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PPOOLEX Experiments on Thermal Stratification and Mixing

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Abstract

The results of the thermal stratification experiments in 2008 with the PPOOLEX test facility are presented. PPOOLEX is a closed vessel divided into two compartments, dry well and wet well. Extra temperature measurements for capturing different aspects of the investigated phenomena were added before the experiments. The main purpose of the experiment series was to generate verification data for evaluating the capability of GOTHIC code to predict stratification and mixing phenomena.

Altogether six experiments were carried out. Heat-up periods of several thousand seconds by steam injection into the dry well compartment and from there into the wet well water pool were recorded. The initial water bulk temperature was 20 °C. Cooling periods of several days were included in three experiments.

A large difference between the pool bottom and top layer temperature was measured when small steam flow rates were used. With higher flow rates the mixing effect of steam discharge delayed the start of stratification until the pool bulk temperature exceeded 50 °C. The stratification process was also different in these two cases. With a small flow rate stratification was observed only above and just below the blowdown pipe outlet elevation. With a higher flow rate over a 30 °C temperature difference between the pool bottom and pipe outlet elevation was measured. Elevations above the pipe outlet indicated almost linear rise until the end of steam discharge.

During the cooling periods the measurements of the bottom third of the pool first had an increasing trend although there was no heat input from outside. This was due to thermal diffusion downwards from the higher elevations.

Heat-up in the gas space of the wet well was quite strong, first due to compression by pressure build-up and then by heat 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. The gas space temperatures also stratified.

The presence of a boundary layer on the blowdown pipe outer surface was verified by a set of horizontally installed thermocouples with a two millimeters interval. A rising film of water, hotter than the ambient temperature, existed on the pipe surface almost throughout the whole heat-up process.

Key words

condensation pool, steam/air blowdown, thermal stratification

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PPOOLEX EXPERIMENTS ON THERMAL STRATIFICATION AND MIXING

Markku Puustinen, Jani Laine, Antti Räsänen

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The results of the thermal stratification experiments in 2008 with the PPOOLEX test facility are presented. PPOOLEX is a closed vessel divided into two compartments, dry well and wet well. Extra temperature measurements for capturing different aspects of the investigated phenomena were added before the experiments. The main purpose of the experiment series was to generate verification data for evaluating the capability of GOTHIC code to predict stratification and mixing phenomena.

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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 modeling the dry well and wet well compartments of a BWR containment was designed and constructed. The main objective of the CONDEX project is to increase the understanding of different phenomena inside the containment during a postulated main steam line break (MSLB) accident. The studies are funded by the VYR, NKS and Nordic Nuclear Reactor Thermal-Hydraulics Network (NORTHNET).

CONTENTS

NOMENCLATURE

A	area
F	flow rate
p, P	pressure
S	strain
T	temperature
z	vertical movement

Abbreviations

BWR	boiling water reactor
CFD	computational fluid dynamics
CONDEX	condensation experiments with PPOOLEX facility project
DCC	direct contact condensation
ECCS	emergency core cooling system
FINNUS	Finnish Research Programme on Nuclear Power Plant Safety
fps	frames per second
KTH	Kunliga Tekniska Högskolan
LOCA	loss-of-coolant accident
LUT	Lappeenranta University of Technology
MSLB	main steam line break
NKS	Nordic nuclear safety research
NORTHNET	Nordic Nuclear Reactor Thermal-Hydraulics Network
PACTEL	parallel channel test loop
POOLEX	condensation pool test facility, condensation pool experiments project
PPOOLEX	containment test facility
PWR	pressurized water reactor
SAFIR	Safety of Nuclear Power Plants – Finnish National Research Programme
SAFIR2010	The Finnish Research Programme on Nuclear Power Plant Safety 2007 – 2010
SLR	steam line rupture
TVO	Teollisuuden Voima Oy
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. The wet well pool serves as the major heat sink for condensation of steam. Figure 1 shows the schematic of the Olkiluoto type BWR containment.

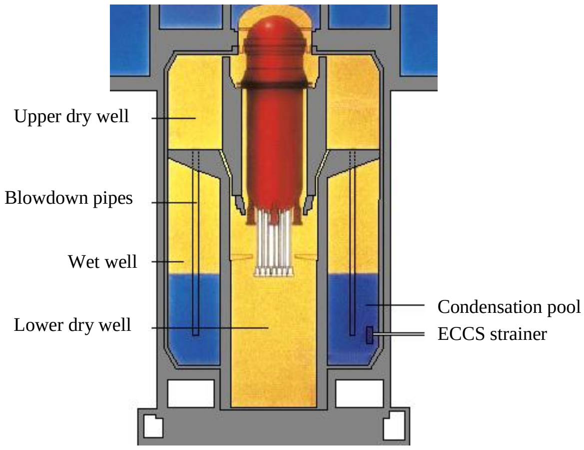

Figure 1. Schematic of the Olkiluoto type BWR containment.

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-440/213 reactor system, or in case of a submerged steam generator pipe break.

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

Experiments with the new PPOOLEX facility started in 2007 by running a series of characterizing tests [1]. They focused on observing the general behaviour of the facility, on testing instrumentation and the proper operation of the automation, control and safety systems. The next five experiments (SLR series) focused on the initial phase of a postulated MSLB accident inside the containment [2]. Air was used as the flowing substance in these experiments.

The research program continued in September – October 2008 with a series of thermal stratification and mixing experiments. Stratification in the water volume of the wet well during small steam discharge was of special interest. In addition, mixing phenomenon as a function of steam discharge rate was studied. 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 of the thermal stratification experiments 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) modeling 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 [3]. However, the main features of the facility and its instrumentation are introduced below. Some test facility photographs are shown in Appendix 2.

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. The vessel is constructed from three separate plate cylinder segments and from two dome segments. The test facility is able to withstand considerable structural loads caused by rapid condensation of steam. The vessel sections modeling dry well and wet well are volumetrically scaled according to the compartment volumes of the Olkiluoto containment buildings. The DN200 (∅ 219.1 x 2.5 mm) blowdown pipe is positioned inside the pool in a non-axisymmetric location, i.e. 300 mm away from the centre of the condensation pool. Horizontal piping (inlet plenum) for injection of gas and steam penetrates through the side wall of the dry well compartment. The length of the inlet plenum is 2.0 m and the inner diameter 214.1 mm. There are several windows for visual observation in the walls of both compartments. A DN100 (∅ 114.3 x 2.5 mm) drain pipe with a manual valve is connected to the bottom of the vessel. A relief valve connection is mounted on the vessel head. The large removable vessel head and a man hole (DN500) in the wet well compartment wall provide access to the interior of the vessel for maintenance and modifications of internals and instrumentation. A sketch of the test vessel is presented in Figure 2. Table 1 lists the main dimensions of the test facility compared to the conditions in the Olkiluoto plant.

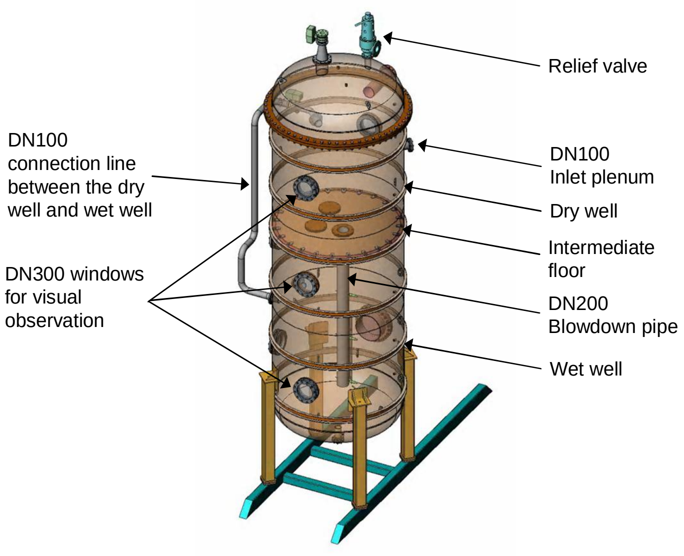

Figure 2. PPOOLEX test vessel.

Table 1. Test facility vs. Olkiluoto BWR

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

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

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 [4] test facility, which has a core section of 1 MW heating power and three steam generators. Steam is led through a thermally insulated steam line, made of sections of standard DN80 (Ø 88.9 x 2.0 mm) and DN50

(Ø 60.3 x 2.0 mm) pipes, from the PACTEL steam generators towards the test vessel. The steam line is connected to the DN200 inlet plenum with a 0.47 m long cone section. Accumulators connected to the compressed air network of the lab can be used for providing non-condensable gas injection. A schematic illustration of the air and steam line piping is presented in Figure 3.

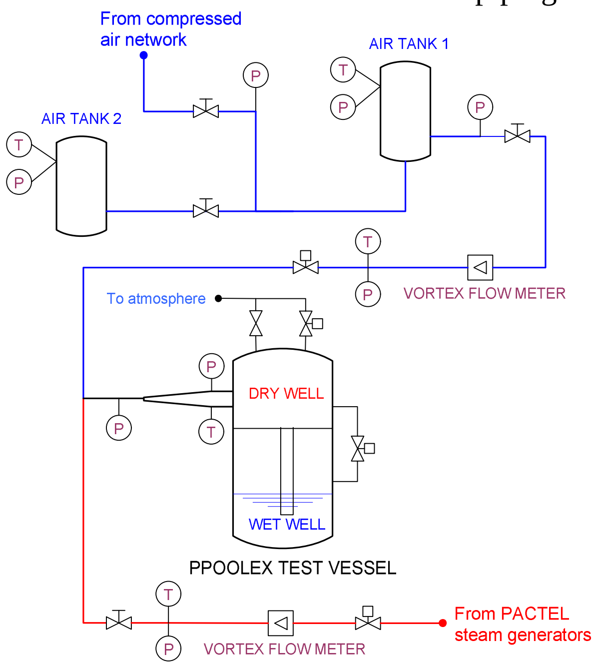

Figure 3. Arrangement of air and steam supply in the PPOOLEX facility.

2.3 MEASUREMENT INSRUMENTATION

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 compartment, inside the blowdown pipe, at the condensation pool bottom and in the gas phase of the wet well compartment. 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. After the characterizing test series, thermocouple measurements were added to the dry well compartment for capturing the temperature distribution in more detail.

A vertical rod with sixteen evenly distributed thermocouples was installed below the wet well water surface for the stratification experiments, Figure 4. Eight were at the elevations below the blowdown pipe outlet and eight above. Furthermore, seven horizontally positioned thermocouples with two millimeters interval were added on the outer surface of the blowdown pipe at the elevation of 555 mm above the pipe outlet. Another set of seven thermocouples was added on the inner wall of the wet well pool at the same elevation. These sets were for capturing the boundary layer phenomenon during the heat up and stratification processes of the experiments. A list of different types of measurements of the PPOOLEX facility during the stratification experiments is presented in Table 2. The figures in Appendix 1 show the exact locations of the measurements and the table in Appendix 1 lists the identification codes and error estimations of the measurements. The error estimations are calculated on the basis of variance analysis. The results agree with normal distributed data with 95% confidence interval.

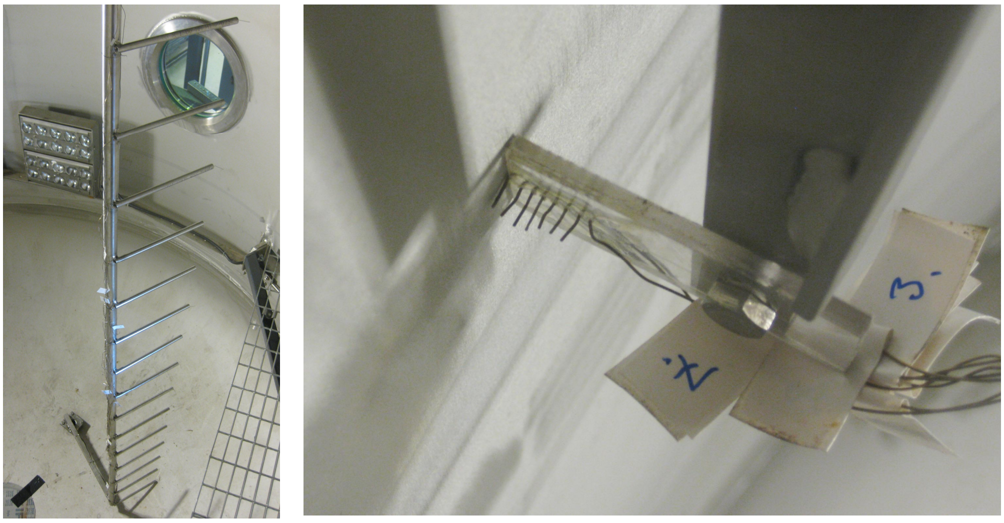

Figure 4. Measurement of vertical temperature distribution and wall boundary layer.

Table 2. Instrumentation of the PPOOLEX test facility

Quantity measured		No.	Range	Accuracy
Pressure	Dry well	1	0-6 bar	±0.06 bar
	Wet well	3	0-6/0-10 bar	±0.4/0.5 bar
	Blowdown pipe	1	0-10 bar	±0.7 bar
	Inlet plenum	1	0-6 bar	±0.06 bar
	Steam line	1	1-51 bar	±0.5 bar
	Air line	2	0-6/1-11 bar	±0.06/0.1 bar
	Air tanks 1&2	2	0-16/0-11 bar	±0.15/0.11 bar
Temperature	Dry well	4	-40-200 °C	±3.2 °C
	Wet well water volume	32	0-250 °C	±2.0 °C
	Wet well gas space	3	0-250 °C	±2.0 °C
	Blowdown pipe	3	0-250 °C	±2.0 °C
	Inlet plenum	1	-40-200 °C	±3.2 °C
	Steam line	2	0-400 °C	±3.6 °C
	Air line	1	-20-100 °C	±2.8 °C
	Air tanks 1&2	2	-20-100/200 °C	±2.8/3.1 °C
	Vessel wall	4	0-200 °C	±2.0 °C
Mass flow rate	Steam line	1	0-285 l/s	±4.9 l/s
	Gas line	1	0-575 m^3/h	±18 g/s
Water level in the wet well		1	0-30000 Pa	±0.06 m
Pressure difference across the floor		1	-499-505 kPa	± 9.7 kPa
Steam partial pressure in the blowdown pipe		1	N/A	N/A
Loads on structures		4	N/A	N/A
Vertical movement of the pool		1	N/A	N/A

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 equal size parts and look at the view of four cameras on the same screen. High-speed video was not used in these experiments.

2.4 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 measurements. The maximum recording speed depends on the number of measurements and is in the region of three hundred thousand samples per second. Measurement software is LabView 8.6. The data acquisition system is discussed in more detail in reference [5].

Separate HPVee based software is used for monitoring and recording the essential measurements of the PACTEL facility. Both data acquisition systems measure signals as volts. After the experiments, the voltage readings are converted to engineering units with conversion software.

In the thermal experiments, the used data recording frequency of both systems (LabView and HPVee) was only 1 Hz due to the long duration of the experiments. During the measured cooling periods the recording frequency was even smaller (once in ten or sixty seconds).

A separate measurement channel is used for the steam line valve position information. Approximately 3.6 V means that the valve is fully open, and 1.1 V that it is fully closed. Voltage under 1.1 V means the valve is opening. Both HPVee and LabView record the channel.

3 TEST PROGRAMME

The thermal stratification and mixing experiments were carried out in September – October 2008. The objective was to study thermohydraulic loading of the wet well structures due to stratification as well as to get comparison data for evaluating the capability of GOTHIC code to predict stratification and mixing phenomena. Before the experiments, an array of properly positioned thermocouples was added to the pool volume according to the recommendations by KTH [6]. Altogether, six experiments (labeled from STR-01 to STR-06) were carried out. The first one was a simple cooling test with 50 °C tap water without any steam discharge. The rest included a heat-up period, ranging from ~3000 seconds to ~14000 seconds, with small or moderate steam discharge. Steam was generated with the PACTEL facility. In three experiments, the cooling period (of several days) was measured with a reduced recording interval.

In STR-01 and STR-02, the wet well was initially filled with water 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. In STR-03 … STR-06, the initial water level was lower (2.0 m) in order to avoid the submergence of the lower end of the connection line between the compartments due to slow level increase caused by the long duration of the experiments. In the heat-up experiments (STR-02 … STR-06), the initial pool water bulk temperature was 20 °C i.e. isothermal conditions prevailed. Steam discharge rate was (manually) controlled with the help of 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. In the experiments with a low steam flow rate, only small steam bubbles were detected at the blowdown pipe outlet and the steam-water interface could even remain inside the pipe for extended periods.

In STR-06, the temperature measurement at the lowest elevation inside the blowdown pipe (T1) broke down. All other measurements worked properly during the test programme. Table 3 lists the test parameters of the thermal stratification experiments.

Table 3. Test parameters of the thermal stratification experiments in the PPOOLEX facility

Exp.	Initial water level [m]	Initial water temperature [°C]	Steam source pressure [MPa]	Steam flow rate [g/s]	Pre-heating of dry well	Cooling period
STR-01	2.14	50	-	-	No	Yes
STR-02	2.14	20	0.27-0.45	72-127	No	Yes
STR-03	2.0	20	0.18-0.39	50-100	No	Yes
STR-04	2.0	20	0.15-0.33	42-105	No	No
STR-05	2.0	20	0.37-0.50	300-425	Yes	No
STR-06	2-0	20	0.28-0.35	190-250	Yes	Yes

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 THE 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. Some minor differences may come from the fact that the initial temperatures differ by a few degrees from one experiment to another.

Figure 5 shows the pressure build-up of the test vessel during experiment STR-03 and Figure 6 the corresponding temperature behavior of the gas space. Measurement X1102 (steam partial pressure) indicates the moment when flow in the blowdown pipe changes to pure steam.

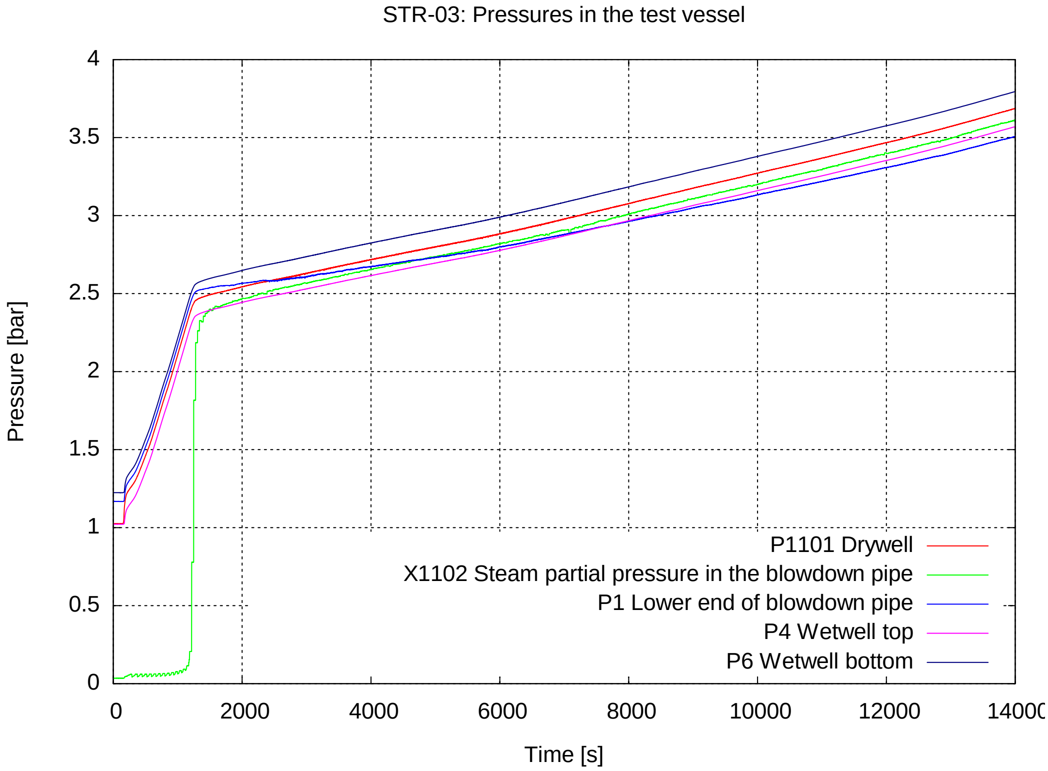

Figure 5. Pressure build-up in the test vessel in STR-03.

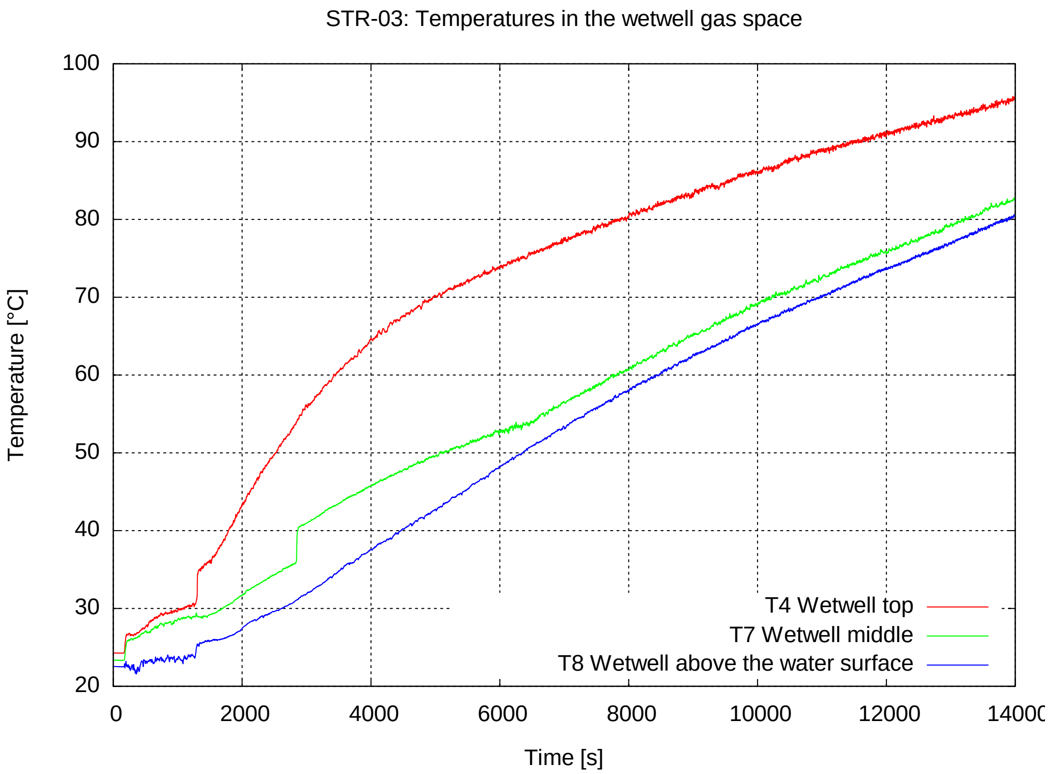

Figure 6. Behavior of temperatures in the gas space of the wet well in STR-03.

The highest temperature rise experienced in any of the stratification experiments by T4 is about 72 °C (from the initial value of 23 to 95 °C). The largest temperature difference between the wet well top and 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 at the end of the discharge.

4.2 THERMAL STRATIFICATION AND MIXING IN THE WET WELL POOL

4.2.1 Experiments with no mixing effects (STR-02, STR-03, STR-04)

In STR-02, STR-03 and STR-04, the heat-up process of the wet well water volume follows the same pattern. Measurements clearly below the blowdown pipe outlet elevation (T501 … T505) indicate almost no change in temperature throughout the experiments. Measurements slightly below the pipe outlet (T506 … T507) indicate a small or moderate increase in temperature, while T508, just below, and T509 … T516, above the pipe outlet elevation, show an almost linear increase starting from the beginning of the pure steam discharge period. In these three experiments, the steam discharge into the pool was not strong enough to cause any mixing effects to occur clearly below the pipe outlet elevation. Figure 7 presents the vertical temperature distribution in STR-03 during the heat-up phase.

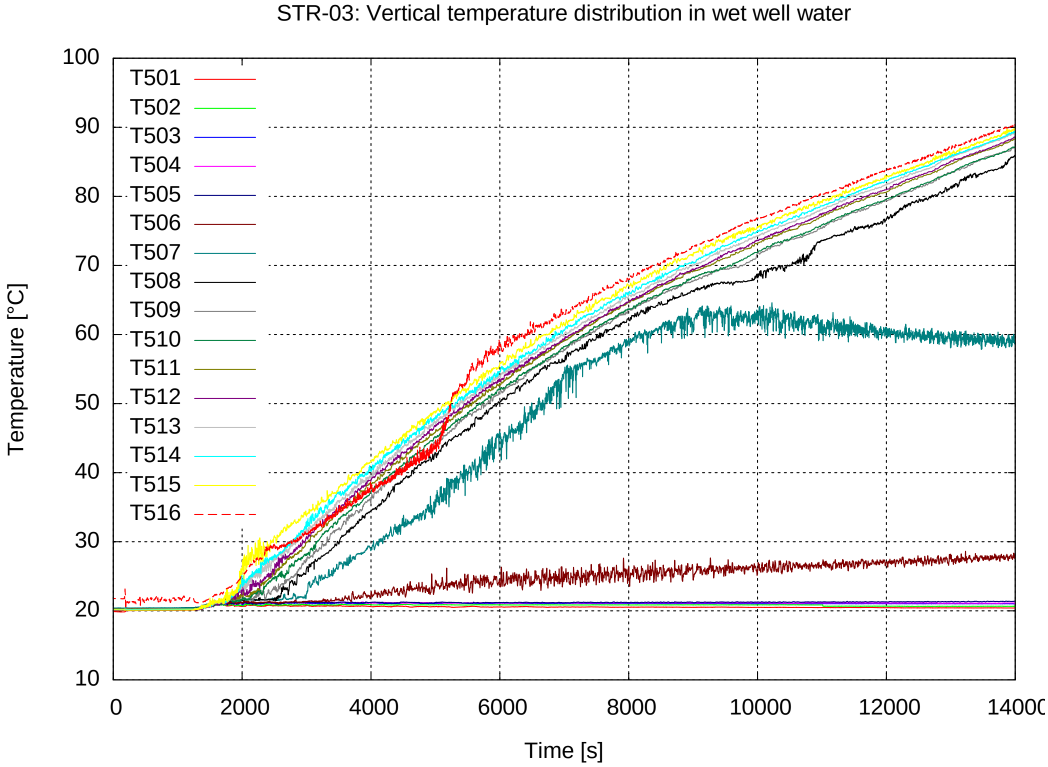

Figure 7. Vertical temperature distribution of wet well water in STR-03.

In STR-02 and STR-03, the temperature difference between T509 and T516 is only about 5 °C at the end of the discharge. This indicates that the top half of the water volume is practically not stratified. In STR-04, the temperature difference of T509 and T516 is about 15 °C and water layers with some kind of different temperatures do exist. This is due to the fact that the very small steam discharge rate in STR-04 is not able to mix the water volume above the pipe outlet elevation at all and slight stratification can develop. In STR-02 and STR-03, the small mixing effect by steam discharge is enough to prevent clear stratification of water above the pool mid-elevation. Furthermore, in STR-02 and STR-03 a small heat-up effect can be noticed in measurement T506 (705 mm from the bottom) but in STR-04 the first measurement from the bottom upwards to indicate some kind of change is T507 (887 mm from the bottom).

4.2.2 Experiments with mixing effects (STR-05, STR-06)

As seen above, with low steam flow rates the stratification process starts almost immediately after the initiation of the experiment and intensifies as the fraction of non-condensable gas among the blowdown pipe flow diminishes. The situation changes with higher flow rates (STR-05 and STR-06). The mixing effect of steam discharge delays significantly the start of the stratification process. Practically, the whole water inventory of the wet well mixes and heats up uniformly until the pool bulk temperature exceeds 45–50 °C, see Figure 8. Only after that, the stratification process starts, in STR-06 slightly before than in STR-05 due to smaller flow.

However, the stratification process differs from that of the low flow experiments. Now, the water layers clearly below the pipe outlet elevation are also affected. Instead of having a uniform temperature in the bottom third of the pool, as in STR-02…STR-04, there can now be over a 30 °C temperature difference between T501 and T507. Measurements above (T509 … T516) and just below (T508) the pipe outlet indicate again almost a linear rise until the end of the discharge.

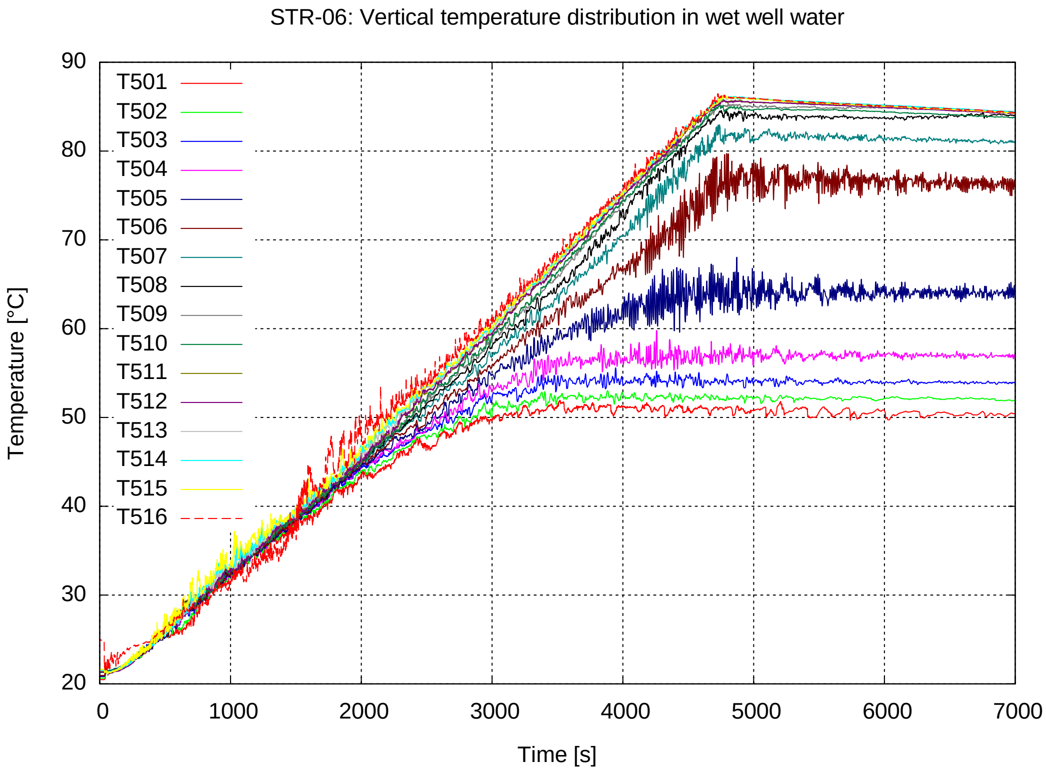

Figure 8. With higher flow rates thermal stratification starts only after the pool water has warmed up (Steam discharge stopped at about 4750 s).

Although the steam discharge rate is strong enough to cause some kind of mixing during the first two thousand seconds of the heating periods in STR-05 and STR-06, it is not able prevent stratification (or to mix the already stratified layers) after the pool bulk temperature has risen to about 50 °C. Driving forces for mixing disappear along the slowing down of the DCC process due to increasing water temperature. In Table 4, some measured key values and observations related to stratification and mixing are listed from STR-02 … STR-06.

.

Table 4. Stratification related observations from STR-02… STR-06

Exp.	Steam flow rate [g/s]	Final top layer temperature [°C]	Temperature difference between T501 and T516 [°C]	Stratification at the bottom five elevations (T501… T505)	Stratification at the top eight elevations (T509… T516)
STR-02	72-127	~ 91	~ 70	No	No
STR-03	50-100	~ 92	~ 70	No	No
STR-04	42-105	~ 74	~ 53	No	Yes
STR-05	300-425	~ 86	~ 30	Yes	No
STR-06	190-250	~ 87	~ 36	Yes	No

4.3 BOUNDARY LAYERS

In the earlier stratification experiments with the open POOLEX facility it was noticed from video clips that a boundary layer develops on the blowdown pipe outer surface due to heat conduction through the pipe wall and due to a film of warm water rising upwards along the pipe from the pipe mouth to the pool surface. To measure this it was decided to install a set of seven horizontally positioned thermocouples with a 2 mm interval from each other close to the pipe surface for the PPOOLEX stratification experiments. Another set of thermocouples was installed on the wet well inner wall. Both sets were half way between the pipe outlet and water surface.

The strongest indication of the presence of a boundary layer on the pipe outer surface can be found from STR-04, where the steam discharge rate was the smallest. From the measurement curve of T601, at two millimeters distance from the pipe wall, it can be concluded that a rising film of water, hotter than the ambient temperature, exists almost throughout the whole heat-up process (Figure 9). The film starts to develop at the same time (just before 2000 seconds) as the overall stratification process and reaches its peak (regarding the temperature difference) between 4000 and 6000 seconds. The six other measurements at 4 to 14 mm distance from the pipe wall indicate clearly smaller increase compared with the ambient temperature. All measurements show strong oscillations (noise) revealing the constant changes in the thicknesses of the layers.

In STR-05 and STR-06, where the discharge rate was higher, no constant water film of clearly higher temperature can be observed. However, the same kind of oscillation is present in the temperature measurements as in the low flow cases. The amplitude of the highest peaks can be over 20 °C. It can be assumed that the developing film is constantly broken due to mixing processes caused by the higher discharge flow.

On the wet well inner wall, a thin layer of water, colder than the ambient temperature, develops during the STR-04 experiment. Heat losses through the wet well wall to the atmosphere of the laboratory contribute to this. However, the temperature difference between the measurement closest to the wall and the rest of the set of seven thermocouples seems to be less than one degree (Figure 10). In the other experiments, the difference is even smaller.

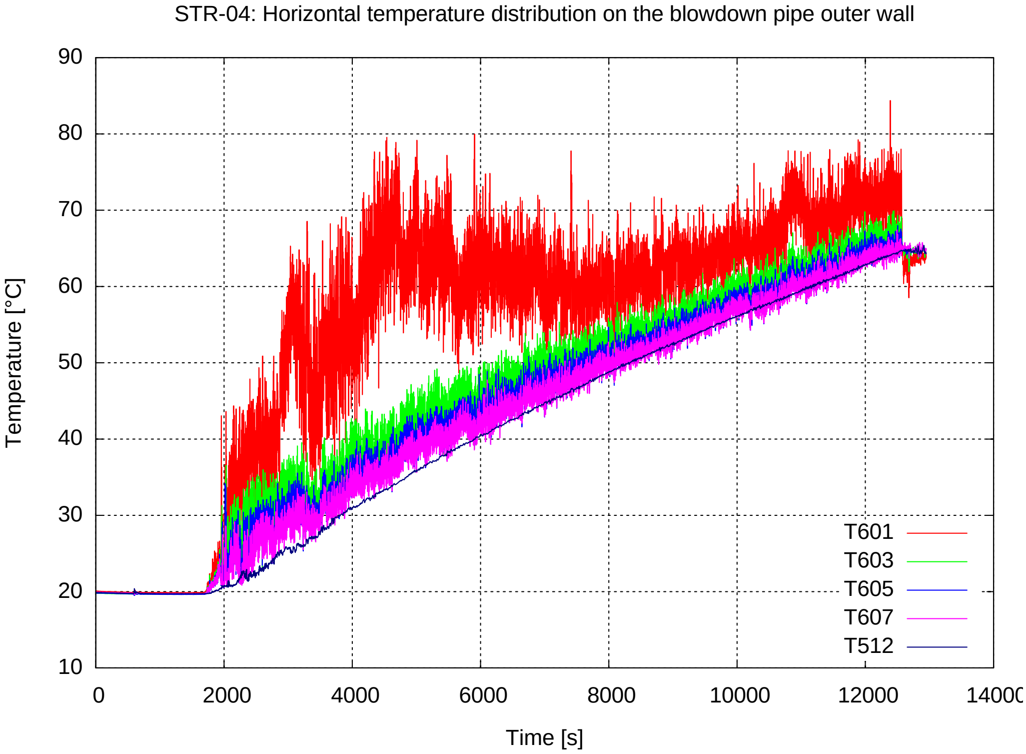

Figure 9. Temperature distribution on the blowdown pipe outer wall at 2, 6, 10 and 14 mm distance from the pipe wall at the elevation of 555 mm above the pipe outlet. Reference ambient temperature T512 is from a 35 mm lower elevation. (Steam discharge period 570…12550 s).

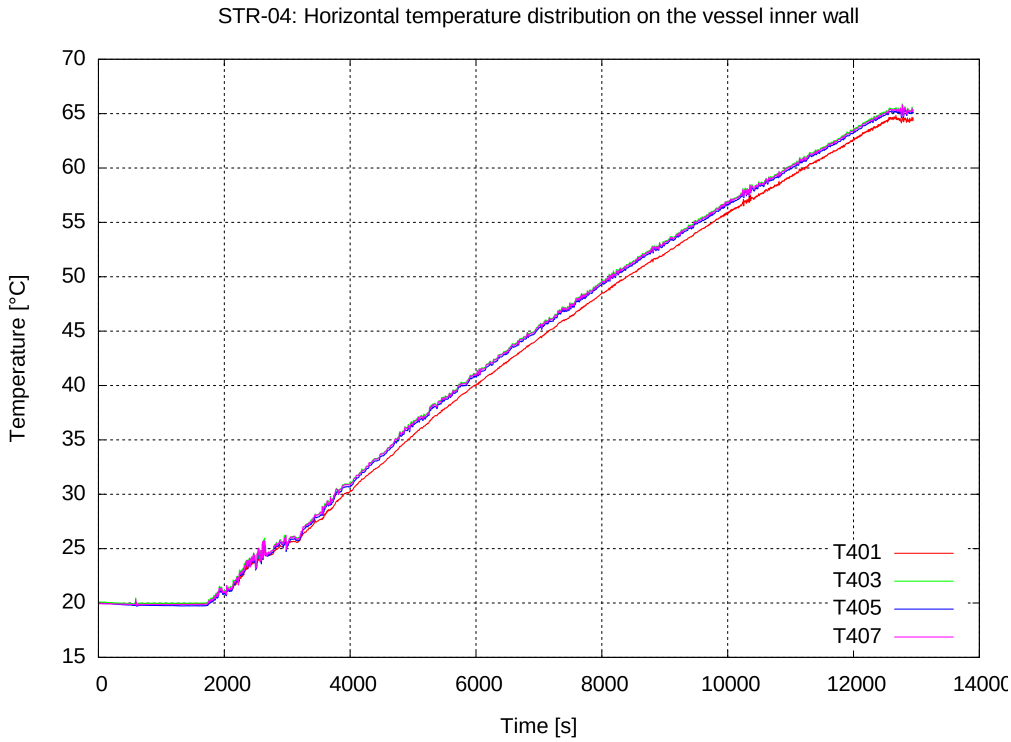

Figure 10. Temperature distribution on the wet well inner wall at 2, 6, 10 and 14 mm distance from the wall surface at the elevation of 550 mm above the pipe outlet.

In STR-05 and STR-06, small oscillations can be observed in the temperature measurements on the wet well wall. Their amplitude is 3–4 °C at the most and decreasing towards the end of the experiments. The reason for these temperature changes is probably an internal flow pattern induced by the higher steam discharge rate used in these two experiments. Since all seven thermocouples indicate the oscillations simultaneously, it can be assumed that the thickness of the water layer involved in this process is over 14 mm.

4.4 COOLING PERIOD

Since the PPOOLEX test facility is not thermally insulated, the facility structures, the water inventory and the gas atmosphere start to cool-off immediately due to heat losses when the heat-up process is terminated. Recording of the cooling phase was included in three of the heat-up experiments (STR-02, STR-03 and STR-06). Furthermore, STR-01 was a plain cool-off experiment with 50 °C tap water and no steam discharge.

The final conditions after the heat-up process dictate the general trend of the cooling period. In STR-02 and STR-03, there were no mixing effects during the heat-up period and therefore the bottom third of the wet well water volume remained in the original temperature of 20 °C throughout the experiments. In these cases, the temperatures measured by T501…T506 increase due to thermal diffusion from the higher elevations during the cooling phase. The rest of the measurements have a decreasing trend all the time. The layers above the pipe outlet elevation (T509…T516) with a uniform temperature at the end of the heat-up period decrease as a group. From the two mid-elevation measurements T508 joins the top layer values in a few thousand seconds but T507 not until at the end of the cooling period when the temperatures have decreased close to 30 °C (Figure 11).

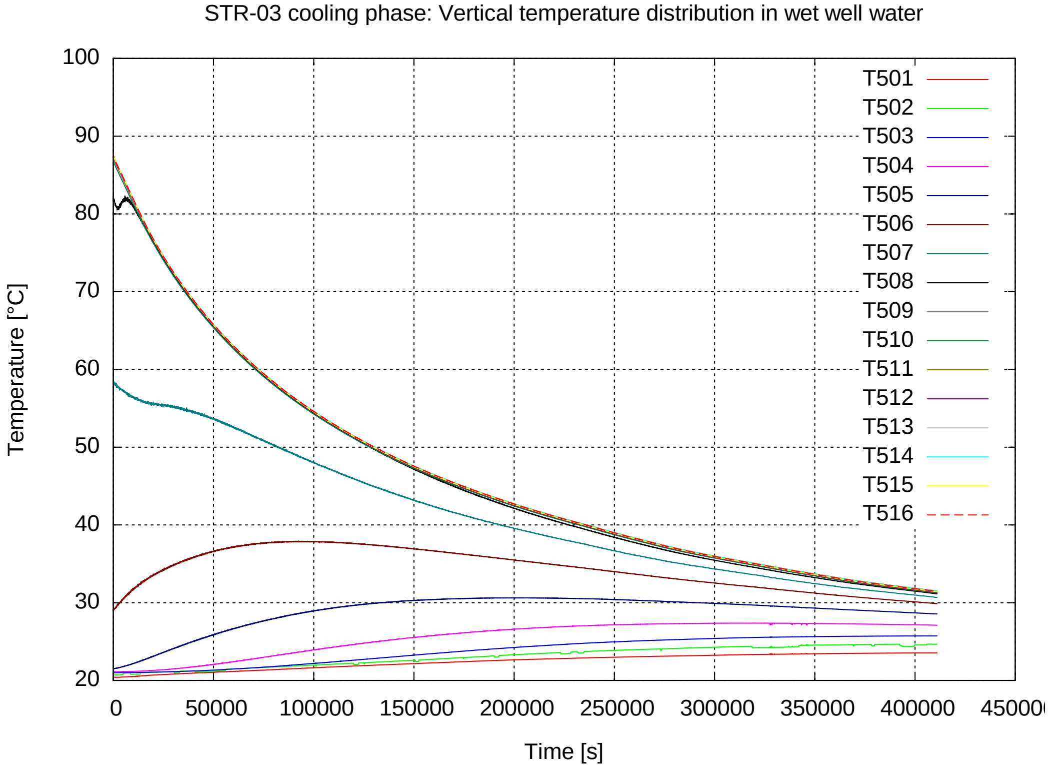

Figure 11. Cooling phase in the wet well water volume in STR-03.

In STR-06, mixing effects during the heat-up period prevented stratification until the pool bulk temperature was 45-50 °C. Therefore, the initial conditions in the beginning of the cooling phase are different from those in STR-02 and STR-03. Even at the pool bottom the temperature is over 50 °C and the whole bottom half of the water volume is stratified. The top layers are at a uniform temperature. Now, all measurements have a decreasing trend from the beginning of the cooling period. Thermal diffusion downwards is strongest from the top layers and as the cooling phase proceeds the bottom half curves join the decreasing group of the top layer curves one by one (Figure 12). A couple of mid-elevation measurements experience a short increasing trend before they join the top layer group.

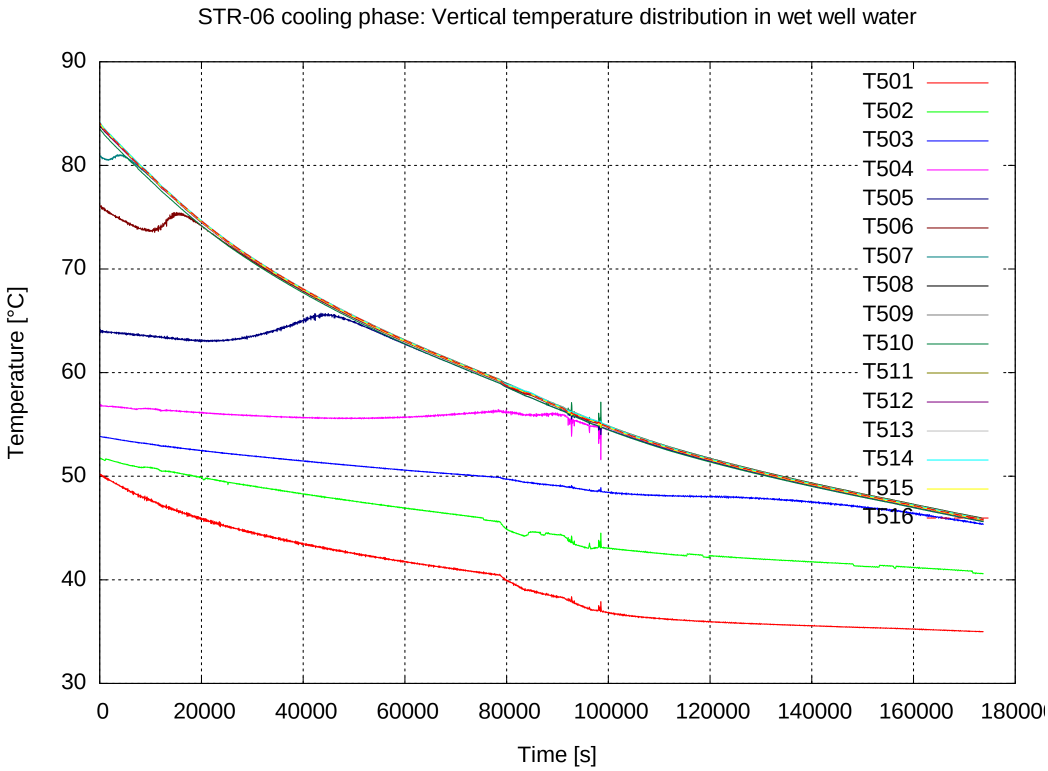

Figure 12. Cooling phase in the wet well water volume in STR-06.

In the gas space of the wet well, the behavior is very much like the one in the water volume. The cool-off rate and the form of the curves are similar. In the beginning of the cooling period, the gas space temperatures are slightly below the top layer temperature of the water. In a few thousand seconds the three measured gas space temperatures join each other and then decrease with a gently sloping curve keeping the same difference to the values of the top water layer throughout the cooling phase.

4.5 STR-01

In STR-01, the wet well pool was filled with 50 °C tap water and let to cool down for almost 45 hours. Because isothermal conditions prevailed in the beginning of the cool down period there was no driving force for thermal diffusion. Only heat losses to the surrounding laboratory dictated the cool down rate.

Measurement T501, the lowest thermocouple of the sixteen measurements in the vertical rod, indicates faster cool down than the other thermocouples (Figure 13). After 60000 seconds, also T502 parts from the others but the difference is only about one degree at the end of the recorded test. Other thermocouples of the measurement rod indicate practically uniform temperatures throughout the whole cooling process. Faster cool down of the bottom region is verified by measurement T6, which is located at the pool bottom but is separate from the thermocouples in the vertical rod. Both T501 and T6 indicate about 17 °C decrease in temperature during the 45 hour period while T502…T516 show only a decrease of 13-14 °C.

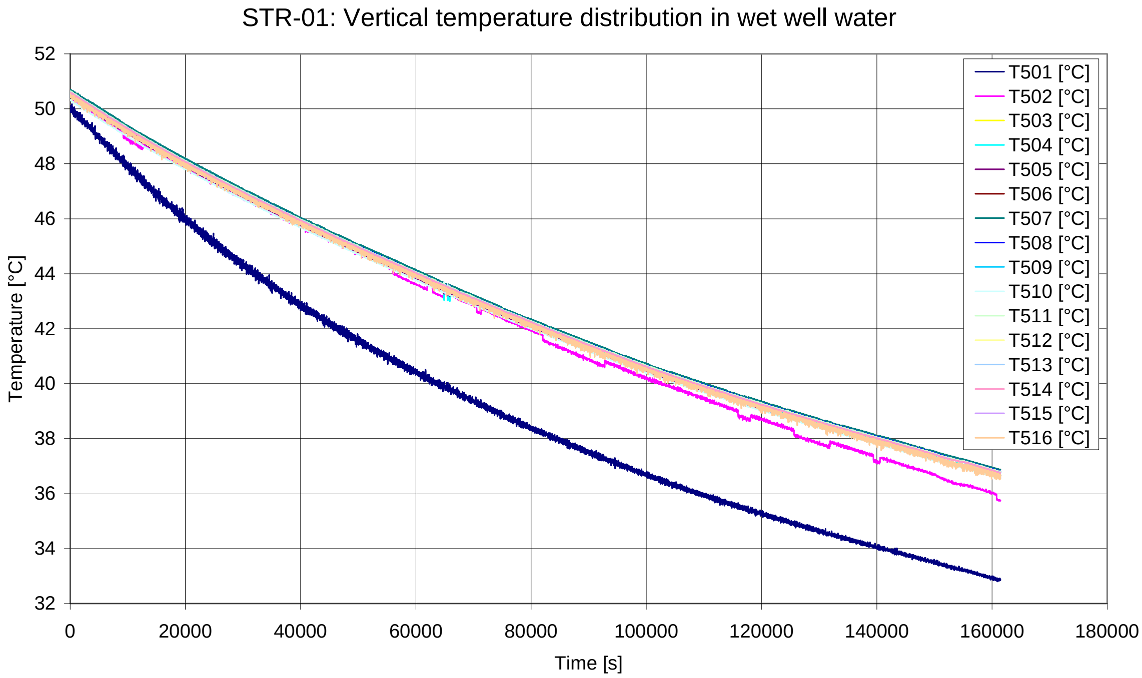

Figure 13. Cooling of water volume in STR-01.

4.6 COMPARISON TO POOLEX STRATIFICATION EXPERIMENTS

In the preceding research project with the open pool test facility (POOLEX), a series of thermal stratification experiments was also carried out [7]. The test conditions differed somewhat from those used in the current series since the initial water level and temperature were higher. Very small steam flow rates were used to allow the stratification to develop freely. No significant bubble formation at the pipe outlet was observed. In the current experiments, the flow rate of STR-04 corresponds best to that used in the POOLEX series. Due to the initial gas atmosphere in the dry well there is, however, a larger amount of non-condensables present among the flow during the first phase of the discharge in the PPOOLEX experiments than in the POOLEX experiments.

The closed design of the PPOOLEX facility changes the situation regarding the behavior of the water surface and gas space. Free convection to the atmosphere of the laboratory was possible in the POOLEX experiments but is now prevented. Only heat losses through the test facility walls are possible. Furthermore, heat input from the hot dry well compartment through the intermediate floor into the gas space of the wet well adds thermal loading there.

The overall behavior of the water volume both during the heating and cooling phase is similar with the two facilities. Due to a little bit smaller steam flow rate the initial start-up of the stratification process at different elevations takes slightly longer in the POOLEX series. In addition, some differences can be observed in the behavior of the top elevations. In the PPOOLEX series the uppermost temperature measurements indicate almost uniform values throughout the experiments, while in the POOLEX series they show that stratification can take place also in the top elevations, if the test conditions are suitable. The behavior of the water volume below the blowdown pipe outlet elevation is identical in the small flow rate cases of the both experiment series. There are no mixing effects and therefore the temperatures at the bottom half don't change at all during the experiments. Thermal diffusion from higher elevations downwards is evident in both test facility versions during the cooling phase, since temperatures rise at the lower elevations without any heat input from outside.

5 SUMMARY AND CONCLUSIONS

This report summarizes the results of the thermal stratification experiments in 2008 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 code to predict stratification and mixing phenomena and to study thermohydraulic loading of the wet well structures.

Altogether six experiments were carried out. The first one was a cool down test with 50 °C tap water without any heat input. The rest included heat-up periods of several thousand seconds by steam injection into the dry well compartment and from there into the wet well water pool. The initial water bulk temperature was 20 °C. The cooling period was recorded in three experiments.

A large difference between the pool bottom and top layer temperatures was measured when small steam flow rates were used. With higher flow rates the mixing effect of steam discharge delayed the start of stratification until the pool bulk temperature exceeded 50 °C. The stratification process was also different in these two cases. With a small flow rate stratification was observed only above and slightly below the blowdown pipe outlet elevation. With a higher flow rate over a 30 °C temperature difference between the pool bottom and pipe outlet elevation was measured. Elevations above the pipe outlet indicated almost linear rise until the end of steam discharge.

During the cooling periods the six measurements closest to the bottom first had an increasing trend although there was no heat input from outside. This was due to thermal diffusion downwards from the higher elevations.

Heat-up in the gas space of the wet well was quite strong, first due to compression by pressure build-up and then by heat conduction from the hot dry well compartment via the intermediate floor and test vessel walls and by convection from the top layers of the hot pool water. The gas space temperatures also stratified. Temperatures increased most on the topmost measurement elevation. Towards the end of the experiments the temperature difference between the water surface and the top elevation had a slightly decreasing trend but was still usually over 15 °C at the end of the discharge.

The presence of a boundary layer on the blowdown pipe outer surface was verified by set horizontally installed thermocouples with a two millimeters interval. A rising film of water, hotter than the ambient temperature, existed on the pipe surface almost throughout the whole heat-up process. The film started to develop at the same time as the overall stratification process and reached its peak (regarding the temperature difference) between 4000 and 6000 seconds from the beginning of the experiments. Oscillations in the measured temperature revealed that the thickness of the boundary layer changed along the experiments.

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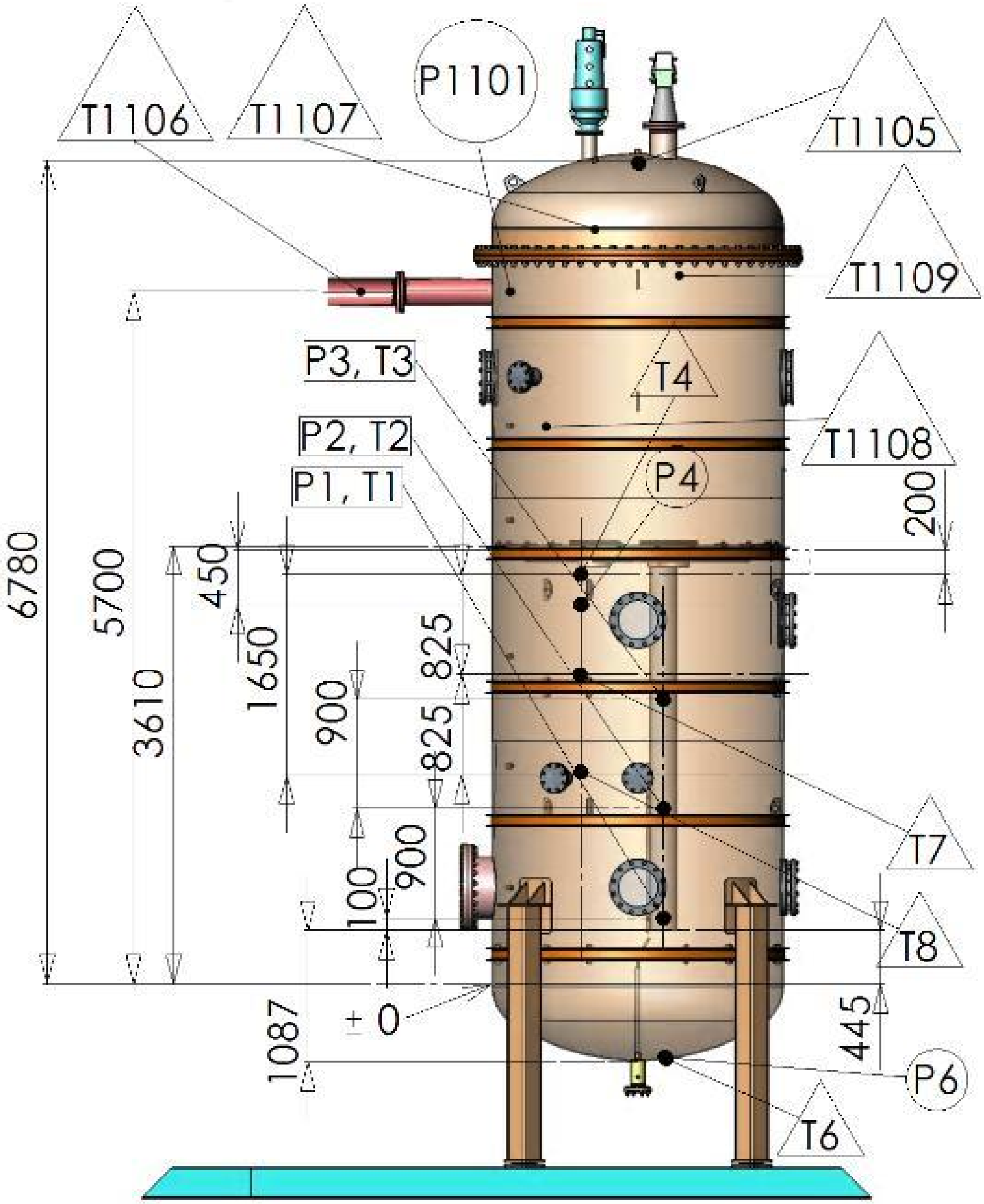
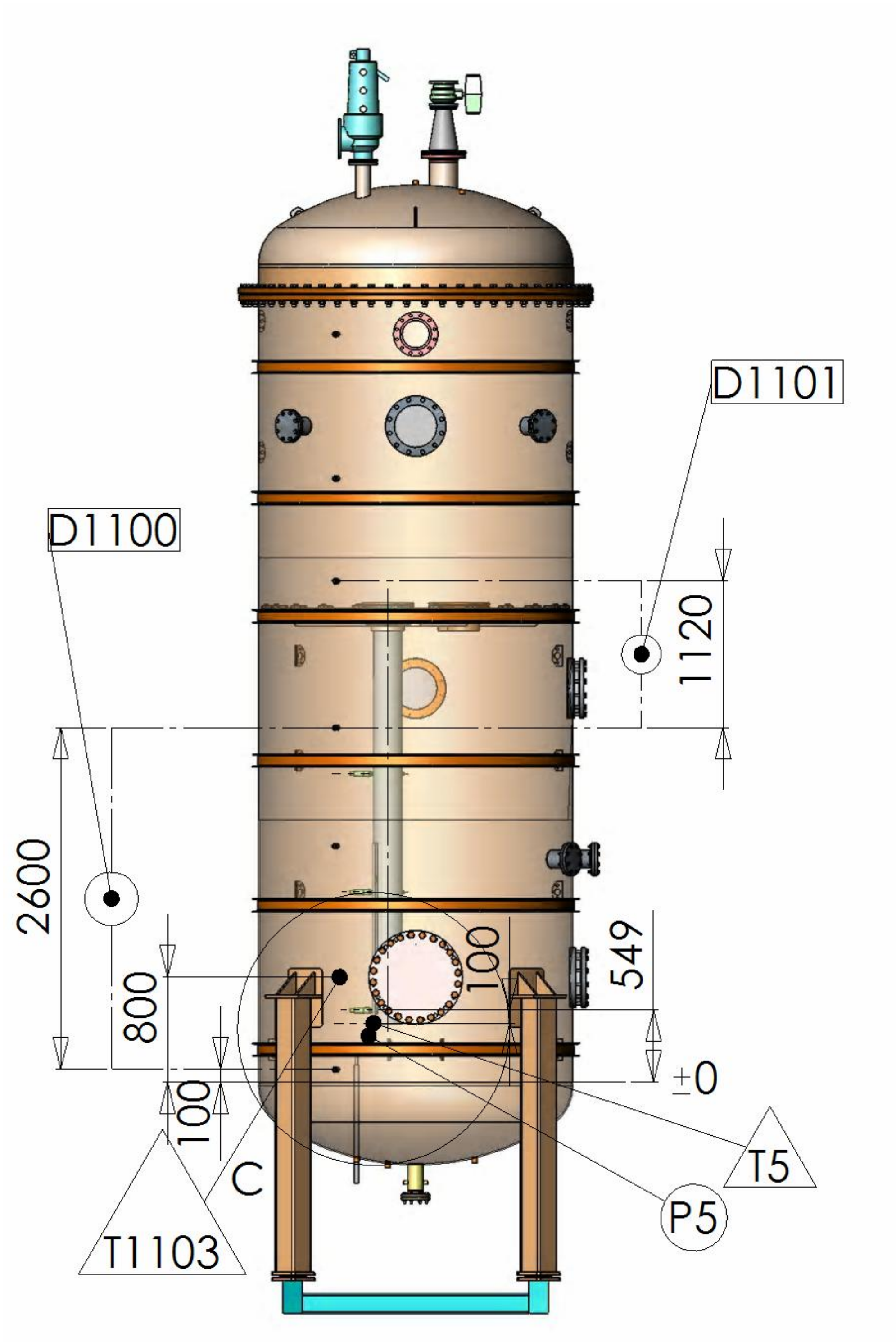
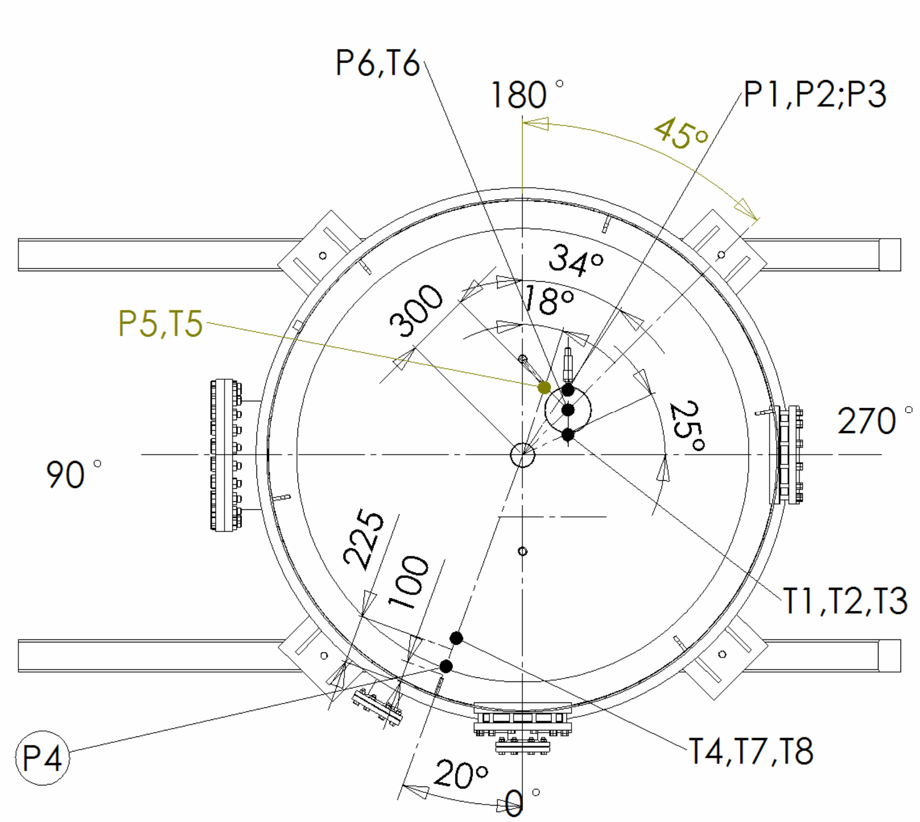
APPENDIX 1: INSTRUMENTATION OF THE PPOOLEX TEST FACILITY



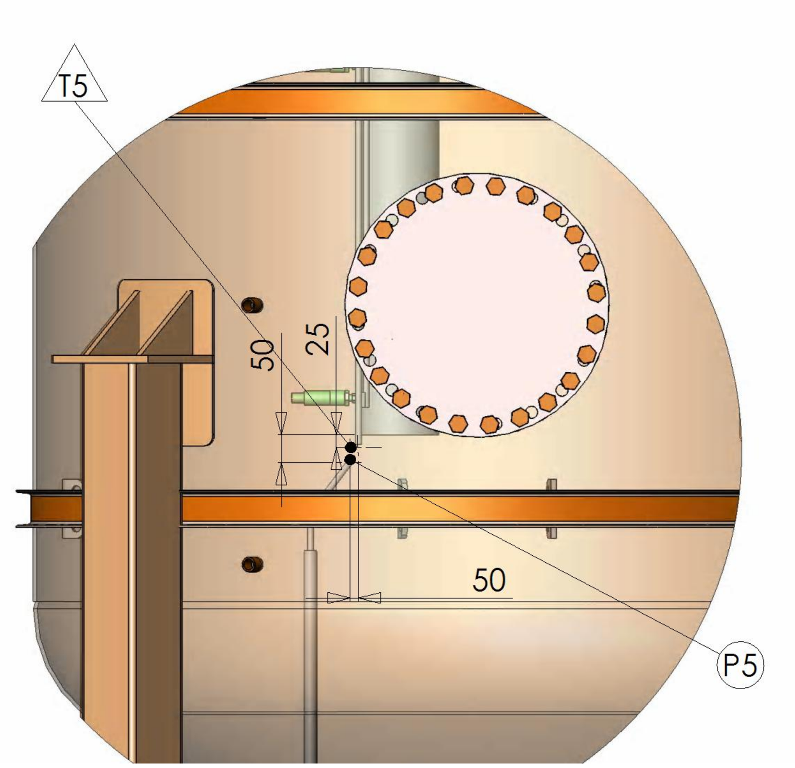
Test vessel measurements.



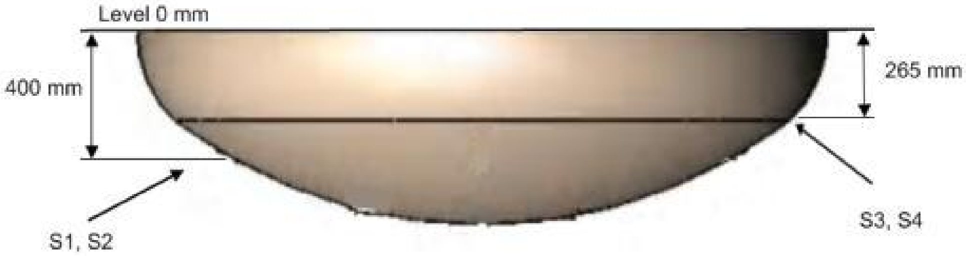
Test vessel measurements.

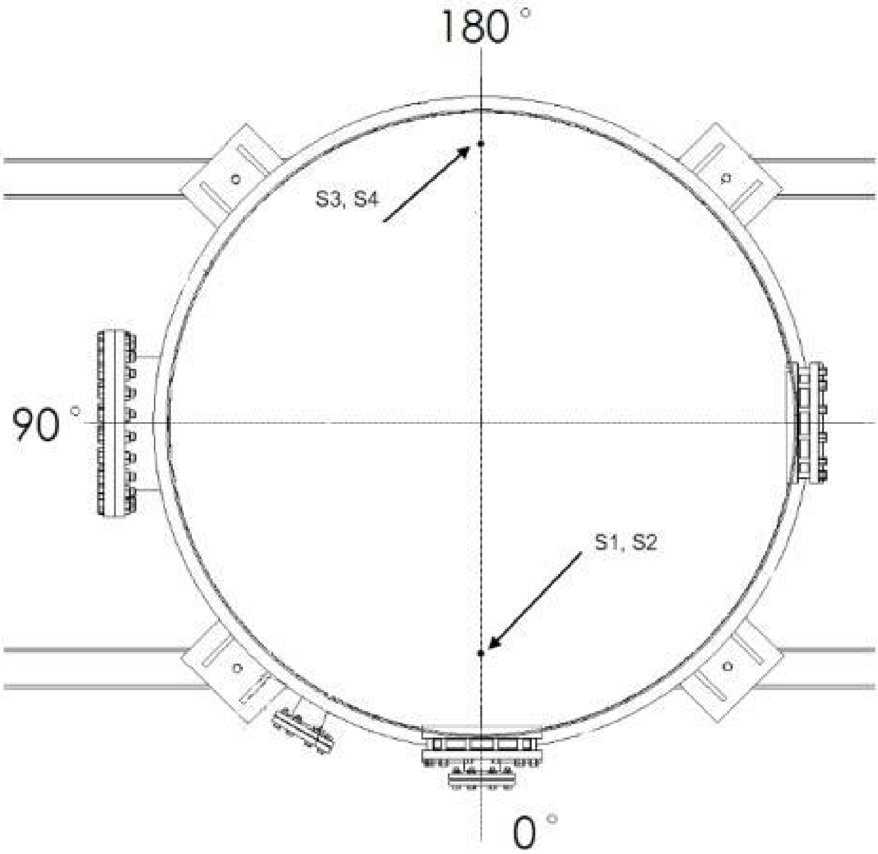


Measurement directions.



Pressure and temperature at the blowdown pipe outlet.





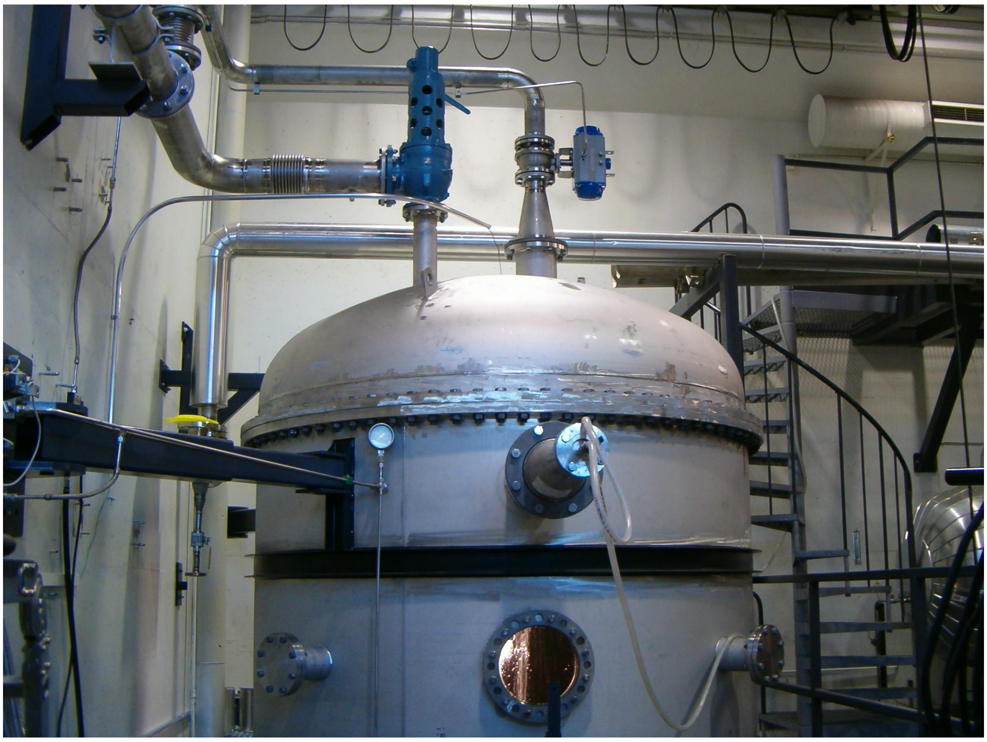
Strain gauges on the outer wall of the pool.

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
Temperature	T2	1445	245	Blowdown pipe	±1.8 °C
Temperature	T3	2345	245	Blowdown pipe	±1.8 °C
Pressure	P4	3160	20	Wet well gas space	±0.4 bar
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	-1045	225	Wet well bottom	±0.5 bar
Temperature	T6	-1045	225	Wet well bottom	±1.8 °C
Temperature	T7	2585	20	Wet well	±1.8 °C
Temperature	T8	1760	20	Wet well	±1.8 °C
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	T407	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	945	30	Wet well	±1.8 °C
Temperature	T602	945	30	Wet well	±1.8 °C
Temperature	T603	945	30	Wet well	±1.8 °C
Temperature	T604	945	30	Wet well	±1.8 °C
Temperature	T605	945	30	Wet well	±1.8 °C
Temperature	T606	945	30	Wet well	±1.8 °C
Temperature	T607	945	30	Wet well	±1.8 °C
Pressure	P1101	5700	90	Dry well	±0.06 bar

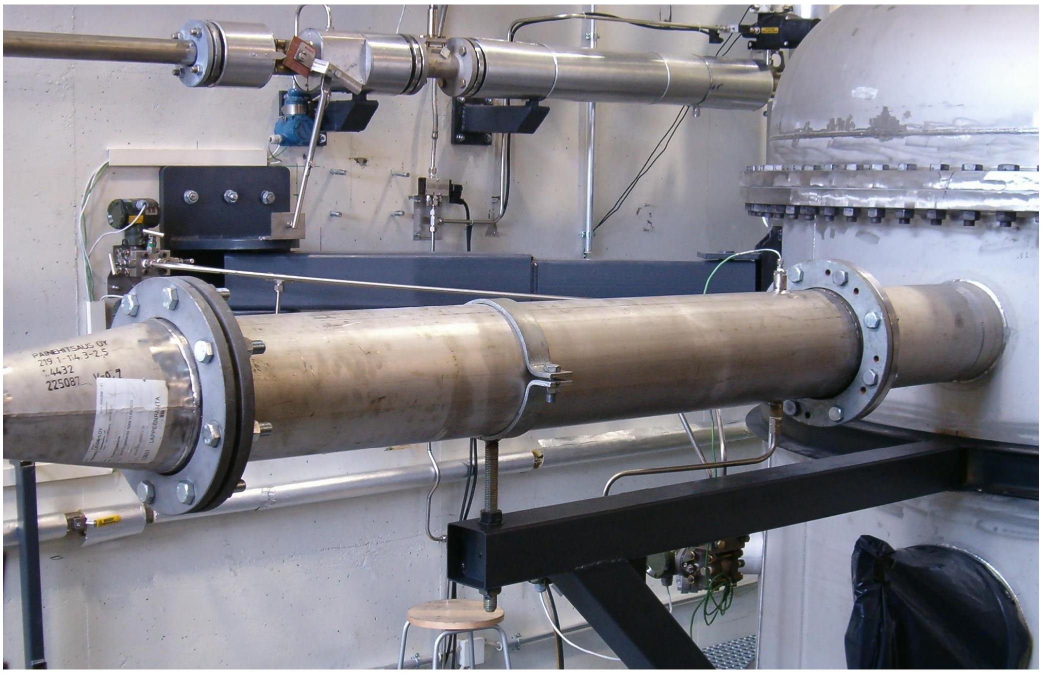
Temperature	T1104	-245	180	Outside wall	±2.9 °C
Temperature	T1105	6780	-	Dry well top	±3.2 °C
Temperature	T1107	6085	45	Dry well middle	±3.2 °C
Temperature	T1108	4600	120	Dry well bottom	±3.2 °C
Temperature	T1109	5790	225	Dry well lower middle	±3.2 °C
Temperature	T1110	6550	90	Dry well outer wall	±1.8 °C
Temperature	T1111	6300	270	Dry well outer wall	±1.8 °C
Temperature	T1112	4600	90	Dry well outer wall	±1.8 °C
Flow rate	F1101	5700	-	Inlet plenum	±99 g/s
Pressure	P1102	5700	-	Inlet plenum	±0.06 bar
Temperature	T1106	5700	-	Inlet plenum	±3.2 °C
Pressure	P1103	-	-	Air/steam line	±0.06 bar
Pressure diff.	D1100	100-2700	120	Wet well	±0.06 m
Pressure diff.	D1101	2700-3820	120	Across the floor	±0.10 bar
Flow rate	F1100	-	-	Steam line	±4.9 l/s
Temperature	T1102	-	-	At the steam line vortex	±3.6 °C
Pressure	P1100	-	-	At the steam line vortex	±0.5 bar
Flow rate	F9001	-	-	Air line	±2.7 l/s / ±30 g/s
Temperature	T9001	-	-	At the air line vortex	±3.0 °C
Pressure	P9002	-	-	At the air line vortex	±15.6 kPa
Pressure	P9000	-	-	Air tank 1	±10.8 kPa
Temperature	T9000	-	-	Air tank 1	±3.0 °C
Pressure	P9001	-	-	Air tank 2	±10.8 kPa
Temperature	T0460	-	-	Air tank 2	±3.0 °C
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	-	-	Below pool bottom	c
Steam partial pressure	X1102	2345		Blowdown pipe	Temperature
Valve position	X1100	-	-	Steam line	Not defined

Measurements in the PPOOLEX facility.

APPENDIX 2: TEST FACILITY PHOTOGRAPHS



Dry well compartment and relief valves.



Inlet plenum.

Blowdown pipe and intermediate floor.

Pressure and temperature measurements at the blowdown pipe outlet.

Title	PPOOLEX Experiments on Thermal Stratification and Mixing
Author(s)	Markku Puustinen, Jani Laine, Antti Räsänen
Affiliation(s)	Lappeenranta University of Technology, Finland Nuclear Safety Research Unit
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No. of illustrations	13 + 9
No. of references	7

Abstract

The results of the thermal stratification experiments in 2008 with the PPOOLEX test facility are presented. PPOOLEX is a closed vessel divided into two compartments, dry well and wet well. Extra temperature measurements for capturing different aspects of the investigated phenomena were added before the experiments. The main purpose of the experiment series was to generate verification data for evaluating the capability of GOTHIC code to predict stratification and mixing phenomena.

Altogether six experiments were carried out. Heat-up periods of several thousand seconds by steam injection into the dry well compartment and from there into the wet well water pool were recorded. The initial water bulk temperature was 20 °C. Cooling periods of several days were included in three experiments.

A large difference between the pool bottom and top layer temperature was measured when small steam flow rates were used. With higher flow rates the mixing effect of steam discharge delayed the start of stratification until the pool bulk temperature exceeded 50 °C. The stratification process was also different in these two cases. With a small flow rate stratification was observed only above and just below the blowdown pipe outlet elevation. With a higher flow rate over a 30 °C temperature difference between the pool bottom and pipe outlet elevation was measured. Elevations above the pipe outlet indicated almost linear rise until the end of steam discharge.

During the cooling periods the measurements of the bottom third of the pool first had an increasing trend although there was no heat input from outside. This was due to thermal diffusion downwards from the higher elevations.

Heat-up in the gas space of the wet well was quite strong, first due to compression by pressure build-up and then by heat 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. The gas space temperatures also stratified.

The presence of a boundary layer on the blowdown pipe outer surface was verified by a set of horizontally installed thermocouples with a two millimeters interval. A rising film of water, hotter than the ambient temperature, existed on the pipe surface almost throughout the whole heat-up process.

Key words condensation pool, steam/air blowdown, thermal stratification

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