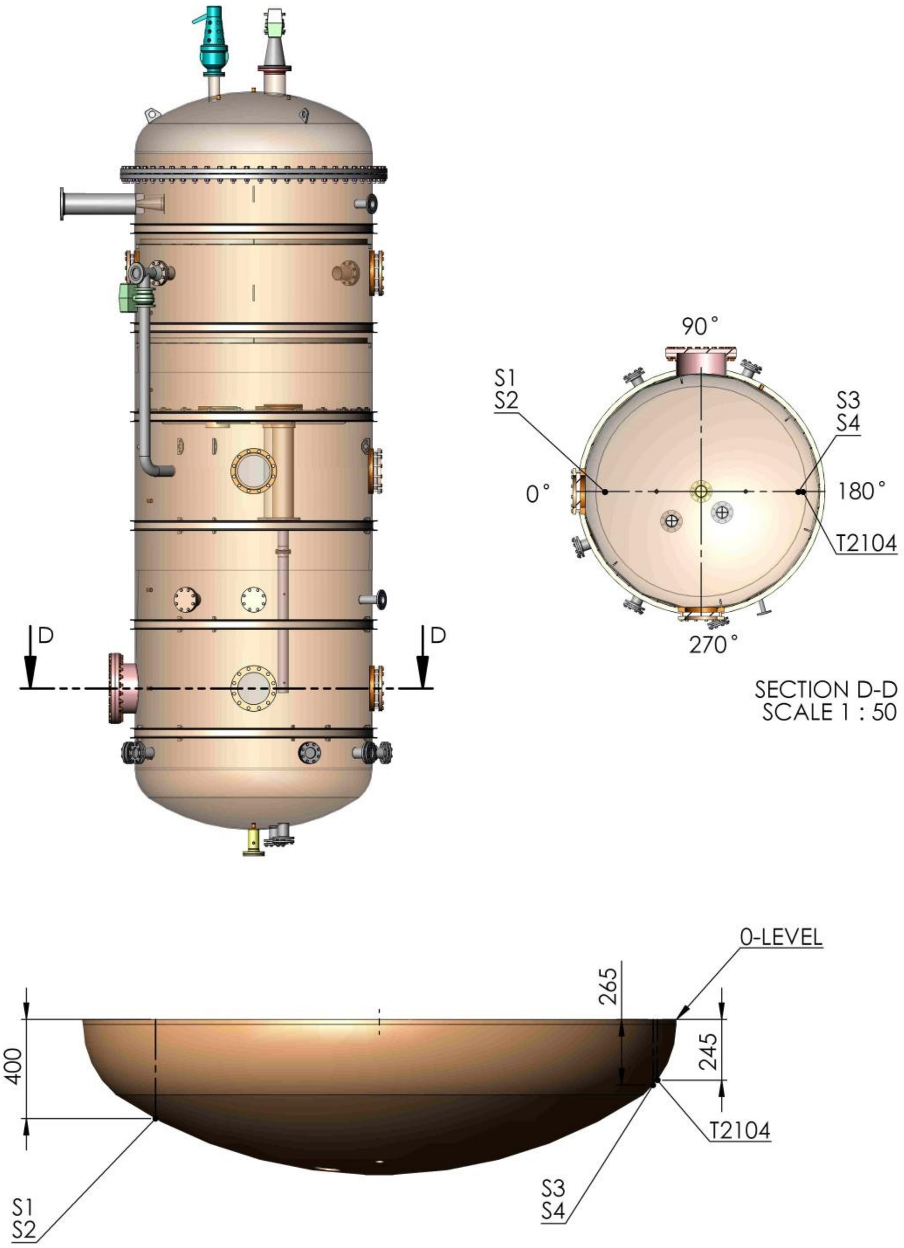
Temperature measurements in the wetwell pool for the detection of thermal stratification.



Pressure difference measurements. Nominal water level is 2.4 m.



Measurements in the steam line.



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

Measurement	Code	Elevation	Location	Error estimation	Measurement software
High speed camera trigger	C1	-	Wetwell	Not defined	LabView
Pressure difference	D2100	100–2700	Wetwell	±0.05 m	FieldPoint
Pressure difference	D2101	2700–3820	Across the floor	±4000 Pa	FieldPoint
Flow rate	F2100	-	DN50 Steam line	±4.9 l/s	FieldPoint
Flow rate	F2102	-	DN25 Steam line	±0.7 l/s	FieldPoint
Pressure	P1	857	Blowdown pipe	±0.7 bar	LabView
Pressure	P2	1757	Blowdown pipe	±0.7 bar	LabView
Pressure	P5	707	Blowdown pipe outlet	±0.7 bar	LabView
Pressure	P6	-615	Wetwell bottom	±0.5 bar	LabView
Pressure	P2100	-	DN50 Steam line	±0.2 bar	FieldPoint
Pressure	P2101	5700	Drywell	±0.03 bar	FieldPoint
Pressure	P2102	-	Inlet plenum	±0.03 bar	FieldPoint
Pressure	P2104	3454	Blowdown pipe	±0.03 bar	FieldPoint
Pressure	P2106	-	DN25 Steam line	±0.06 bar	FieldPoint
Pressure	P2241	3600	Wetwell gas space	±0.05 bar	FieldPoint
Control valve position	S2002	-	DN50 Steam line	Not defined	FieldPoint
Strain	S1	-400	Bottom segment	Not defined	LabView
Strain	S2	-400	Bottom segment	Not defined	LabView
Strain	S3	-265	Bottom segment	Not defined	LabView
Strain	S4	-265	Bottom segment	Not defined	LabView
Temperature	T5	707	Blowdown pipe outlet	±1.8 °C	LabView
Temperature	T1279	-3860	Laboratory	±1.8 °C	FieldPoint
Temperature	T1280	-1860	Laboratory	±1.8 °C	FieldPoint
Temperature	T1281	140	Laboratory	±1.8 °C	FieldPoint
Temperature	T1282	2140	Laboratory	±1.8 °C	FieldPoint
Temperature	T1283	4140	Laboratory	±1.8 °C	FieldPoint
Temperature	T1284	6140	Laboratory	±1.8 °C	FieldPoint
Temperature	T1285	8140	Laboratory	±1.8 °C	FieldPoint
Temperature	T2100	-	Steam line beginning	±3.5 °C	FieldPoint
Temperature	T2102	-	DN50 Steam line	±1.8 °C	FieldPoint
Temperature	T2103	-	DN25 Steam line	±1.8 °C	FieldPoint
Temperature	T2104	-245	Wetwell outer wall	±1.8 °C	FieldPoint
Temperature	T2105	6780	Drywell top	±1.8 °C	FieldPoint
Temperature	T2106	-	Inlet plenum	±1.8 °C	FieldPoint
Temperature	T2107	6085	Drywell middle	±1.8 °C	FieldPoint
Temperature	T2108	4600	Drywell bottom	±1.8 °C	FieldPoint
Temperature	T2109	5790	Dry well lower middle	±1.8 °C	FieldPoint
Temperature	T2110	6550	Drywell outer wall	±1.8 °C	FieldPoint
Temperature	T2111	5700	Drywell outer wall	±1.8 °C	FieldPoint
Temperature	T2112	4600	Drywell outer wall	±1.8 °C	FieldPoint
Temperature	T2113	3454	Blowdown pipe	±1.8 °C	LabView
Temperature	T2114	3574	Blowdown pipe	±1.8 °C	FieldPoint
Temperature	T2115	3664	Blowdown pipe	±1.8 °C	FieldPoint
Temperature	T2116	3600	Drywell floor	±1.8 °C	FieldPoint
Temperature	T2117	5700	Drywell inner wall	±1.8 °C	FieldPoint
Temperature	T2118	5700	Drywell, 10 mm from the wall	±1.8 °C	FieldPoint
Temperature	T2119	4600	Drywell inner wall	±1.8 °C	FieldPoint

Temperature	T2204	3410	Wetwell gas space	±1.8 °C	FieldPoint
Temperature	T2206	-615	Wetwell bottom	±1.8 °C	FieldPoint
Temperature	T2207	2585	Wetwell gas space	±1.8 °C	FieldPoint
Temperature	T2208	1760	Wetwell gas space	±1.8 °C	FieldPoint
Temperature	T2501	-530	Wetwell	±1.8 °C	FieldPoint
Temperature	T2502	-390	Wetwell	±1.8 °C	FieldPoint
Temperature	T2503	-260	Wetwell	±1.8 °C	FieldPoint
Temperature	T2504	-125	Wetwell	±1.8 °C	FieldPoint
Temperature	T2505	10	Wetwell	±1.8 °C	FieldPoint
Temperature	T2506	150	Wetwell	±1.8 °C	FieldPoint
Temperature	T2507	287	Wetwell	±1.8 °C	FieldPoint
Temperature	T2508	427	Wetwell	±1.8 °C	FieldPoint
Temperature	T2509	560	Wetwell	±1.8 °C	FieldPoint
Temperature	T2510	695	Wetwell	±1.8 °C	FieldPoint
Temperature	T2511	830	Wetwell	±1.8 °C	FieldPoint
Temperature	T2512	965	Wetwell	±1.8 °C	FieldPoint
Temperature	T2513	1103	Wetwell	±1.8 °C	FieldPoint
Temperature	T2514	1236	Wetwell	±1.8 °C	FieldPoint
Temperature	T2515	1369	Wetwell	±1.8 °C	FieldPoint
Temperature	T2516	1505	Wetwell	±1.8 °C	FieldPoint
Temperature	T2517	1640	Wetwell	±1.8 °C	FieldPoint
Temperature	T2518	1775	Wetwell	±1.8 °C	FieldPoint
Temperature	T2519	1910	Wetwell	±1.8 °C	FieldPoint
Temperature	T2520	2045	Wetwell	±1.8 °C	FieldPoint
Temperature	TC01	790	Blowdown pipe	±1.8 °C	LabView
Temperature	TC115	807	Blowdown pipe	±1.8 °C	LabView
Temperature	TC02	824	Blowdown pipe	±1.8 °C	LabView
Temperature	TC125	841	Blowdown pipe	±1.8 °C	LabView
Temperature	TC03	857	Blowdown pipe	±1.8 °C	LabView
Temperature	TC135	882	Blowdown pipe	±1.8 °C	LabView
Temperature	TC04	907	Blowdown pipe	±1.8 °C	LabView
Temperature	TC145	932	Blowdown pipe	±1.8 °C	LabView
Temperature	TC05	957	Blowdown pipe	±1.8 °C	LabView
Temperature	TC06	1017	Blowdown pipe	±1.8 °C	LabView
Temperature	TC07	1077	Blowdown pipe	±1.8 °C	LabView
Temperature	TC08	1137	Blowdown pipe	±1.8 °C	LabView
Temperature	TC09	1197	Blowdown pipe	±1.8 °C	LabView
Temperature	TC10	1257	Blowdown pipe	±1.8 °C	LabView
Temperature	TC11	1317	Blowdown pipe	±1.8 °C	LabView
Temperature	TC12	1427	Blowdown pipe	±1.8 °C	LabView
Temperature	TC13	1537	Blowdown pipe	±1.8 °C	LabView
Temperature	TC14	1647	Blowdown pipe	±1.8 °C	LabView
Temperature	TC15	1757	Blowdown pipe	±1.8 °C	LabView
Temperature	TC16	1867	Blowdown pipe	±1.8 °C	LabView
Temperature	TC17	1977	Blowdown pipe	±1.8 °C	LabView
Temperature	TC18	2087	Blowdown pipe	±1.8 °C	LabView
Temperature	TC201	657	Below blowdown pipe	±1.8 °C	LabView
Temperature	TC202	707	Below blowdown pipe	±1.8 °C	LabView
Temperature	TC303	857	Blowdown pipe outer surface	±1.8 °C	LabView
Cut-off valve position	V1	-	DN50 Steam line	Not defined	LabView

Cut-off valve position	X2100	-	DN50 Steam line	Not defined	FieldPoint
Steam partial pressure	X2102	4600	Drywell	Not defined	FieldPoint
High speed camera trigger	X2103	-	Wetwell	Not defined	FieldPoint
Cut-off valve position	X2106	-	DN50 Steam line	Not defined	FieldPoint

Measurements of the PPOOLEX facility in the DCC-05 experiment.

APPENDIX 2: PPOOLEX TEST FACILITY PHOTOGRAPHS

Mineral wool insulated dry well compartment and steam line.

DN100 blowdown pipe.

Title	Chugging Test with DN100 Blowdown Pipe in the PPOOLEX Facility
Author(s)	Markku Puustinen, Jani Laine, Antti Räsänen, Elina Hujala
Affiliation(s)	Lappeenranta University of Technology, Nuclear Safety Research Unit
ISBN	978-87-7893-388-1
Date	June 2014
Project	NKS-R / ENPOOL
No. of pages	19 p. + app. 12 p.
No. of tables	2
No. of illustrations	9 + 7
No. of references	19

Abstract
max. 2000 characters

This report summarizes the results of the DCC-05 direct contact condensation experiment in 2013 with the scaled down PPOOLEX test facility designed and constructed at Lappeenranta University of Technology. The main purpose of the DCC-05 experiment was to obtain high quality measurement data from the chugging condensation mode for the validation of DCC models used in CFD codes and to make 3D high speed video recordings to be used in the development work of pattern recognition algorithms. During the experiment the DN100 blowdown pipe was equipped with extra temperature measurements for capturing different aspects of the investigated phenomena.

The general trend of the measured parameters in the DCC-05 experiment was similar with those of the corresponding chugging experiments carried out with the DN200 blowdown pipe. Temperatures in the gas space of the wetwell rose due to compression by pressure build-up. As the gas space temperatures increased, they also stratified. During the DCC-05 experiment the pool water stratified, too. Temperatures at the pool bottom remained close to the initial value but increased from the blowdown pipe outlet elevation upwards so that water was warmest on the pool surface.

During the chugging mode high pressure loads were measured inside the blowdown pipe and at the pool bottom. However, the oscillating movement of the steam/water-interface inside the blowdown pipe during the chugging periods was not very wide. The interface reached the elevations of 200 mm (TC05) and 260 mm (TC06) above the pipe outlet few times. In the previous experiments with the DN200 blowdown pipe the up and down movement of the steam/water-interface has been much larger.

The high frequency measurement data of the DCC-05 experiment in PPOOLEX can be used in the validation of DCC models of CFD codes. Furthermore, the pattern recognition algorithms being developed and improved at LUT can be later used to assess the steam bubble surface area and volume as well as the chugging frequencies from the video material as a function of pool water temperature and steam mass flux.

Key words: chugging, steam blowdown

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