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PPOOLEX EXPERIMENTS ON THE DYNAMICS OF FREE WATER SURFACE IN THE BLOWDOWN PIPE

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April 2013

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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 dry well compartment and from there through the vertical DN200 blowdown pipe to the condensation pool filled with sub-cooled water. The main objective of the experiments was to obtain verification data for the development of the Effective Momentum Source (EMS) and Effective Heat Source (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. Altogether six experiments were carried out. The experiments consisted of a small steam flow rate stratification period and of a higher flow rate mixing period. The dry well structures were heated up to approximately 130 °C before the stratification period was initiated. The initial water bulk temperature in the condensation pool was 13-16 °C. During the low steam flow rate (85–105 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 wet well pool water. In the end of the stratification period the temperature difference between the pool bottom and surface was 15–30 ºC depending on the test parameters and the duration of the low flow rate period. In the beginning of the mixing phase the steam flow rate was increased rapidly to 300–425 g/s to mix the pool water totally. Depending on the used steam flow rate and initial pool water temperature it took 150–500 s to achieve total mixing. If the test was continued long enough the water pool began to stratify again after the water bulk temperature had reached ~50 °C despite of steam mass flux belonging to the chugging region of the condensation mode map. During the mixing period the steam/water-interface oscillated inside the blowdown pipe with amplitude of 29–999 mm and with an average frequency of ~1 Hz.

Key words

condensation pool, steam/air blowdown, thermal stratification and mixing

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Altogether six experiments were carried out. The experiments consisted of a small steam flow rate stratification period and of a higher flow rate mixing period. The dry well structures were heated up to approximately 130 °C before the stratification period was initiated. The initial water bulk temperature in the condensation pool was 13-16 °C.

During the low steam flow rate (85–105 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 wet well pool water. In the end of the stratification period the temperature difference between the pool bottom and surface was 15–30 ºC depending on the test parameters and the duration of the low flow rate period.

In the beginning of the mixing phase the steam flow rate was increased rapidly to 300–425 g/s to mix the pool water totally. Depending on the used steam flow rate and initial pool water temperature it took 150–500 s to achieve total mixing. If the test was continued long enough the water pool began to stratify again after the water bulk temperature had reached ~50 °C despite of steam mass flux belonging to the chugging region of the condensation mode map. During the mixing period the steam/water-interface oscillated inside the blowdown pipe with amplitude of 29–999 mm and with an average frequency of ~1 Hz.

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PREFACE

Condensation pool studies started in Nuclear Safety Research Unit at Lappeenranta University of Technology (LUT) in 2001 within the Finnish Research Programme on Nuclear Power Plant Safety (FINNUS). The experiments were designed to correspond to the conditions in the Finnish boiling water reactors (BWR) and the experiment programme was partially funded by Teollisuuden Voima Oy (TVO). Studies continued in 2003 within the Condensation Pool Experiments (POOLEX) project as a part of the Safety of Nuclear Power Plants - Finnish National Research Programme (SAFIR). The studies were funded by the State Nuclear Waste Management Fund (VYR) and by the Nordic Nuclear Safety Research (NKS).

In these research projects, the formation, size and distribution of non-condensable gas and steam bubbles in the condensation pool was studied with an open scaled down pool test facility. Also the effect of non-condensable gas on the performance of an emergency core cooling system (ECCS) pump was examined. The experiments were modelled with computational fluid dynamics (CFD) and structural analysis codes at VTT.

A 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 dry well and wet well 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 a modern high speed camera have been installed to the PPOOLEX facility in 2011. 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 and ESA projects of SAFIR2014. The studies are funded by the VYR, NKS and NORTHNET.

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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
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
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
POOLEX	condensation pool experiments project
PPOOLEX	pressurized condensation pool experiments project
PWR	pressurized water reactor
SAFIR	Safety of Nuclear Power Plants - Finnish National Research Programme
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 dry well to the condensation pool through the blowdown pipes in the Olkiluoto type BWR, see Figure 1. The wet well pool serves as the major heat sink for condensation of steam.

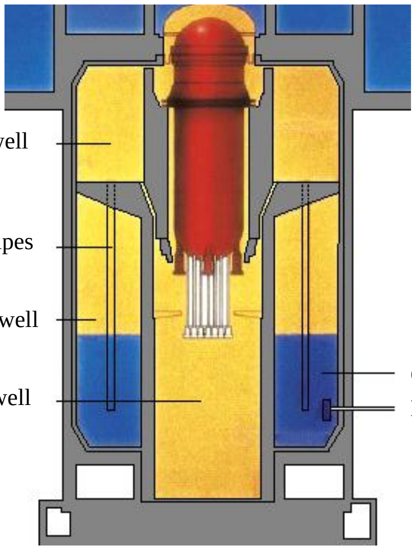

Figure 1. Schematic of the Olkiluoto type BWR containment.

The main objective of the EXCOP project is to improve understanding and increase fidelity in quantification of different phenomena inside the dry and wet well compartments of BWR containment during steam discharge. These phenomena could be connected, for example, to bubble dynamics issues, thermal stratification and mixing, wall condensation, direct contact condensation (DCC) and interaction of parallel blowdown pipes. Steam bubbles interact with pool water by heat transfer, condensation and momentum exchange via buoyancy and drag forces. Pressure oscillations due to rapid condensation can occur frequently.

To achieve the project objectives, a combined experimental/analytical/computational study programme is being carried out. Experimental part at LUT is responsible for the development of a database on condensation pool dynamics and heat transfer at well controlled conditions. Analytical/computational part at VTT, KTH and LUT use the developed 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 dry and wet well (condensation pool) compartments of the containment and withstands prototypical system pressures. Experience gained with the operation of the preceding open POOLEX facility was extensively utilized in the design and construction process of the new facility.

Experiments with the 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 of a postulated MSLB accident inside the containment [2]. Air was used as the flowing substance in these experiments. The research program continued in 2008 with a series of thermal stratification and mixing experiments [3]. Stratification in the water volume of the wet well during small steam discharge was of special interest. In December 2008 and January 2009 a test series focusing on steam condensation in the dry well compartment was carried out [4]. Experiments to study the effect of the Forsmark type blowdown pipe outlet collar design on loads caused by chugging phenomena were also done in 2009 [5]. Then the research programme continued with eleven experiments (TRA and PAR series) studying the effect of the number of blowdown pipes (one or two) on loads caused by chugging phenomenon [6]. In January 2010, experiments focusing on dynamic loading (DYN series) during steam discharge were carried out [7]. Stratification and mixing in the wet well 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].

Work with the PPOOLEX facility continued in June–October 2012 with a series of thermal stratification and mixing experiments (labeled as MIX-01…06). For the test series additional thermocouples were installed inside the 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 [12]. In this report, the results of the MIX experiments 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 of the experiment series.

2 PPOOLEX TEST FACILITY

Condensation studies at LUT started with an open pool test facility (POOLEX) modelling the suppression pool of the BWR containment. During the years 2002–2006, the facility had several modifications and enhancements as well as improvements of instrumentation before it was replaced with a more versatile PPOOLEX facility in the end of 2006. The PPOOLEX facility is described in more detail in reference [13]. However, the main features of the facility and its instrumentation are introduced below.

2.1 TEST VESSEL

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

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

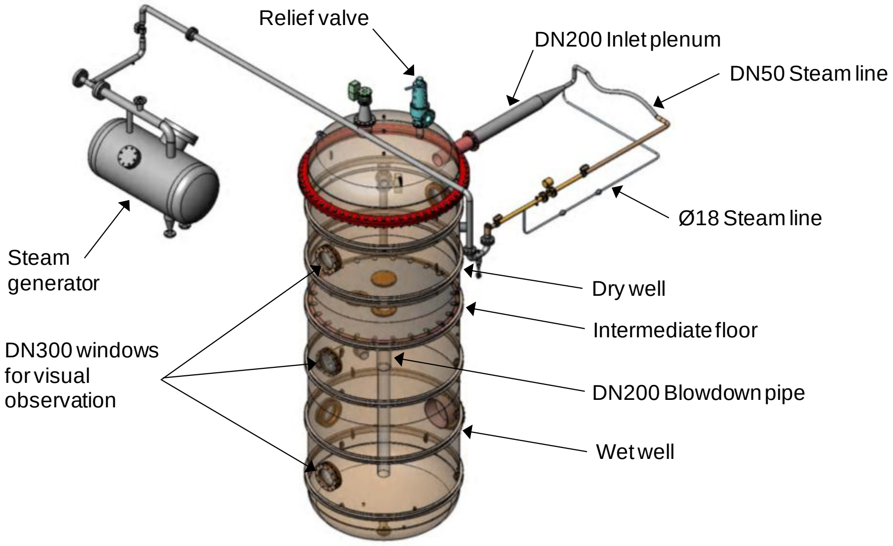

Figure 2. PPOOLEX test vessel.

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

	PPOOLEX test facility	Olkiluoto 1 and 2
Number of blowdown pipes	1-2	16
Inner diameter of the blowdown pipe [mm]	214.1	600
Suppression pool cross-sectional area [m^2]	4.45	287.5
Dry well volume [m^3]	13.3	4350
Wet well volume [m^3]	17.8	5725
Nominal water volume in the suppression pool [m^3]	8.38*	2700
Nominal water level in the suppression pool [m]	2.14*	9.5
Pipes submerged [m]	1.05	6.5
A_{pipes}/A_{pool}x100%	0.8 / 1.6**	1.6

* Water volume and level can be chosen according to the experiment type in question. The values listed in the table are based on the ratio of nominal water and gas volumes in the plant.
** With one / two blowdown pipes.

2.2 PIPING

In the plant, there are vacuum breakers between the dry and wet well compartments in order to keep the pressure in wet well in all possible accident situations less than 0.05 MPa above the dry well pressure. In the PPOOLEX facility, the pressure difference between the compartments is controlled via a connection line (Ø 114.3 x 2.5 mm) from the wet well gas space to the dry well. A remotely operated valve in the line can be programmed to open with a desired pressure difference according to test specifications. However, the pressure difference across the floor between the compartments should not exceed the design value of 0.2 MPa.

Steam needed in the experiments is produced with the nearby PACTEL [14] 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.

2.3 BLOWDOWN PIPE

The DN200 blowdown pipe 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. The total length of the blowdown pipe is 3209 mm. The pipe is made from austenitic stainless steel AISI 304L (Ø219.1x2.5).

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 dry well, inside the blowdown pipes, at the condensation pool bottom and in the gas phase of the wet well. Steam flow rate is measured with a vortex flow meter (F) in the steam line. Additional instrumentation includes, for example, strain gauges (S) on the pool outer wall and valve position sensors.

For the thermal stratification and mixing experiments an extensive net of temperature measurements (thermocouples TC1–TC15) were installed in the 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.

The 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

Standard video cameras and digital videocassette recorders were used for visual observation of the test vessel interior during the test series. A Phantom v9.1 high speed camera was used for capturing the chugging phenomena at the blowdown pipe outlet at the end of 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 [15].

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 June – October 2012 consisted of six experiments (labeled from MIX-01 to MIX-06). 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 [16]. All experiments had a small flow rate stratification period and a higher flow rate mixing period.

Before the experiments, the wet well pool was filled with isothermal water (13–16 °C) to the level of 2.1 m i.e. the blowdown pipe outlet was submerged by 1.0 m. 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.

Initially, the dry well compartment of the test vessel was filled with air at atmospheric pressure. After the correct initial conditions had been reached, the remote-controlled cut-off valve in the steam line was opened. As a result, the dry well compartment was filled with steam that mixed there with the initial air content. Pressure build-up in the dry well then pushed water in the blowdown pipe downwards and after a while the pipe cleared and air/steam flow into the wet well compartment started. After air was displaced from the dry well into the gas space of the wet well, the stratification process with a small pure steam flow began. 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-04, new thermocouples TC13 and TC14 were added inside the blowdown pipe and after MIX-05 TC303 and TC315 were attached on the outer wall of the blowdown pipe. Thermocouple TC2 and pressure transducer P2102 were not in use in MIX-06.

The main parameters of the MIX-01–MIX-06 experiments are listed in Table 2. The path of each experiment defined by the steam mass flux and pool bulk temperature is marked on the condensation mode map in Figure 3.

Table 2. Parameter values of the MIX-01–MIX-06 experiments in 2012.

Exp.	Initial water level [m]	Initial water temperature [°C]	Steam source pressure [MPa]	Steam flow rate [g/s]	Comments
MIX-01	2.09	13	0.55–0.6	50–350	TC13, TC14, TC303 and TC315 not in use
MIX-02	2.09	13	0.53–0.6	10–430	TC13, TC14, TC303 and TC315 not in use
MIX-03	2.09	13	0.5–0.6	80–440	TC13, TC14, TC303 and TC315 not in use
MIX-04	2.10	16	0.58–0.65	50–320	TC13, TC14, TC303 and TC315 not in use
MIX-05	2.10	15	0.57–0.63	80–365	TC303 and TC315 not in use
MIX-06	2.10	15	0.55–0.64	90–475	TC2 and P2102 not in use

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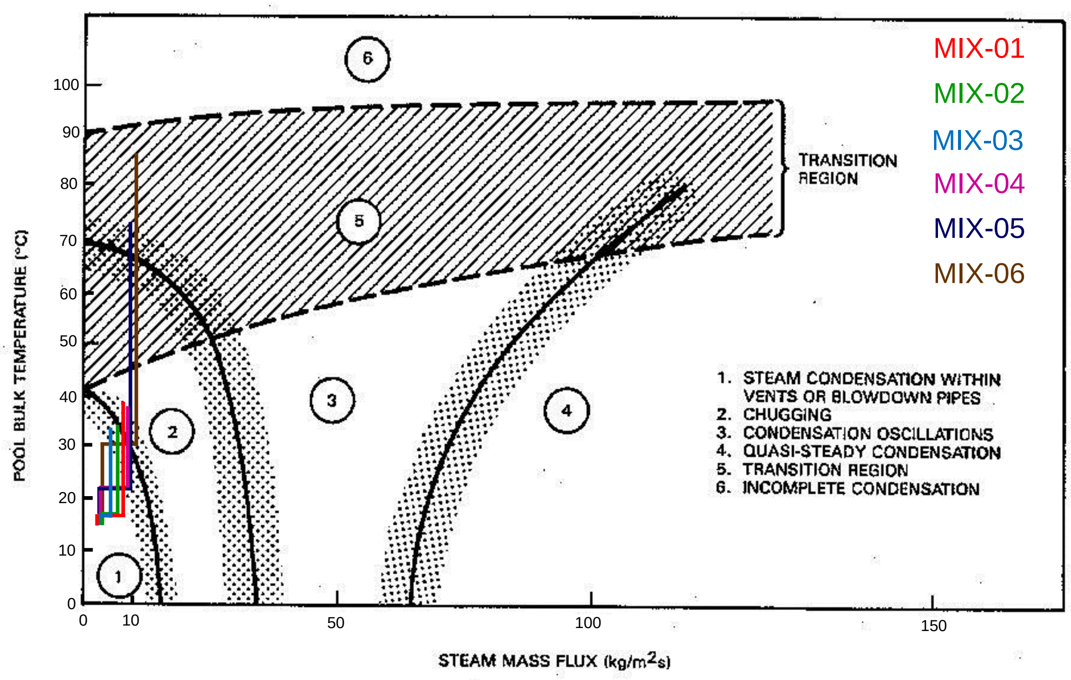

Figure 3. Condensation mode map for pure steam discharge [17].

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 WET WELL GAS VOLUME

The gas space of the wet well 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 dry well 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 and T2208).

Figure 4 shows the pressure build-up of the test vessel during the MIX-05 experiment and Figure 5 the corresponding temperature behavior of the wet well 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 77 °C (from the initial value of 23 to 100 °C), see Figure 5 and Table 3. The largest temperature difference between the wet well top and the elevation above the water surface (T2204–T2208) was 47 °C (at ~5 500 s). During the mixing phase the temperature difference started to decrease and was no more than 30 °C when the test was terminated.

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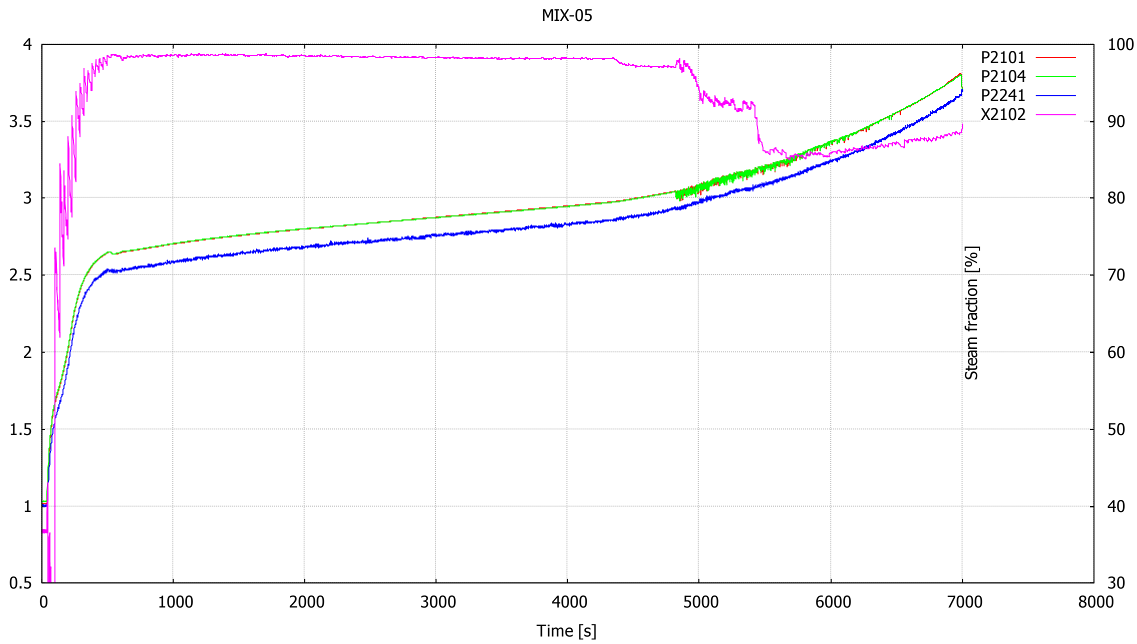

Figure 4. Pressure build-up in the test vessel in MIX-05.

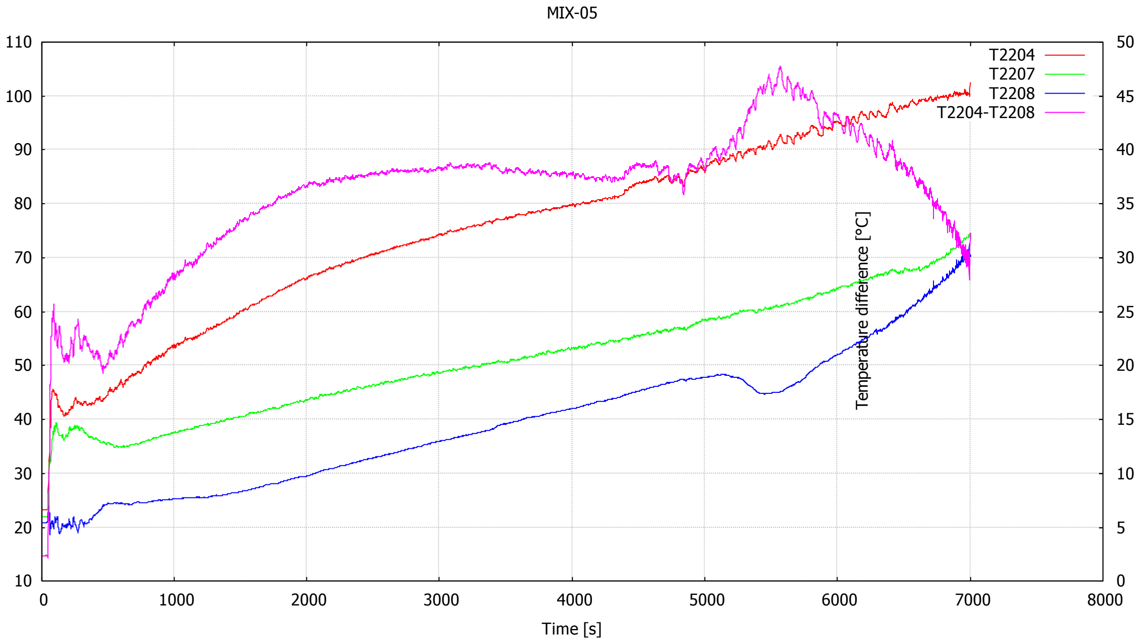

Figure 5. Thermal stratification in the wet well gas space in MIX-05.

Table 3. Observations in the wet well gas space during the MIX experiments.

Exp.	Initial gas temperature [°C]	Max. T2204 temperature [°C]	T2204 increase [°C]	Max. temperature difference between T2204 and T2208 [°C]
MIX-01	22–26	77	51	25
MIX-02	21–28	75	47	26
MIX-03	22–29	75	46	25
MIX-04	22–24	80	56	27
MIX-05	21–23	100	77	47
MIX-06	22–24	90	66	39

4.2 THERMAL STRATIFICATION AND MIXING IN WET WELL POOL

The MIX experiments consisted of three parts; a heat up period, a thermal stratification period and a mixing period. First, the steam flow rate was set to 190–240 g/s to heat up the dry well structures to the level of ~130 °C (the bottom ~80 °C) in order to prevent steam condensation in the dry well compartment later during the thermal stratification and mixing periods, Figure 6 and Table 4. The pool bulk temperature rose approximately 2 °C during the heat up period, which lasted for about 500 seconds in every experiment. An additional motive for the heat-up period was to move the original air content of the dry well to the gas space of the wet well.

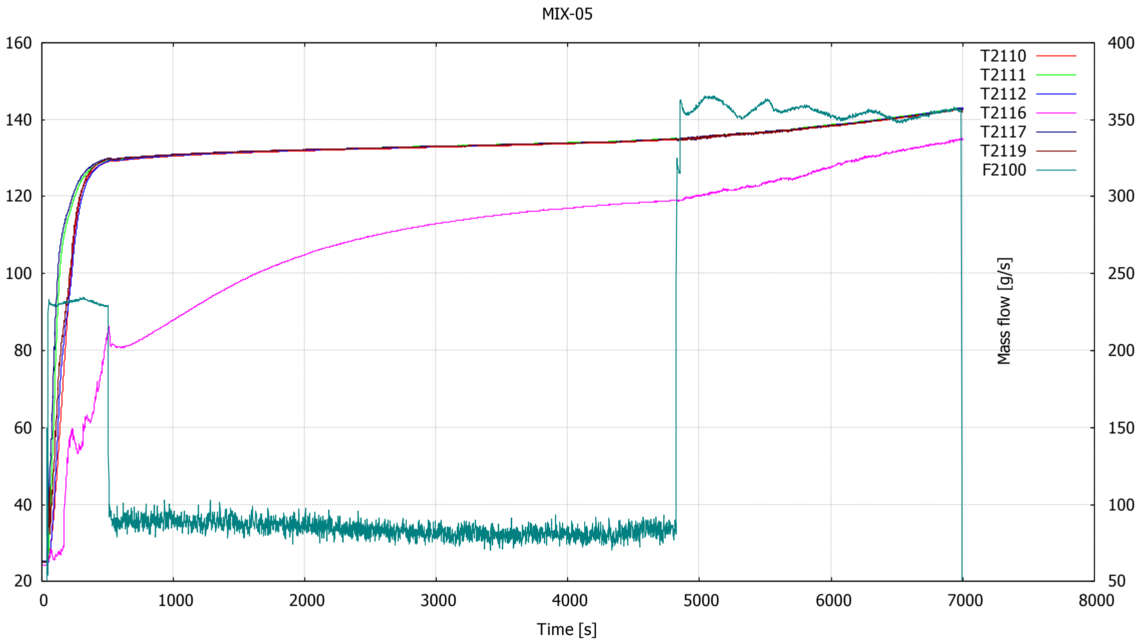

Figure 6. Dry well structural temperatures (T2110–T2119) and steam flow (F2100) in MIX-05.

Table 4. Parameters of the heat-up phase of the MIX experiments.

Exp.	Time period [s]	Steam flow rate [g/s]	Initial dry well structural temperature [°C]	Final dry well structural temperature [bottom/wall, °C]	Pool water temperature increase [°C]
MIX-01	39–553	~210	29	71 / 128	13→15
MIX-02	26–520	~200	35	83 / 129	13→15
MIX-03	33–534	~205	35	88 / 129	13→15
MIX-04	71–580	~190	26	78 / 129	16→18
MIX-05	39–515	~230	25	85 / 130	15→17
MIX-06	40–515	~240	26	90 / 129	15→17

After the dry well structures had been heated up the steam flow rate was rapidly decreased to the level of 85–105 g/s in order to condense steam mainly inside the blowdown pipe or at the pipe outlet and thus to create suitable conditions for thermal stratification to occur. As a result of this reduced inflow of steam temperatures below the blowdown pipe outlet remained constant while they rose towards the pool surface layers indicating strong thermal stratification of the wet well pool water, Figure 7 and Figure 8. The heat-up process was driven by flow of warm condensed water upwards from the pipe outlet as well as by conduction through the pipe wall. The stratification period was continued as long as the temperature difference between the pool bottom (measured by thermocouple T2501) and surface (T2516) had reached the target value given by KTH i.e. 15–30 ºC depending of the test. The largest temperature difference due to the longest stratification period was recorded in MIX-05, Figure 9, Figure 10 and Table 5. In MIX-01, MIX-02 and MIX-03 the development of stratification layers was very similar to each other because of the identical test parameters.

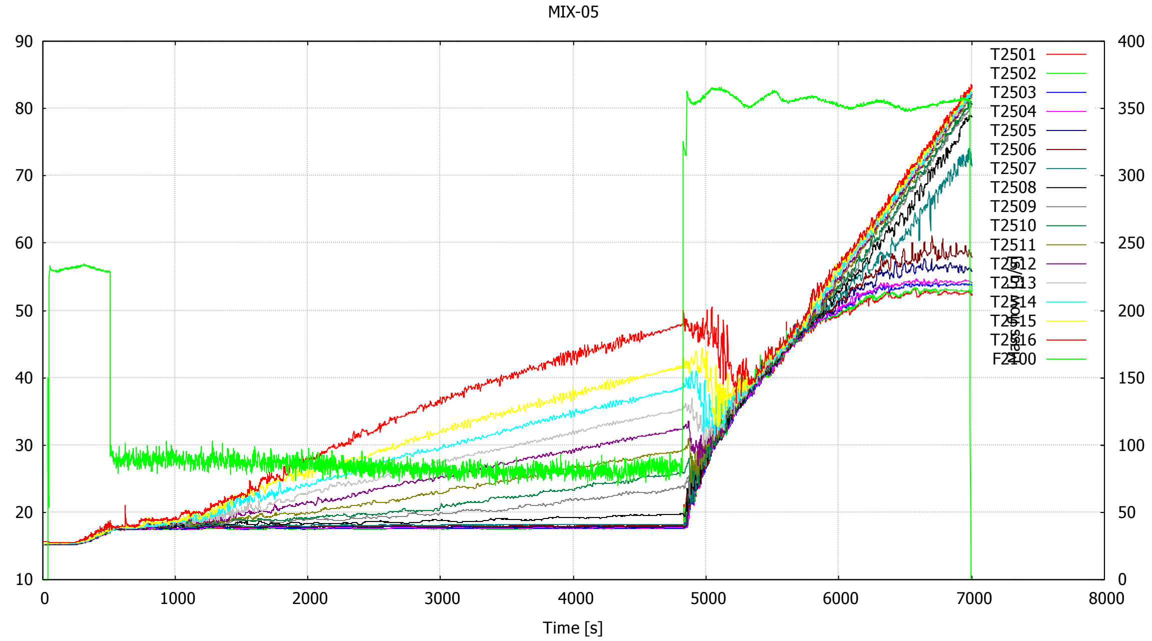

Figure 7. Temperatures in wet well water (T2501–T2516) and steam flow rate (F2100) in MIX-05.

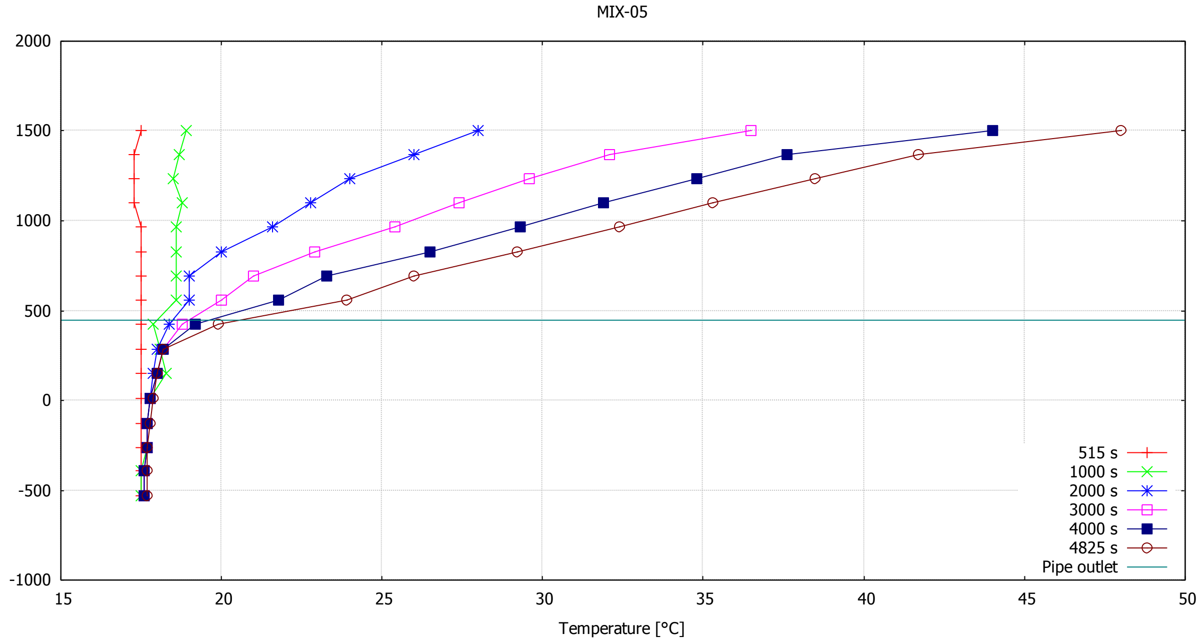

Figure 8. Development of vertical temperature profile of pool water in MIX-05.

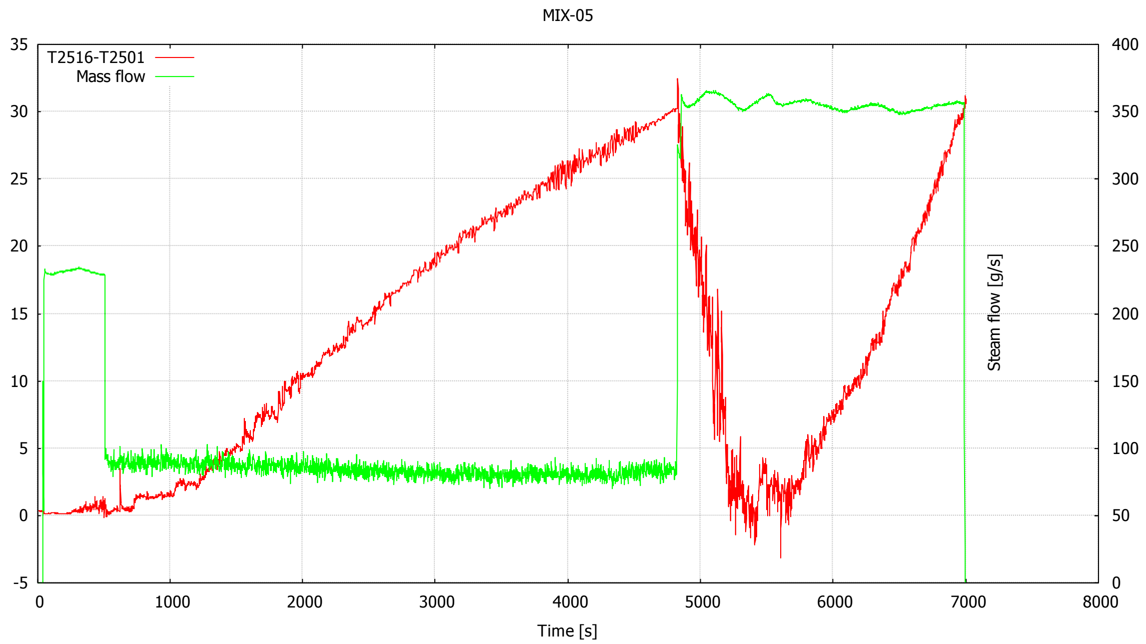

Figure 9. Temperature difference between the bottom and surface of the condensation pool (T2516–T2501) and steam flow (F2100) in MIX-05.

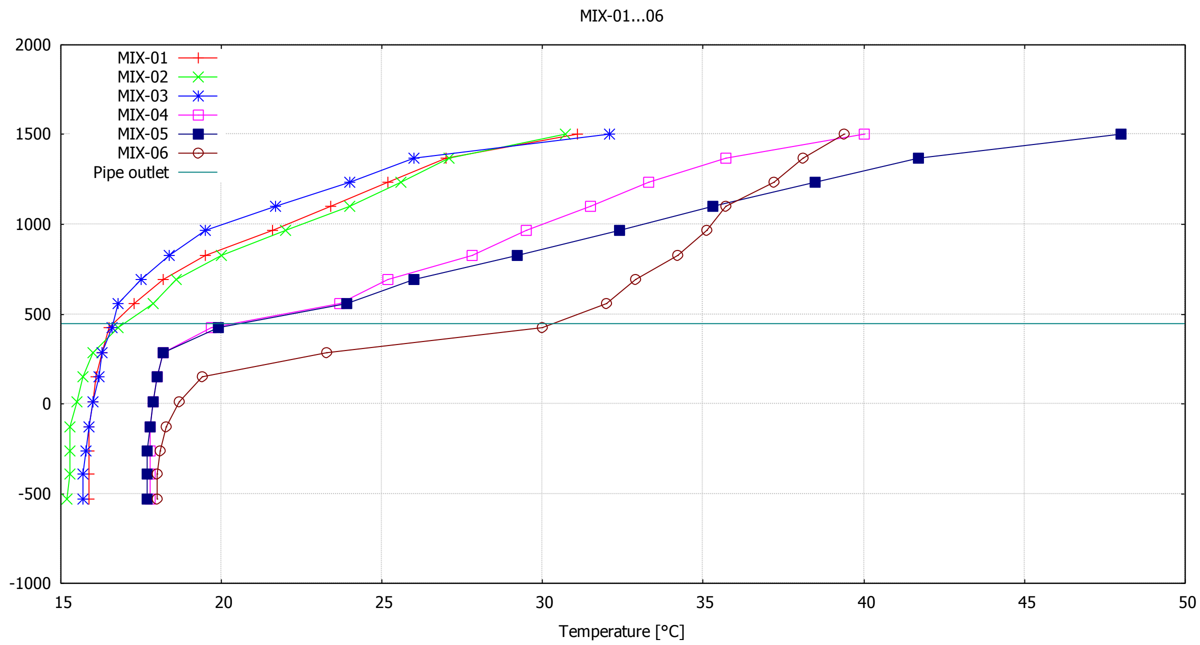

Figure 10. Vertical temperature profile of pool water in the end of the stratification period in MIX-01…06 tests.

Table 5. Stratification related observations of the MIX experiments in 2012.

Exp.	Time period [s]	Initial water temperature [°C]	Steam flow rate [g/s]	Stratification time [s]	Final water temperature of T2501 and T2516 [°C]	Final temperature difference between T2501 and T2516 [°C]
MIX-01	553–2 620	15	~90	2067	16–31	15
MIX-02	520–2 260	15	~100	1740	16–31	15
MIX-03	534–2 290	15	~90	1756	16–32	16
MIX-04	580–3 435	18	~90	2855	18–40	22
MIX-05	515–4 825	17	~85	4310	18–48	30
MIX-06	515–2 645	17	~105	2130	18–40	22

After the desired temperature difference between the pool bottom and surface was attained the steam mass flow rate was rapidly increased up to 300–425 g/s to get the steam/water-interface moving up and down inside the blowdown pipe and further to mix the condensation pool water inventory totally. Depending of the used steam flow rate and initial pool water temperature it took 150–500 s to achieve total mixing of the pool water volume, Table 6.

In MIX-01, MIX-02 and MIX-03 the effect of steam flow rate on the mixing of the pool water inventory was tested. With the lowest steam flow rate (325 g/s in MIX-01) it took 300 s before the whole pool water inventory was mixed (Figure 11 and Figure 12). When the steam flow rate was increased to 375 g/s the mixing time decreased to 250 s. With the highest steam flow rate (425 g/s in MIX-03) the mixing time was only 150 s, Figure 13. In MIX-01, MIX-02, MIX-03 and MIX-04 the pool water was practically isothermal after mixing and remained so until the end of the experiments.

Table 6. Mixing related observations of the MIX experiments in 2012.

Exp.	Time period [s]	Steam flow rate [g/s]	Mixing time [s]	Isothermal temperature [°C]	Re-stratification [Yes/No]
MIX-01	2 620–3 500	~325	300	27→39	No
MIX-02	2 260–2 900	~375	250	26→35	No
MIX-03	2 290–2 800	~425	150	23→34	No
MIX-04	3 435–4 050	~300	450	35→37	No
MIX-05	4 825–6 990	~350	500	38→49	Yes
MIX-06	2 645–4 580	~425	300	38→51	Yes

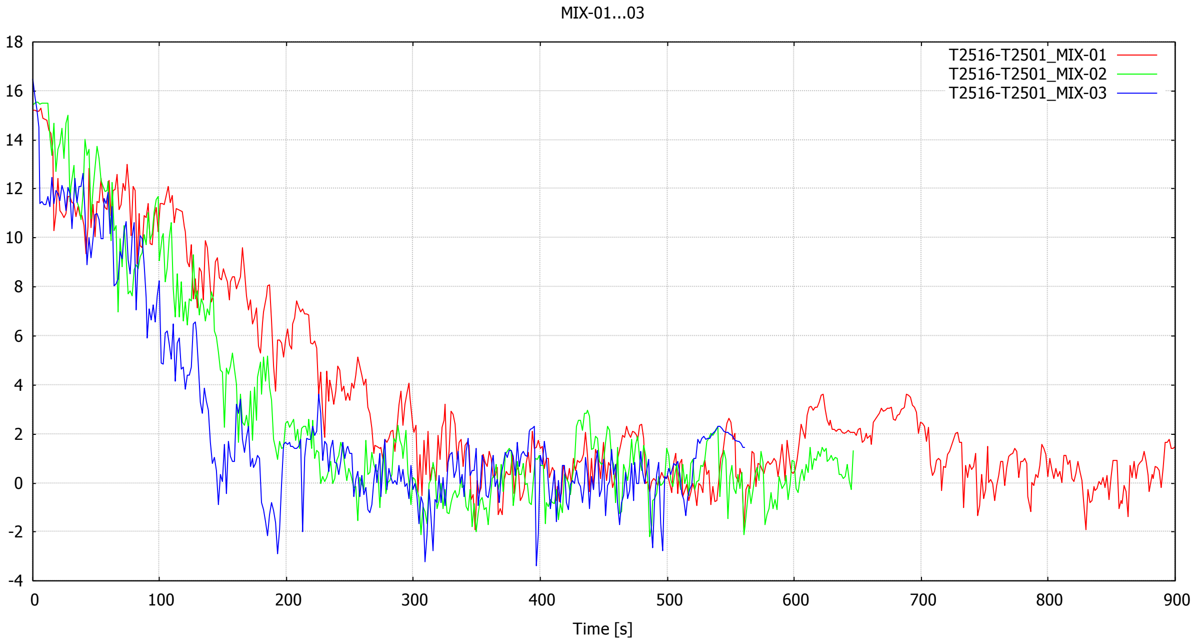

Figure 11. Temperature difference between the bottom and surface of the condensation pool (T2516–T2501) in MIX-01…03. 0 s is the moment when the steam flow rate was increased to mix the pool water inventory.

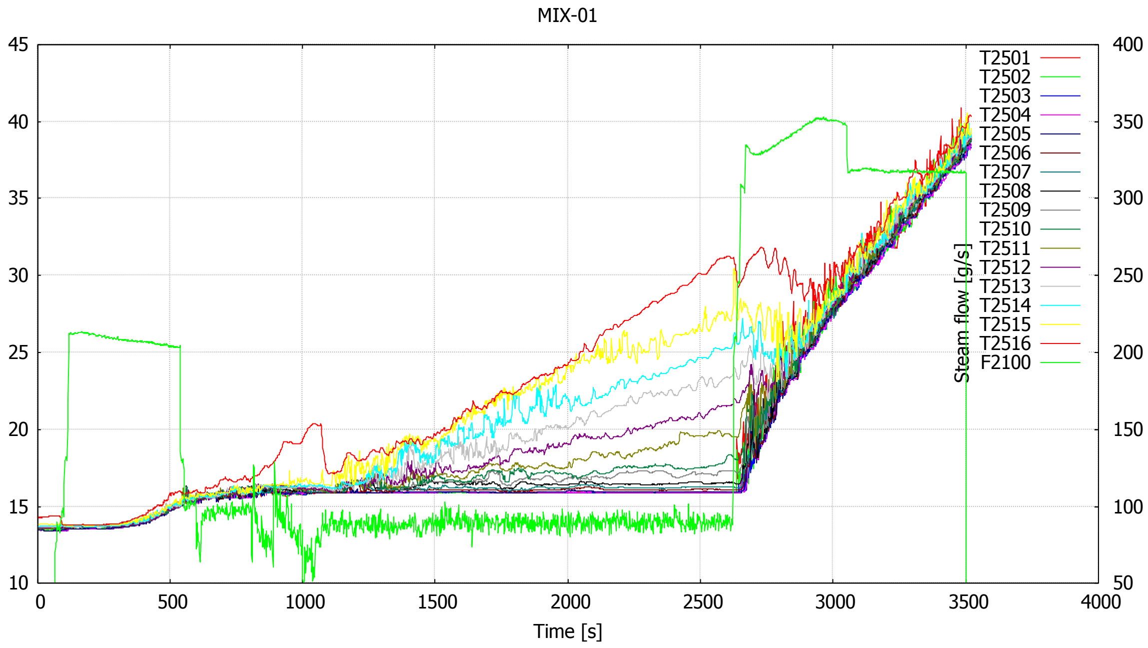

Figure 12. Temperatures in wet well water and steam flow in MIX-01.

In MIX-05 and MIX-06, the steam blowdown was continued longer on the wish of the EMS and EHS model developers. When the pool water bulk temperature reached ~50 °C the water inventory began to stratify again in spite of the large steam discharge into the pool, Figure 7 and Figure 14. This restratification had been predicted in the pre-calculations with GOTHIC code by the personnel of KTH and was thus verified in the experiments.

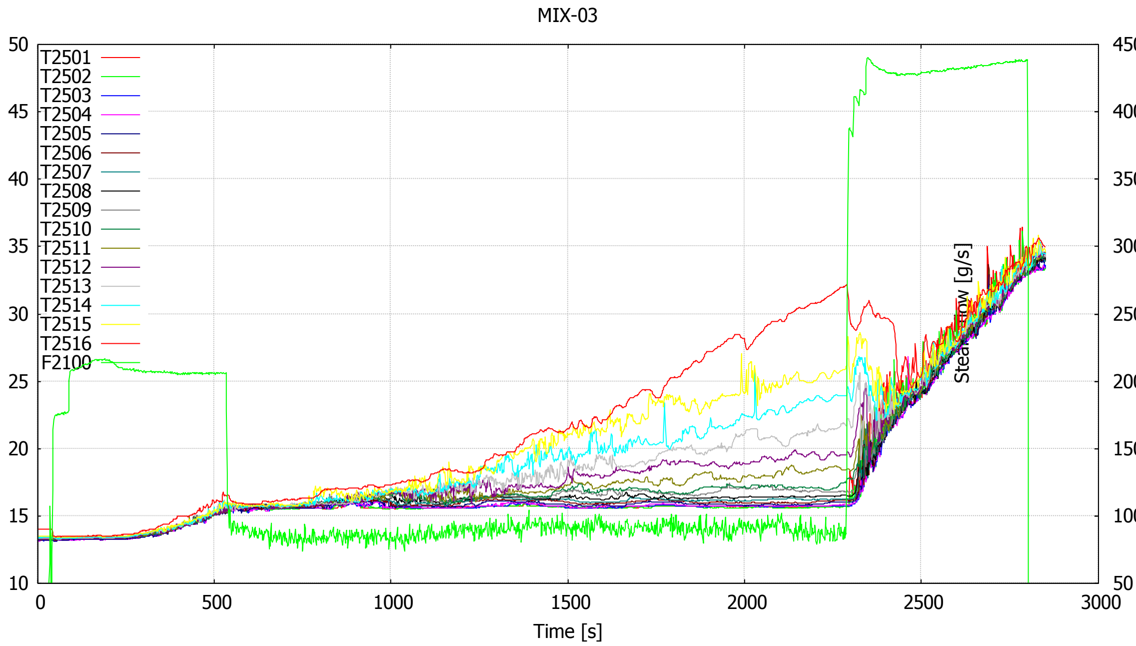

Figure 13. Temperatures in wet well water and steam flow in MIX-03.

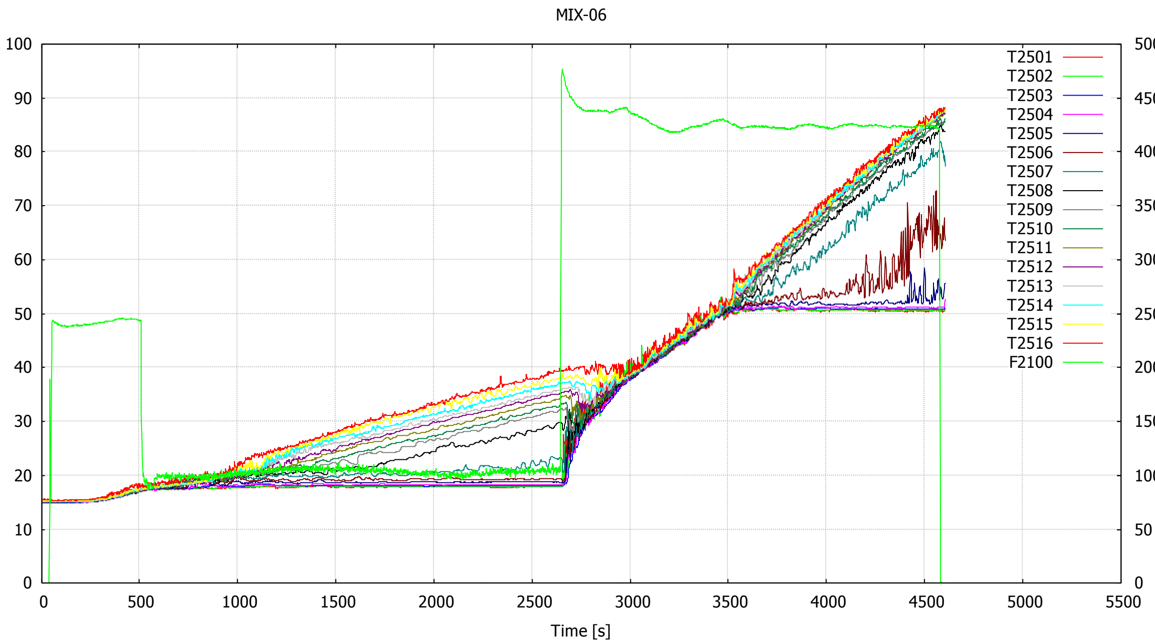

Figure 14. Temperatures in wet well water and steam flow in MIX-06.

4.3 OSCILLATION OF STEAM/WATER INTERFACE IN BLOWDOWN PIPE

Before the MIX test series new thermocouples (TC01–TC15) 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 a one meter section upwards from the pipe outlet, see Appendix 1. The distance between two thermocouples ranged from 34 to 111 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. Up and down movement of the interface was even registered few times in every test by the thermocouple TC15 which was located 999 mm above the blowdown pipe outlet.

Table 7 lists some oscillation related observations from the MIX experiments. The presented 10 seconds time interval was chosen so that it begins 30 s after the mixing phase was initiated in every single test. The oscillation amplitude was determined from the readings of thermocouples TC01–TC15. Because thermocouples TC13 and TC14 were not in use in MIX-01…04, the average amplitudes can be larger in those tests than presented in Table 7. During the tests the steam/water-interface oscillated inside the blowdown pipe with amplitude of 29–999 mm and frequency of 0.6–1.82 Hz.

Table 7. Oscillation related observations in MIX-01…06.

Exp.	Time period [s]	Amplitude [mm]	Average amplitude [mm]	Frequency [Hz]	Average frequency [Hz]
MIX-01	2650.36–2659.96	29–668	318	0.80–1.56	0.99
MIX-02	2290.84–2299.90	268–999	533	0.77–1.06	0.90
MIX-03	2320.41–2329.90	100–668	493	0.60–1.23	0.90
MIX-04	3466.09–3474.66	153–668	337	0.75–1.43	0.98
MIX-05	4855.23–4864.29	208–888	538	0.75–1.04	0.89
MIX-06	2675.00–2684.35	153–888	443	0.67–1.82	1.04

Table 8 and Figure 15 show oscillation related observations and Figure 16 the measured temperatures inside the blowdown pipe in MIX-05. The steam/water-interface began to oscillate intensely up and down after the steam flow rate was increased to ~350 g/s at 4 825 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 18. The pool water began to stratify again after ~5 800 s, Figure 7. The average amplitude of oscillations had then decreased below 150 mm, Figure 19. In the period of 4 825–6 010 s the average amplitude and frequency were 265 mm and 1.1 Hz, correspondingly.

Table 8. Oscillation related observations in MIX-05.

Time period [s]	Amplitude [mm]	Average amplitude [mm]	Frequency [Hz]	Average frequency [Hz]
4825.40–4835.00	100–777	416	0.62–1.32	0.99
4855.23–4864.29	208–888	538	0.75–1.04	0.89
4901.00–4910.30	153–888	457	0.80–1.12	0.98
5001.25–5010.95	100–777	327	0.55–2.04	1.09
5101.14–5110.20	29–492	169	0.72–2.27	1.22
5200.63–5210.60	153–777	425	0.80–1.06	0.92
5300.00–5310.05	100–777	291	0.69–2.00	1.11
5400.81–5410.30	100–668	325	0.75–2.22	1.14
5500.00–5510.00	63–492	249	0.65–1.82	1.10
5600.21–5610.04	29–434	159	0.68–2.22	1.33
5700.00–5710.00	29–492	166	0.61–1.92	1.24
5800.54–5809.89	29–326	148	0.22–1.59	1.15
5900.55–5909.90	29–268	97	0.64–2.27	1.30
6000.55–6009.85	63–208	106	0.91–1.64	1.34

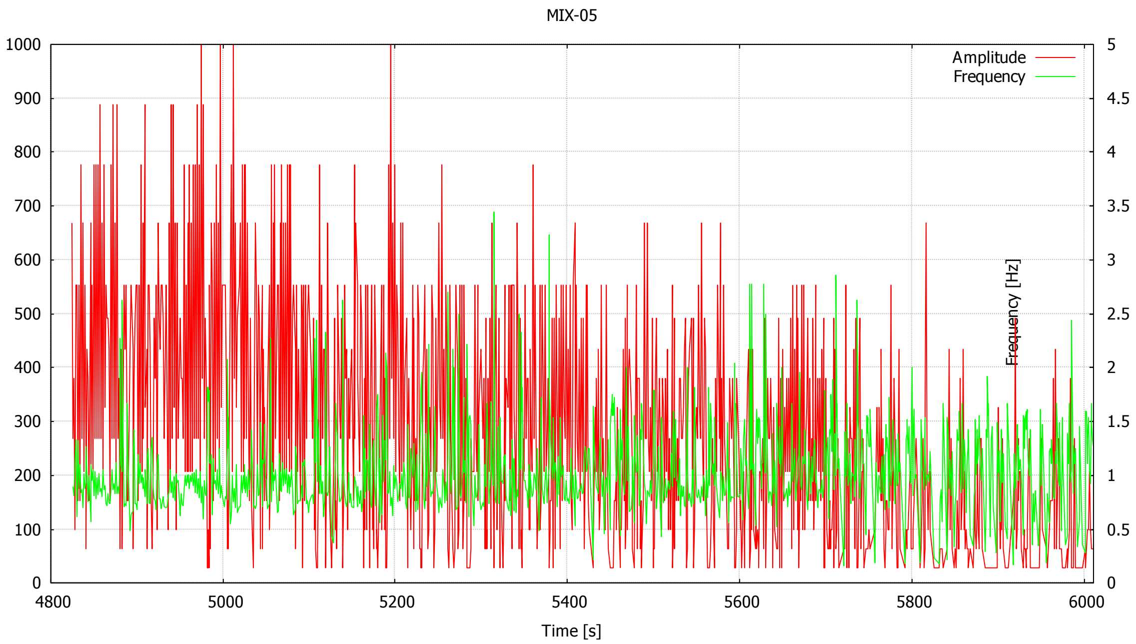

Figure 15. Amplitude and frequency of the oscillation of steam/water-interface inside the blowdown pipe in MIX-05 between 4 825…6 010 s.

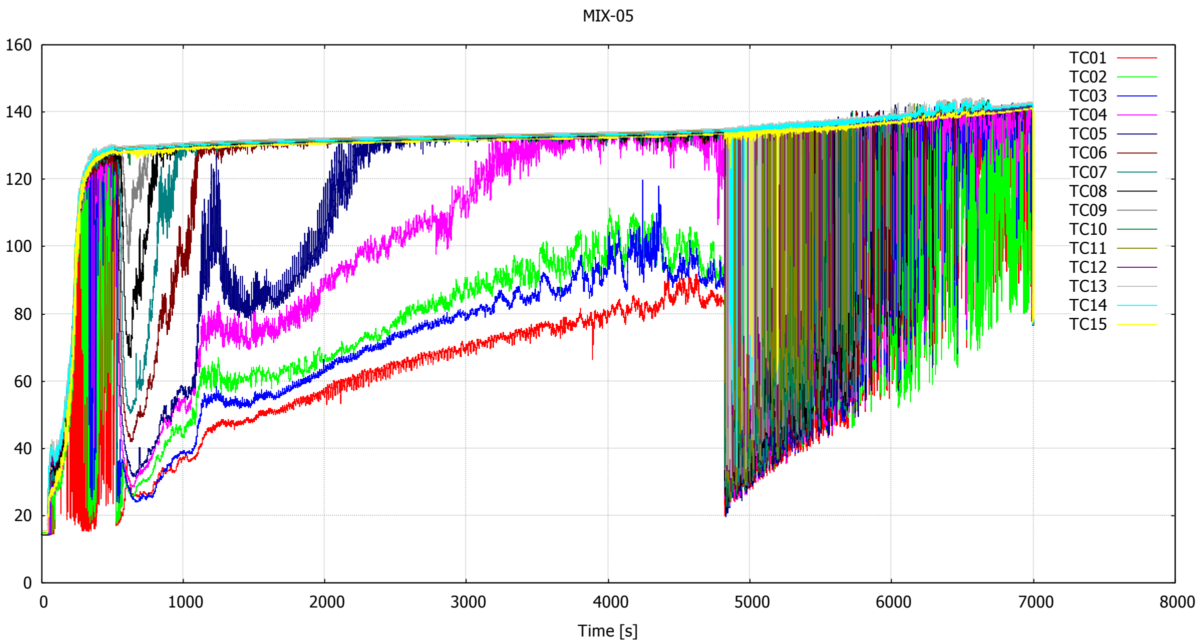

Figure 16. Temperatures inside the blowdown pipe in MIX-05.

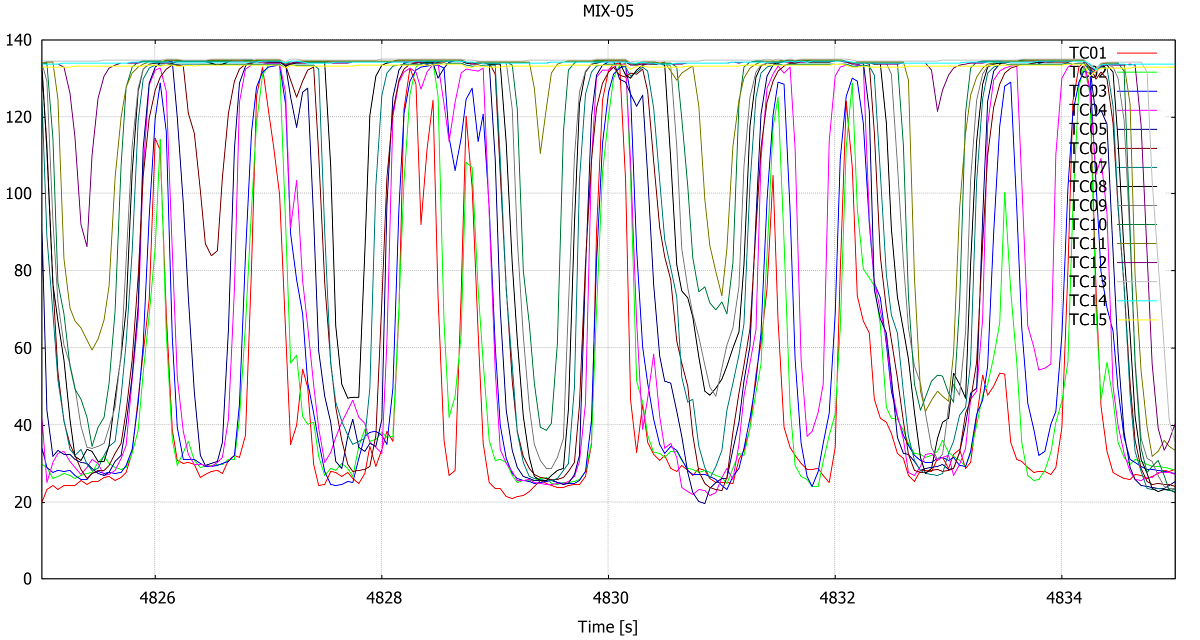

Figure 17. Temperatures inside the blowdown pipe in MIX-05 between 4 825…4 835 s.

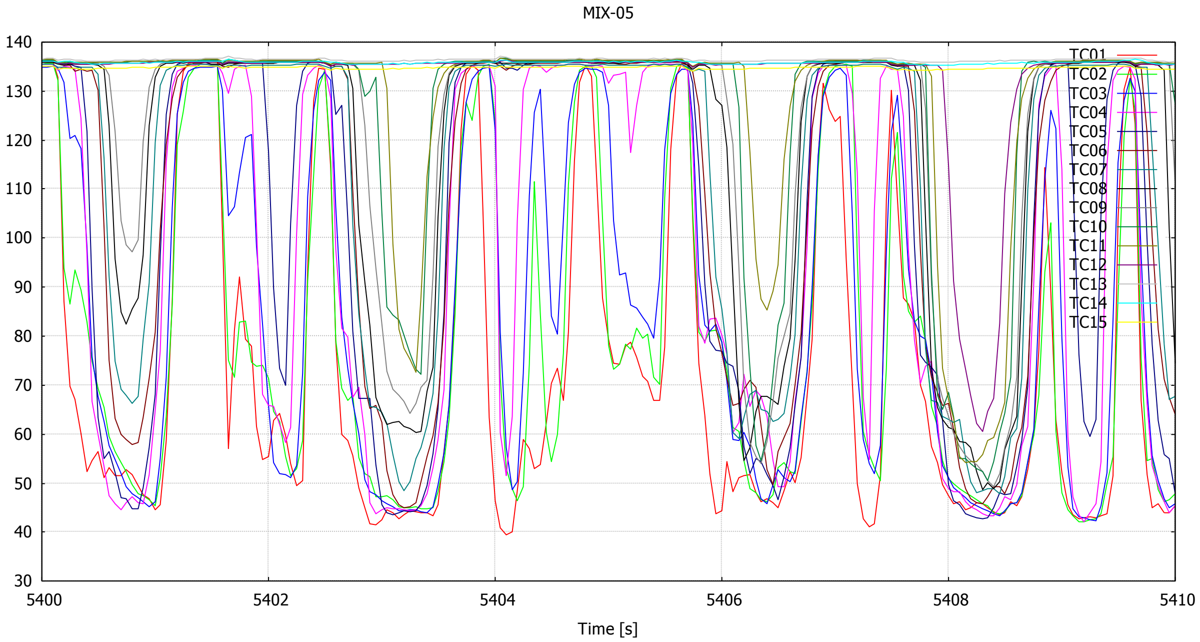

Figure 18. Temperatures inside the blowdown pipe in MIX-05 between 5 400…5 410 s.

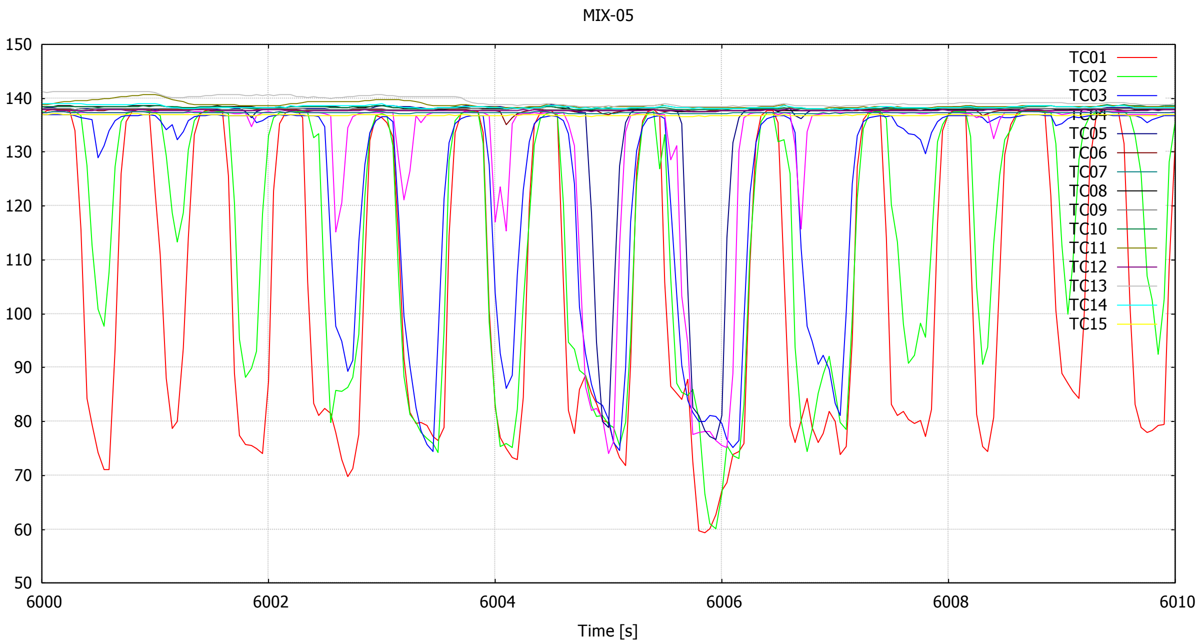

Figure 19. Temperatures inside the blowdown pipe in MIX-05 between 6 000…6 010 s.

5 SUMMARY AND CONCLUSIONS

This report summarizes the results of the thermal stratification and mixing experiments (MIX test series) in 2012 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, dry well and wet well. 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 experiments was to obtain verification data for the development of Effective Momentum Source (EMS) and Effective Heat Source (EHS) models to be implemented in GOTHIC code by KTH.

Altogether six experiments were carried out according to a test plan written by KTH. The experiments consisted of a small steam flow rate stratification period and of a higher flow rate mixing period. To prevent excessive steam condensation in the dry well during the stratification and mixing periods the dry well structures were heated up before the stratification period was initiated. The initial water bulk temperature in the condensation pool was 13–16 °C.

During the low steam flow rate (85–105 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 wet well pool water. In the end of the stratification period the temperature difference between the pool bottom and surface was 15–30 ºC depending on the test in question.

During the mixing period the steam flow rate was increased rapidly to 300–425 g/s to mix the pool water inventory. Total mixing of the pool was obtained in every experiment. Depending on the used steam flow rate and initial pool water temperature it took 150–500 s to achieve total mixing. If the test was continued long enough the water pool began to stratify again after the water bulk temperature had reached ~50 °C despite of steam mass flux belonging to the chugging region of the condensation mode map. During the mixing period the steam/water-interface oscillated inside the blowdown pipe with amplitude of 29–999 mm and with an average frequency of ~1 Hz.

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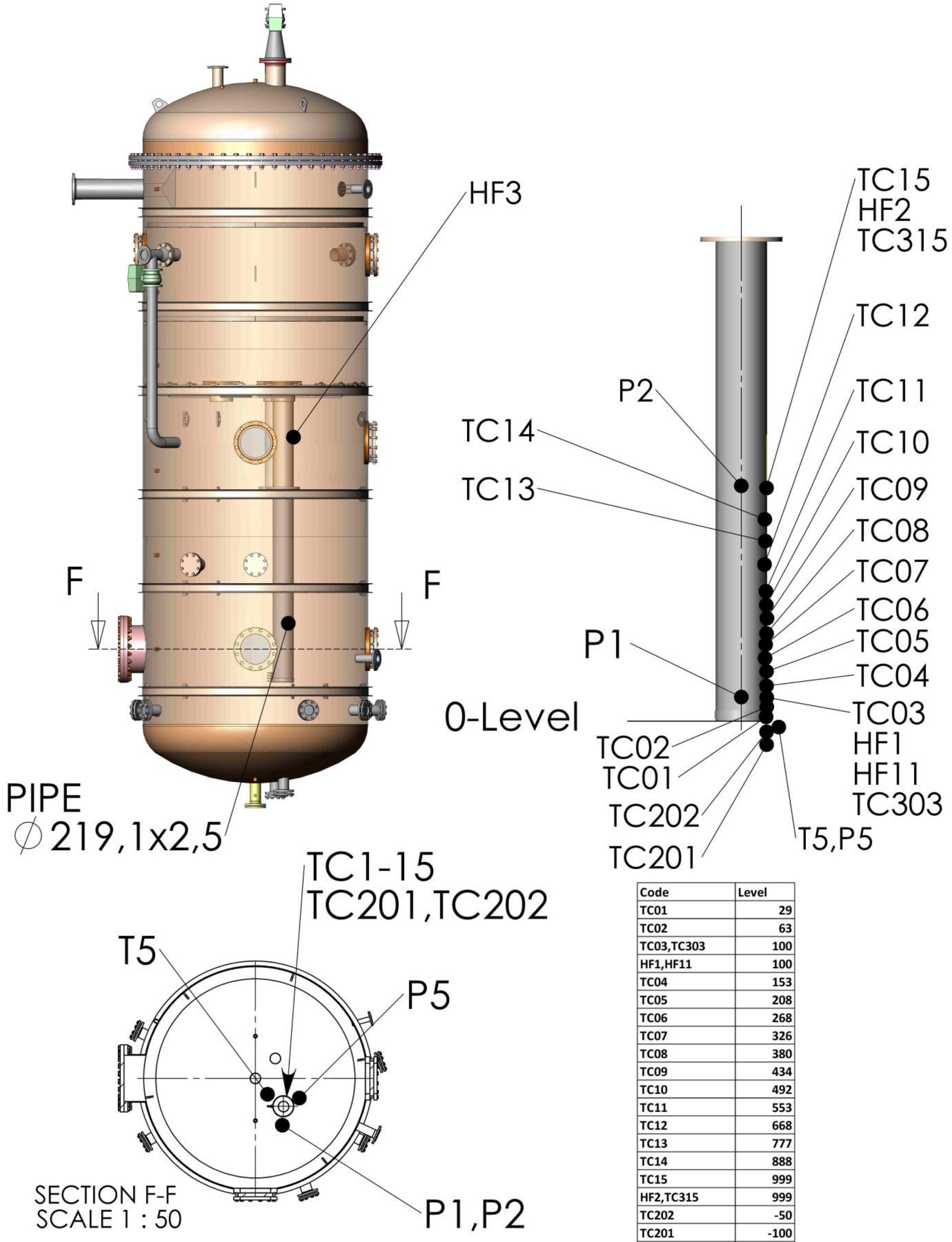
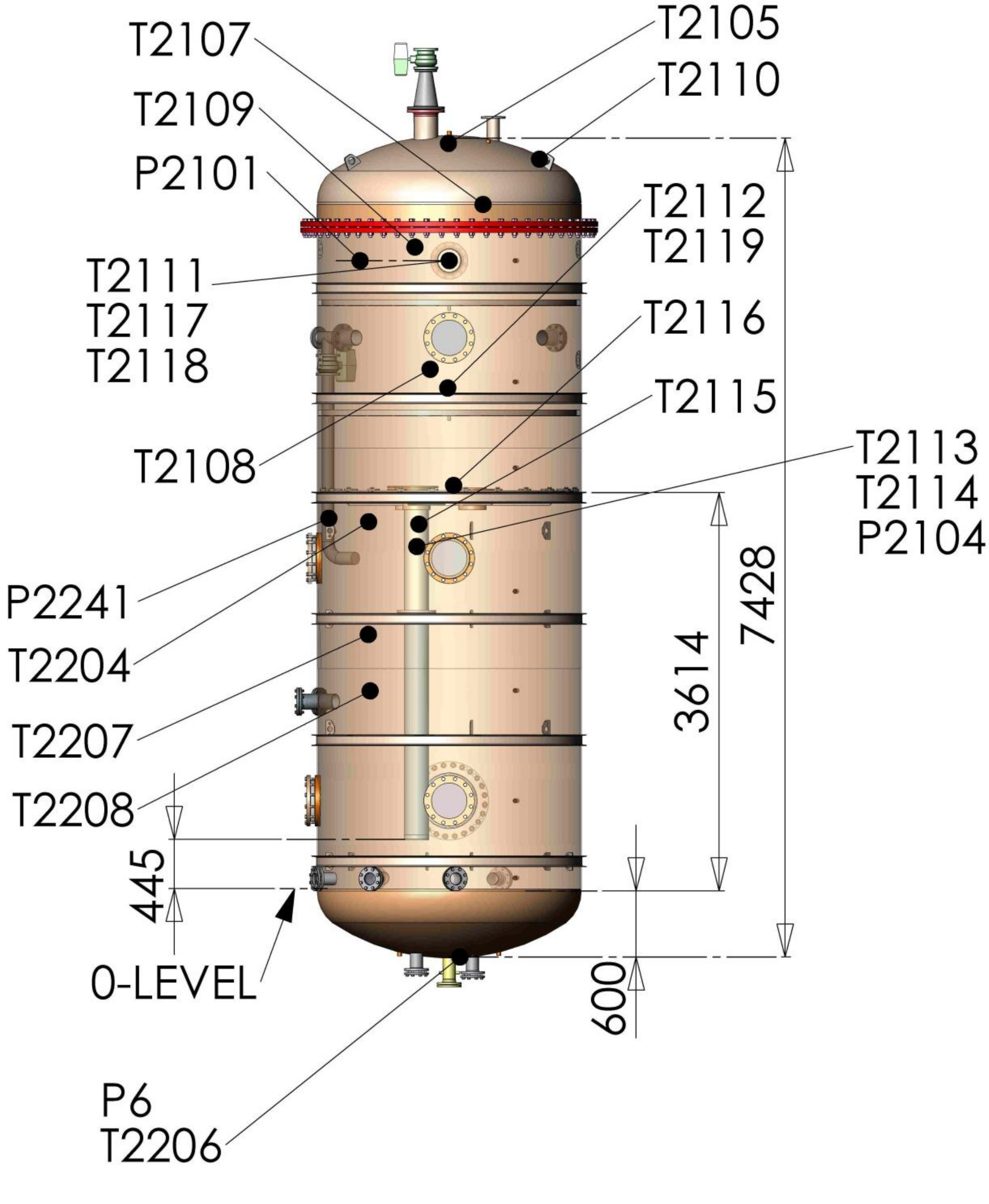
APPENDIX 1: PPOOLEX INSTRUMENTATION

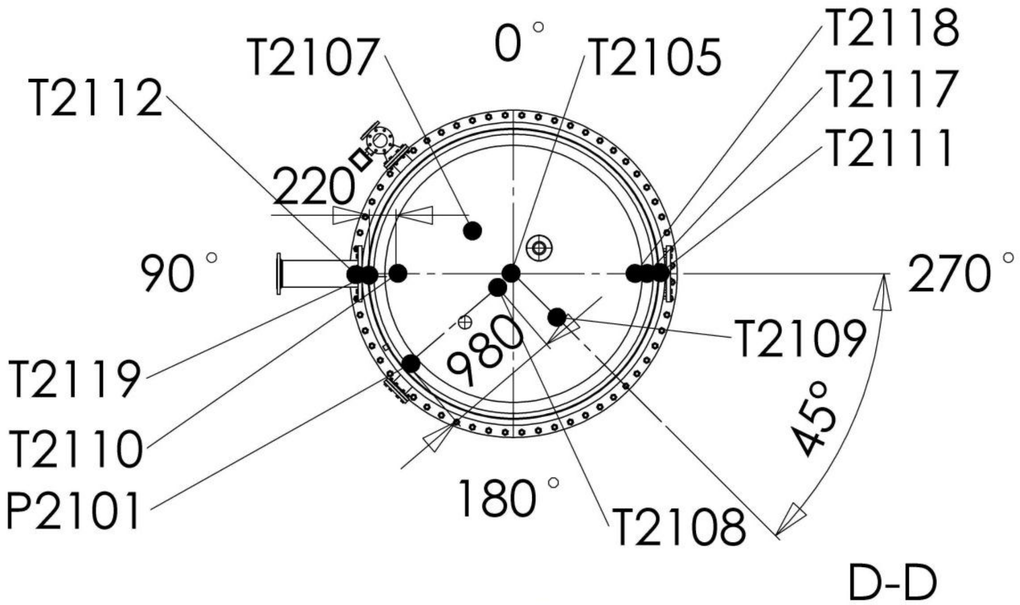


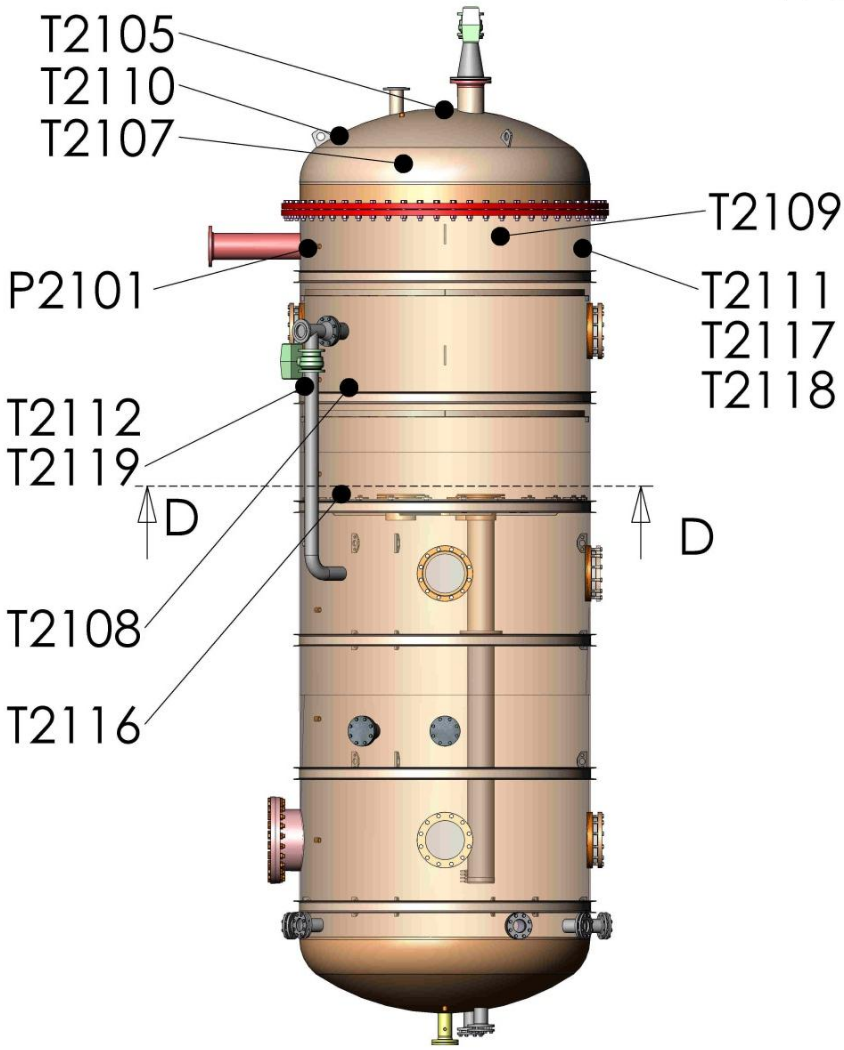
Code	Level
TC01	29
TC02	63
TC03,TC303	100
HF1,HF11	100
TC04	153
TC05	208
TC06	268
TC07	326
TC08	380
TC09	434
TC10	492
TC11	553
TC12	668
TC13	777
TC14	888
TC15	999
HF2,TC315	999
TC202	-50
TC201	-100
HF3	2926

Blowdown pipe measurements in the MIX test series.

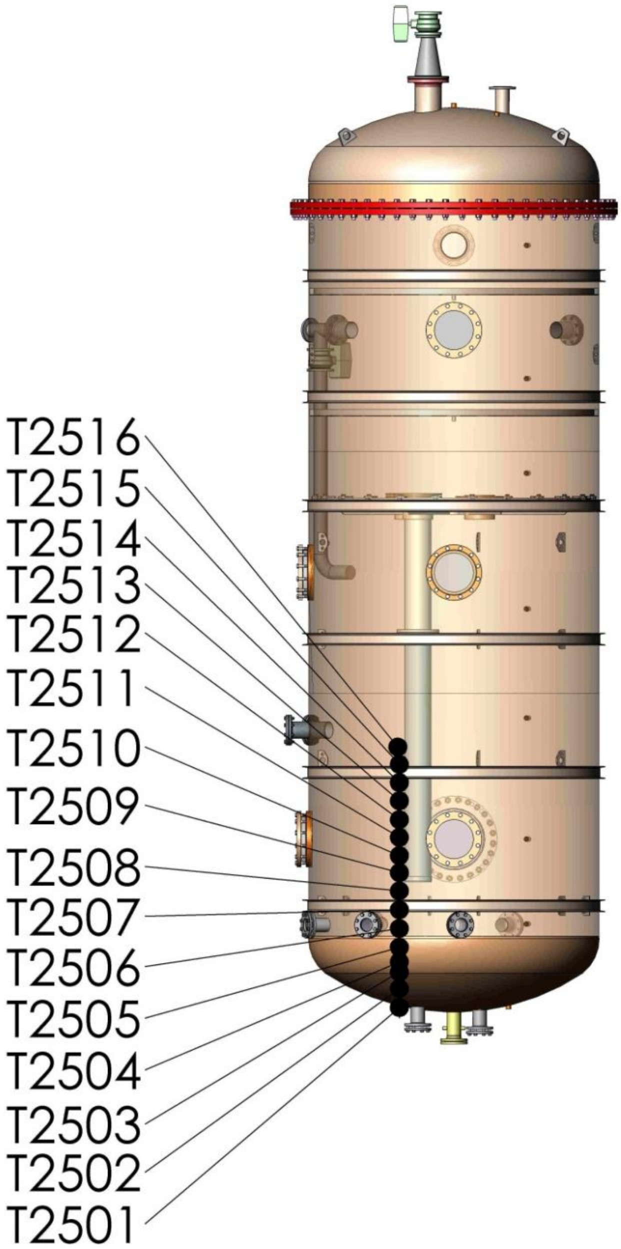


Test vessel measurements.

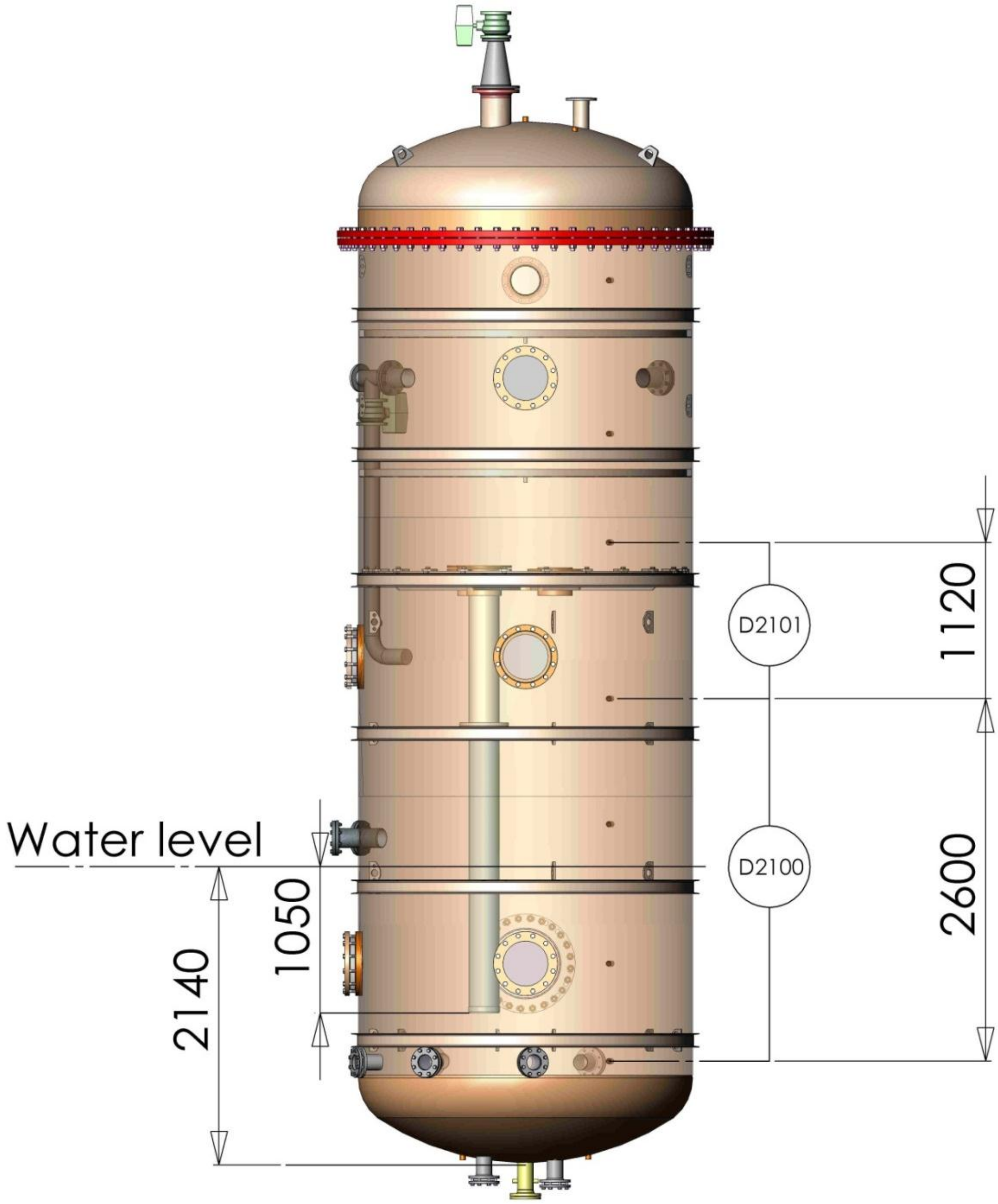




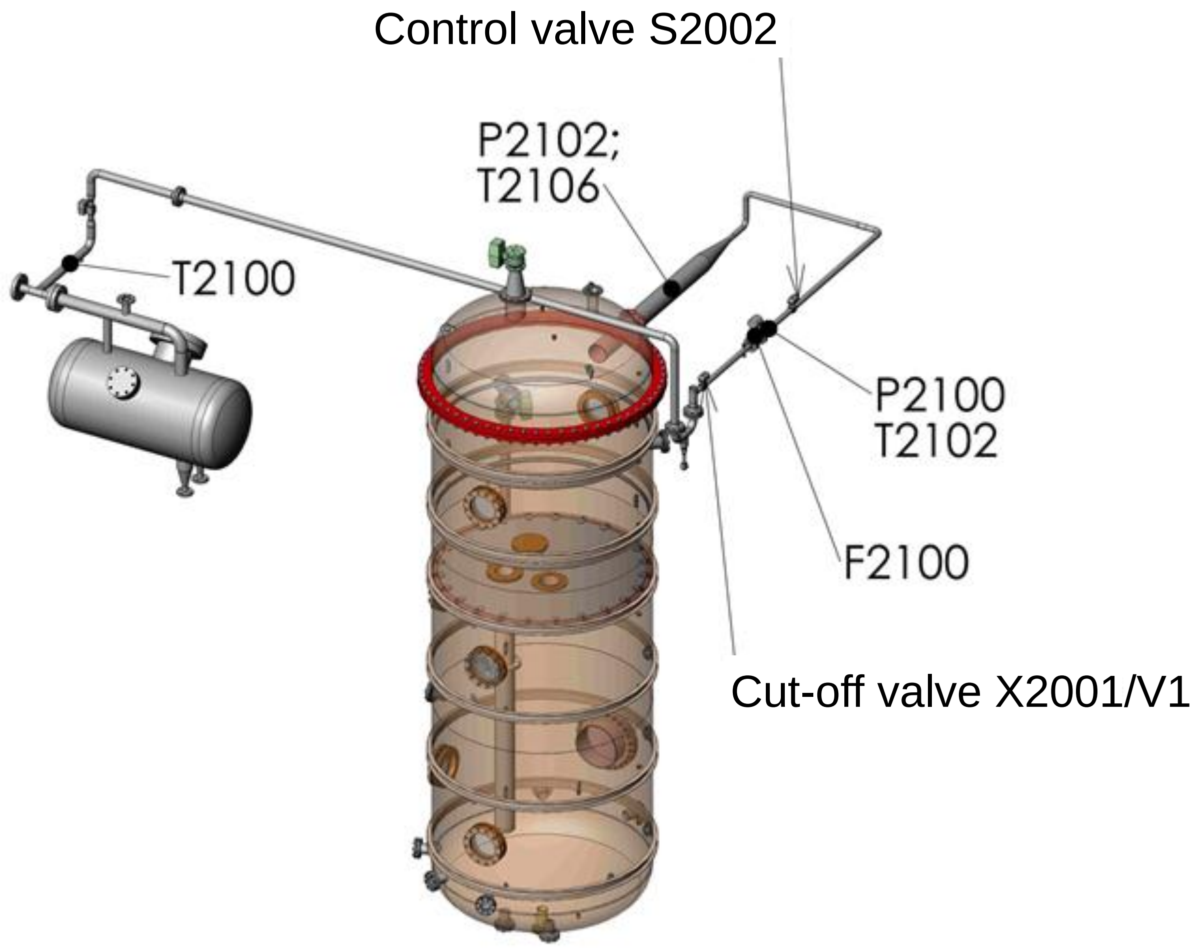
Dry well measurements.



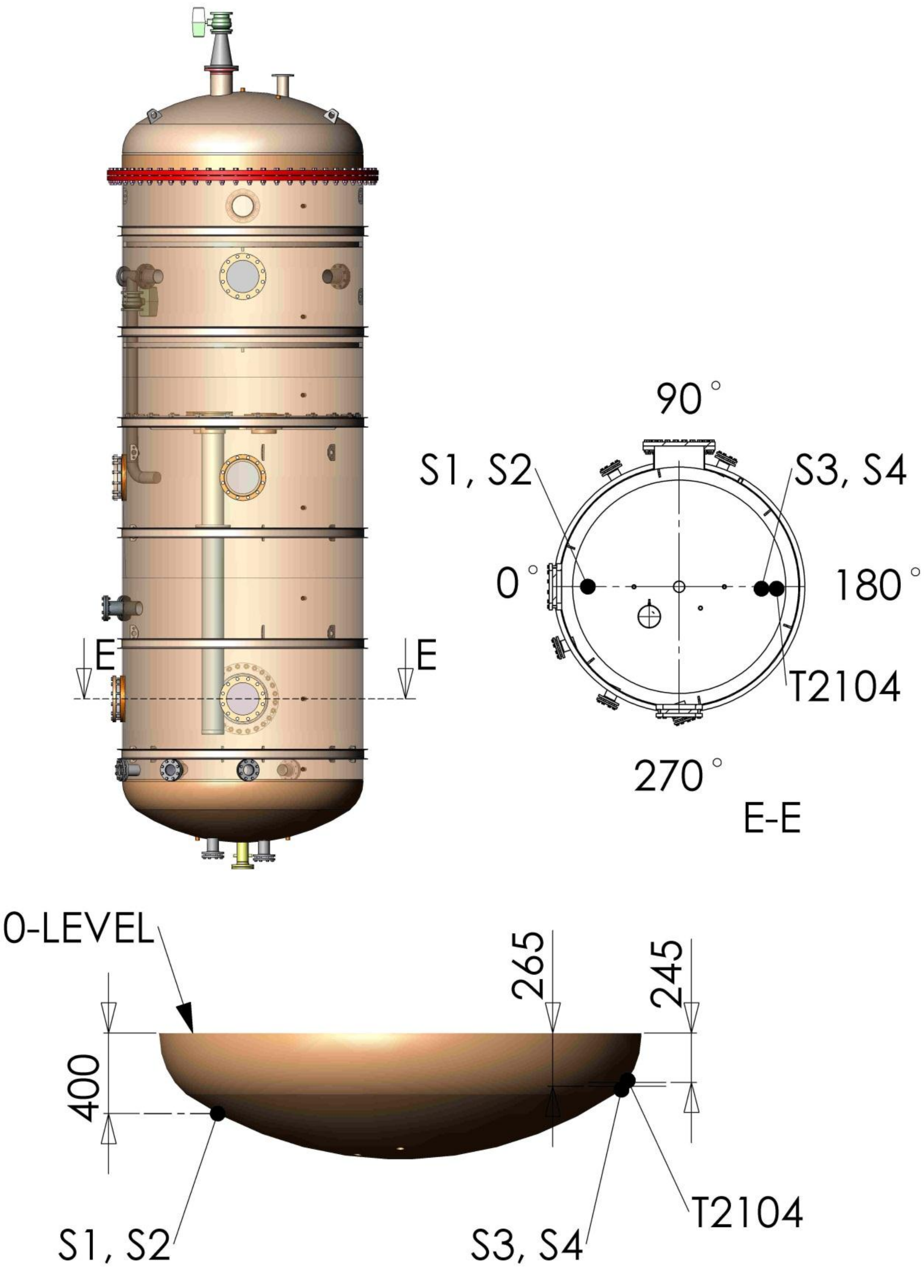
Temperature measurements in the wet well pool for the detection of thermal stratification.



Pressure difference measurements. Nominal water level is 2.14 m.



Measurements in the steam line.



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

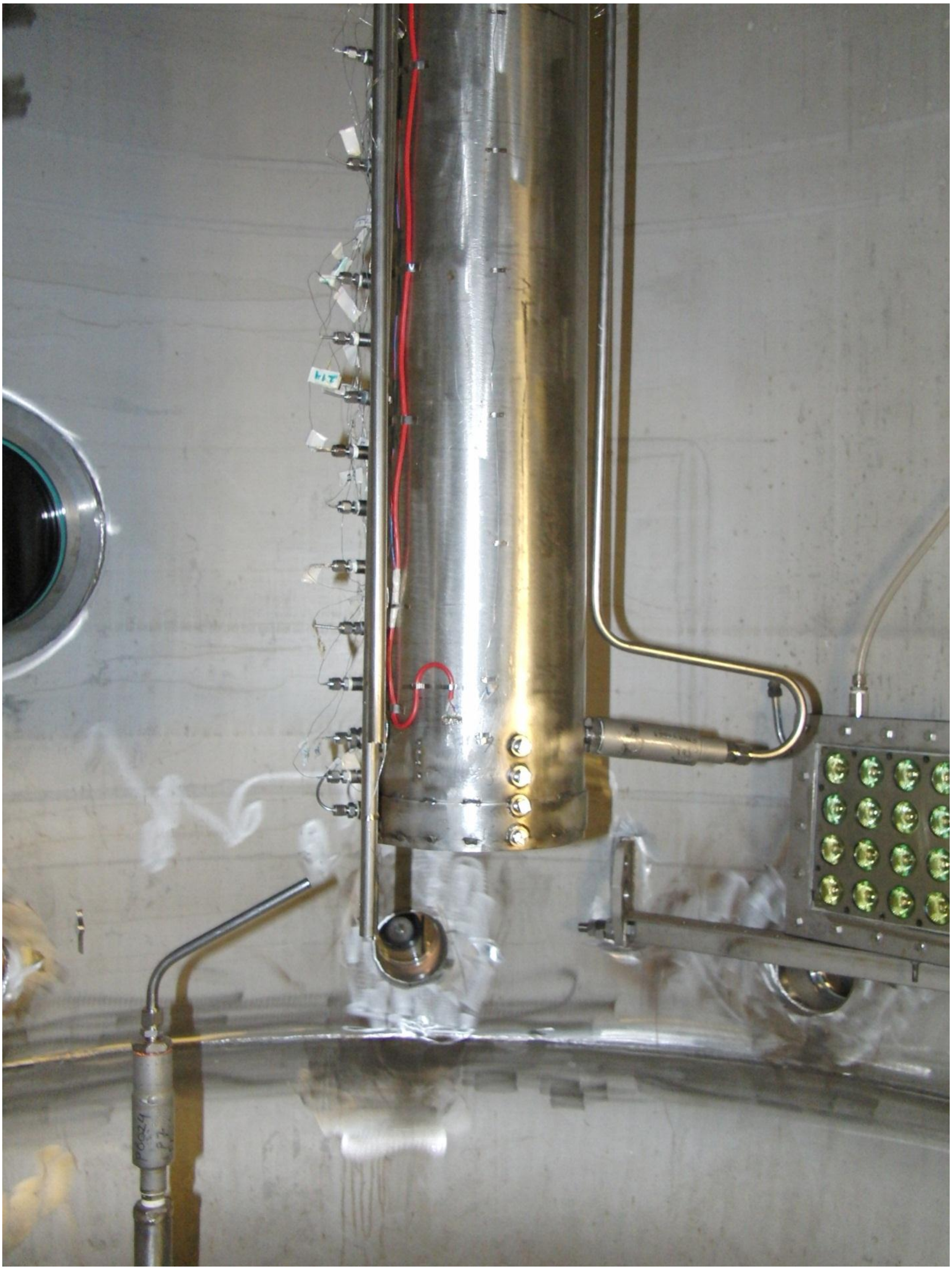
Measurement	Code	Elevation	Location	Error estimation	Measurement software
Camera trigger	C1	-	Wet well	Not defined	LabView
Pressure difference	D2100	100–2700	Wet well	±0.06 m	FieldPoint
Pressure difference	D2101	2700–3820	Across the floor	±0.09 bar	FieldPoint
Heat flux	HF1	545	Blowdown pipe	Not defined	LabView
Heat flux	HF2	1444	Blowdown pipe	Not defined	LabView
Heat flux	HF3	3400	Blowdown pipe	Not defined	LabView
Heat flux	HF11	545	Blowdown pipe	Not defined	LabView
Flow rate	F2100	-	Steam line	±4.9 l/s	FieldPoint
Pressure	P1	545	Blowdown pipe	±0.7 bar	LabView
Pressure	P2	1445	Blowdown pipe	±0.7 bar	LabView
Pressure	P5	395	Blowdown pipe outlet	±0.7 bar	LabView
Pressure	P6	-615	Wet well bottom	±0.5 bar	LabView
Pressure	P2100	-	Steam line	±0.5 bar	FieldPoint
Pressure	P2101	5700	Dry well	±0.06 bar	FieldPoint
Pressure	P2102	-	Inlet plenum	±0.06 bar	FieldPoint
Pressure	P2104	3400	Blowdown pipe	±0.06 bar	FieldPoint
Pressure	P2241	3600	Wet well gas space	±0.1 bar	FieldPoint
Control valve position	S0035/ S2002	-	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	395	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	-	Steam line	±3.5 °C	FieldPoint
Temperature	T2104	-245	Wet well outer wall	±1.8 °C	FieldPoint
Temperature	T2105	6780	Dry well top	±1.8 °C	FieldPoint
Temperature	T2106	-	Inlet plenum	±1.8 °C	FieldPoint
Temperature	T2107	6085	Dry well middle	±1.8 °C	FieldPoint
Temperature	T2108	4600	Dry well bottom	±1.8 °C	FieldPoint
Temperature	T2109	5790	Dry well lower middle	±1.8 °C	FieldPoint
Temperature	T2110	6550	Dry well outer wall	±1.8 °C	FieldPoint
Temperature	T2111	5700	Dry well outer wall	±1.8 °C	FieldPoint
Temperature	T2112	4600	Dry well outer wall	±1.8 °C	FieldPoint
Temperature	T2113	3400	Blowdown pipe	±1.8 °C	LabView
Temperature	T2114	3400	Blowdown pipe	±1.8 °C	FieldPoint
Temperature	T2115	3550	Blowdown pipe	±1.8 °C	FieldPoint
Temperature	T2116	3600	Dry well floor	±1.8 °C	FieldPoint
Temperature	T2117	5700	Dry well inner wall	±1.8 °C	FieldPoint
Temperature	T2118	5700	Dry well, 10 mm from the wall	±1.8 °C	FieldPoint

Temperature	T2119	4600	Dry well inner wall	±1.8 °C	FieldPoint
Temperature	T2204	3410	Wet well gas space	±1.8 °C	FieldPoint
Temperature	T2206	-615	Wet well bottom	±1.8 °C	FieldPoint
Temperature	T2207	2585	Wet well gas space	±1.8 °C	FieldPoint
Temperature	T2208	1760	Wet well gas space	±1.8 °C	FieldPoint
Temperature	T2501	-530	Wet well	±1.8 °C	FieldPoint
Temperature	T2502	-390	Wet well	±1.8 °C	FieldPoint
Temperature	T2503	-260	Wet well	±1.8 °C	FieldPoint
Temperature	T2504	-125	Wet well	±1.8 °C	FieldPoint
Temperature	T2505	10	Wet well	±1.8 °C	FieldPoint
Temperature	T2506	150	Wet well	±1.8 °C	FieldPoint
Temperature	T2507	287	Wet well	±1.8 °C	FieldPoint
Temperature	T2508	427	Wet well	±1.8 °C	FieldPoint
Temperature	T2509	560	Wet well	±1.8 °C	FieldPoint
Temperature	T2510	695	Wet well	±1.8 °C	FieldPoint
Temperature	T2511	830	Wet well	±1.8 °C	FieldPoint
Temperature	T2512	965	Wet well	±1.8 °C	FieldPoint
Temperature	T2513	1103	Wet well	±1.8 °C	FieldPoint
Temperature	T2514	1236	Wet well	±1.8 °C	FieldPoint
Temperature	T2515	1369	Wet well	±1.8 °C	FieldPoint
Temperature	T2516	1505	Wet well	±1.8 °C	FieldPoint
Temperature	TC01	474	Blowdown pipe	±1.8 °C	LabView
Temperature	TC02	508	Blowdown pipe	±1.8 °C	LabView
Temperature	TC03	545	Blowdown pipe	±1.8 °C	LabView
Temperature	TC04	598	Blowdown pipe	±1.8 °C	LabView
Temperature	TC05	653	Blowdown pipe	±1.8 °C	LabView
Temperature	TC06	713	Blowdown pipe	±1.8 °C	LabView
Temperature	TC07	771	Blowdown pipe	±1.8 °C	LabView
Temperature	TC08	825	Blowdown pipe	±1.8 °C	LabView
Temperature	TC09	879	Blowdown pipe	±1.8 °C	LabView
Temperature	TC10	937	Blowdown pipe	±1.8 °C	LabView
Temperature	TC11	998	Blowdown pipe	±1.8 °C	LabView
Temperature	TC12	1113	Blowdown pipe	±1.8 °C	LabView
Temperature	TC13	1222	Blowdown pipe	±1.8 °C	LabView
Temperature	TC14	1333	Blowdown pipe	±1.8 °C	LabView
Temperature	TC15	1444	Blowdown pipe	±1.8 °C	LabView
Temperature	TC201	-100	Below blowdown pipe	±1.8 °C	LabView
Temperature	TC202	-50	Below blowdown pipe	±1.8 °C	LabView
Temperature	TC303	545	Blowdown pipe outer surface	±1.8 °C	LabView
Temperature	TC315	1444	Blowdown pipe outer surface	±1.8 °C	LabView
Cut-off valve position	V1	-	Steam line	Not defined	LabView
Cut-off valve position	X2100	-	Steam line	Not defined	FieldPoint
Steam partial pressure	X2102	4600	Dry well	Not defined	FieldPoint

Measurements of the PPOOLEX facility in the MIX test series.

APPENDIX 2: PPOOLEX TEST FACILITY PHOTOGRAPHS

Mineral wool insulated dry well compartment and steam line.



Lower part of the blowdown pipe.

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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 dry well compartment and from there through the vertical DN200 blowdown pipe to the condensation pool filled with sub-cooled water. The main objective of the experiments was to obtain verification data for the development of the Effective Momentum Source (EMS) and Effective Heat Source (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. Altogether six experiments were carried out. The experiments consisted of a small steam flow rate stratification period and of a higher flow rate mixing period. The dry well structures were heated up to approximately 130 °C before the stratification period was initiated. The initial water bulk temperature in the condensation pool was 13-16 °C. During the low steam flow rate (85–105 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 wet well pool water. In the end of the stratification period the temperature difference between the pool bottom and surface was 15–30 ºC depending on the test parameters and the duration of the low flow rate period. In the beginning of the mixing phase the steam flow rate was increased rapidly to 300–425 g/s to mix the pool water totally. Depending on the used steam flow rate and initial pool water temperature it took 150–500 s to achieve total mixing. If the test was continued long enough the water pool began to stratify again after the water bulk temperature had reached ~50 °C despite of steam mass flux belonging to the chugging region of the condensation mode map. During the mixing period the steam/water-interface oscillated inside the blowdown pipe with amplitude of 29–999 mm and with an average frequency of ~1 Hz.

Key words: condensation pool, steam/air blowdown, thermal stratification and mixing