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PPOOLEX EXPERIMENTS ON STRATIFICATION AND MIXING IN THE WET WELL POOL

Jani Laine, Markku Puustinen, Antti Räsänen, Vesa Tanskanen

Nuclear Safety Research Unit
Lappeenranta University of Technology
Finland

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Abstract

This report summarizes the results of the thermal stratification and mixing experiments carried out in 2010 with the scaled down, two compartment PPOOLEX test facility designed and constructed at LUT. Steam was blown into the thermally insulated dry well compartment and from there through the DN200 vertical blowdown pipe to the condensation pool filled with sub-cooled water. The main purpose of the experiment series was to generate verification data for evaluating the capability of GOTHIC and APROS codes to predict stratification and mixing phenomena. Another objective was to test the sound velocity measurement system.

Altogether five experiments were carried out. The experiments consisted of a small steam flow rate stratification period and of a mixing period with continuously or stepwise increasing flow rate. The dry well structures were heated up to the level of approximately 90 °C before the actual experiments. The initial water bulk temperature was 20 °C.

When the steam flow rate was low enough (typically ~100–150 g/s) temperatures below the blowdown pipe outlet remained constant while increasing heat-up occurred towards the pool surface layers indicating strong thermal stratification of the wet well pool water. During the stratification period the highest measured temperature difference between pool bottom and surface was approximately 40 ºC.

During the mixing period total mixing of the pool volume was not achieved in any of the experiments. The bottom layers heated up significantly but never reached the same temperature as the topmost layers. The lowest measured temperature difference between the pool bottom and surface was 7–8 ºC.

According to the test results, it seems that a small void fraction doesn't have an effect on the speed of sound in water and that the acquired sound velocity measurement system cannot be used for the estimation of void fraction in the wet well water pool. However, more tests on this issue have to be executed before a final conclusion can be made.

Key words

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

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NKS Secretariat
NKS-776
P.O. Box 49
DK - 4000 Roskilde, Denmark
Phone +45 4677 4045
Fax +45 4677 4046
www.nks.org
e-mail nks@nks.org

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Jani Laine, Markku Puustinen, Antti Räsänen, Vesa Tanskanen

Lappeenranta University of Technology
Faculty of Technology
LUT Energy
Nuclear Safety Research Unit
P.O. Box 20, FIN-53851 LAPPEENRANTA, FINLAND
Phone +358 5 621 11

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Research organization and address	Customer	
Lappeenranta University of Technology Nuclear Safety Research Unit P.O. Box 20 FIN-53851 LAPPEENRANTA, FINLAND	VYR / SAFIR2010 NKS NORTHNET	
Project manager	**Contact person**	
Markku Puustinen	Eija-Karita Puska (SAFIR) Karoliina Myllymäki (Fortum)	
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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 modeled with computational fluid dynamics (CFD) and structural analysis codes at VTT.

A new research project called Condensation Experiments with PPOOLEX Facility (CONDEX) started in 2007 within the SAFIR2010 - The Finnish Research Programme on Nuclear Power Plant Safety 2007–2010. The CONDEX project focuses on different containment issues and continues further the work done in this area within the FINNUS and SAFIR programs. For the new experiments, a closed test facility modelling the dry well and wet well compartments of BWR containment was designed and constructed. The main objective of the CONDEX project is to increase the understanding of different phenomena inside the containment during a postulated main steam line break (MSLB) accident. The studies are funded by the VYR, NKS and Nordic Nuclear Reactor Thermal-Hydraulics Network (NORTHNET).

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CONTENTS

NOMENCLATURE

c	speed of sound
E	bulk modulus elasticity
k	ratio of specific heats
R	gas constant
T	temperature

Greek symbols

ρ	density

Abbreviations

BWR	boiling water reactor
CCTV	closed circuit television
CFD	computational fluid dynamics
CONDEX	Condensation experiments
DCC	direct contact condensation
ECCS	emergency core cooling system
LOCA	loss-of-coolant accident
LUT	Lappeenranta University of Technology
MOV	QuickTime
MSLB	main steam line break
NKS	Nordic nuclear safety research
PACTEL	parallel channel test loop
PC	polycarbonate
POOLEX	condensation pool experiments project
PPOOLEX	pressurized condensation pool experiments project
PWR	pressurized water reactor
SAFIR	Safety of Nuclear Power Plants - Finnish National Research Programme
SD	secure digital
SLR	steam line rupture
SRV	safety/relief valve
SS	stainless steel
TRA	experiment series with transparent blowdown pipe
TVO	Teollisuuden Voima Oyj
VTT	Technical Research Centre of Finland
VYR	State Nuclear Waste Management Fund
VVER	Vodo Vodjanyi Energetitseskij Reaktor

1 INTRODUCTION

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

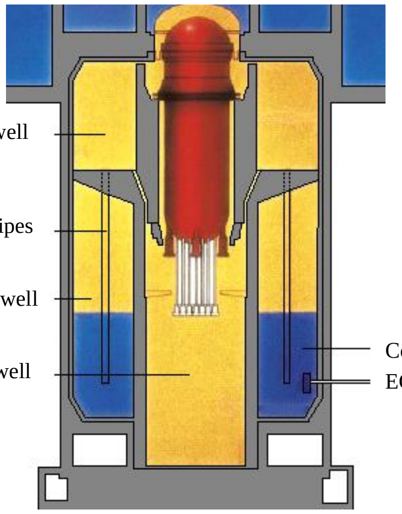

Figure 1. Schematic of the Olkiluoto type BWR containment.

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

To achieve the project objectives, a combined experimental/analytical/computational study programme is being carried out. Experimental part at LUT is responsible for the development of a database on condensation pool dynamics and heat transfer at well controlled conditions. Analytical/computational part at VTT, KTH and LUT use the developed experimental database for the improvement and validation of models and numerical methods including CFD and system codes. Also analytical support is provided for the experimental part by pre- and post-calculations of the experiments. Furthermore, the (one-directional or bi-directional) coupling of CFD and structural analysis codes in solving fluid-structure interactions can be facilitated with the aid of load measurements of the steam blowdown experiments. Some of the bubble dynamics models are applicable also outside the BWR scenarios, e.g. for the quench tank operation in the pressurizer vent line of a Pressurized Water Reactor (PWR), for the bubble condenser in a VVER-440/V213 reactor system, or in case of a submerged steam generator pipe break.

In 2006, a new test facility, called PPOOLEX, related to BWR containment studies was designed and constructed by Nuclear Safety Research Unit at LUT. It models both the dry and wet well (condensation pool) compartments of the containment and withstands prototypical system pressures. Experience gained with the operation of the preceding open POOLEX facility was extensively utilized in the design and construction process of the new facility.

Experiments with the new PPOOLEX facility began in 2007 by running characterizing tests [1]. They focused on observing the general behavior of the facility, on testing instrumentation and the proper operation of the automation, control and safety systems. The SLR experiments focused on the initial phase of a postulated MSLB accident inside the containment [2]. Air was used as the flowing substance. The research program continued in 2008 with the first series of thermal stratification and mixing experiments (STR-01…06) [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 (WLL series) [4]. In April and May 2009, experiments to study the effect of the Forsmark type blowdown pipe outlet collar design on loads caused by chugging phenomenon (COL series) were conducted [5]. In the second half of 2009, the research programme continued with eleven experiments (TRA and PAR series) studying the effect of the number of blowdown pipes (one or two) on loads caused by chugging phenomenon [6]. In January 2010, experiments focusing on dynamic loading (DYN series) during steam discharge were carried out [7].

The research program continued in August–November 2010 with a second series of thermal stratification and mixing experiments (STR-07…11). Before the test series the dry well compartment was thermally insulated with mineral wool. The main purpose of the experiments was to generate verification data for evaluating the capability of GOTHIC and APROS codes to predict stratification and mixing phenomena. In this report, the results of these 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 shortly discussed in chapter four. Chapter five summarizes the findings of the experiment series.

2 PPOOLEX TEST FACILITY

Condensation studies at LUT started with an open pool test facility (POOLEX) modelling the suppression pool of the BWR containment. During the years 2002–2006, the facility had several modifications and enhancements as well as improvements of instrumentation before it was replaced with a more versatile PPOOLEX facility in the end of 2006. The PPOOLEX facility is described in more detail in reference [8]. 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 from 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 approximately 1:320). Horizontal 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 bottom of the vessel. 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. 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.

For the thermal stratification experiments the dry well compartment was thermally insulated with 100 mm thick mineral wool (thermal conductivity 0.037 W/mK). Calculated coefficients of heat passage (U-values) for the dome and cylinder segments of the dry well are presented in Table 2.

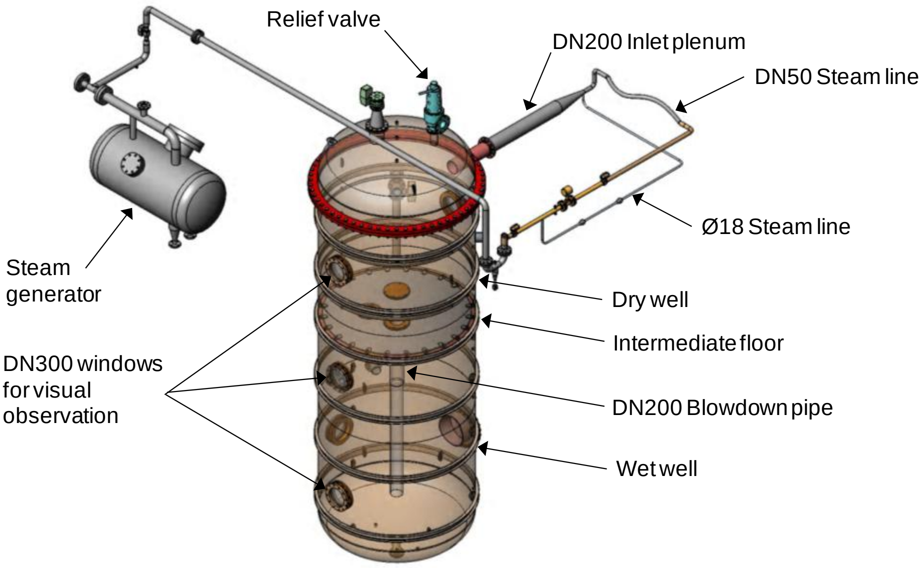

Figure 2. PPOOLEX test vessel.

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

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

* Water volume and level can be chosen according to the experiment type in question. The values listed in the table are based on the ratio of nominal water and gas volumes in the plant.
** With one / two DN200 blowdown pipes.

Table 2. U-values for dome and cylinder segments of the dry well compartment.

Insulation	U-value [W/m^2K]	
	Dome	Cylinder
No insulation	1 500	1 875
100 mm mineral wool	0.37	0.37

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 (Ø114.3x2.5 mm) from the wet well gas space to the dry well. A remotely operated valve in the line can be programmed to open with a desired pressure difference according to test specifications. However, the pressure difference across the floor between the compartments should not exceed the design value of 0.2 MPa.

Steam needed in the experiments is produced with the nearby PACTEL [9] test facility, which has a core section of 1 MW heating power and three horizontal steam generators. Steam is led through a thermally insulated steam line, made of sections of standard DN80 (Ø88.9x3.2) and DN50 (Ø60.3x3.9) pipes, from the PACTEL steam generators towards the test vessel. For the stratification experiments in 2010, a short Ø18x1.5 bypass section (with its own flow meter) was installed in parallel to the DN50 line to be used in the small flow rate cases. The steam line is connected to the DN200 inlet plenum with a 0.47 m long cone section. Accumulators connected to the compressed air network of the lab can be used for providing non-condensable gas injection. A schematic illustration of the air and steam line piping is presented in Figure 3.

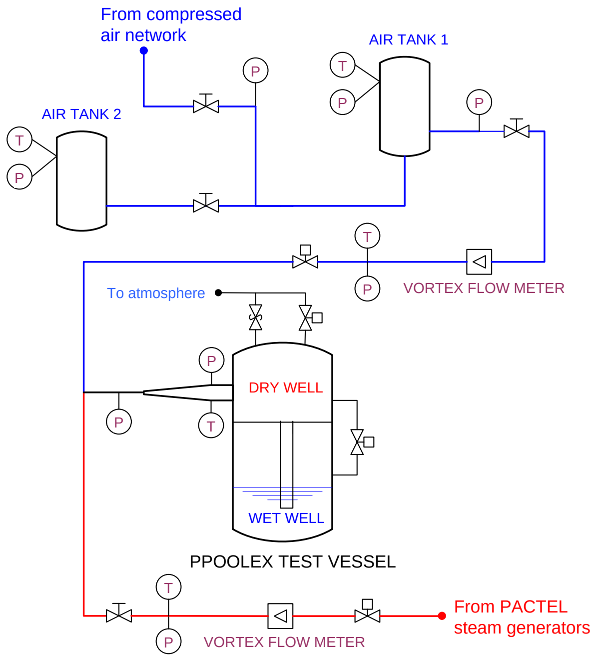

Figure 3. Arrangement of air and steam supply in the PPOOLEX facility.

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

2.3 MEASUREMENT INSTRUMENTATION

Investigation of the steam/gas injection phenomenon requires high-grade measuring techniques. For example, to estimate the loads on pool structures by condensation pressure oscillations the frequency and amplitude of the oscillations have to be measured. Experience on the use of suitable instrumentation and visualization equipment was achieved already during the preceding research projects dealing with condensation pool issues.

The applied instrumentation depends on the experiments in question. Normally, the test facility is equipped with several thermocouples (T) for measuring air/steam and pool water temperatures and with pressure transducers (P) for observing pressure behavior in the dry well, inside the blowdown pipe, at the condensation pool bottom and in the gas phase of the wet well. Steam and air flow rates are measured with vortex flow meters (F) in the steam and air lines. Additional instrumentation includes, for example, strain gauges (S) on the pool outer wall and valve position sensors. Strains are measured both in circumferential and axial direction.

For the 2010 stratification experiments an ultrasound measurement system, more thermocouples and a new flow meter were installed. The ultrasound measurement system (manufactured by the Polish company OPTEL) consists of a 300 kHz ultrasonic transducer/receiver for measuring sonic speed in water (installed in the wet well) and of a 50 kHz ultrasonic transducer/receiver for air measurement (dry well). Four new thermocouples (NiCrNi, type K, Ø 0.5 mm) were installed inside the lower part of the blowdown pipe (after STR-08) to be able to estimate the oscillatory up and down motion of the steam-water interface caused by the chugging condensation mode. A small measuring range (max. 10 l/s) vortex-type flow meter (Yokogawa Yewflo YF101-AAUD6D-S3S3*E) was installed to the parallel Ø18 mm steam line section.

A list of different types of measurements of the PPOOLEX facility during the STR experiments is presented in Table 3. The figures in Appendix 1 show the exact locations of the measurements and the table in Appendix 1 lists the identification codes and error estimations of the measurements. The error estimations are calculated on the basis of variance analysis. The results agree with normal distributed data with 95 % confidence interval.

Table 3. Instrumentation of the PPOOLEX test facility.

Quantity measured		No.	Range	Accuracy
Pressure	Dry well	1	0–6 bar	±0.06 bar
	Wet well	4	0–6/0–10 bar	±0.4/0.5 bar
	Blowdown pipe	3	0–10 bar	±0.7 bar
	Inlet plenum	1	0–6 bar	±0.06 bar
	Steam line	2	1–51/0–6 bar	±0.5 bar/0.06 bar
Temperature	Dry well	5	-40–200 °C	±3.2 °C
	Dry well outer wall	3	0–250 °C	±2.0 °C
	Wet well gas space	3	0–250 °C	±2.0 °C
	Wet well water volume	31	0–250 °C	±2.0 °C
	Wet well outer wall	1	0–250 °C	±2.0 °C
	Blowdown pipe	10	0–250 °C	±2.0 °C
	Inlet plenum	1	-40–200 °C	±3.2 °C
	Steam line	3	0–400 °C	±3.6 °C
	Structures	3	0–200 °C	±2.6 °C
Flow rate	Steam line	2	0–285 l/s 0–12 l/s	±4.9 l/s ±0.2 l/s
Steam fraction in the dry well		1	0-100 %	N/A
Water level in the wet well		1	0–30000 Pa	±0.06 m
Pressure difference across the floor		1	-499–505 kPa	± 9.7 kPa
Loads on structures		4	N/A	N/A
Vertical movement of the pool bottom		1	N/A	N/A
Vertical acceleration of the pool bottom		1	N/A	N/A
Sonic speed		2	N/A	N/A

2.4 CCTV SYSTEM

In the stratification experiments, standard video cameras, digital videocassette recorders and a quad processor were used for visual observation of the test vessel interior. With a digital color quad processor it is possible to divide the TV screen into four parts and look at the view of four cameras on the same screen, Figure 4.

For more accurate observation of air/steam bubbles at the blowdown pipe outlet, a Casio Exilim EX-F1 digital camera [11] was used. The camera is also capable of recording high-speed videos. The recordings are at first stored to the Secure Digital (SD) memory card in the camera in the QuickTime (.MOV) file format. From there they can be transferred to the PC hard disk via a USB-cable. The camera can achieve a recording speed of 1 200 frames/second (fps) with 336x96 pixels resolution. During the experiments recording modes VGA (STR-09…11) and FHD (STR-08) were used. Table 4 shows the recording speed and resolution combinations that can be attained with the camera.

Figure 4. Typical camera views from the STR experiments in 2010 (STR-09, chugging condensation mode).

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

Recording mode	Recording speed [fps]	Resolution [pixels]
VGA	30	640x480
HD	30	1280x720
FHD	60	1920x1080
HS300	300	512x384
HS600	600	432x192
HS1200	1 200	336x96

2.5 DATA ACQUISITION

National Instruments PCI-PXI-SCXI PC-driven measurement system is used for data acquisition. The system enables high-speed multi-channel measurements. The maximum number of measurement channels is 96 with additional eight channels for strain gauge measurements. The maximum recording capacity depends on the number of measurements and is in the region of three hundred thousand samples per second. Measurement software is LabView 8.6, Figure 5. The data acquisition system is discussed in more detail in reference [12].

Self-made software running in the National Instruments FieldPoint measurement system is used for monitoring and recording the essential measurements of the PACTEL facility producing the steam. Both data acquisition systems measure signals as volts. After the experiments, the voltage readings are converted to engineering units with conversion software. OPTELs OPBOX – 2.0 USB software is used for monitoring and recording the ultrasound measurements, Figure 6.

The used data measurement frequency of LabView was 1 Hz (STR-07 and STR-08) or 10 Hz (STR-09…11). OPBOX measured with a frequency of 1 Hz in STR-08 and 0.33 Hz in STR-10. The rest of the measurements (for example temperature, pressure and flow rate in the steam line) were measured by the self-made software with the frequency of 0.67 Hz.

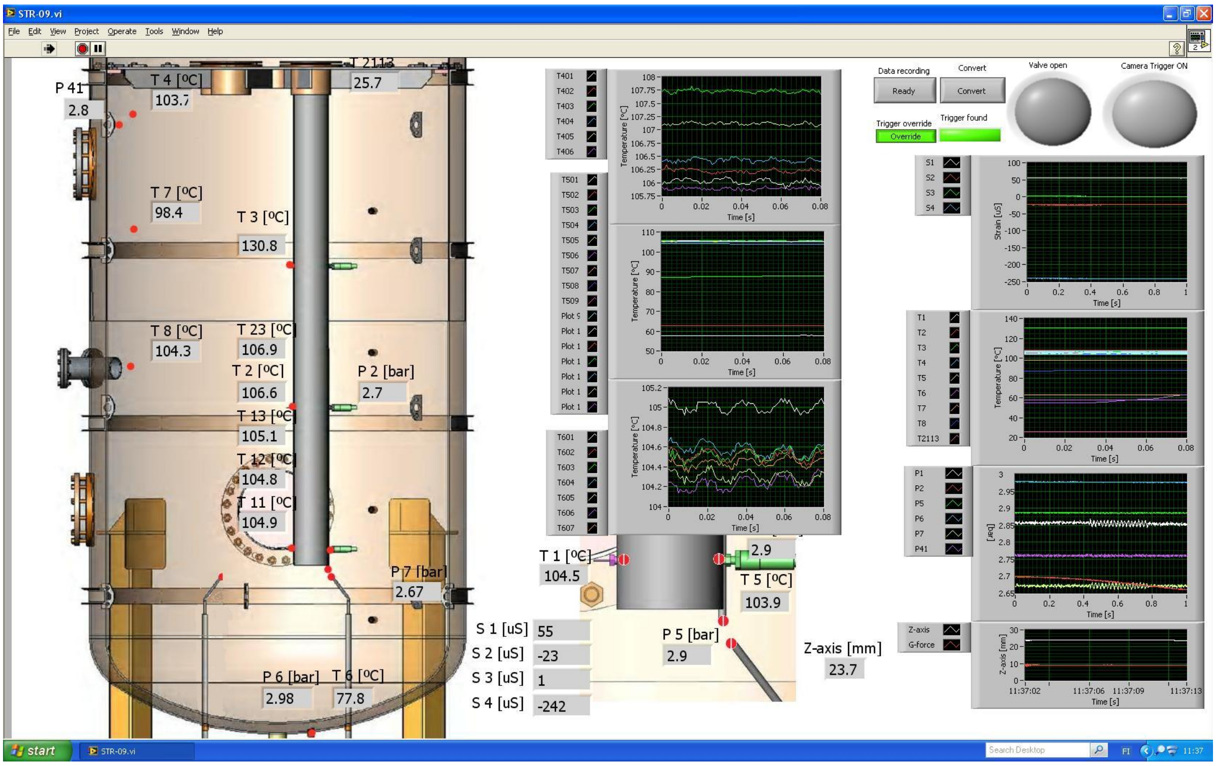

Figure 5. Monitoring of STR experiment with LabView 8.6 software.

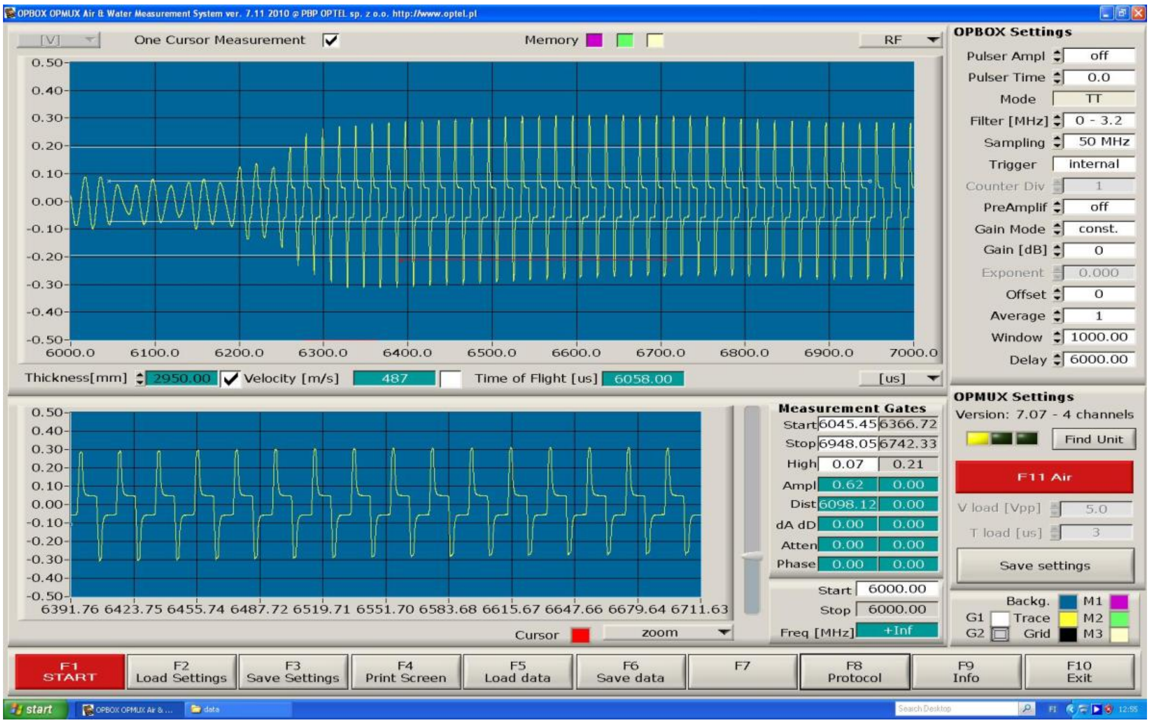

Figure 6. Monitoring of STR experiment with OPBOX – USB 2.0 software.

3 TEST PROGRAMME

The thermal stratification and mixing experiments were carried out in August–November 2010. The main objective was to study thermohydraulic loading of the wet well structures due to thermal stratification as well as to get comparison data for evaluating the capability of GOTHIC and APROS codes to predict stratification and mixing phenomena. Furthermore, the sound velocity measurement system was tested in the wet well pool. Altogether, five experiments (labeled from STR-07 to STR-11) were carried out. The first one (STR-07) was a simple practice case to find out a suitable steam flow rate and to test the new measurement instrumentation and experiment procedure. The rest of the experiments consisted of a small flow rate stratification period and of a mixing period with continuously or stepwise increasing flow rate. The dry well structures were heated up before the actual experiments. Steam was generated with the PACTEL facility.

Before the experiments, the wet well pool was filled with isothermal water (20 °C) to the level of 2.14 m i.e. the blowdown pipe outlet was submerged by 1.05 m. This air/water distribution corresponds to the scaled gas and liquid volumes in the containment of the reference plant. The steam discharge rate was (manually) controlled through the pressure level of the steam source.

After the correct initial conditions had been reached, the remote-controlled shut-off valve in the steam line was opened. As a result, the dry well compartment was filled with steam that mixed there with the initial air content. Pressure build-up in the dry well then pushed water in the blowdown pipe downwards and after a while the pipe cleared and 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 actual heat-up process with pure steam flow started.

During the experiment series a lot of problems were met with the OPBOX software. The software didn't work at all during STR-07 and 09. In STR-10 the system crashed after 1 260 s. After STR-08, new thermocouples T12, T13, T14 and T23 were added inside the blowdown pipe. Table 5 lists the initial test parameters of the thermal stratification experiments in 2010. The measurement range of the F2100 flow meter was exceeded in STR-10 and 11.

Table 5. Initial parameter values of the STR experiments in 2010.

Exp.	Initial water level [m]	Initial water temperature [°C]	Steam source pressure [MPa]	Steam flow rate [g/s]	Pre-heating of dry well	Comments
STR-07	2.14	20	0.71–0.23	12–165	Yes	OPBOX didn't work
STR-08	2.14	20	0.29–0.81	67–590	Yes	-
STR-09	2.14	20	0.18–0.65	80–550	Yes	OPBOX didn't work, thermocouples T12, T13, T14, T23 and T3 were installed
STR-10	2.14	20	0.22–0.65	60–<595	Yes	OPBOX crashed after 1260 s, measurement range of F2100 was exceeded
STR-11	2.14	20	0.19–0.80	100–<780	Yes	Measurement range of F2100 was exceeded

4 ANALYSIS OF THE EXPERIMENTS

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

4.1 THERMAL STRATIFICATION IN WET WELL GAS VOLUME

The gas space of the wet well heats up during the experiments. First, the heat-up 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 topmost measurement elevation (T4) than on the lower elevations (T7 and T8). The general behavior of the wet well gas space is similar in all experiments. Minor differences come from the fact that the initial temperatures differ by a few degrees from one experiment to another.

Figure 7 shows the pressure build-up of the test vessel during the experiment STR-08 and Figure 8 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 T4 is about 78 °C (from the initial value of 25 to 103 °C). The largest temperature difference between the wet well top and just above water surface (T4–T8) ranges from 27 to 31°C and is usually found a few thousand seconds into the experiment when the stratification process of the water volume is in good progress. Towards the end of the experiments this temperature difference has a slightly decreasing trend, but it is usually still over 15 °C until the thermocouple T8 is submerged by the rising water surface of the wet well.

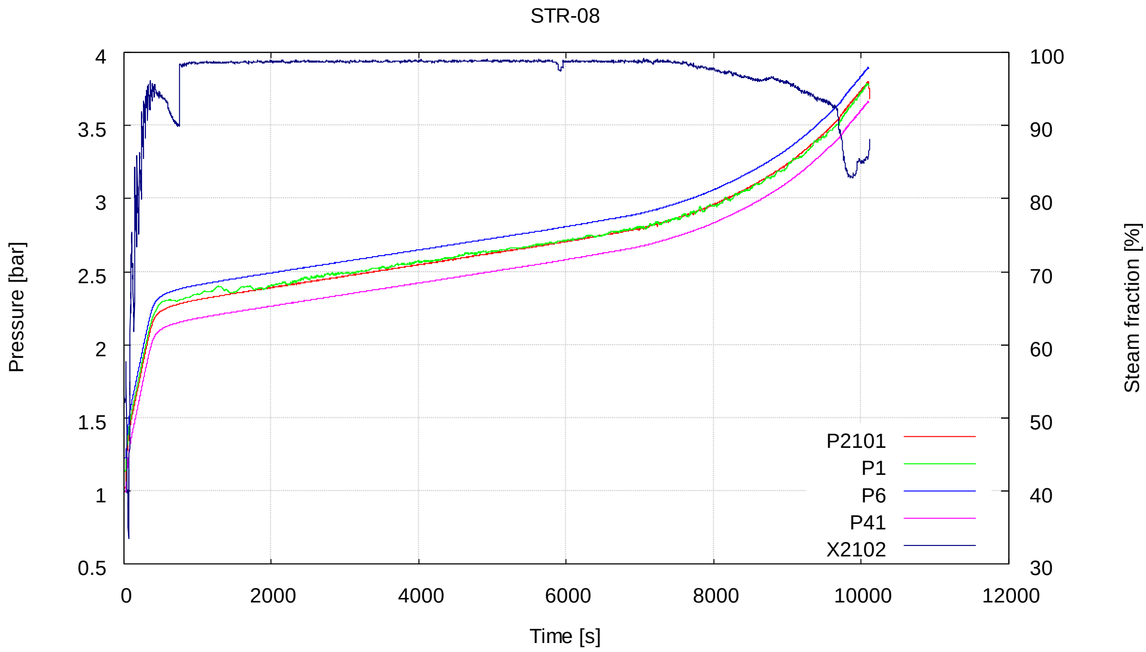

Figure 7. Pressure build-up in the test vessel in STR-08.

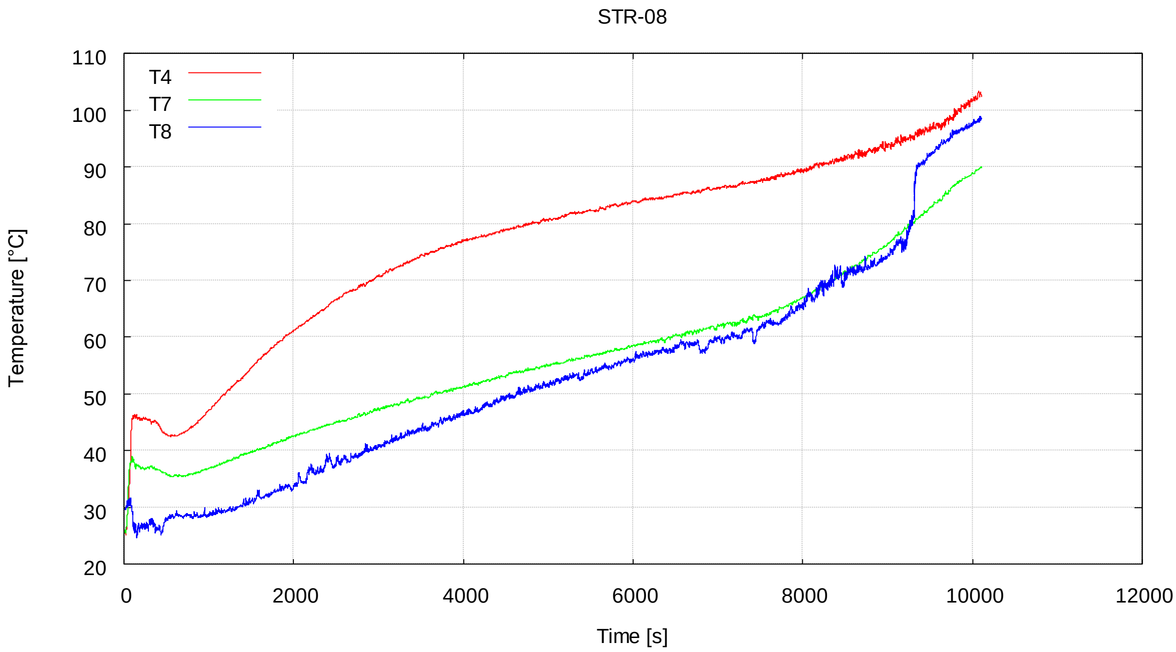

Figure 8. Temperatures in wet well gas space in STR-08.

4.2 THERMAL STRATIFICATION AND MIXING IN WET WELL POOL

The experiments consisted of a thermal stratification period and a mixing period. During the first half of the experiments steam flow rate was adjusted so that steam condensed mainly inside the blowdown pipe and water in the wet well pool stratified.

When steam flow rate was low enough (typically ~100–150 g/s) temperatures below the blowdown pipe outlet remained constant while increasing heat-up occurred towards the pool surface indicating strong thermal stratification of the wet well pool water. In STR-08, the initial steam flow rate was approximately 100 g/s and the stratification process began almost immediately after the initiation of the experiment, see Figure 9. In STR-10, the whole water inventory of the wet well remained mixed and heated up uniformly until the steam flow rate was adjusted below the level of 150 g/s, see Figure 11. During the stratification period the highest temperature difference between the thermocouples T501 and T516 was approximately 40 ºC and it was measured in STR-08, see Figure 9, Figure 10 and Table 6.

After the thermocouple T516 indicated a temperature of approximately 50 ºC (38 ºC in STR-07 and 60 ºC in STR-08), the pressure of the steam generators was increased in order to get a higher steam flow rate for trying to mix the whole pool water inventory. Steam flow was increased continuously except in STR-11 where it was increased "stepwise". Total mixing of the wet well pool water was not achieved in any of the experiments. The bottom layers heated up significantly during the mixing period but never reached the same temperature as the topmost layers.

During the mixing period the smallest temperature difference (7–8 ºC) between thermocouples T501 and T516 was measured in STR-10 and STR-11, see Figure 11, Figure 12 and Table 7. However, in both experiments the difference began to grow again after the pool water bulk temperature exceeded approximately 50 ºC. After the steam blowdown was terminated the temperature difference was 45 ºC and 25 ºC in STR-10 and STR-11, correspondingly.

In STR-11, steam was blown into the pool with several 200 second periods. The steam line valve was closed between the blowdowns. After the valve had been closed steam condensed inside the blowdown pipe and the pipe filled with water to the pool water level. This caused some movement in the pool water volume and as a result a stream of hotter water flowed from a higher elevation along the vessel inner wall to the pool bottom. It was registered by thermocouple T6, see Figure 13. When the next blowdown was initiated, steam flow pushed hot water from the blowdown pipe towards the pool bottom as indicated again by T6, Figure 13. As a result of the ingress of these water plugs better mixing of pool water was attained than with the continuously increasing steam flow.

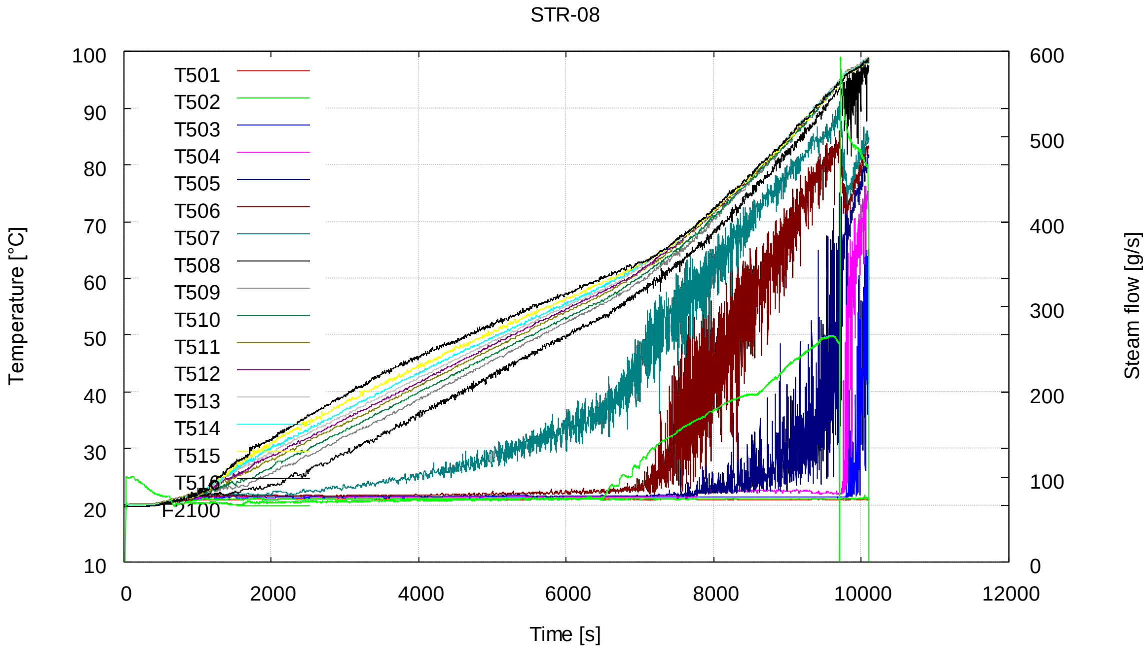

Figure 9. Temperatures in wet well water and steam flow in STR-08.

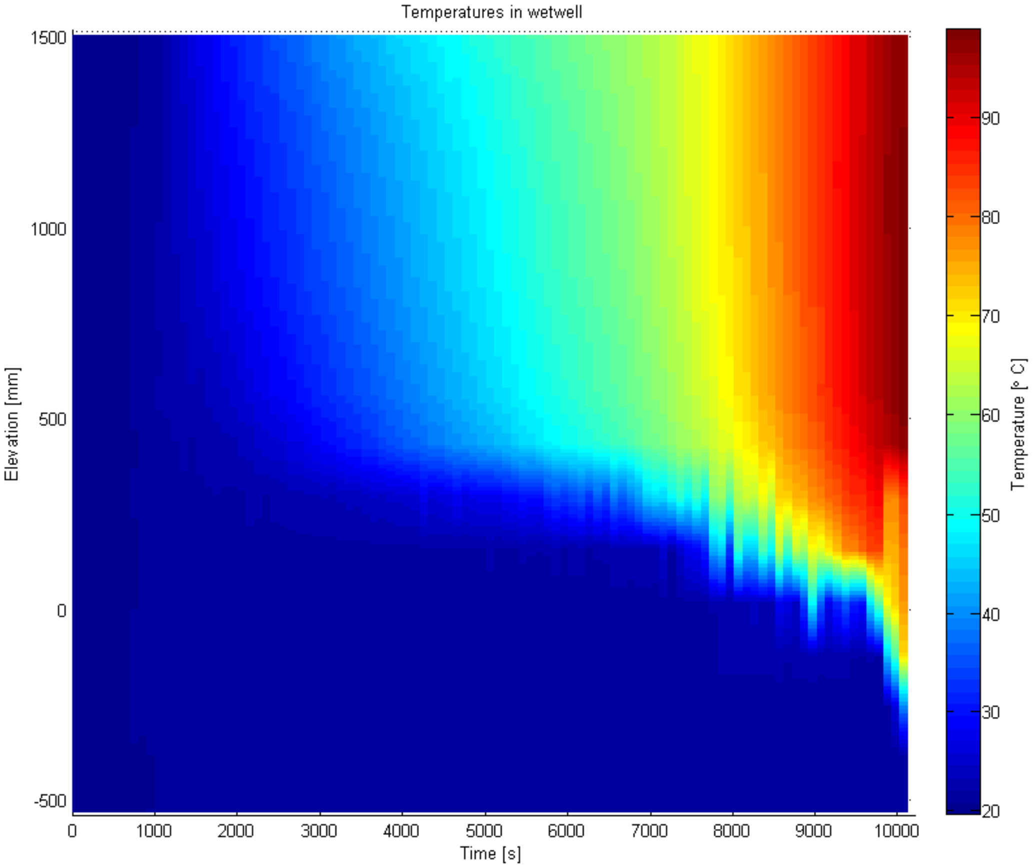

Figure 10. Vertical temperature distribution in wet well water in STR-08.

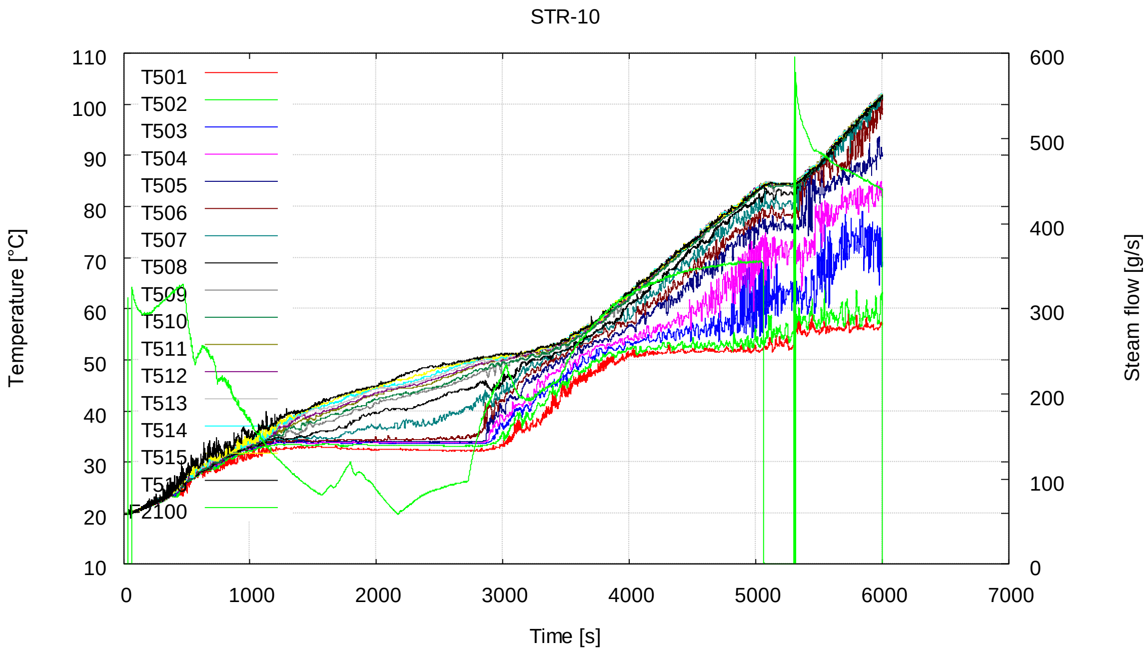

Figure 11. Temperatures in wet well water and steam flow in STR-10.

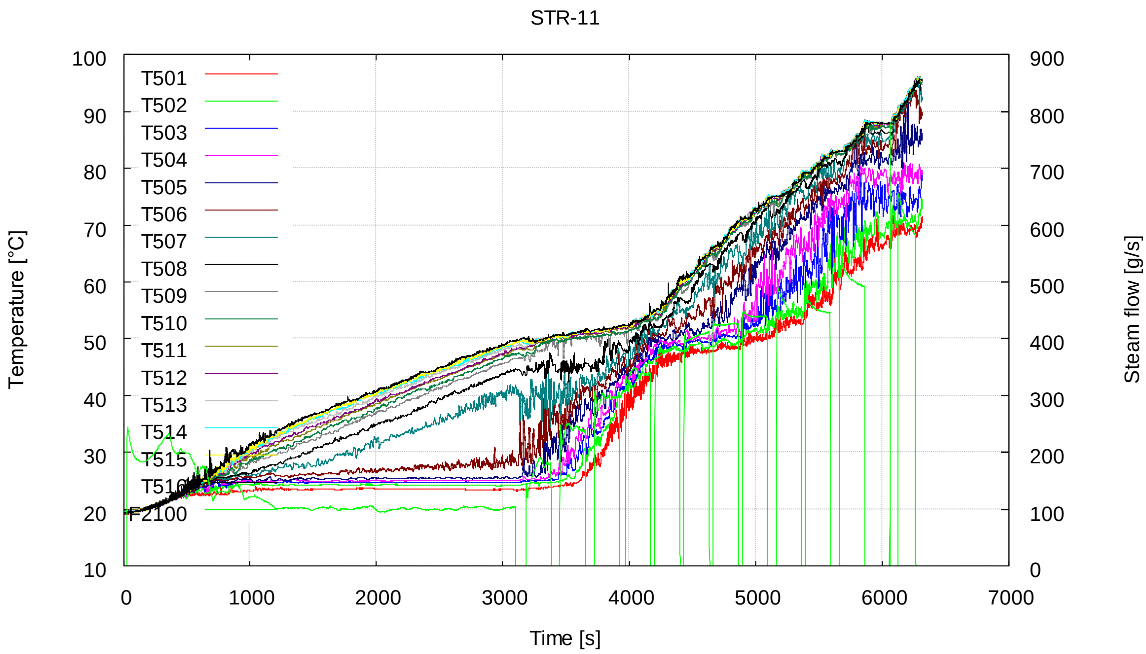

Figure 12. Temperatures in wet well water and steam flow in STR-11.

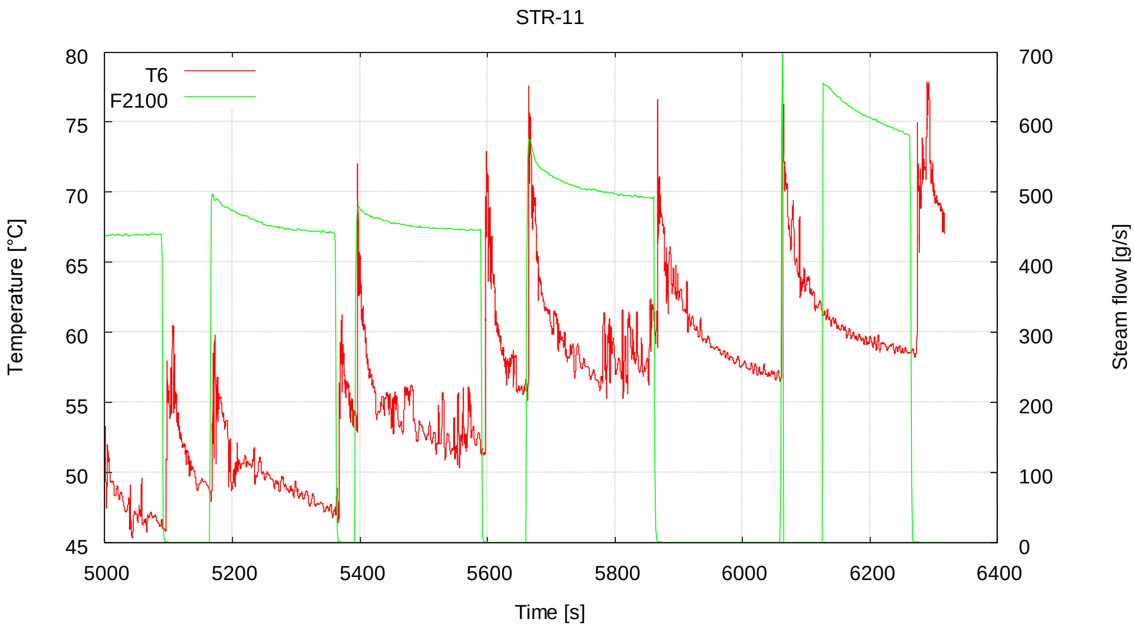

Figure 13. Temperature at pool bottom and steam flow in STR-11 in period 5 000…6 260 s.

Table 6. Stratification related observations of the STR experiments in 2010.

Exp.	Time period [s]	Steam flow rate [g/s]	Final top layer temperature [°C]	Final temperature difference between T501 and T516 [°C]
STR-07	85–4090	12–33	~38	~18
STR-08	20–6480	67–100	~60	~39
STR-09	40–2240	80–307	~50	~21
STR-10	30–2700	60–330	~50	~18
STR-11	25–3100	96–245	~50	~27

Table 7. Mixing related observations of the STR experiments in 2010.

Exp.	Time period [s]	Steam flow rate [g/s]	Final top layer temperature [°C]	Minimum temperature difference between T501 and T516 [°C]	Final temperature difference between T501 and T516 [°C]
STR-07	4090–6215	36–165	~48	~11	~23
STR-08	6480–10100	90–590	~99	~21	~78
STR-09	2240–6160	149–550	~105	~21	~45
STR-10	2700–6000	192–<595	~102	~8	~45
STR-11	3180–6260	120–<780	~96	~7	~25

4.3 OSCILLATION OF STEAM/WATER INTERFACE IN BLOWDOWN PIPE

After STR-08, four new thermocouples (T12, T13, T14 and T23) were installed inside the lower part of the blowdown pipe to evaluate more accurately the oscillatory up and down flow motion of the steam/water interface inside the pipe caused by the chugging condensation mode. On the basis of the movement of the interface GOTHIC calculators will make an attempt to estimate the effective momentum term of the simulation model. The location of the thermocouples can be seen from Appendix 1.

The most intensified chugging occurred in STR-10, see Figure 14. This happened already during the beginning of the stratification period when the steam flow rate was adjusted to a correct value. Up and down movement of the steam/water interface inside the blowdown pipe was registered by thermocouples T1, T12, T13 and T14, see Figure 15. Thermocouple T14 was located 775 mm above the blowdown pipe outlet. The pipe was initially submerged by 1 050 mm. The steam/water interface did not reach the elevation of thermocouple T2 or higher during the stratification or mixing periods in none of the STR experiments in 2010.

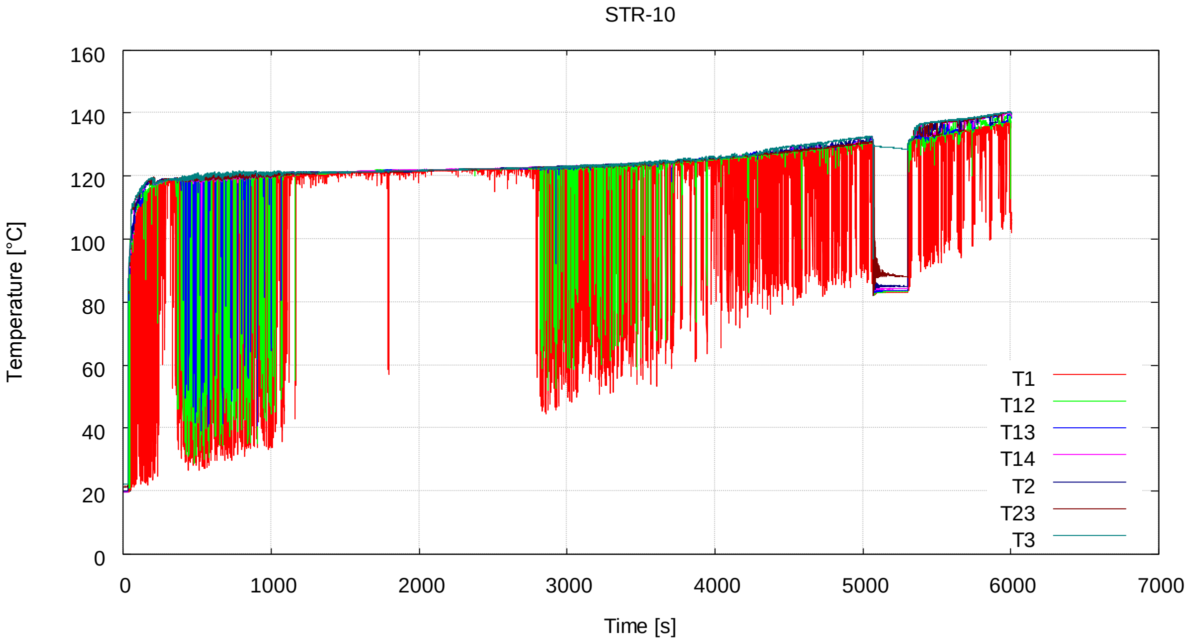

Figure 14. Temperatures inside blowdown pipe in STR-10.

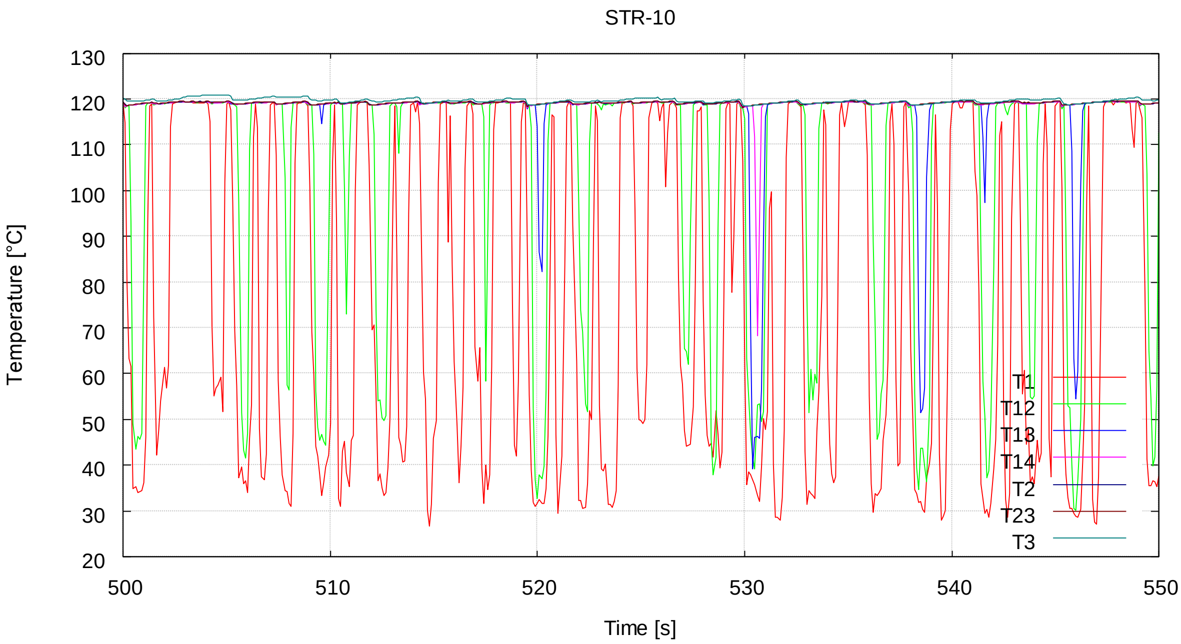

Figure 15. Temperatures inside blowdown pipe in STR-10 in period 500…550 s.

4.4 SPEED OF SOUND

During the experiments sonic speed was measured both in the wet well water pool and in the dry well compartment with an ultrasound measurement system. The ultrasonic system was installed for testing purposes and to ultimately find out if void fraction has an influence on sonic speed in the wet well water pool. If the measurement system would work as planned some kind of estimations of local void fractions in the wet well pool could be done with the help of sonic speed measurements.

The wet well transducers were installed below the water level to the opposite walls of the pool. They were 495 mm above the blowdown pipe outlet so that the straight line between the transducers passes the outer wall of the blowdown pipe at the distance of approximately 50 mm, see Appendix 1.

The speed of sound in gases, fluids and solids can be expressed with the Hook's Law as follows:

$$c = \sqrt{\frac{E}{\rho}}$$

where E is bulk modulus elasticity [Pa], and
ρ is density [kg/m^3].

For ideal gas the speed of sound can be expressed as follows:

$$c = \sqrt{kRT}$$

where k is the ratio of specific heats [-],
R is gas constant [J/kgK], and

T is temperature [K].

The sound travels faster through media with a higher density. For instance the speed of sound is in a range of 1450…1550 m/s and 400…500 m/s for water and steam, correspondingly, see Table 8.

Table 8. Speed of sound in saturated water and steam and air as a function of temperature.

Temperature [°C]	c [m/s]		
	Water	Steam	Air
20	1483	423	343
40	1531	437	354
60	1554	449	366
80	1557	461	377
100	1545	472	387
120	1521	482	397
140	1487	490	407
160	1443	496	417

Figure 16 shows the measured and analytically calculated speed of sound in the wet well pool in STR-11. The speed was calculated on the basis of temperature measurement T512 which was the closest thermocouple installed in relation to the speed of sound transducers (520 mm above the blowdown pipe outlet). To avoid crashing of the measurement system the data was recorded in 18 separate time periods each lasting 150…500 seconds.

During STR-11 a lot of noise was registered by the speed of sound transducers. The most probably source of the noise are the dynamic loads caused by rapid condensation of steam bubbles. The noise resulted to unphysical values (out of range spikes in the plotted curves) in the measurement signal. If the noise is disregarded, approximately a 10 m/s difference between the measurement data and the calculated results can be observed, see Figure 16. In STR-10, similar results were obtained, see Figure 17.

According to the test results, it seems that a small void fraction doesn’t have an effect on the speed of sound in the wet well water pool and that the measurement system cannot be used for the estimation of void fraction in such cases. Furthermore, a lot of different kinds of problems were encountered while testing the speed of sound measurement system. It is therefore unclear at the moment if the system is reliable enough to be used for the purpose it was originally though for. At least further tests have to be executed before a final conclusion can be made.

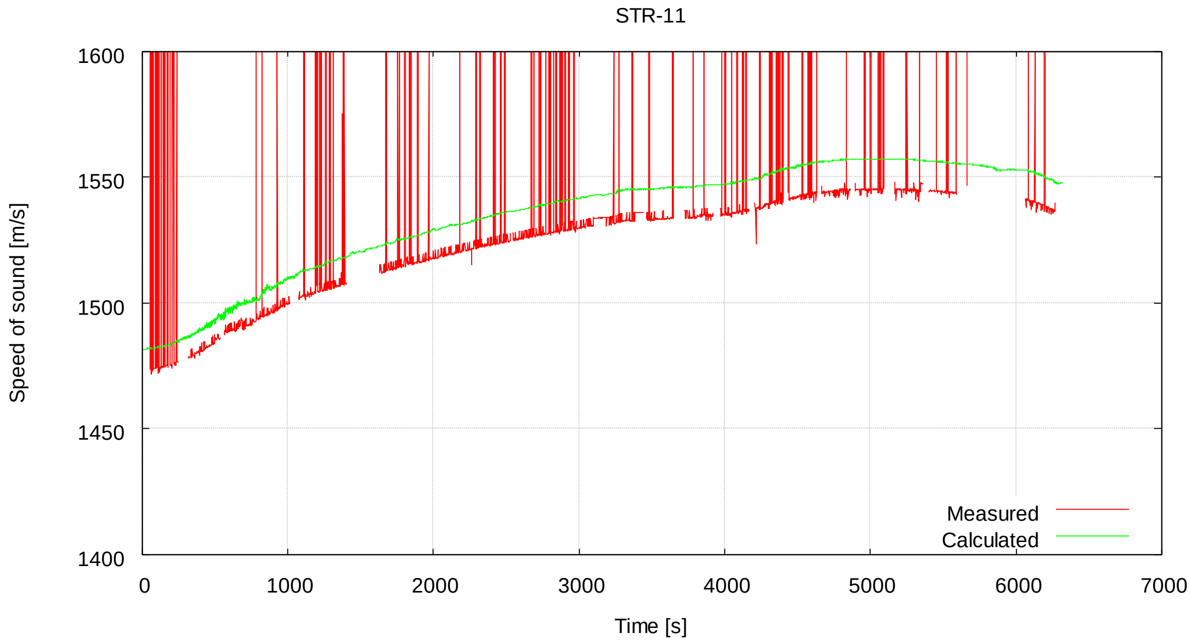

Figure 16. Speed of sound in wet well in STR-11.

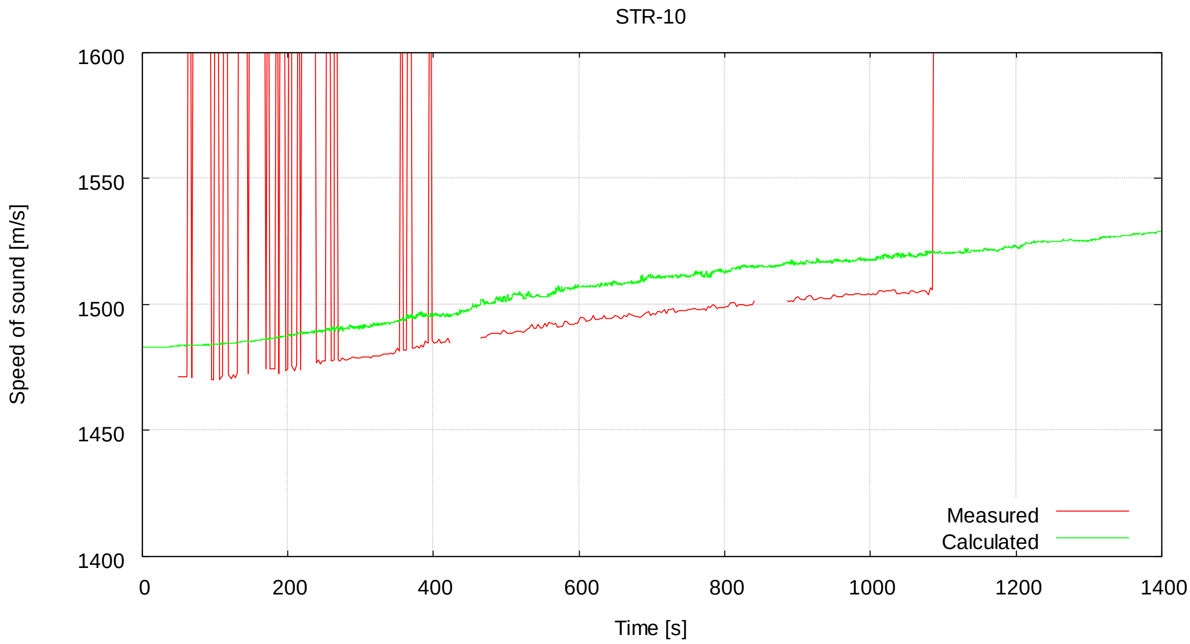

Figure 17. Speed of sound in wet well in STR-10.

4.5 COMPARISON TO POOLEX STRATIFICATION EXPERIMENTS IN 2005

In the preceding research project with the open pool test facility (POOLEX), two thermal stratification experiments were also carried out [13]. One of the tests (STB-21) consisted of a similar small steam flow rate stratification period and a mixing period with continuously increasing flow rate as in the STR experiments in 2010. From 2010 the experiment STR-10 corresponds best to STB-21.

In STB-21, the steam flow rate had to be as low as ~50 g/s before the temperatures below the blowdown pipe outlet remained constant while increasing heat-up occurred towards the pool surface layers, see Figure 18. In STR-10, a three times higher steam flow (~150 g/s) was small enough to cause a similar stratification effect. In both tests the pool water bulk temperature was approximately 35 °C when stratification was initiated.

In STB-21, the steam flow rate of 210 g/s was large enough to mix the pool water inventory completely. In STR-10, a uniform temperature distribution was not attained despite of the three times higher steam flow rate (more than 600 g/s).

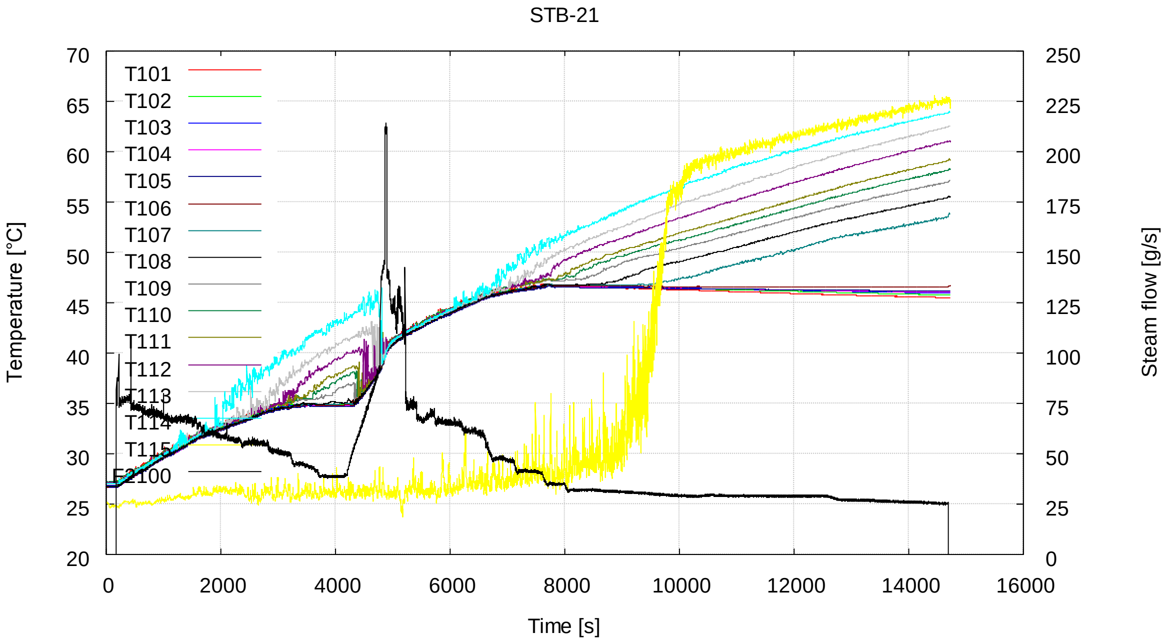

Figure 18. Temperatures in wet well water and steam flow in STB-21. Note that thermocouple T115 was totally submerged by rising water surface after 10 000 s.

One explanation for this contradiction between the results of the two experiments could be found from the different shapes of the pool bottoms in the POOLEX and PPOOLEX test facilities. In POOLEX the bottom is conical while in PPOOLEX it is hemispherical. Mixing effects are probably enhanced by the "sharp corners" of the conical bottom and therefore smaller flow rates could prevent stratification from occurring and could mix the pool volume totally in the experiment with the POOLEX facility.

In PPOOLEX, the dry well compartment can also act as some kind of a buffer, which dampens the flow surges in both directions. Therefore, water ingress back into the pipe does not reach as high as in POOLEX and the resulting water plug, ejected into the pool during the next chugging cycle, is smaller in volume and has less mixing force.

5 SUMMARY AND CONCLUSIONS

This report summarizes the results of the thermal stratification experiments in 2010 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 for capturing different aspects of the investigated phenomena. The nearby PACTEL facility was used as a steam source. The main purpose of the experiment series was to get verification data for evaluating the capability of GOTHIC and APROS codes to predict stratification and mixing phenomena and to study thermohydraulic loading of the wet well structures. Another objective was to test the sound velocity measurement system planned to be used in various experiment series later. The ultimate goal in using this system is to find out if void fraction has an influence on sonic speed in the wet well water pool.

Altogether five experiments were carried out. The first one was a simple practice to find out a suitable steam flow rate and to test the new measurement instrumentation and experiment procedure. The rest of the experiments consisted of a small flow rate stratification period and of a mixing period with continuously or stepwise increasing flow rate. The dry well structures were heated up to the level of 90 °C before the actual experiments. The initial water bulk temperature was 20 °C.

When the steam flow rate was low enough (typically ~100–150 g/s) temperatures below the blowdown pipe outlet remained constant while increasing heat-up occurred towards the pool surface layers indicating strong thermal stratification of the wet well pool water. During the stratification period the highest measured temperature difference between the pool bottom and surface was approximately 40 ºC.

During the mixing period total mixing of the pool volume was not achieved in any of the experiments. The bottom layers heated up significantly but never reached the same temperature as the topmost layers. The lowest measured temperature difference between the pool bottom and surface was 7–8 ºC.

According to the test results, it seems that a small void fraction doesn’t have an effect on the speed of sound in the wet well water pool and that the acquired sound velocity measurement system cannot be used for the estimation of void fraction. However, more tests on this issue have to be executed before a final conclusion can be made.

6 REFERENCES

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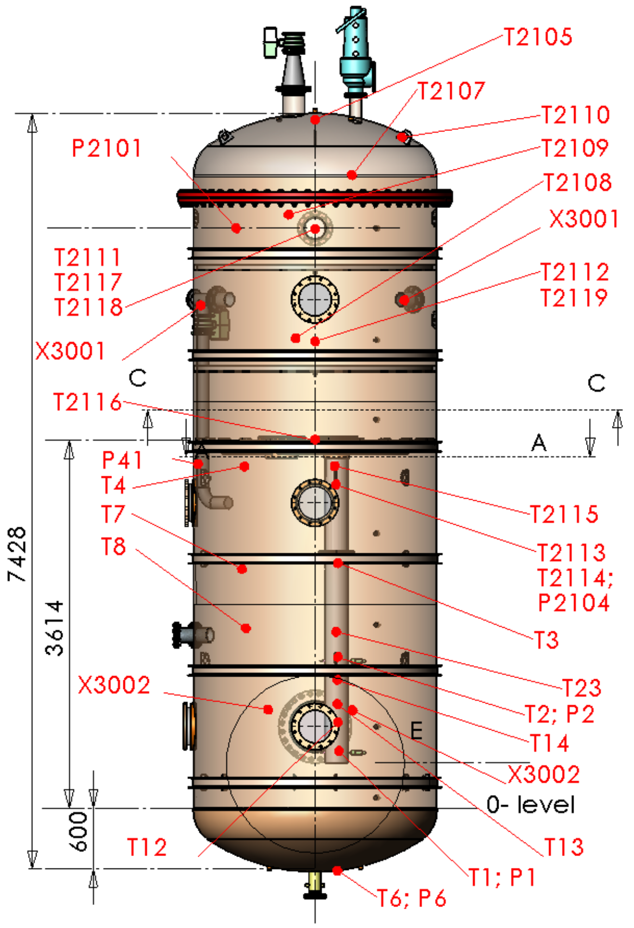
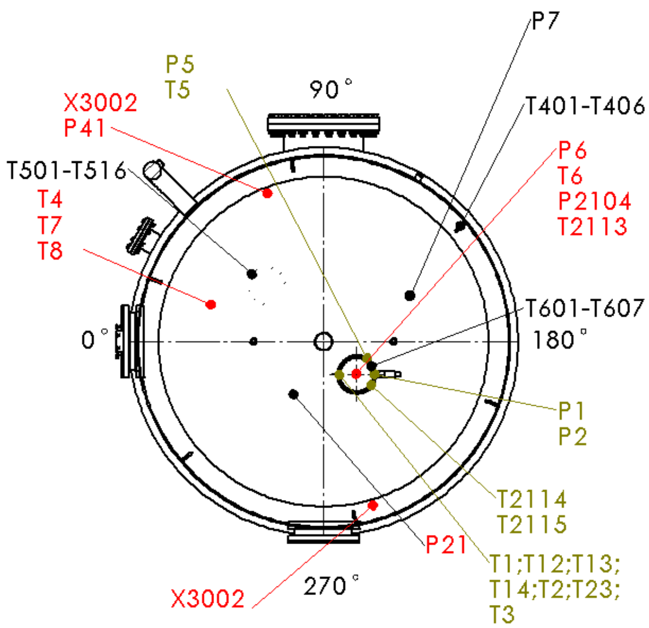
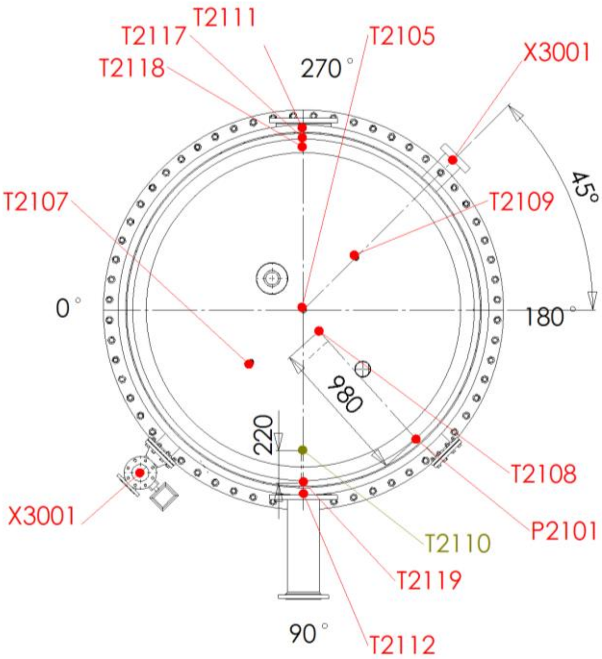
APPENDIX 1: PPOOLEX INSTRUMENTATION



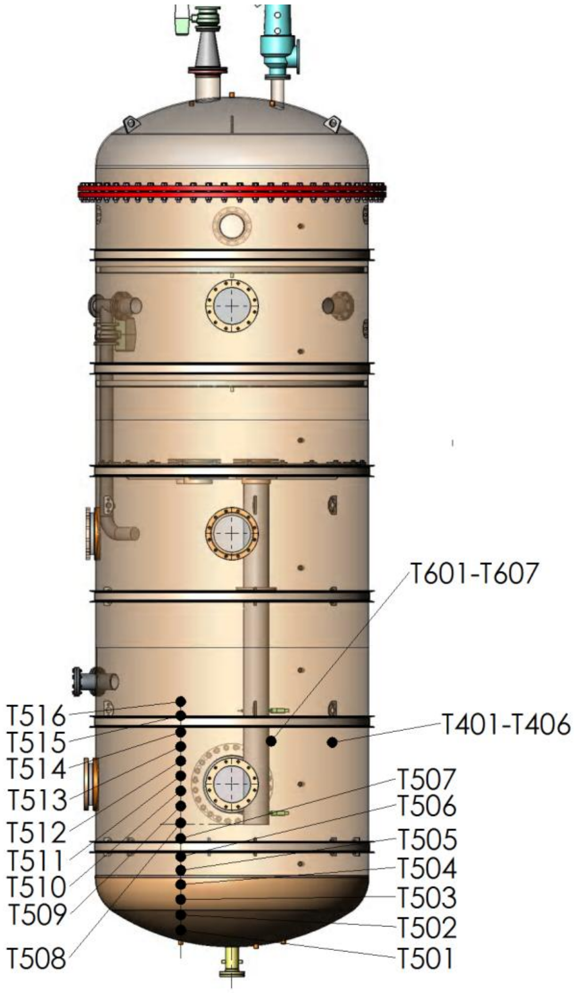
Test vessel measurements.



Cross-section A-A.



Cross-section C-C.



Thermocouples T401…T607.

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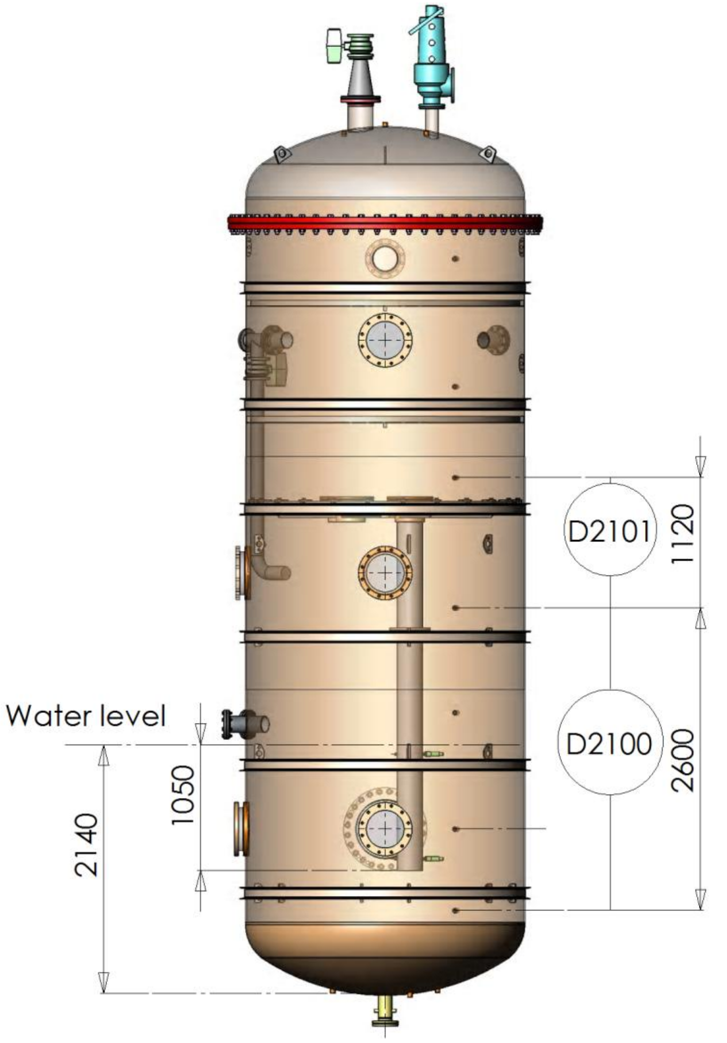
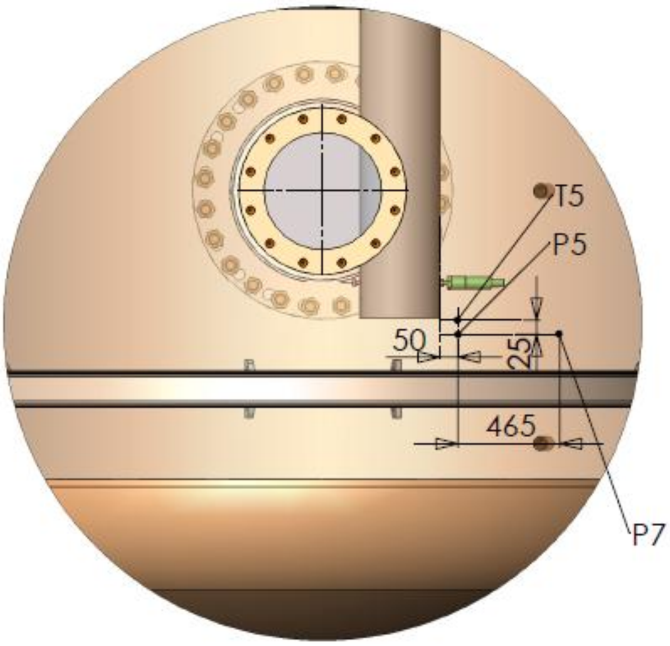
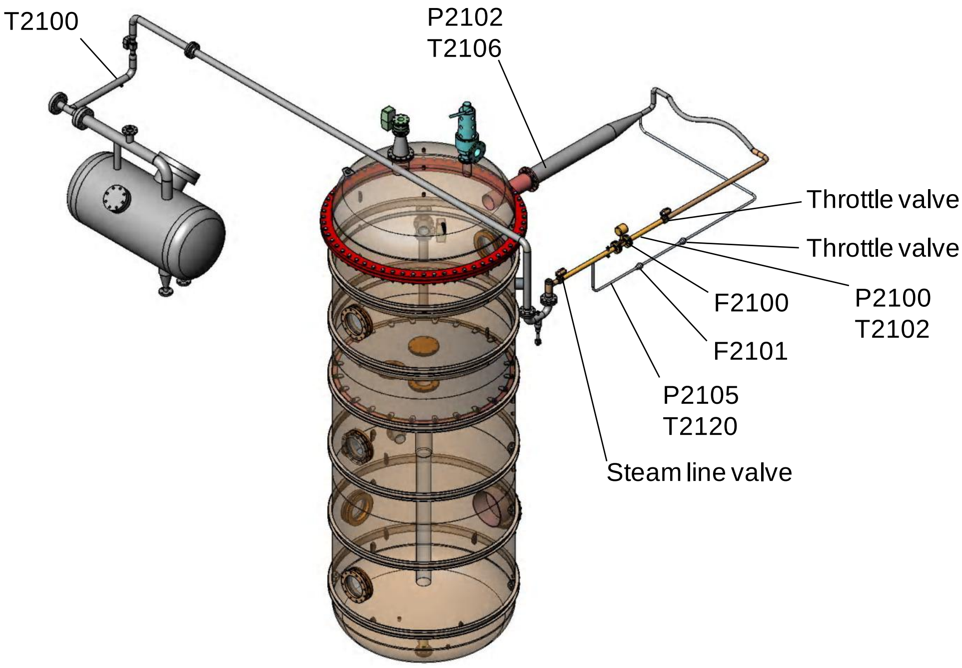


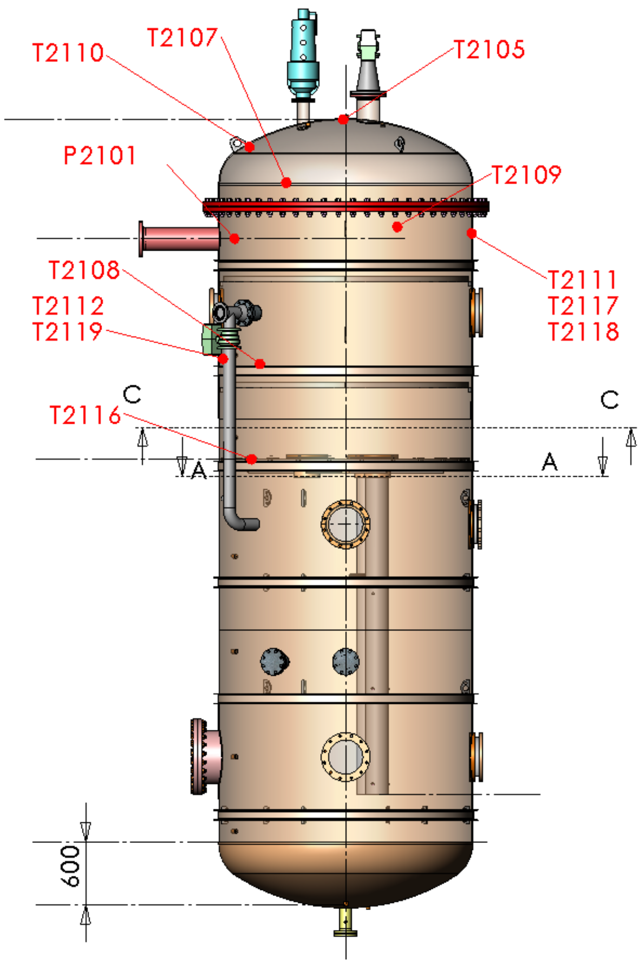
Pressure difference measurements. Nominal water level is 2.14 m.



Pressure and temperature measurements at the blowdown pipe outlet.



Measurements in the steam line.



Measurements in the dry well.

Measurement	Code	Elevation	Angle	Location	Error estimation
Pressure	P1	545	214	Blowdown pipe	±0.7 bar
Temperature	T1	545	245	Blowdown pipe	±1.8 °C
Pressure	P2	1445	214	Blowdown pipe	±0.7 bar
Temperature	T2	1445	245	Blowdown pipe	±1.8 °C
Temperature	T3	2345	245	Blowdown pipe	±1.8 °C
Temperature	T4	3410	20	Wet well gas space	±1.8 °C
Pressure	P5	395	198	Blowdown pipe outlet	±0.7 bar
Temperature	T5	420	198	Blowdown pipe outlet	±1.8 °C
Pressure	P6	-615	202	Wet well bottom	±0.5 bar
Temperature	T6	-615	202	Wet well bottom	±1.8 °C
Pressure	P7	395	145	Wet well	±0.4 bar
Temperature	T7	2585	20	Wet well gas space	±1.8 °C
Temperature	T8	1760	20	Wet well gas space	±1.8 °C
Temperature	T12	770	245	Blowdown pipe	±1.8 °C
Temperature	T13	995	245	Blowdown pipe	±1.8 °C
Temperature	T14	1220	245	Blowdown pipe	±1.8 °C
Temperature	T23	1670	245	Blowdown pipe	±1.8 °C
Pressure	P41	3600	45	Wet well gas space	±0.1 bar
Temperature	T401	1000	140	Wet well	±1.8 °C
Temperature	T402	1000	140	Wet well	±1.8 °C
Temperature	T403	1000	140	Wet well	±1.8 °C
Temperature	T404	1000	140	Wet well	±1.8 °C
Temperature	T405	1000	140	Wet well	±1.8 °C
Temperature	T406	1000	140	Wet well	±1.8 °C
Temperature	T501	-530	45	Wet well	±1.8 °C
Temperature	T502	-390	45	Wet well	±1.8 °C
Temperature	T503	-260	45	Wet well	±1.8 °C
Temperature	T504	-125	45	Wet well	±1.8 °C
Temperature	T505	10	45	Wet well	±1.8 °C
Temperature	T506	150	45	Wet well	±1.8 °C
Temperature	T507	287	45	Wet well	±1.8 °C
Temperature	T508	427	45	Wet well	±1.8 °C
Temperature	T509	560	45	Wet well	±1.8 °C
Temperature	T510	695	45	Wet well	±1.8 °C
Temperature	T511	830	45	Wet well	±1.8 °C
Temperature	T512	965	45	Wet well	±1.8 °C
Temperature	T513	1103	45	Wet well	±1.8 °C
Temperature	T514	1236	45	Wet well	±1.8 °C
Temperature	T515	1369	45	Wet well	±1.8 °C
Temperature	T516	1505	45	Wet well	±1.8 °C
Temperature	T601	1000	202	Wet well	±1.8 °C
Temperature	T602	1000	202	Wet well	±1.8 °C
Temperature	T603	1000	202	Wet well	±1.8 °C
Temperature	T604	1000	202	Wet well	±1.8 °C
Temperature	T605	1000	202	Wet well	±1.8 °C
Temperature	T606	1000	202	Wet well	±1.8 °C
Temperature	T607	1000	202	Wet well	±1.8 °C
Flow rate	F2100	-	-	Steam line	±4.9 l/s
Pressure	P2100	-	-	Steam line	±0.5 bar
Flow rate	F2101	-	-	Steam line	±13 l/min

Temperature	T2100	-	-	Steam line beginning	±3.5 °C
Pressure	P2101	5700	90	Dry well	±0.06 bar
Pressure	P2102	-	-	Inlet plenum	±0.06 bar
Temperature	T2102	-	-	Steam line	±3.5 °C
Pressure	P2104	3400	202	Blowdown pipe	±0.06 bar
Pressure	P2105	-	-	Steam line	±0.06 bar
Temperature	T2104	-245	180	Wet well outer wall	±1.8 °C
Temperature	T2105	6780	-	Dry well top	±1.8 °C
Temperature	T2106	-	-	Inlet plenum	±1.8 °C
Temperature	T2107	6085	45	Dry well middle	±1.8 °C
Temperature	T2108	4600	120	Dry well bottom	±1.8 °C
Temperature	T2109	5790	225	Dry well lower middle	±1.8 °C
Temperature	T2110	6550	90	Dry well outer wall	±1.8 °C
Temperature	T2111	5700	270	Dry well outer wall	±1.8 °C
Temperature	T2112	4600	90	Dry well outer wall	±1.8 °C
Temperature	T2113	3400	225	Blowdown pipe	±1.8 °C
Temperature	T2114	3400	212	Blowdown pipe	±1.8 °C
Temperature	T2115	3250	212	Blowdown pipe	±1.8 °C
Temperature	T2116	3600	135	Dry well floor	±1.8 °C
Temperature	T2117	5700	270	Dry well inner wall	±1.8 °C
Temperature	T2118	5700	270	Dry well, 10 mm from the wall	±1.8 °C
Temperature	T2119	4600	90	Dry well inner wall	±1.8 °C
Temperature	T2120	-	-	Steam line	±3.5 °C
Pressure difference	D2100	100–2700	120	Wet well	±0.06 m
Pressure difference	D2101	2700–3820	120	Across the floor	±0.09 bar
Strain	S1	-400	0	Bottom segment	Not defined
Strain	S2	-400	0	Bottom segment	Not defined
Strain	S3	-265	180	Bottom segment	Not defined
Strain	S4	-265	180	Bottom segment	Not defined
Vertical pool movement	Z-axis	892	180	Below pool bottom	Not defined
Pool bottom acceleration	G-force	892	180	Pool bottom	Not defined
Valve position	X2100	-	-	Steam line	Not defined
Steam fraction	X2102	4600	120	Dry well	Not defined
Sonic speed	X3001	5000	45 225	Dry well	Not defined
Sonic speed	X3002	940	70 255	Wet well	Not defined
Valve position	V1	-	-	Steam line	Not defined
Camera trigger	Camera trigger	-	-	Wet well	Not defined

Measurements in the PPOOLEX facility during the STR experiments in 2010.

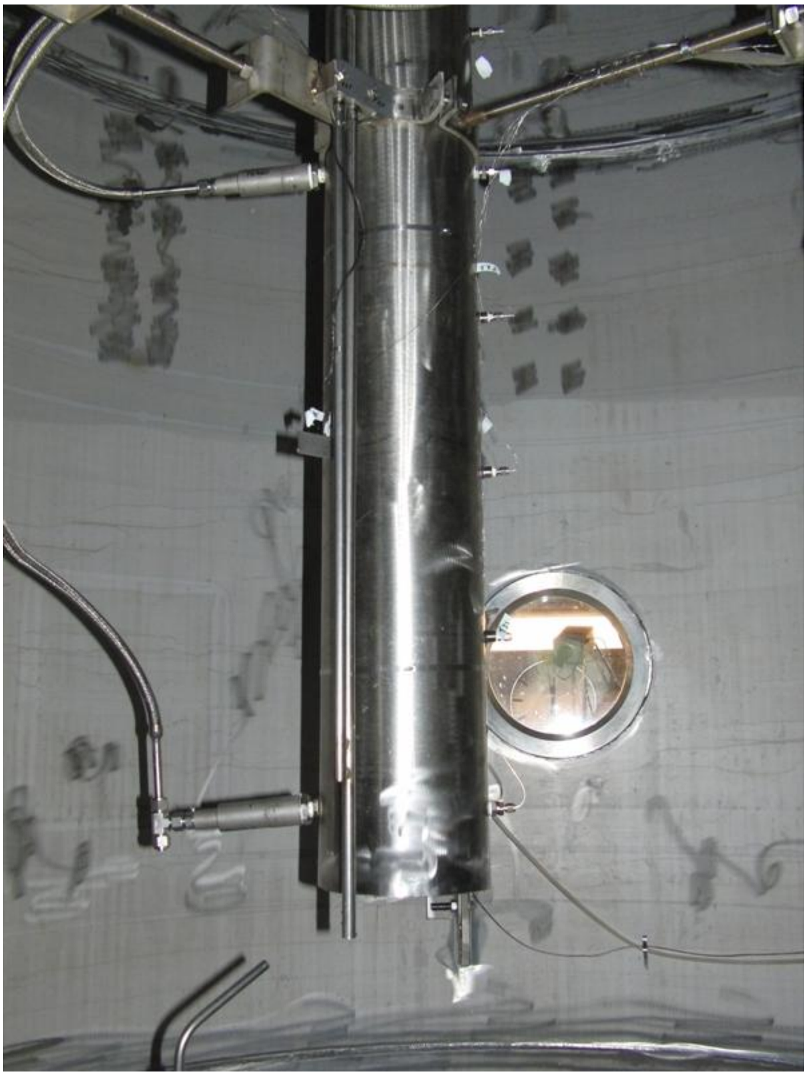
APPENDIX 2: PPOOLEX TEST FACILITY PHOTOGRAPHS

Thermally insulated dry well compartment and inlet plenum.

Steam lines.

Close-up view of the ultrasonic transducer installed in the wet well compartment.

Thermocouples(T501…T516) for measuring vertical temperature distribution.



Lower part of the blowdown pipe.

Title	PPOOLEX EXPERIMENTS ON STRATIFICATION AND MIXING IN THE WET WELL POOL
Author(s)	Jani Laine, Markku Puustinen, Antti Räsänen, Vesa Tanskanen
Affiliation(s)	Lappeenranta University of Technology, Nuclear Safety Research Unit
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Abstract

This report summarizes the results of the thermal stratification and mixing experiments carried out in 2010 with the scaled down, two compartment PPOOLEX test facility designed and constructed at LUT. Steam was blown into the thermally insulated dry well compartment and from there through the DN200 vertical blowdown pipe to the condensation pool filled with sub-cooled water. The main purpose of the experiment series was to generate verification data for evaluating the capability of GOTHIC and APROS codes to predict stratification and mixing phenomena. Another objective was to test the sound velocity measurement system.

Altogether five experiments were carried out. The experiments consisted of a small steam flow rate stratification period and of a mixing period with continuously or stepwise increasing flow rate. The dry well structures were heated up to the level of approximately 90 °C before the actual experiments. The initial water bulk temperature was 20 °C.

When the steam flow rate was low enough (typically ~100–150 g/s) temperatures below the blowdown pipe outlet remained constant while increasing heat-up occurred towards the pool surface layers indicating strong thermal stratification of the wet well pool water. During the stratification period the highest measured temperature difference between pool bottom and surface was approximately 40 ºC.

During the mixing period total mixing of the pool volume was not achieved in any of the experiments. The bottom layers heated up significantly but never reached the same temperature as the topmost layers. The lowest measured temperature difference between the pool bottom and surface was 7–8 ºC.

According to the test results, it seems that a small void fraction doesn't have an effect on the speed of sound in water and that the acquired sound velocity measurement system cannot be used for the estimation of void fraction in the wet well water pool. However, more tests on this issue have to be executed before a final conclusion can be made.

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

Available on request from the NKS Secretariat, P.O.Box 49, DK-4000 Roskilde, Denmark.
Phone (+45) 4677 4045, fax (+45) 4677 4046, e-mail nks@nks.org, www.nks.org