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PPOOLEX Mixing Experiments

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Abstract

This report summarizes the results of the thermal stratification and mixing experiments carried out with the scaled down PPOOLEX test facility designed and constructed at Lappeenranta University of Technology. Steam was blown into the drywell compartment and from there through the vertical DN100 blowdown pipe to the condensation pool filled with sub-cooled water.

The main objective of the experiments was to obtain verification data to be used by KTH in the validation of the Nariai and Aya model for prediction of oscillations in a blowdown pipe. The second objective was to obtain measurement data from those regions of the condensation mode map of Lahey and Moody which were not previously covered in the PPOOLEX tests. A detailed test matrix and procedure put together on the basis of pre-test calculations was provided by KTH before the experiments.

Altogether six experiments (MIX-07…12) were carried out. The experiments consisted of a clearing phase, of a small steam flow rate stratification period and of a higher flow rate mixing period.

During the low steam flow rate (25–40 g/s) period steam condensed mainly inside the blowdown pipe. As a result temperatures remained constant below the blowdown pipe outlet while they increased towards the pool surface layers indicating strong thermal stratification of the wetwell pool water. In the end of the stratification period the temperature difference between the pool bottom and surface was 18–22 ºC depending on the steam flow rate and the duration of the stratification period.

During the mixing period the steam flow rate was increased rapidly to 75–275 g/s to mix the pool water inventory. The pool water inventory was not mixed completely because of low exit jet velocity in the blowdown pipe. Also the distance between the pipe outlet and the pool bottom was now ~300 mm longer than in the mixing tests carried out in 2012 with the DN200 blowdown pipe, where total mixing was achieved. Thus, the jet did not reach the bottom of the pool to enhance mixing. During the mixing period the steam/water-interface oscillated inside the blowdown pipe with an amplitude of 33–200 mm and with an average frequency of ~2 Hz.

Key words

condensation pool, steam blowdown, thermal stratification, mixing

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PPOOLEX MIXING EXPERIMENTS

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Altogether six experiments (MIX-07…12) were carried out. The experiments consisted of a small steam flow rate stratification period and of a higher flow rate mixing period. The drywell structures were heated up to approximately 130 °C and non-condensables were blown to the wetwell compartment during a clearing phase before the stratification period was initiated. The initial water bulk temperature in the condensation pool was 14 °C.

During the low steam flow rate (25–40 g/s) period steam condensed mainly inside the blowdown pipe. As a result temperatures remained constant below the blowdown pipe outlet while they increased towards the pool surface layers indicating strong thermal stratification of the wetwell pool water. In the end of the stratification period the temperature difference between the pool bottom and surface was 18–22 ºC depending on the steam flow rate and the duration of the stratification period.

During the mixing period the steam flow rate was increased rapidly to 75–275 g/s to mix the pool water inventory. The pool water inventory was not mixed completely because of low exit jet velocity in the blowdown pipe. Also the distance between the pipe outlet and the pool bottom was now ~300 mm longer than in the mixing tests carried out in 2012 with the DN200 blowdown pipe, where total mixing was achieved. Thus, the jet did not reach the bottom of the pool to enhance mixing. During the mixing period the steam/water-interface oscillated inside the blowdown pipe with an amplitude of 33–200 mm and with an average frequency of ~2 Hz.

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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 were modelled with computational fluid dynamics (CFD) and structural analysis codes at VTT.

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 NKS/ENPOOL project. Analytical and numerical work of Kungliga Tekniska Högskolan (KTH) is combined to EXCOP, ELAINE, NUMPOOL, ESA and nuFoam projects of SAFIR2014. The studies are funded by the VYR, NKS and NORTHNET.

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CONTENTS

NOMENCLATURE

v	velocity

Greek symbols

Δ	change
ε	strain

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
EMS	effective momentum source
EXCOP	experimental studies on containment phenomena project
FINNUS	Finnish Research Programme on Nuclear Power Plant Safety
KTH	Kungliga Tekniska Högskolan
LOCA	loss-of-coolant accident
LUT	Lappeenranta University of Technology
MSLB	main steam line break
MIX	mixing experiment series
NKS	Nordic nuclear safety research
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
PWR	pressurized water reactor
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
SRV	safety/relief valve
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.

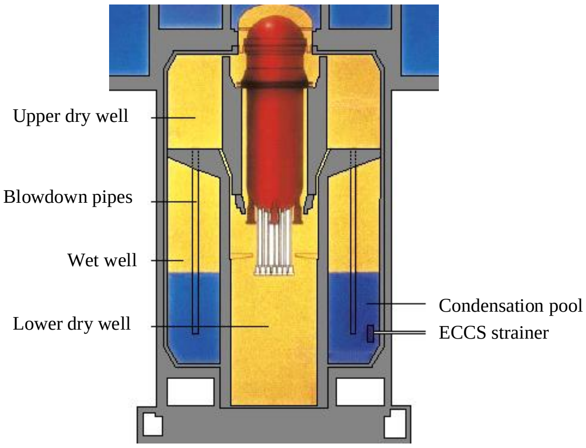

Figure 1. Schematic of the Olkiluoto type BWR containment.

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). For the test series the blowdown pipe diameter was reduced to DN100 and the amount of thermocouples inside the pipe was further increased. In this report, the results of the second series of the MIX tests are presented. First, chapter two gives a short description of the test facility and its measurements as well as of the data acquisition system used. The test programme is introduced in chapter three. The test results are presented and discussed in chapter four. Chapter five summarizes the findings.

The main objective of the experiment series was to obtain verification data for the validation of the Nariai and Aya model for prediction of oscillations in a blowdown pipe to be done by KTH. The second objective was to obtain measurement data from those regions of the condensation mode map of Lahey and Moody which were not previously covered in the PPOOLEX tests.

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 [14]. 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.

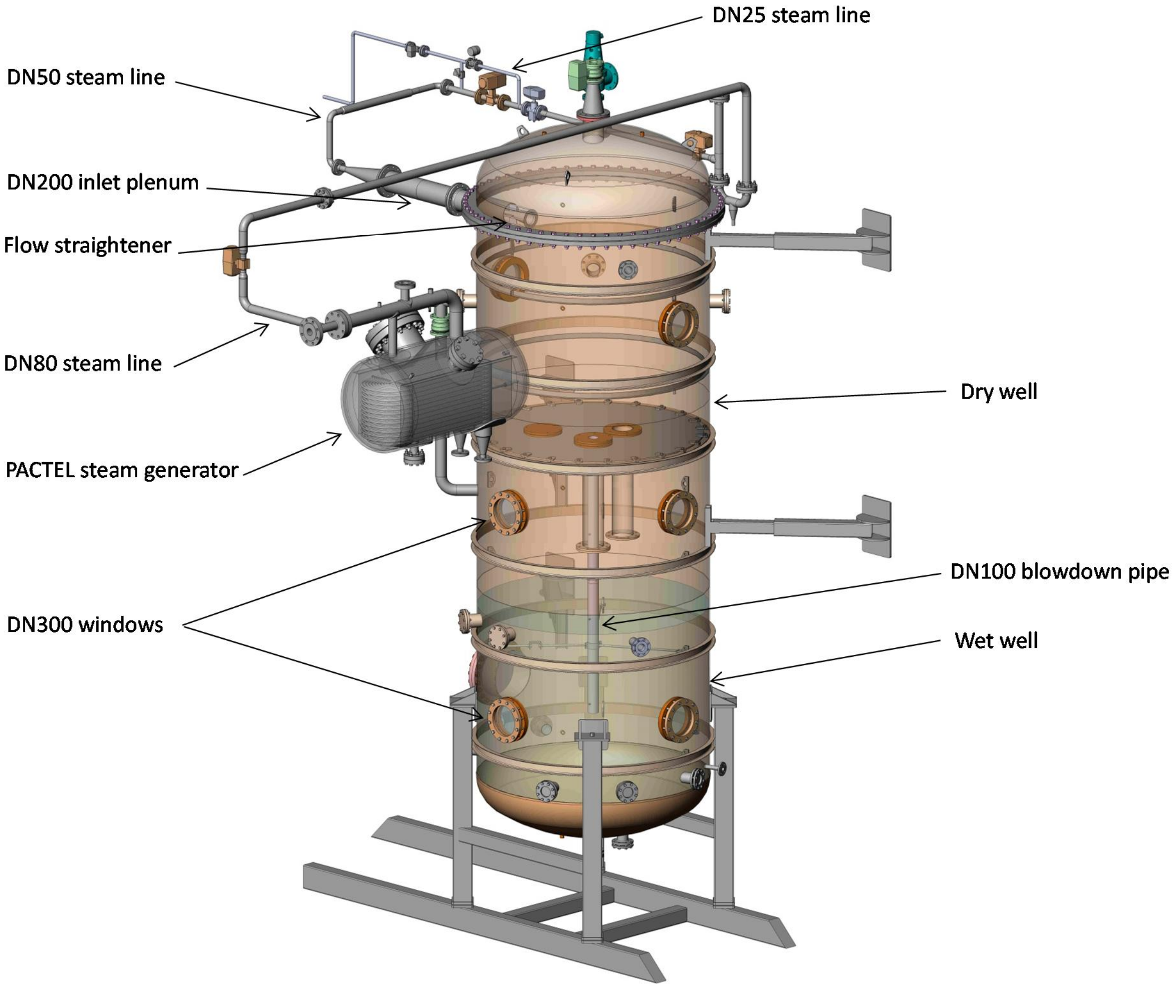

Figure 2. PPOOLEX test vessel.

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 [15] 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

For the second MIX test series the blowdown pipe diameter was reduced from DN200 to DN100 (∅ 114.3 x 2.5 mm). The blowdown pipe, made from austenitic stainless steel EN 1.4301 (AISI 304), is positioned inside the pool in a non-axisymmetric location, i.e. the pipe is 300 mm away from the centre of the condensation pool. To enable better conditions for the PIV-measurements the total length of the blowdown pipe was decreased from 3209 mm to 2917 mm. Thus the outlet of the DN100 pipe is located 292 mm higher than the outlet of the DN200 pipe. The water level of the condensation pool was increased accordingly in order to keep the submergence depth of the blowdown pipe the same as in the preceding MIX series.

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 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 during the chugging condensation mode (mixing phase of the experiments). This data is needed for the assessment of the effective momentum source term.

Figures in Appendix 1 show the locations of the PPOOLEX measurements during the MIX series and 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 during the mixing period.

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 [16].

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 TEST PROGRAM

The test program in November – December 2013 consisted of six experiments (labeled from MIX-07 to MIX-12). The main purpose of the MIX experiment series was to obtain data for the development of the EMS and EHS models to be implemented in GOTHIC code by KTH. A detailed test matrix and procedure put together on the basis of pre-test calculations was provided by KTH before the experiments [17]. All experiments had a clearing phase, a stabilization period, a small flow rate stratification period and a higher flow rate mixing period.

Before the experiments, the wetwell pool was filled with isothermal water (13 °C) to the level of 2.4 m i.e. 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 clearing phase the steam flow rate was 220-230 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. After air was displaced from the drywell into the gas space of the wetwell, at 360–445 seconds depending on the experiment, the stabilization period began. Its purpose was to calm down all internal flows in the wetwell pool in order to start the stratification period without any mixing effects present. During the stabilization period the steam flow rate was decreased so much (to about 16 g/s) that the water level inside the blowdown pipe rose above the water level in the pool side and as a result there was no heat transfer from the blowdown pipe to the pool water. However, the steam flow could not be stopped completely to avoid water ingress into the drywell. The stabilization period lasted for about 500-600 seconds. Then, the stratification process with a small pure steam flow began. The steam flow rate ranged from 25 to 40 g/s during the stratification period depending on the test in question. The mixing phase (chugging mode) was started by rapidly increasing steam flow rate into the test vessel after the predetermined temperature difference between the bottom and surface layers had been reached.

After MIX-07, thermocouples TC16, TC18 were removed from the middle part of the blowdown pipe and thermocouples TC115, TC125, TC135 and TC145 were added to lower part of the blowdown pipe. Thermocouples TC201 and TC202 broke down during MIX-08 and TC115 during MIX-10.

The main parameters of the MIX-07–MIX-12 experiments are listed in Table 2. The path of each experiment during the thermal stratification and mixing periods defined by the steam mass flux and pool bulk temperature is 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.

Table 2. Parameter values of the MIX-07–MIX-12 experiments in 2013.

Exp.	Initial water level [m]	Initial water temperature [°C]	Steam source pressure [MPa]	Steam flow rate [g/s]	Comments
MIX-07	2.4	13	0.58–0.60	16–220	TC115, TC125, TC135 and TC145 not in use
MIX-08	2.4	13	0.55–0.61	16–290	TC16 and TC18 not in use, TC201 and TC202 broke down
MIX-09	2.4	13	0.56–0.62	16–230	TC16 and TC18 not in use
MIX-10	2.4	13	0.58–0.62	16–230	TC16 and TC18 not in use, TC115 broke down at 6 950 s
MIX-11	2.4	13	0.56–0.62	16–230	TC16 and TC18 not in use
MIX-12	2.4	13	0.58–0.62	16–230	TC16 and TC18 not in use

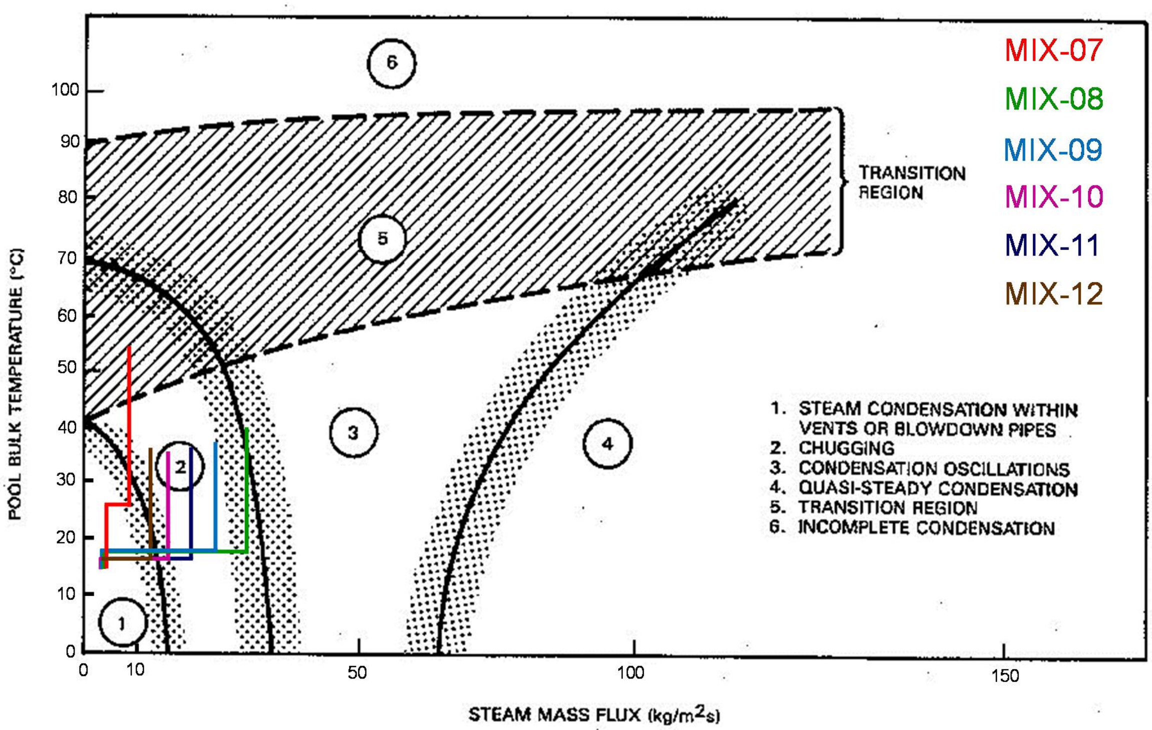

Figure 3. Condensation mode map of Lahey and Moody for pure steam discharge [18].

4 EXPERIMENT RESULTS

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

4.1 THERMAL STRATIFICATION IN THE WETWELL GAS VOLUME

The gas space of the wetwell warms up during the experiments. First, it is 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 elevation (T2207).

Figure 4 shows the pressure build-up of the test vessel during the MIX-10 experiment and Figure 5 the corresponding temperature behavior of the wetwell gas space. Measurement X2102 (steam fraction) indicates the moment when the flow in the blowdown pipe changes to pure steam.

The highest temperature rise measured during the experiments by T2204 was about 59 °C (from the initial value of 24 to 83 °C), see Figure 5 and Table 3. The largest temperature difference between the wetwell top and the elevation above the water surface (T2204–T2207, T2208 submerged during the tests) was 27 °C (in period ~7 700–8 900 s). After 8 900 s the temperature difference began to decrease and was 15 °C when the test was terminated at 11 000 s.

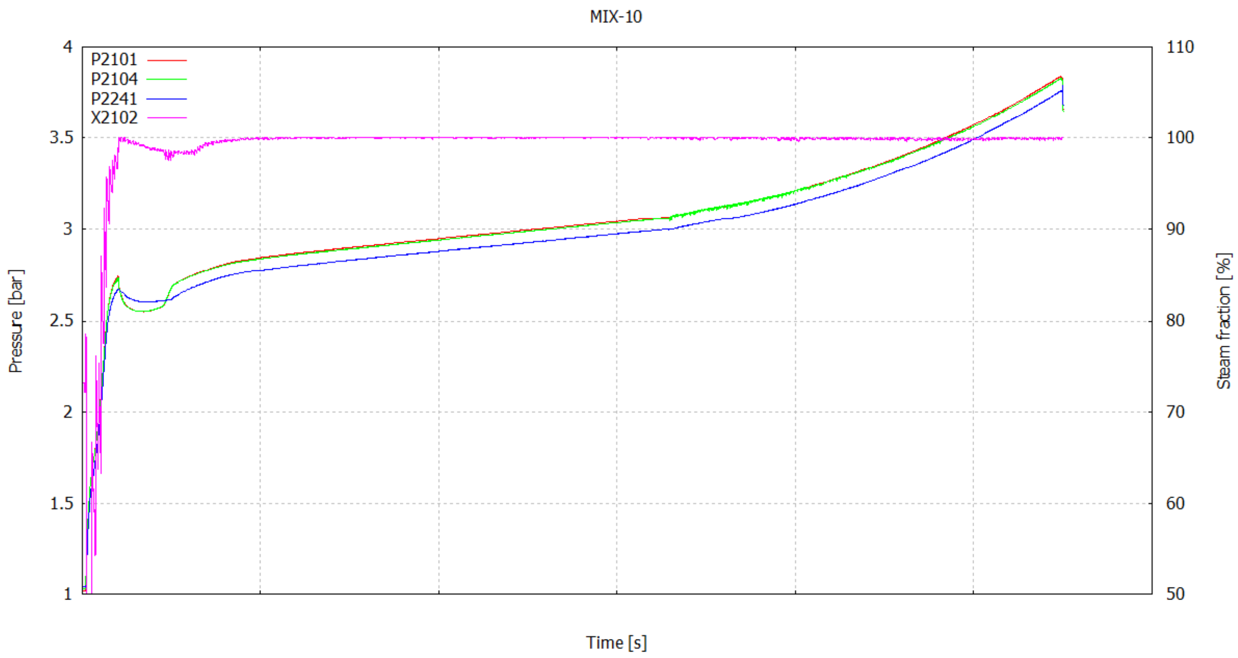

Figure 4. Pressure build-up in the test vessel in MIX-10.

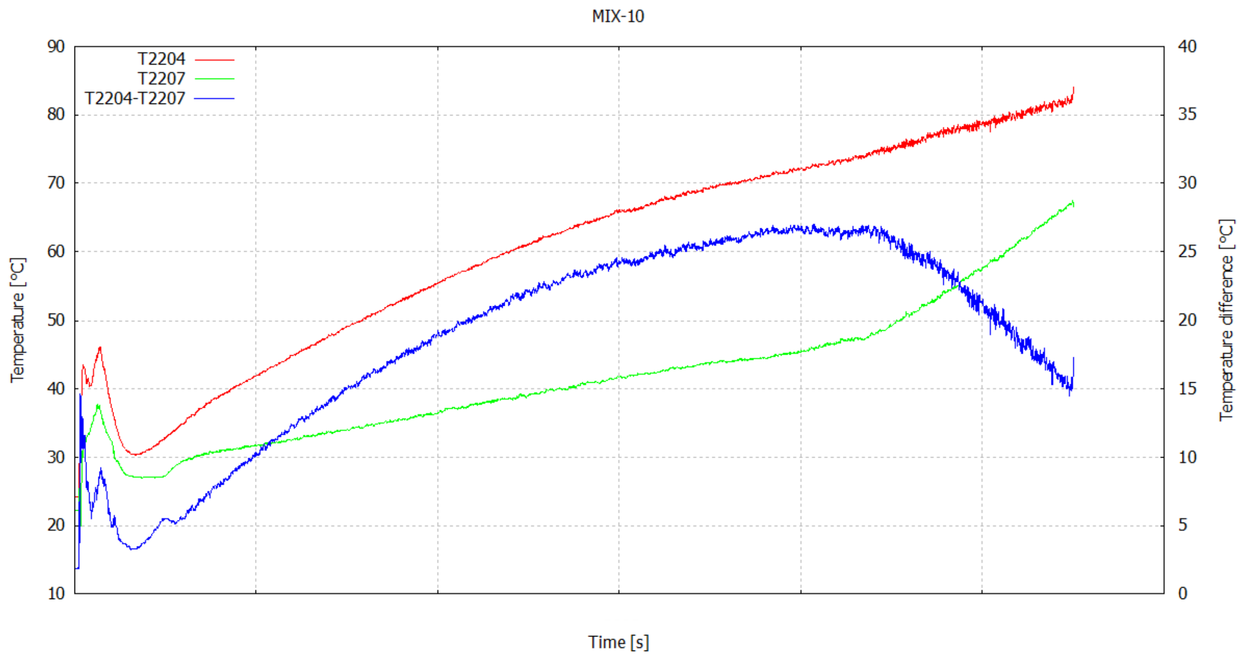

Figure 5. Thermal stratification in the wetwell gas space in MIX-10.

Table 3. Observations in the wetwell gas space during the MIX experiments 2013.

Exp.	Initial gas temperature [°C]	Max. T2204 temperature [°C]	T2204 increase [°C]	Max. temperature difference between T2204 and T2207 [°C]
MIX-07	22–23	80	57	27
MIX-08	23–25	80	55	26
MIX-09	22–23	80	57	27
MIX-10	22–24	83	59	27
MIX-11	22–23	80	58	27
MIX-12	24–27	84	57	27

4.2 THERMAL STRATIFICATION AND MIXING IN WETWELL POOL

The MIX experiments consisted of four parts; clearing phase, stabilization period, thermal stratification period and mixing period. First, the steam flow rate was set to ~220–230 g/s to move the original air content of the drywell to the gas space of the wetwell and to heat up the drywell structures to the level of ~130 °C (the bottom ~50–60 °C) in order to prevent steam condensation in the drywell compartment later during the thermal stratification and mixing periods,

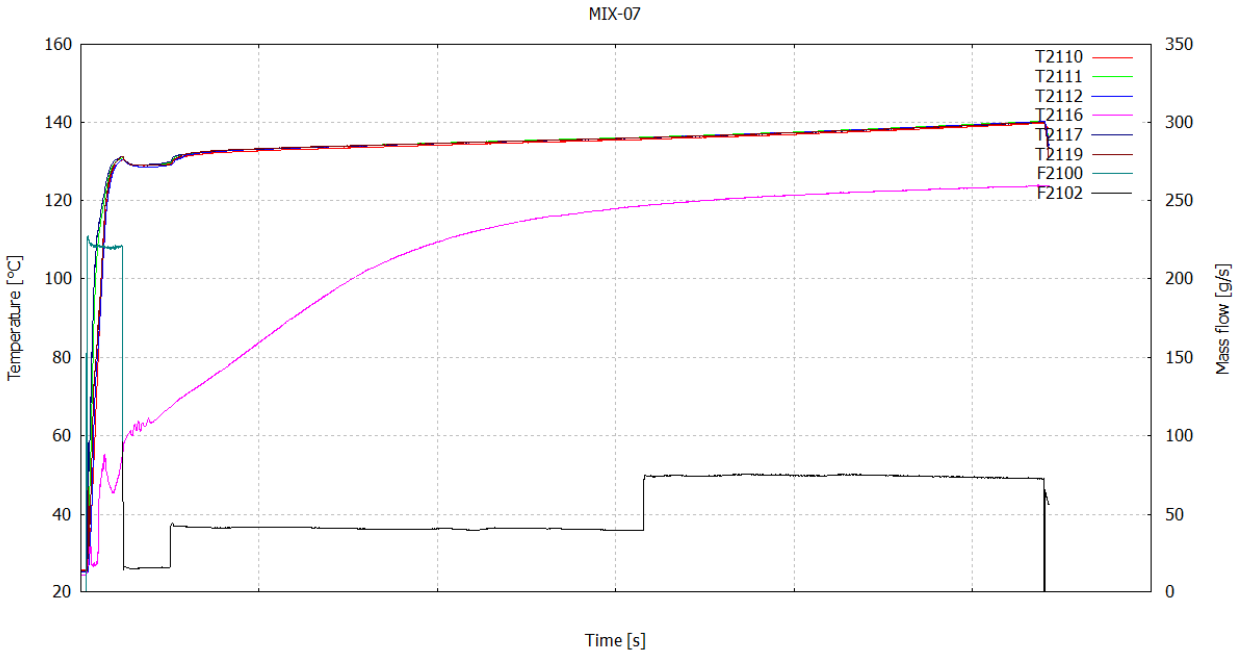

Figure *6* and Table 4. The pool bulk temperature rose approximately 1 °C during the clearing phase, which lasted for 360–445 seconds.

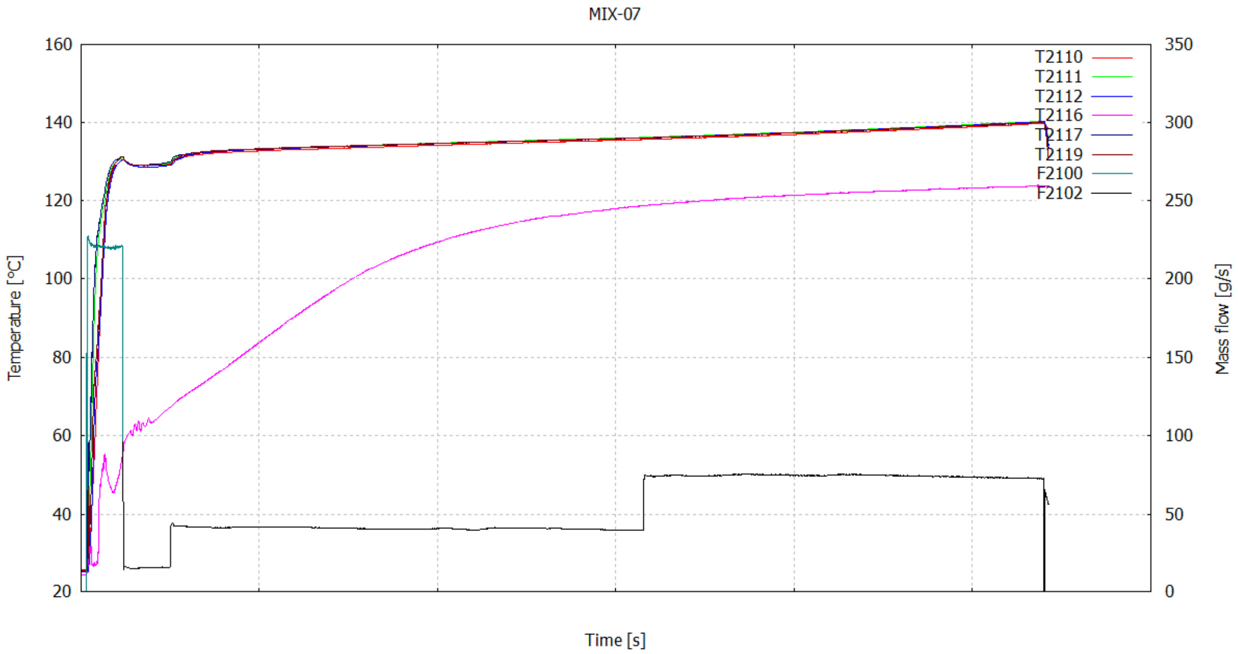

Figure 6. Drywell structural temperatures (T2110–T2119) and steam flow (F2100, F2102) in MIX-07.

Table 4. Parameters of the clearing phase of the MIX experiments 2013.

Exp.	Time period [s]	Steam flow rate [g/s]	Initial drywell structural temperature [bottom/wall, °C]	Final drywell structural temperature [bottom/wall, °C]	Pool water temperature increase [°C]
MIX-07	60–470	~220	25/25	56 / 131	13→14
MIX-08	10–430	~220	25 / 27	55 / 130	13→14
MIX-09	25–470	~220	25 / 27	60 / 131	13→14
MIX-10	40–400	~230	25 / 28	50 / 130	13→14
MIX-11	40–420	~230	25 / 27	53 / 130	13→14
MIX-12	25–455	~230	28 / 32	63 / 131	13→14

After the drywell structures had been heated up to the desired level and air had been displaced from the drywell, the stabilization period was initiated by decreasing the steam flow rate to 16 g/s, Table 5. With this flow steam condensed inside the upper part of the blowdown pipe and the water level inside the pipe rose above the water level in the pool side. The main purpose of the stabilization period was to calm down the internal flows in the wetwell pool and to equalize the drywell structural temperatures before the stratification phase. During the stabilization period (duration 500–580 seconds) the drywell bottom was heated up by 11–14 °C.

Table 5. Parameters of the stabilization period of the MIX experiments 2013.

Exp.	Time period [s]	Steam flow rate [g/s]	Initial drywell structural temperature [°C]	Final drywell structural temperature [bottom/wall, °C]	Pool water temperature [°C]
MIX-07	470–1 000	~16	56 / 131	67 / 130	14
MIX-08	430–1 000	~16	55 / 130	67 / 129	14
MIX-09	470–1 000	~16	60 / 131	71 / 130	14
MIX-10	400–900	~16	50 / 130	64 / 128	14
MIX-11	420–1 000	~16	53 / 130	66 / 129	14
MIX-12	455–1 000	~16	63 / 131	75 / 130	14

The stratification period was initiated by adjusting the steam flow rate to 25–40 g/s. With this flow the steam/water interface was close to the blowdown pipe outlet and steam condensed mainly inside the pipe thus creating suitable conditions for thermal stratification to occur. The stratification period was continued as long as the temperature difference between the pool bottom (measured by TC T2501) and surface (T2518) had reached the target value given by KTH i.e. 18–22 °C depending of the test.

The highest steam flow rate (40 g/s) was used in MIX-07. With this flow temperatures in the wetwell pool below the thermocouple T2508 elevation (330 mm below the pipe outlet) remained constant while they rose towards the pool surface layers indicating thermal stratification of the wetwell pool water, Figure 7 and Figure 8. In the end of the stratification period a 22 °C temperature difference was measured between TCs T2518 and T2501, Figure 11 and Table 6.

In MIX-08…12 the steam flow rate was adjusted to 25–30 g/s. In all these tests temperatures in the wetwell pool below the blowdown pipe outlet remained constant while they rose towards the pool surface layers indicating strong thermal stratification of the wetwell pool water, Figure 9 and Figure 10. In the end of the stratification period a very similar vertical temperature profile was attained because of identical test parameters, Figure 11.

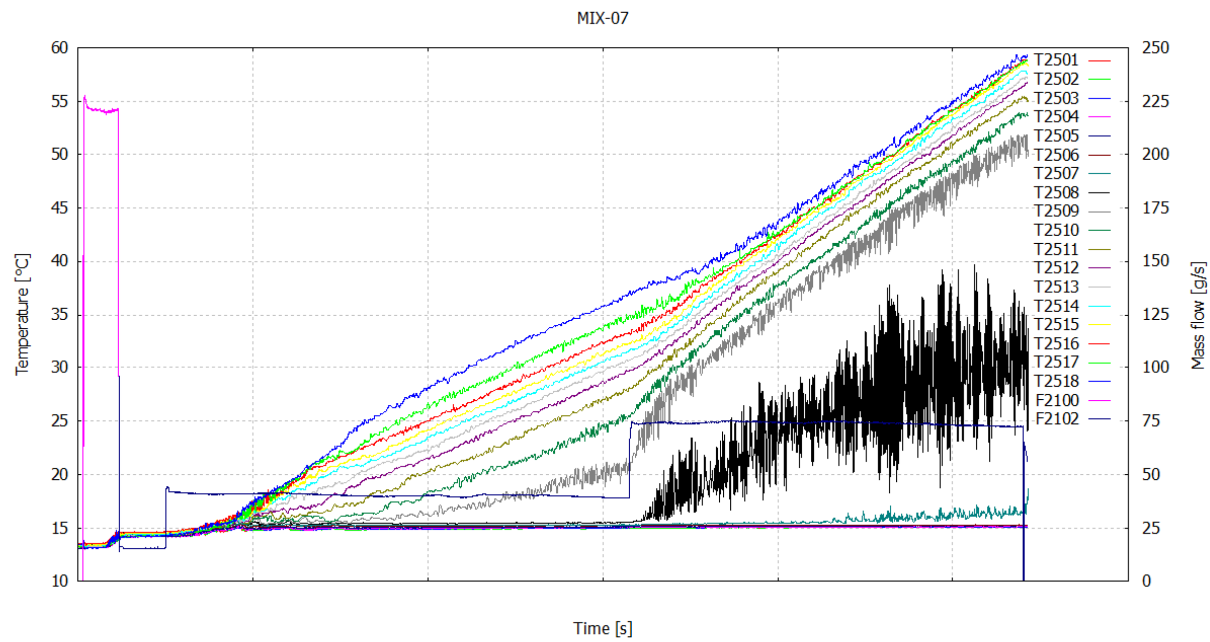

Figure 7. Temperature of wetwell water (T2501–T2518) and steam flow rate (F2100, F2102) in MIX-07.

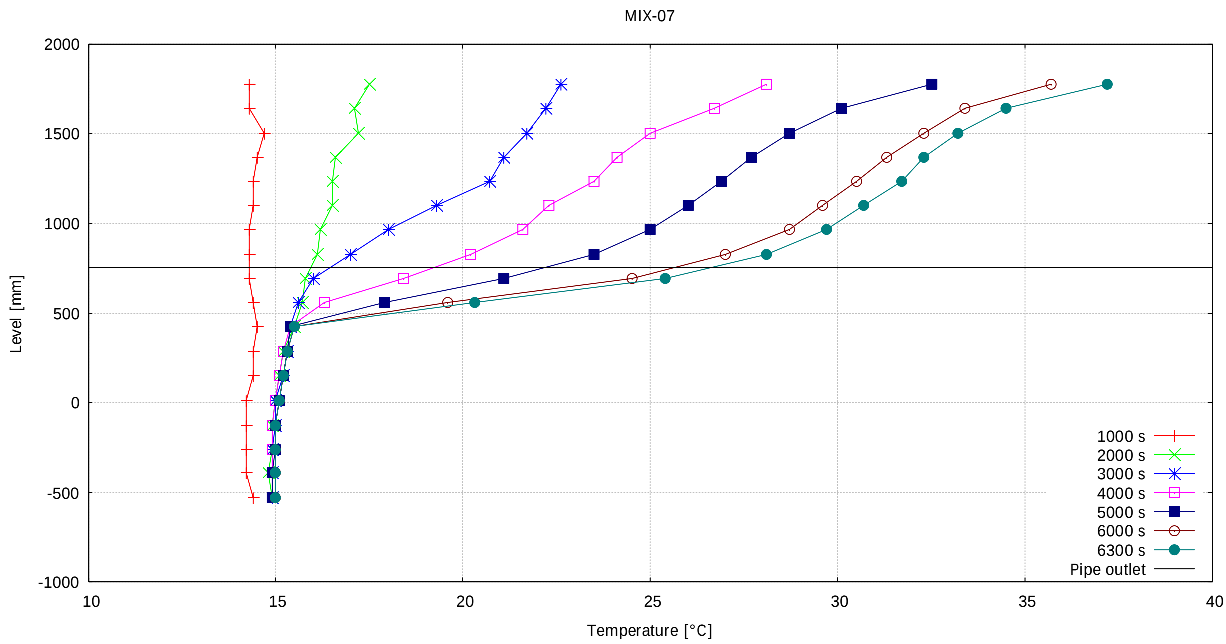

Figure 8. Development of the vertical temperature profile of pool water in MIX-07 during the stratification period.

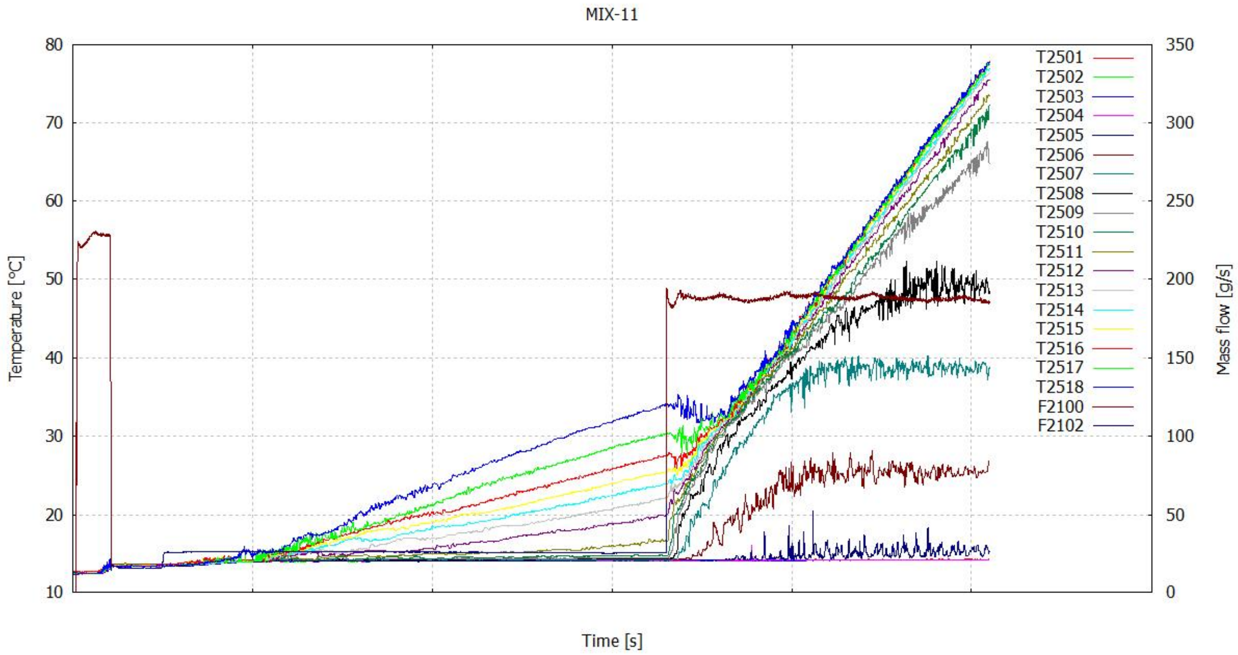

Figure 9. Temperature of wetwell water (T2501–T2518) and steam flow rate (F2100, F2102) in MIX-11.

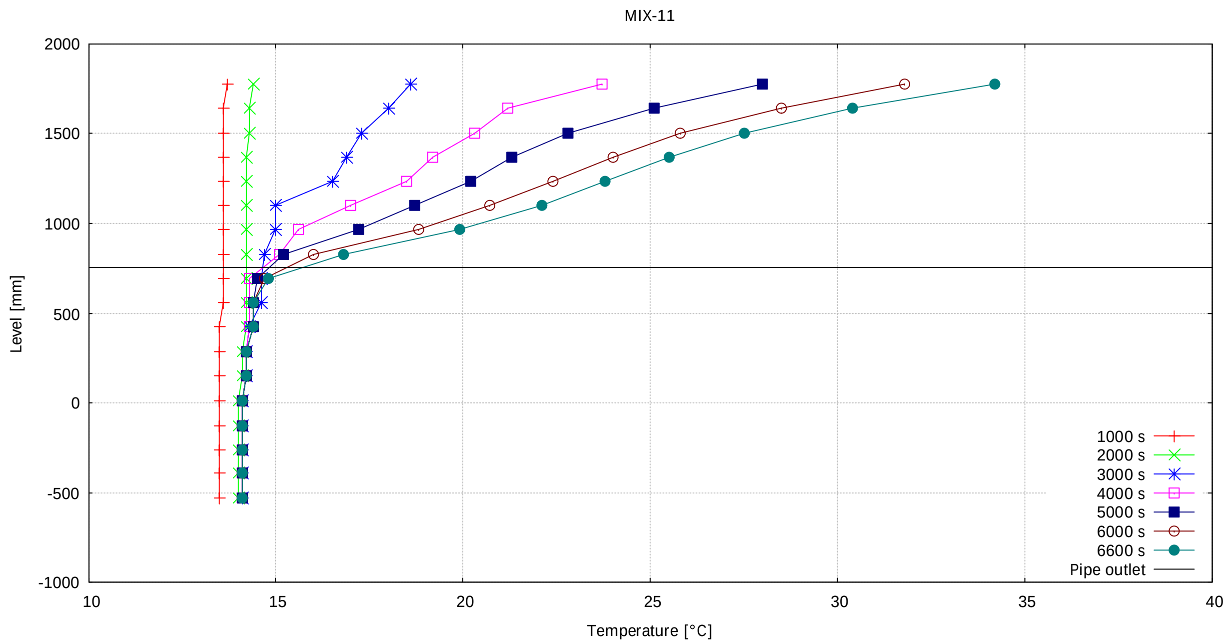

Figure 10. Development of the vertical temperature profile of pool water in MIX-11.

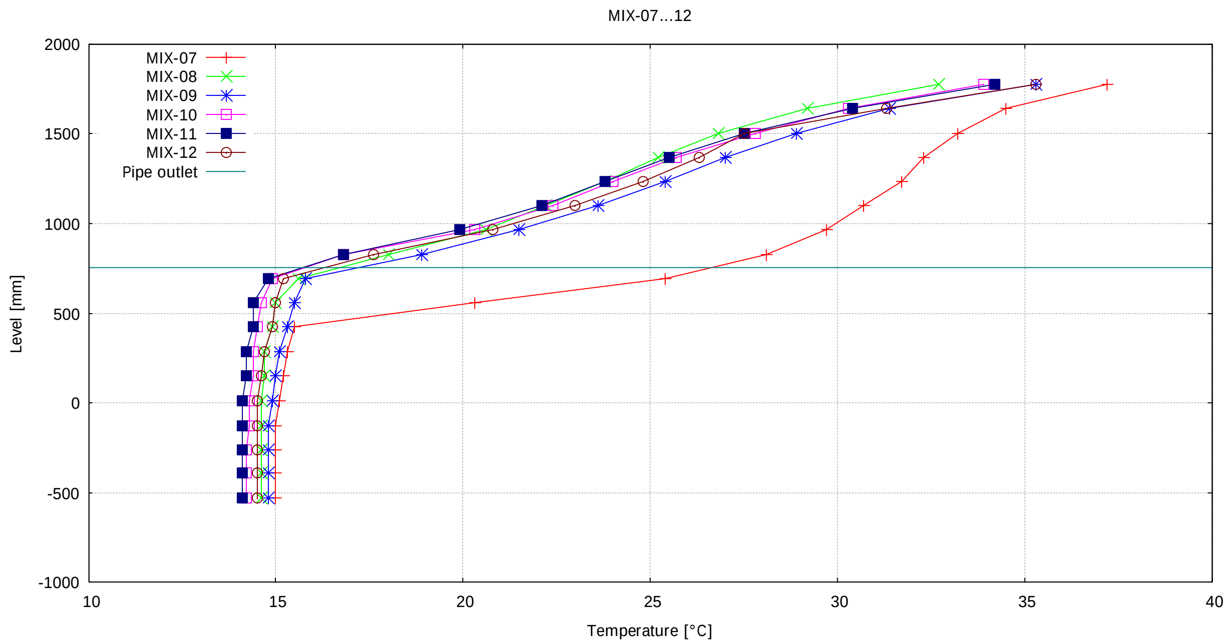

Figure 11. Vertical temperature profile of pool water in the end of the stratification period in MIX-07…12 tests.

Table 6. Stratification related observations of the MIX experiments in 2013.

Exp.	Time period [s]	Initial water temperature [°C]	Steam flow rate [g/s]	Stratification time [s]	Final water temperature of T2501 and T2518 [°C]	Final temperature difference between T2501 and T2518 [°C]
MIX-07	1 000–6 300	14	40	5 300	15–37	22
MIX-08	1 000–5 700	14	30	4 700	15–33	18
MIX-09	1 000–6 375	14	30–25	5 375	15–35	20
MIX-10	900–6 580	14	25	5 680	14–34	20
MIX-11	1 000–6 600	14	25	5 600	14–34	20
MIX-12	1 000–6 600	14	25	5 600	15–35	20

After the desired temperature difference (18–22 °C) between the pool bottom and surface (T2518–T2501) was attained the steam mass flow rate was rapidly increased up to 75–275 g/s to get the steam/water-interface moving up and down inside the blowdown pipe (chugging condensation mode) and further to mix the condensation pool water inventory totally.

Due to the quite low mixing phase steam mass flow (75 g/s) in MIX-07 the temperature difference between the pool bottom and surface did not decrease at all, Figure 7, Figure 12 and Table 7. When the test was terminated the temperature difference was 44 °C.

Meanwhile in MIX-08…12 the temperature difference T2518–T2501 began to decrease after steam flow was increased to 112–275 g/s in the beginning of the mixing period. After 150–560 s the temperature difference had decreased 2–3 °C from the initial values of 18–22 °C. However, the temperature difference began to increase again indicating thermal restratification of the pool water. When the tests were terminated the temperature differences were on the level of 62–70 °C, see Figure 13. Figure 14 shows development of the vertical temperature profile of pool water in MIX-11 during the mixing period.

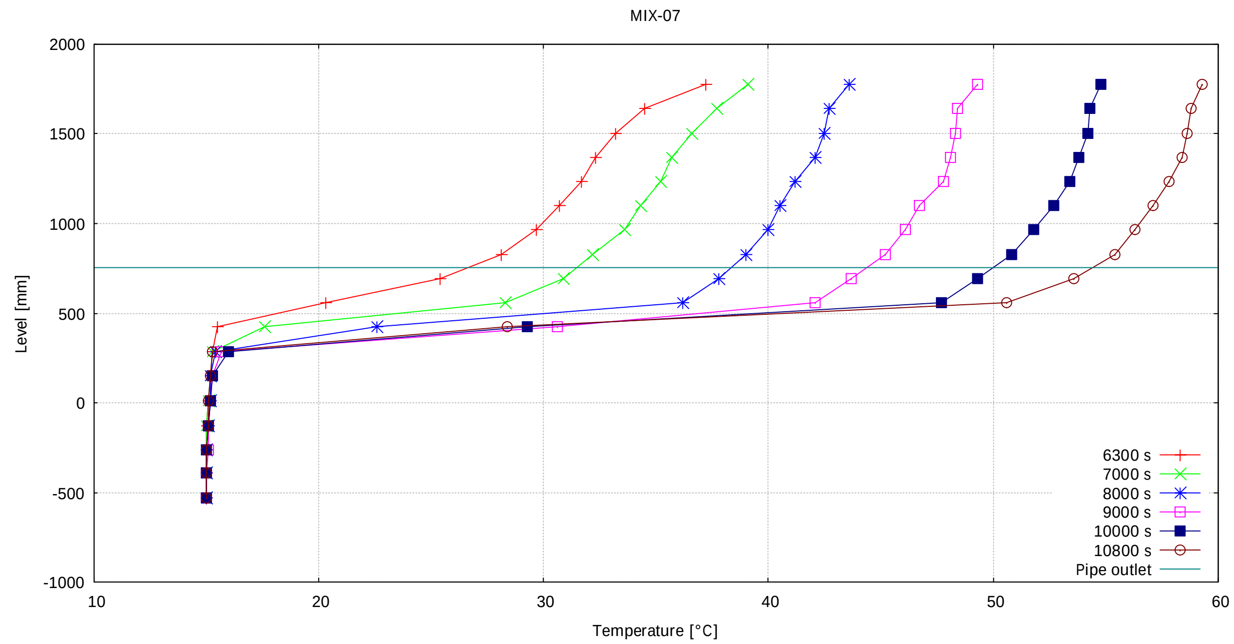

Figure 12. Development of vertical temperature profile of pool water in MIX-07 during the mixing period.

Table 7. Mixing related observations of the MIX experiments in 2013.

Exp.	Time period [s]	Steam flow rate [g/s]	Initial temp. diff. between T2501 and T2518 [°C]	Min. temp. diff. between T2501 and T2518 [°C]	Final temp. diff. between T2501 and T2518 [°C]
MIX-07	6 300–10 800	~75	22	22 at ~6 300 s	44
MIX-08	5 700–8 460	~275	18	16 at ~5 850 s	70
MIX-09	6 375–9 450	~225	20	17 at ~6 640 s	66
MIX-10	6 580–10 985	~150	20	17 at ~7 115 s	62
MIX-11	6 600–10 200	~188	20	17 at ~7 140 s	63
MIX-12	6 600–12 470	~112	20	18 at ~7 160 s	63

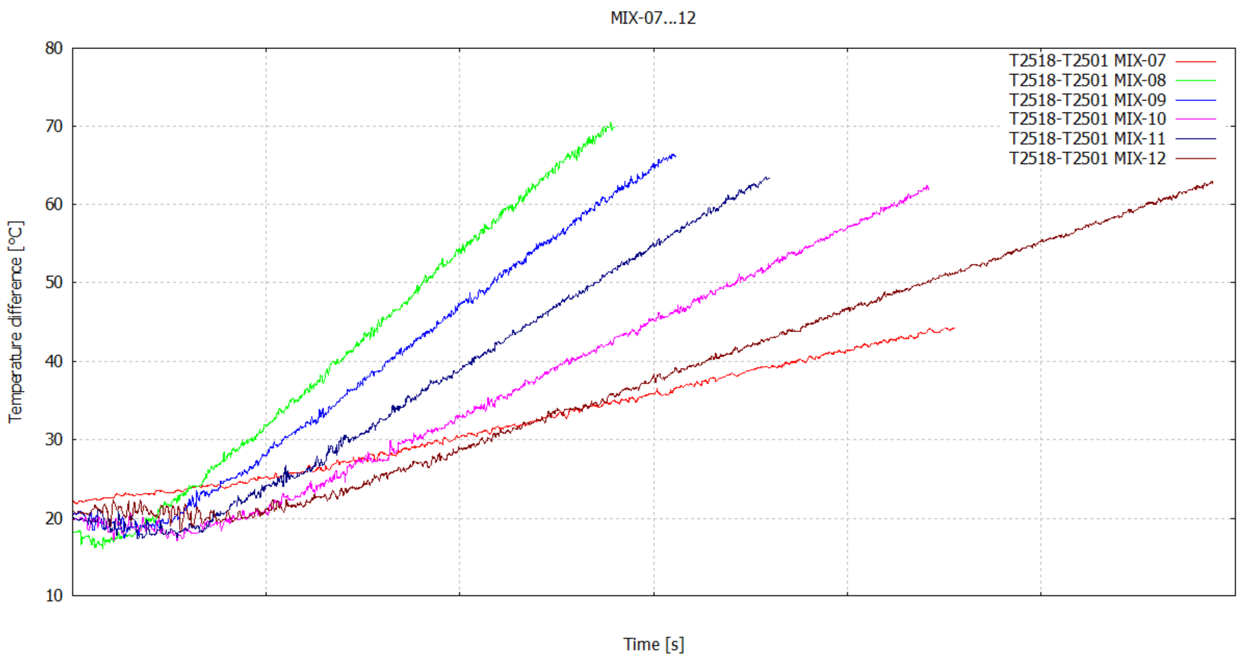

Figure 13. Temperature difference between the bottom and surface of the condensation pool (T2518–T2501) in MIX-07…12. 0 s is the moment when the steam flow rate was increased to try to mix the pool water inventory.

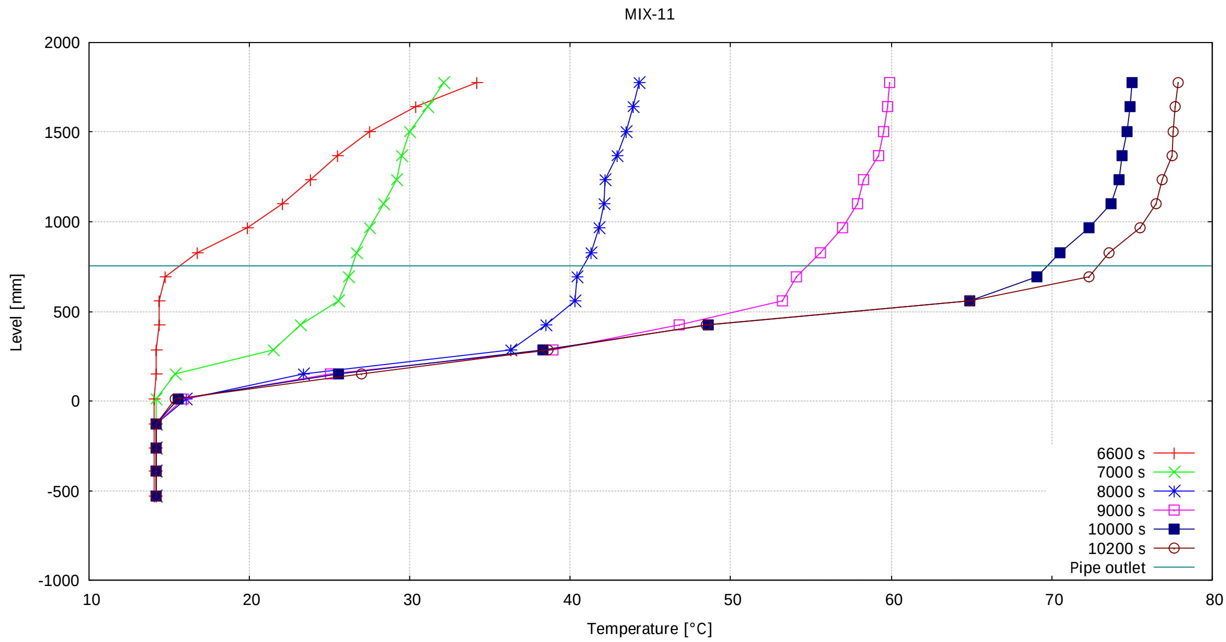

Figure 14. Development of vertical temperature profile of pool water in MIX-11 during the mixing period.

As a comparison, in MIX-01…06 it took only 150–500 s to achieve total mixing of the pool water volume depending of the used steam flow rate and initial pool water temperature. There are two reasons why there was no complete mixing of the pool water inventory in MIX-07…12. First, the exit jet velocity in the blowdown pipe was lower in the MIX-07…12 tests than in the MIX-01…06 tests. Secondly, the distance between the pipe outlet and the pool bottom is ~300 mm larger in the new MIX series tests than in the old tests. Thus, the jet does not reach the bottom of the pool to enhance mixing.

4.3 OSCILLATION OF STEAM/WATER INTERFACE IN BLOWDOWN PIPE

For the MIX 2013 tests a series of thermocouples (TC01–TC145) were installed inside the lower part of the blowdown pipe to measure accurately the oscillatory up and down motion of the steam/water-interface inside the pipe caused by the chugging condensation mode. The thermocouples were along 1 330 mm section upwards from the pipe outlet, see Appendix 1. The distance between two thermocouples ranged from 16 to 110 mm.

The oscillating movement of the steam/water-interface inside the blowdown pipe intensified in every single test after the steam flow rate was increased to mix the pool water inventory. The up and down movement of the interface was registered few times (in MIX-07 and MIX-09) by thermocouple TC07, which is installed 320 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].

Table 8 lists some oscillation related observations from the MIX experiments. The presented 10 seconds time intervals were chosen so that they begin 30 s after the mixing phase was initiated in every single test. The oscillation amplitude was determined from the readings of thermocouples TC01–TC145. Because thermocouples TC115, TC125, TC135 and TC145 were not in use in MIX-07, the actual amplitudes can be few millimeters larger in that test than presented in Table 8. During the tests the steam/water-interface oscillated inside the blowdown pipe with amplitude of 33–200 mm (average ~90 mm) and frequency of 0.40–5.00 Hz (average ~2 Hz). In the MIX-01…06 tests the steam/water-interface oscillated inside the blowdown pipe with amplitude of 29–999 mm (average ~450 mm) and frequency of 0.6–1.82 Hz (average ~1 Hz) [12].

Table 8. Oscillation related observations in MIX-07…12.

Exp.	Time period [s]	Amplitude [mm]	Average amplitude [mm]	Frequency [Hz]	Average frequency [Hz]
MIX-07	6 330–6 340	33–150	59	0.87–1.75	1.41
MIX-08	5 730–5 740	33–150	71	0.40–5.00	2.32
MIX-09	6 405–6 415	33–200	103	0.54–4.17	1.98
MIX-10	6 610–6 620	33–200	100	1.33–3.33	2.18
MIX-11	6 630–6 640	33–200	104	0.79–3.33	1.89
MIX-12	6 630–6 640	33–200	91	0.61–3.12	1.82

Table 9 and Figure 15 show oscillation related observations and Figure 16 the measured temperatures inside the blowdown pipe in MIX-09. The steam/water-interface began to oscillate up and down after the steam flow rate was increased to ~225 g/s at 6 375 s, Figure 17. As expected, the oscillations started to decline once the pool water bulk temperature started to increase and the chugging phenomenon became less violent, Figure 16, Figure 18 and Figure 19.

Table 9. Oscillation related observations in MIX-09.

Time period [s]	Amplitude [mm]	Average amplitude [mm]	Frequency [Hz]	Average frequency [Hz]
6 375–6 385	33–175	77	1.11–4.00	2.19
6 500–6 510	33–125	69	1.11–3.57	1.83
6 600–6 610	33–67	48	0.63–3.13	1.47
6 700–6 710	33–150	68	0.36–2.50	1.55
6 800–6 810	33–200	98	0.51–2.86	1.83
6 900–6 910	33–150	78	0.43–5.00	1.81
7 000–7 010	33–150	75	1.19–2.50	1.82
7 100–7 110	33–150	81	0.96–2.50	1.98
7 200–7 210	33–150	57	0.59–2.78	1.62
7 300–7 310	33–100	48	0.32–3.45	1.19
7 400–7 410	33–100	52	0.65–2.50	1.29
7 500–7 510	33–84	46	0.36–3.33	1.44
7 600–7 610	33–67	39	0.43–1.67	0.94
7 700–7 710	33–100	54	0.67–2.50	1.70
7 800–7 810	33–50	40	0.48–1.89	1.15
7 900–7 910	33–67	42	0.61–1.52	0.93
8 000–8 010	33–50	37	0.28–4.17	1.59
8 100–8 110	33–50	40	0.87–3.23	2.02

8 200–8 210	50–175	113	0.61	0.61
8 300–8 310	33–50	37	0.41–0.75	0.55
8 400–8 410	33–50	39	0.81–0.95	0.88
8 500–8 510	33	33	0.95	0.95

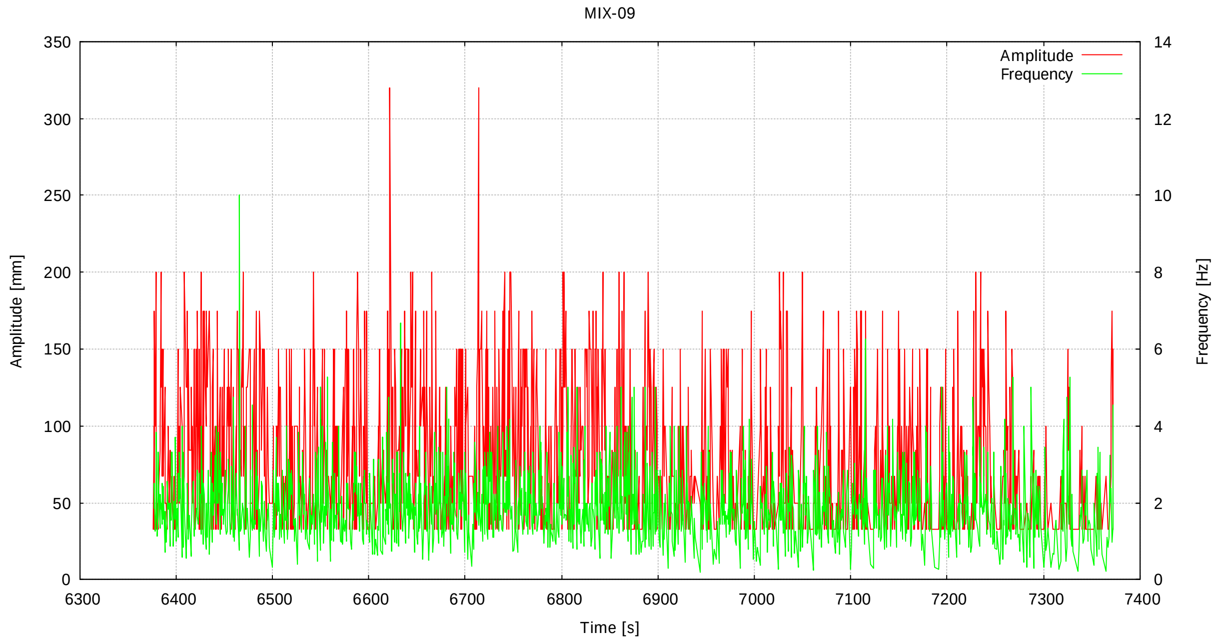

Figure 15. Amplitude and frequency of the oscillation of steam/water-interface inside the blowdown pipe in MIX-09 between 6 375…7 375 s.

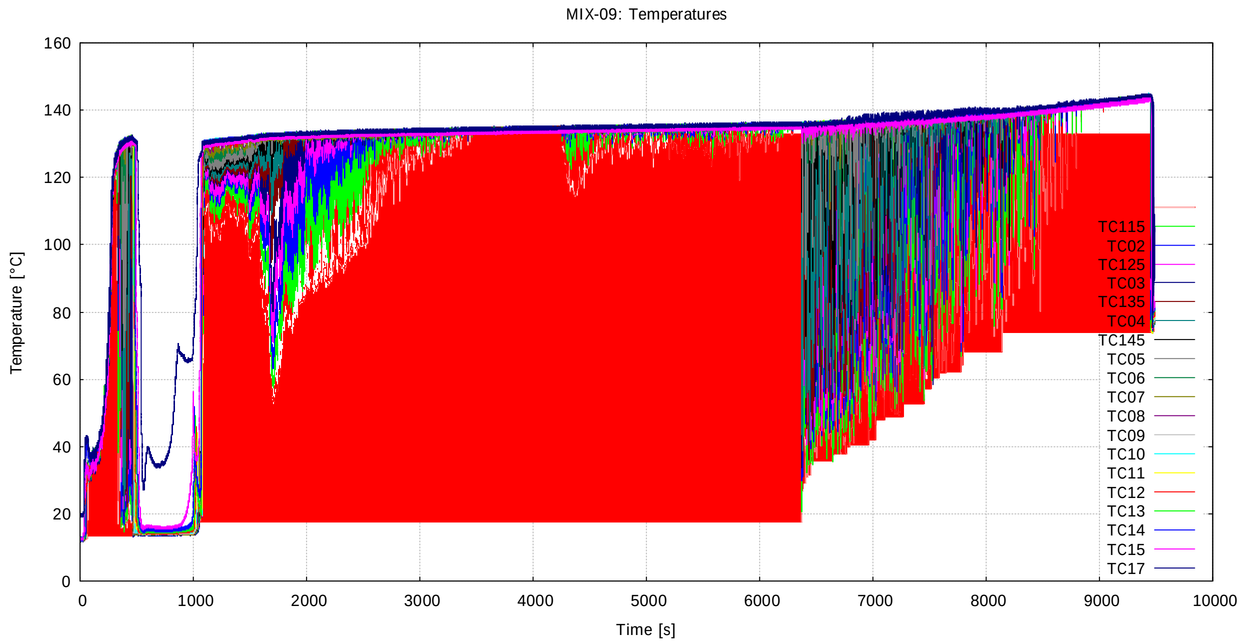

Figure 16. Temperatures inside the blowdown pipe in MIX-09.

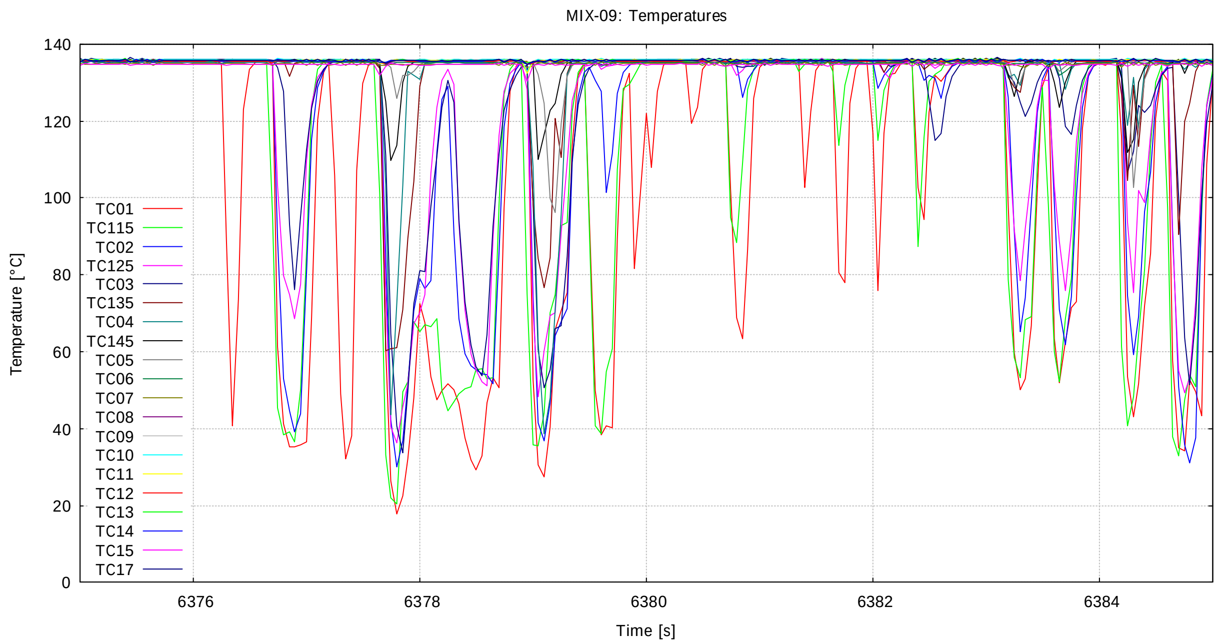

Figure 17. Temperatures inside the blowdown pipe in MIX-09 between 6 375…6 385 s.

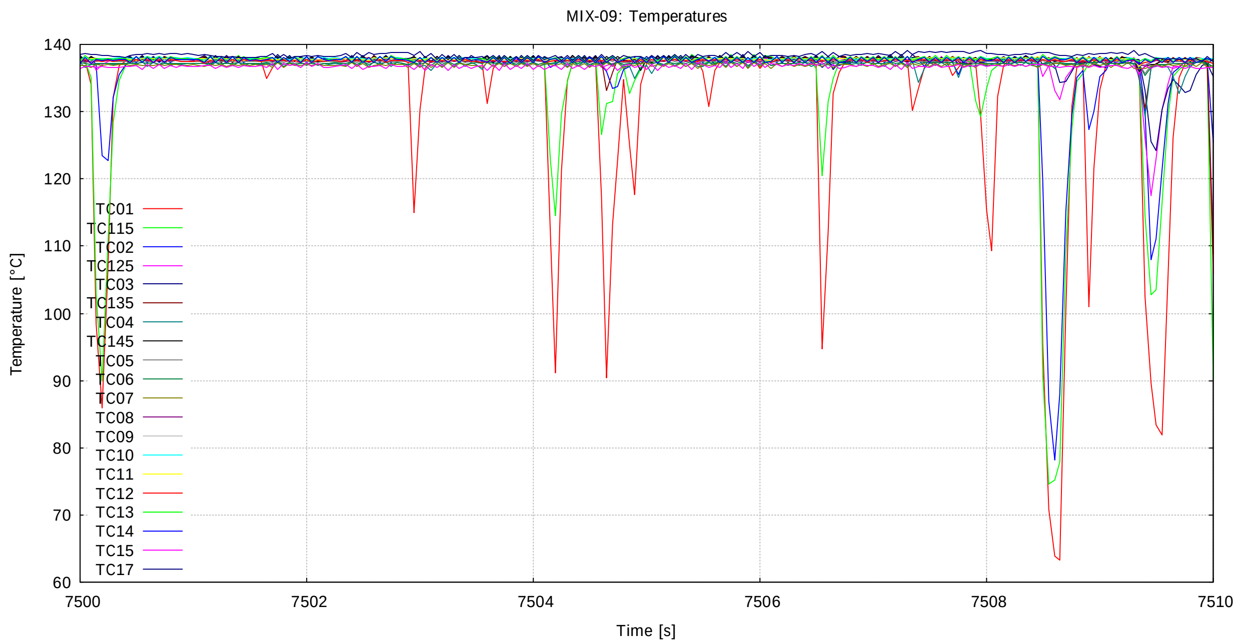

Figure 18. Temperatures inside the blowdown pipe in MIX-09 between 7 500…7 510 s.

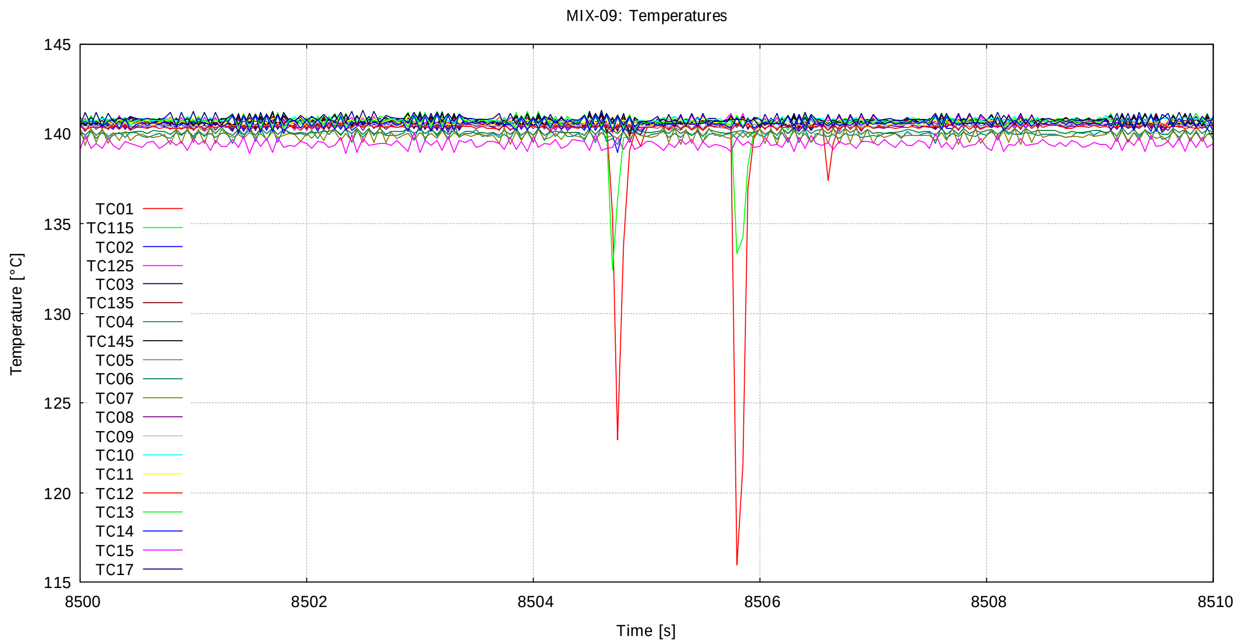

Figure 19. Temperatures inside the blowdown pipe in MIX-09 between 8 510…8 510 s.

5 SUMMARY AND CONCLUSIONS

This report summarizes the results of the thermal stratification and mixing experiments 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 experiments, the test facility was equipped with extra temperature measurements in the blowdown pipe for capturing different aspects of the investigated phenomena. The PACTEL facility was used as a steam source. The main objective of the experiment series was to obtain verification data for the validation of the Nariai and Aya model for prediction of oscillations in a blowdown pipe to be done by KTH. The second objective was to obtain measurement data from those regions of the condensation mode map of Lahey and Moody which were not previously covered in the PPOOLEX tests.

Altogether six experiments (labelled as MIX-07…12) were carried out according to a test plan written by KTH. All experiments had a clearing phase, a stabilization period, a small flow rate stratification period and a higher flow rate mixing period. 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 stratification and mixing periods. The purpose of the stabilization period was to calm down all internal flows in the wetwell pool in order to start the stratification period without any mixing effects present. The initial water bulk temperature in the condensation pool was 14 °C.

During the stratification period (steam flow 25–40 g/s, duration 4 700–5 680 s) steam condensed mainly inside the blowdown pipe. As a result temperatures remained constant below the blowdown pipe outlet while they increased towards the pool surface layers indicating strong thermal stratification of the wetwell pool water. In the end of the stratification period the temperature difference between the pool bottom and surface was 18–22 ºC depending on the test in question.

During the mixing period the steam flow rate was increased rapidly to 75–275 g/s to mix the pool water inventory. With the lowest steam mass flow rate (75 g/s) the temperature difference between the pool bottom and surface did not decrease at all. With the larger flow rates (112–275 g/s) the temperature difference decreased at first 2–3 °C. After that the temperature difference began to increase again indicating thermal restratification of the pool water. When the tests were terminated the temperature difference was on the level of 62–70 °C. The pool water inventory was not mixed completely because of low exit jet velocity in the blowdown pipe. Also the distance between the pipe outlet and the pool bottom was now ~300 mm longer than in the mixing tests carried out in 2012 with the DN200 blowdown pipe. Thus, the jet did not reach the bottom of the pool to enhance mixing.

During the mixing period the steam/water-interface oscillated inside the blowdown pipe with an amplitude and average frequency of 33–200 mm and ~2 Hz, correspondingly.

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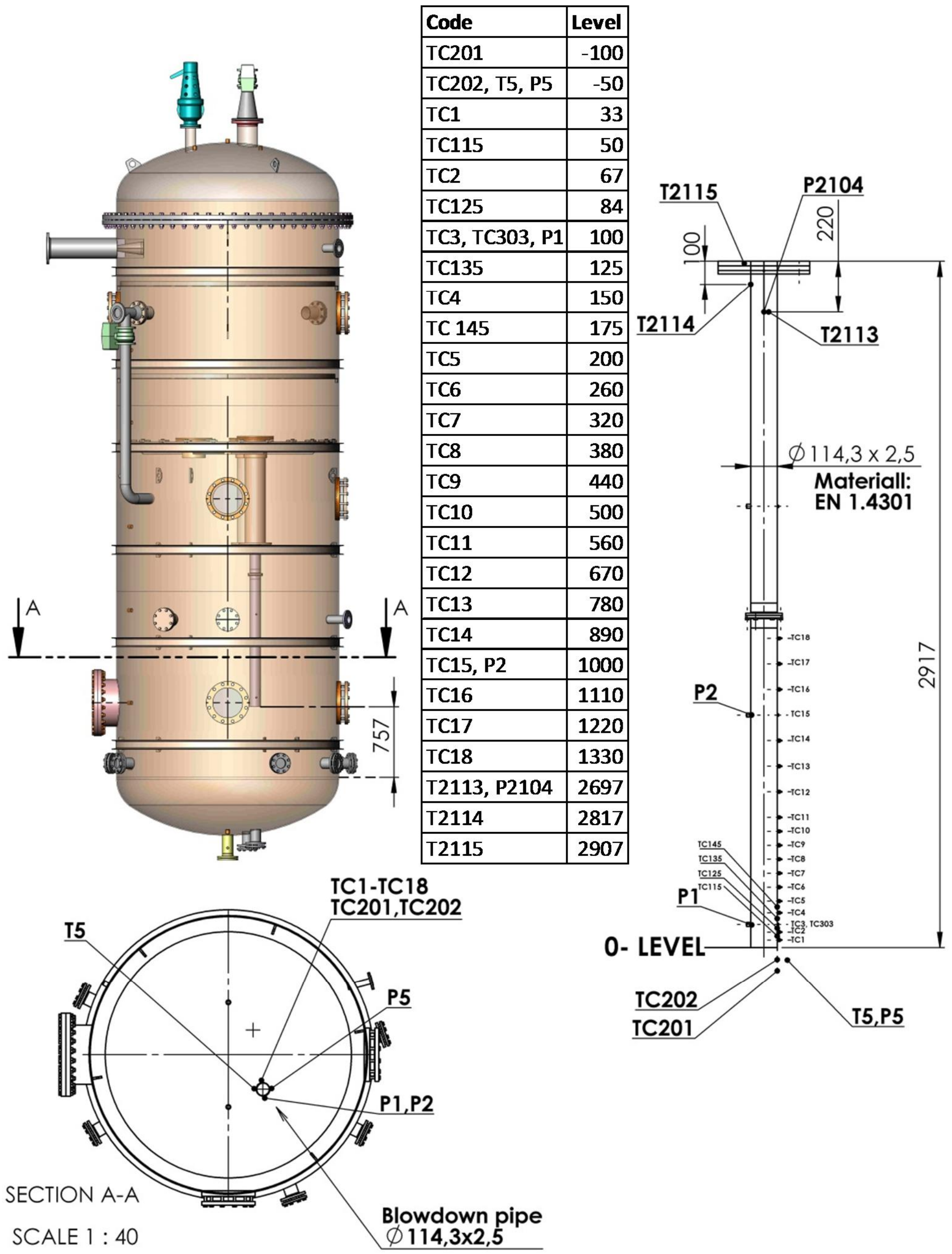
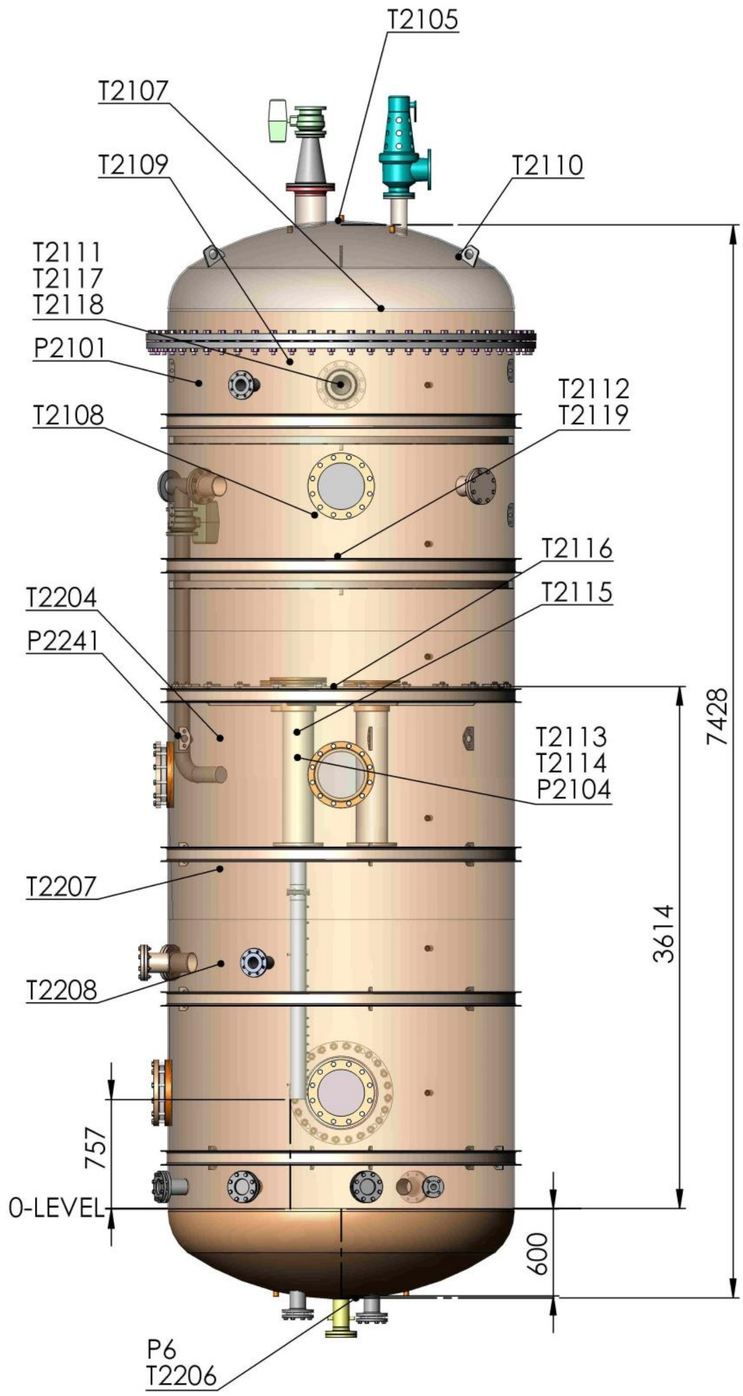
APPENDIX 1: PPOOLEX INSTRUMENTATION

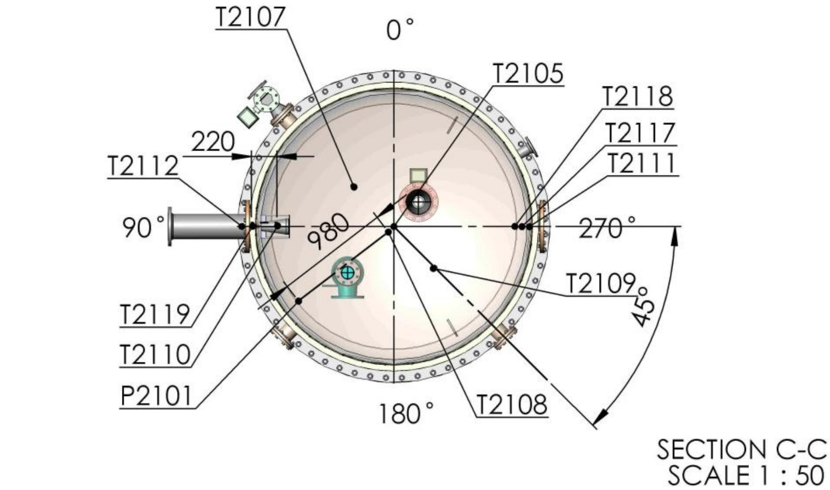


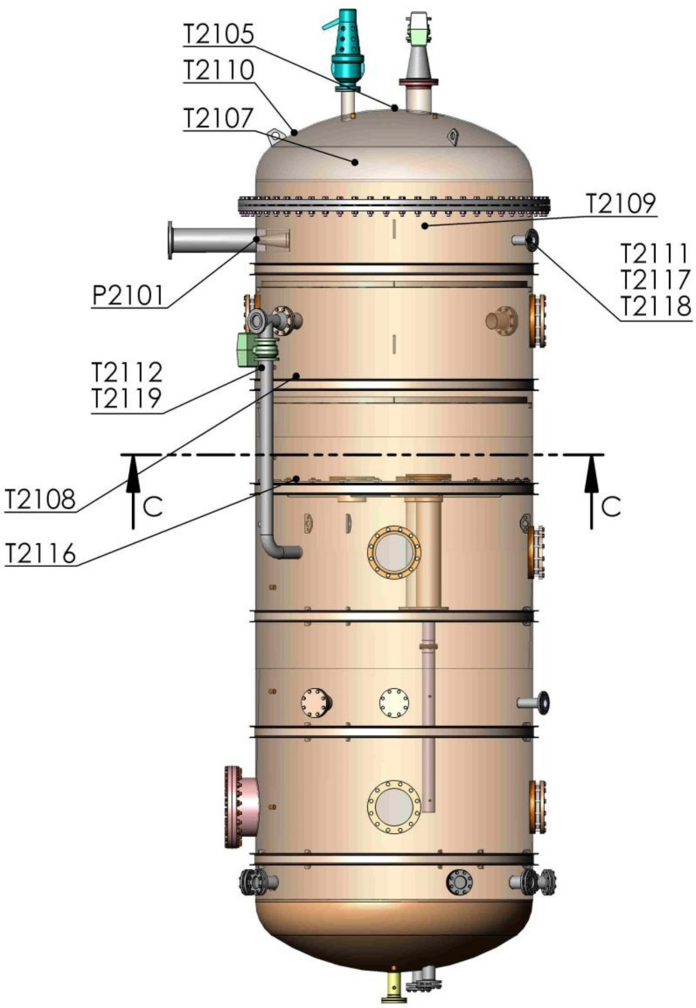
Code	Level
TC201	-100
TC202, T5, P5	-50
TC1	33
TC115	50
TC2	67
TC125	84
TC3, TC303, P1	100
TC135	125
TC4	150
TC 145	175
TC5	200
TC6	260
TC7	320
TC8	380
TC9	440
TC10	500
TC11	560
TC12	670
TC13	780
TC14	890
TC15, P2	1000
TC16	1110
TC17	1220
TC18	1330
T2113, P2104	2697
T2114	2817
T2115	2907

Blowdown pipe measurements in the MIX test series.

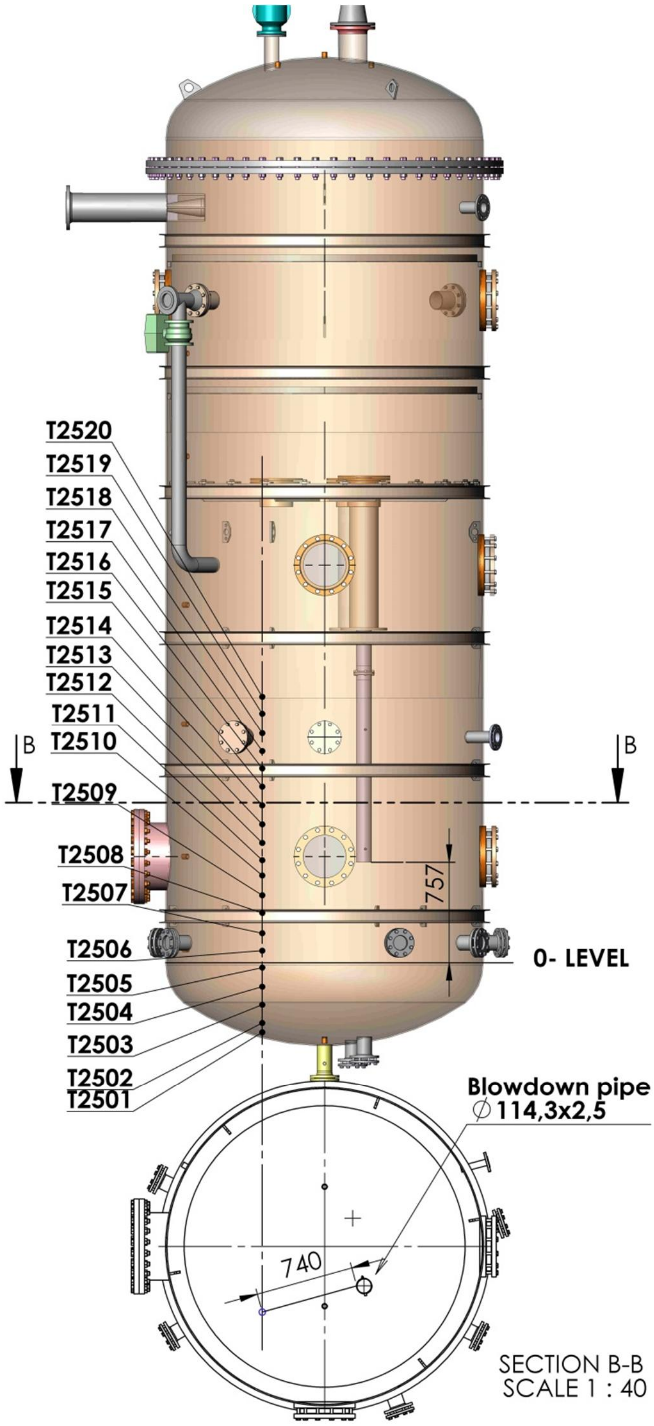


Test vessel measurements.



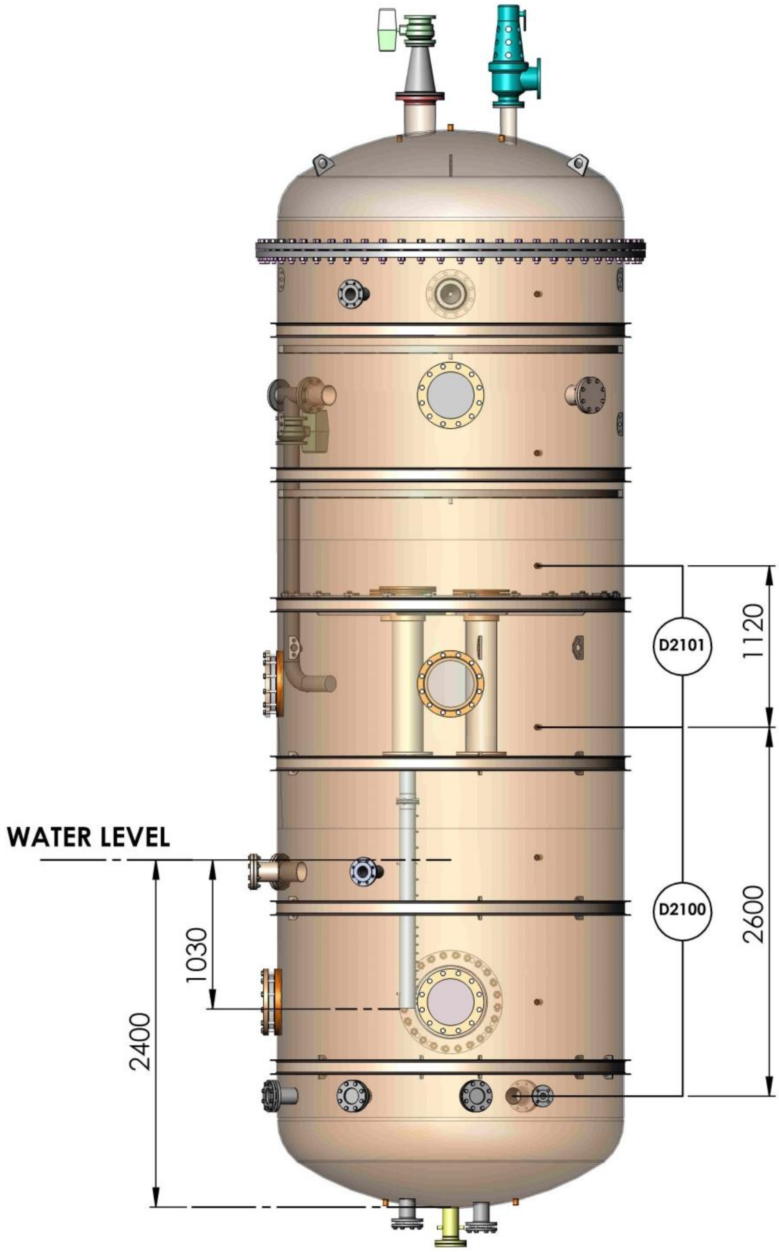


Drywell measurements.

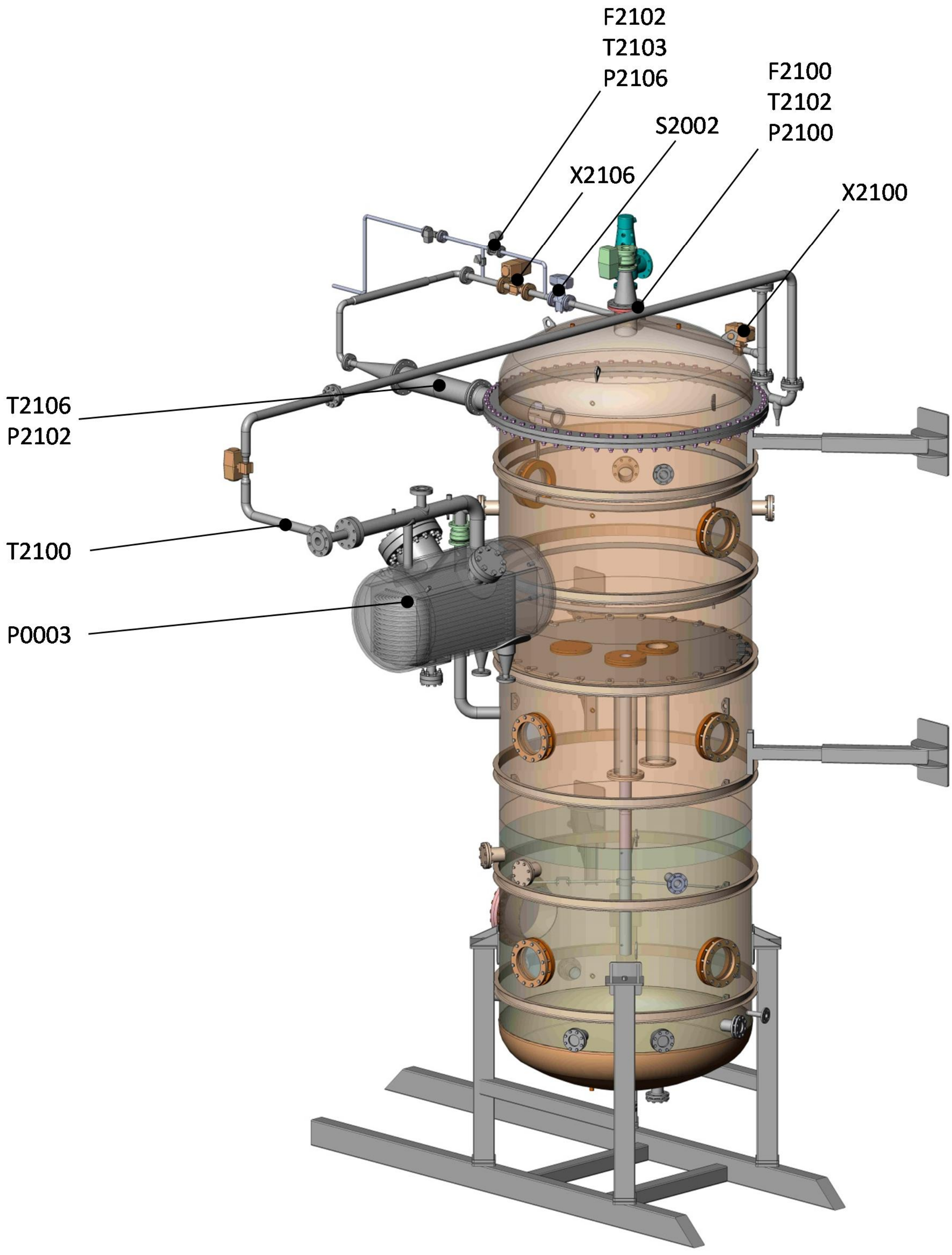


Code	Level
T2501	-530
T2502	-390
T2503	-260
T2504	-125
T2505	10
T2506	150
T2507	287
T2508	427
T2509	560
T2510	695
T2511	830
T2512	965
T2513	1103
T2514	1236
T2515	1369
T2516	1505
T2517	1640
T2518	1775
T2519	1910
T2520	2045

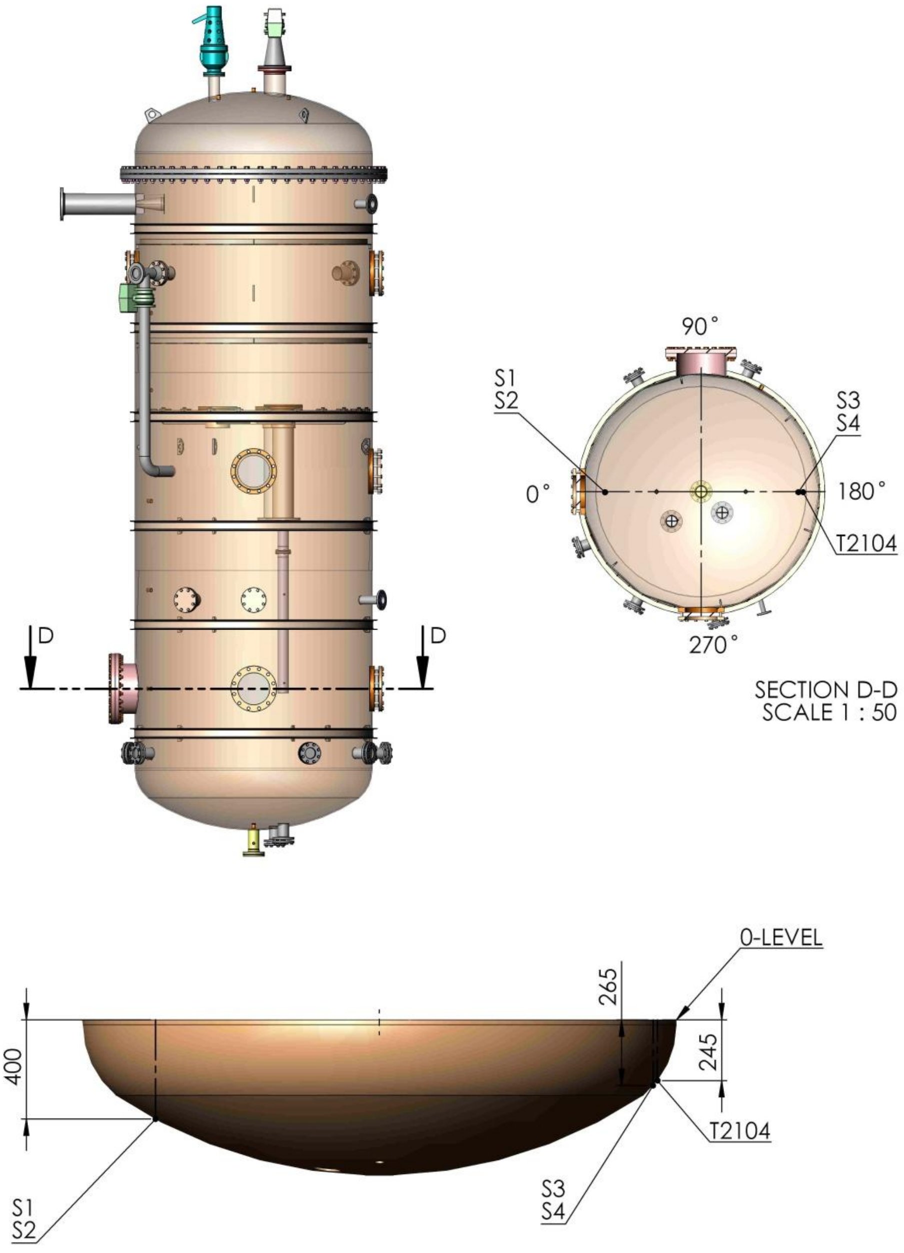
Temperature measurements in the wetwell pool for the detection of thermal stratification.



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 MIX 2013 test series.

APPENDIX 2: PPOOLEX TEST FACILITY PHOTOGRAPHS

Mineral wool insulated dry well compartment and steam line.

DN100 blowdown pipe.

Title	PPOOLEX Mixing Experiments
Author(s)	Jani Laine, Markku Puustinen, Antti Räsänen
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Abstract
max. 2000 characters

This report summarizes the results of the thermal stratification and mixing experiments carried out with the scaled down PPOOLEX test facility designed and constructed at Lappeenranta University of Technology. Steam was blown into the drywell compartment and from there through the vertical DN100 blowdown pipe to the condensation pool filled with sub-cooled water.

The main objective of the experiments was to obtain verification data to be used by KTH in the validation of the Nariai and Aya model for prediction of oscillations in a blowdown pipe. The second objective was to obtain measurement data from those regions of the condensation mode map of Lahey and Moody which were not previously covered in the PPOOLEX tests. A detailed test matrix and procedure put together on the basis of pre-test calculations was provided by KTH before the experiments.

Altogether six experiments (MIX-07…12) were carried out. The experiments consisted of a clearing phase, of a small steam flow rate stratification period and of a higher flow rate mixing period.

During the low steam flow rate (25–40 g/s) period steam condensed mainly inside the blowdown pipe. As a result temperatures remained constant below the blowdown pipe outlet while they increased towards the pool surface layers indicating strong thermal stratification of the wetwell pool water. In the end of the stratification period the temperature difference between the pool bottom and surface was 18–22 ºC depending on the steam flow rate and the duration of the stratification period.

During the mixing period the steam flow rate was increased rapidly to 75–275 g/s to mix the pool water inventory. The pool water inventory was not mixed completely because of low exit jet velocity in the blowdown pipe. Also the distance between the pipe outlet and the pool bottom was now ~300 mm longer than in the mixing tests carried out in 2012 with the DN200 blowdown pipe, where total mixing was achieved. Thus, the jet did not reach the bottom of the pool to enhance mixing. During the mixing period the steam/water-interface oscillated inside the blowdown pipe with an amplitude of 33–200 mm and with an average frequency of ~2 Hz.

Key words: condensation pool, steam blowdown, thermal stratification, mixing

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