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Additional Sparger Tests in PPOOLEX with Reduced Number of Injection Holes

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Abstract

This report summarizes the results of the two sparger pipe tests (SPA-T1 and SPA-T7) carried out in the PPOOLEX test facility at LUT in 2015. Steam was blown through the vertical DN65 sparger type blowdown pipe to the condensation pool filled with sub-cooled water.

The main objective of the tests was to obtain additional data for the development of the Effective Momentum Source (EMS) and Effective Heat Source (EHS) models to be implemented in GOTHIC code by KTH. The test parameters were selected by KTH on the basis of pre-test simulations and analysis of the results of the earlier sparger tests in PPOOLEX. As opposed to the earlier tests only one row of injection holes at the sparger head (SPA-T1) or the holes of the load reduction ring (SPA-T7) were now used for steam injection. Both tests had two stratification periods and two mixing periods. In addition SPA T1 had an extra stratification period at the end of the test.

During the stratification periods the used steam injection flow rate was in the range of 30-45 g/s (75-112 kg/m2s). With these kind of mass fluxes steam flowed through the injection holes of the sparger as small jets and condensed mainly outside the sparger pipe. Because no chugging kind of phenomenon existed and the steam jets were too weak to create much turbulence in the pool, suitable conditions for thermal stratification to occur prevailed.

When the steam injection was vertically downwards from the LRR the transition region between the cold and warm pool water was deeper in the pool than in the horizontal injection case. The vertical length of the transition region was also longer in the LRR case.

Complete mixing was achieved with both tested flow modes, oscillatory cone jet mode (SPA-T1) and oscillatory bubble mode (SPA-T7). In the earlier tests with all the injection holes of the sparger head unblocked a considerably larger flow rate was not enough to mix the pool. Then the flow mode was different and not enough momentum and internal circulation were created for complete mixing to happen. Mixing was observed only above and a short distance below the sparger head outlet elevation.

Key words

condensation pool, steam blowdown, sparger, mixing

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The transition region, where the shift from cold to warm pool water occurred, was practically just below the sparger head elevation when steam injection was through the sparger head. Furthermore, the vertical length of the region was very short and temperatures below that elevation remained almost at their initial value.

When the steam injection was vertically downwards from the LRR the transition region between the cold and warm pool water was deeper in the pool than in the horizontal injection case. The vertical length of the transition region was also longer in the LRR case.

Complete mixing was achieved with both tested flow modes, oscillatory cone jet mode (SPA-T1) and oscillatory bubble mode (SPA-T7). In the earlier tests with all the injection holes of the sparger head unblocked a considerably larger flow rate was not enough to mix the pool. Then the flow mode was different and not enough momentum and internal circulation were created for complete mixing to happen. Mixing was observed only above and a short distance below the sparger head outlet elevation.

Distribution

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NOMENCLATURE

A	area
D	pressure difference measurement
F	flow rate measurement
P	pressure measurement
S	strain measurement
T	temperature measurement

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
EMS	effective momentum source
EXCOP	experimental studies on containment phenomena project
KTH	Kungliga Tekniska Högskolan
LRR	load reduction ring
LOCA	loss-of-coolant accident
LUT	Lappeenranta University of Technology
MSLB	main steam line break
NKS	Nordic nuclear safety research
PACTEL	parallel channel test loop
POOLEX	condensation pool experiments project
PPOOLEX	pressurized condensation pool experiments project
SAFIR	Safety of Nuclear Power Plants - Finnish National Research Programme
SPA	sparger experiment series
SRV	safety/relief valve
TC	thermocouple
VTT	Technical Research Centre of Finland
VYR	State Nuclear Waste Management Fund

1 INTRODUCTION

A pressure suppression pool (PSP) of a BWR reactor containment serves as a heat sink and steam condenser during a postulated main steam line break (MSLB) or loss of coolant accident (LOCA) inside the containment or during safety relief valve (SRV) opening in normal operations. It thus prevents containment pressure build-up when steam released from the reactor vessel is vented through the blowdown pipes (in case of MSLB and LOCA) or through the spargers (in case of SRV operation) to the pool.

Different phenomena inside the drywell and wetwell compartments of BWR containment during steam discharge has been extensively studied in the PPOOLEX test facility at LUT and simulated with computer codes during recent years in the framework of the national research programmes on nuclear power plant safety (SAFIR, SAFIR2014) as well as via participation to NORTHNET RM3 and NKS research projects in co-operation with VTT and Kungliga Tekniska Högskolan (KTH). Research topics have included, for example, dynamic loads caused to PSP structures by direct contact condensation (DCC), behavior of parallel blowdown pipes during the chugging flow mode, effect of blowdown pipe outlet design on structural loads, wall condensation in the drywell and development/break-up of thermal stratification in the PSP [1…10].

The current SAFIR2018/INSTAB project as well as the related NKS-COPSAR and NORTHNET RM3 research efforts aim to broaden the database to cover experiments with SRV spargers, residual heat removal (RHR) system nozzles, strainers and containment spray systems. Calculation models and numerical methods including CFD and system codes are developed and validated on the basis of the PPOOLEX experiment results in the SAFIR2018 NURESA and COVA projects at VTT and within the NORTHNET RM3 program at KTH. Also analytical support is provided for the experimental part by pre- and post-calculations of the experiments.

As a result of steam venting into the suppression pool the coolant temperature in the pool gradually increases. With certain flow modes a thermally stratified condition could develop where the pool's surface temperature is higher than the pool bulk temperature. This leads to a reduction of the pool's pressure suppression capacity because the pool surface temperature determines the steam partial pressure in the wetwell gas space. An increase of the pool's surface temperature due to stratification can therefore lead to a significant increase in containment pressure if mixing of the pool coolant inventory fails [11]. Pool mixing can occur due to steam injection itself if the injection flow mode changes as a result of increasing or decreasing steam flow rate. Mixing can be achieved also with the help of plant systems designed for that purpose or as a result of water suction from the pool by the Emergency Core Cooling System (ECCS) pumps.

KTH has developed the Effective Heat Source (EHS) and Effective Momentum Source (EMS) models for steam injection through a vertical pipe submerged in a pool and proposed them to be used for simulation of thermal stratification and mixing during a steam injection into a large pool of water [12]. These models have been implemented in GOTHIC® software and validated against POOLEX and PPOOLEX tests carried out at LUT. Excellent agreement in averaged pool temperature and water level in the pool between the experiment and simulation has been achieved. The development of thermal stratification and mixing of the pool are also well captured in the simulations. The EMS and EHS models will be available to be implemented also in the APROS containment code for the calculation of phenomena related to pool stratification and mixing.

At the moment KTH is improving the EHS and EMS models for blowdown pipes in order to reduce uncertainties and enhance accuracy in predictions as well as extending the models to SRV spargers. Later the models will be extended further to other elements of the PSP such as nozzles of the residual heat removal system and strainers in order to be able to carry out comprehensive safety analysis of realistic transients in a BWR containment.

Suitable experimental data is limited for validation of the EHS and EMS models. So far, the only available and sufficiently detailed experimental vent pipe data are the POOLEX/PPOOLEX steam discharge experiments with blowdown pipes. The PPOOLEX database was broadened to cover SRV spargers in the test series carried out in 2014 [13]. Main motivation for the additional sparger tests reported here was to extend the database to cases where either part of the injection holes of the sparger head are blocked or injection is through the load reduction ring (LRR) of the sparger. Chapter two gives a short description of the test facility and its measurements as well as of the data acquisition system used. The test parameters, initial conditions and test procedure are introduced in chapter three. The test results are presented and discussed in chapter four. Chapter five summarizes the findings of the test series.

2 PPOOLEX TEST FACILITY

The PPOOLEX test facility was taken into use at LUT in the end of 2006. PPOOLEX models the containment of a BWR plant. During the years the facility has gone through several modifications and enhancements as well as improvements of instrumentation. For the sparger tests described in this report the facility was equipped with a model of a safety relief valve sparger. The PPOOLEX facility is described in more detail in reference [14]. However, the main features of the facility and its instrumentation are introduced below.

2.1 TEST VESSEL

The PPOOLEX facility consists of a wetwell compartment (condensation pool), drywell compartment, inlet plenum and air/steam-line piping. An intermediate floor separates the compartments from each other. Usually a route for gas/steam flow from the drywell to the wetwell is created by a vertical blowdown pipe attached underneath the floor. During the sparger tests the drywell compartment was, however, bypassed i.e. steam was blown directly into the wetwell via the sparger pipe.

The main component of the facility is the ~31 m^3 cylindrical test vessel, 7.45 m in height and 2.4 m in diameter. It is constructed from three plate cylinder segments and two dome segments. The test facility is able to withstand considerable structural loads caused by rapid condensation of steam. The dry and wetwell sections are volumetrically scaled according to the compartment volumes of the Olkiluoto containment (ratio approximately1:320). There are several windows for visual observation in both compartments. A DN100 (∅ 114.3 x 2.5 mm) drain pipe with a manual valve is connected to the vessel bottom. A relief valve connection is mounted on the vessel head. The removable vessel head and a man hole (DN500) in the wetwell compartment wall provide access to the interior of the vessel for maintenance and modifications of internals and instrumentation. The drywell is thermally insulated.

A sketch of the test vessel is shown in Figure 1. Table 1 lists the main dimensions of the test facility compared to the conditions in the Olkiluoto plant.

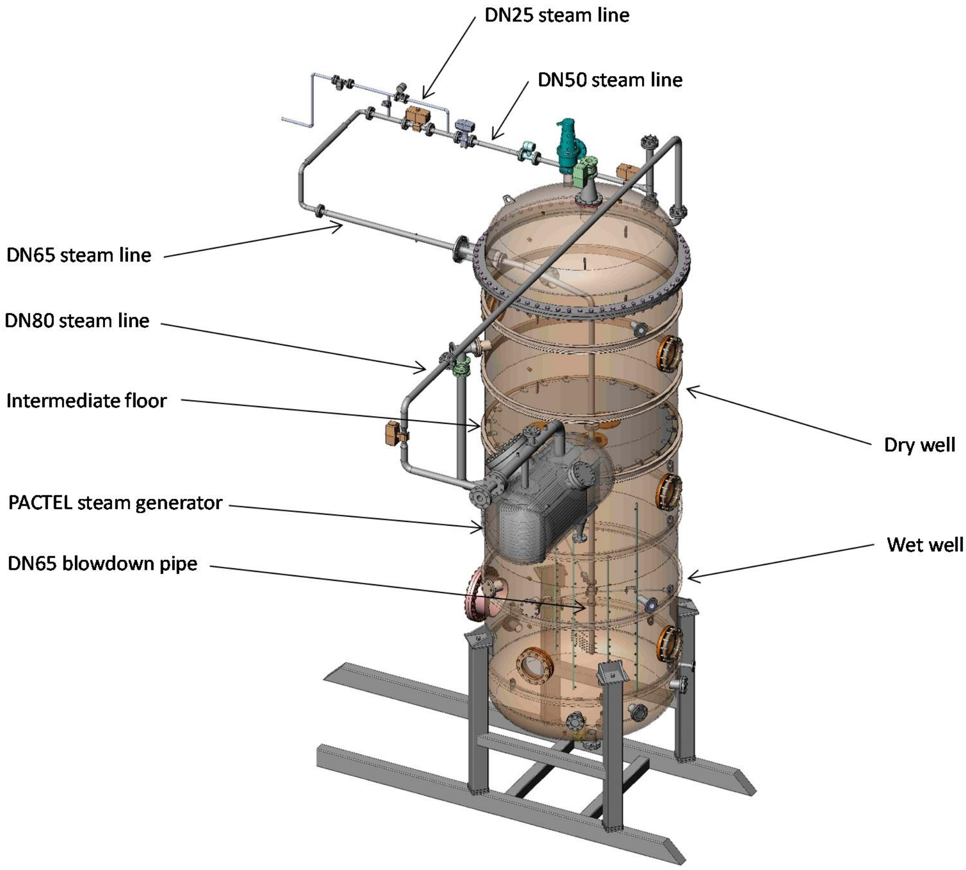

Figure 1. PPOOLEX test vessel.

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

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

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

2.2 PIPING

Steam needed in the tests is generated with the nearby PACTEL [15] test facility, which has a core section of 1 MW heating power and three horizontal steam generators. Steam is led through a thermally insulated steam line, made of sections of standard DN80 (Ø88.9x3.2), DN50 (Ø60.3x3.0) and DN65 (Ø76.1x3.0) pipes, from the PACTEL steam generators towards the PPOOLEX test vessel. The section of the steam piping inside the drywell (bypass) is made of uninsulated DN65 (Ø76.1x3.0) pipe.

2.3 SPARGER PIPE

The DN65 (Ø76.1x4.0) sparger type blowdown pipe is positioned vertically inside the pool in a non-axisymmetric location, i.e. the pipe is 420 mm away from the centre of the condensation pool. The total length of the sparger pipe is approx. 5.0 m. The pipe is made from austenitic stainless steel EN 1.4571.

There are 32 Ø8 mm holes drilled radially in the lower part of the pipe (sparger head). These holes are in four rows, eight holes in each row. There is a load reduction ring 700 mm above the pipe outlet with 8 axially drilled Ø8 mm holes.

2.4 AIR REMOVAL SYSTEM

For the sparger tests the PPOOLEX facility was equipped with an air removal system. The system consists of a filter unit and an air removal device. Air is removed in a vacuum chamber by a vacuum pump during the preparation period for the experiments. However, the system was not used in all experiments.

2.5 MEASUREMENT INSTRUMENTATION

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

For the sparger tests a 6x7 grid of temperature measurements (thermocouples T4000–T4056) was installed in the pool in front of the injection holes of the sparger head. For measuring vertical temperature distribution inside the sparger pipe nine temperature measurements (thermocouples T4070…T4078) were installed with a varying interval. Four trains of temperature measurements (thermocouples T4100…T4112, T4200…T4217, T4300…T4317 and T4400…T4412) were installed in the pool below the water level for detecting vertical temperature distribution. For the SPA-T2 and SPA-T6 tests in 2014 and for the here reported SPA-T1 and SPA-T7 tests in 2015, new thermocouples T4113 and T4413 were added close to the bottom of the wetwell. In addition, thermocouples T4209, T4211, T4309 and T4311 were moved to a lower position and re-named as T4218, T4219, T4318, T4319, correspondingly.

Figures in Appendix 2 show the locations of the PPOOLEX measurements during the SPA series and the table in Appendix 2 lists their identification codes and other details.

2.6 CCTV SYSTEM

Standard video cameras with 25 fps and a digital videocassette recorder were used for visual observation of the test vessel interior during the test series.

2.7 DATA ACQUISITION

National Instruments PXIe PC-driven measurement system was used for data acquisition. The system enables high-speed multi-channel measurements. The maximum number of measurement channels is 64 with additional eight channels for strain gauge measurements. The maximum recording capacity depends on the number of measurements and is in the region of three hundred thousand samples per second. Measurement software was LabView 2014. The data acquisition system is discussed in more detail in reference [16].

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

The used measurement frequency of LabView was 200 Hz for pressures and strains and 20 Hz for temperatures. The rest of the measurements (for example temperature, pressure and flow rate in the steam line) were recorded by the self-made software with the frequency of 0.67 Hz.

3 TEST PROGRAM

Two sparger pipe tests labeled as SPA-T1 and SPA-T7 were carried out in the PPPOLEX facility. The main purpose of the tests was to obtain additional data for the development of the EMS and EHS models to be implemented in GOTHIC code by KTH. In the earlier tests with the sparger pipe in PPOOLEX the injection holes of the LRR were blocked and steam injection into the pool was thus only through the holes at the sparger head (32 holes in four rows). These holes point to horizontal direction. In order to extend the EMS and EHS models to cover also situations where steam injection into the pool is directed vertically downwards these two additional tests, reported here, were carried out. Detailed test specifications put together on the basis of pre-test calculations and analysis of the results of the previous tests were provided by KTH before the tests [17, 18]. In SPA-T1, the holes of the LRR were still blocked and in addition three rows of the holes at the sparger head were blocked, too. Steam injection was thus only through the eight holes in the lowest row at the sparger head. In SPA-T7, all holes at the sparger head were blocked but the eight holes of the LRR were open. Flow was then only through these vertically downwards pointing holes. Both tests had two stratification periods and two mixing periods. In addition SPA-T1 had an extra stratification period at the end of the test.

Before the tests, the wetwell pool was filled with isothermal water (~13 °C in SPA-T1 and ~16 °C in SPA-T7) to the level of 3.0 m i.e. the sparger pipe outlet was submerged by 1.8 m. The steam discharge rate into the PPOOLEX vessel was controlled with the help of the pressure level of the steam source (PACTEL steam generator) and a remote-operated control valve (S2002) in the DN50 steam line.

The tests were started from atmospheric conditions in PPOOLEX. After the correct initial steam generator pressure (0.6 MPa) had been reached, the remote-controlled cut-off valve (X2100) in the DN50 steam line was opened. To remove air from the steam line and to heat up the piping structures, steam mass flow rate was at first adjusted to a higher level for about 200 seconds.

The first stratification process was initiated by reducing the steam flow rate to the desired level. The first mixing period was started by increasing the steam flow rate into the test vessel after the predetermined temperature difference between the bottom and surface layers of the pool had been reached (25 °C in SPA-T1 and 20 °C in SPA-T7). The second stratification process was initiated by reducing the steam flow rate after a uniform temperature distribution in the pool had been reached. The second mixing period was initiated after a predetermined temperature difference between the bottom and surface layers had again been reached (25 °C in SPA-T1 and 20 °C in SPA-T7). In SPA-T1 a third stratification period was initiated after a uniform temperature distribution in the pool had been reached and it was continued until the pool bulk temperature was about 95 °C.

The main parameters of the SPA-T1 and SPA-T7 tests are listed in Table 2, correspondingly. The path of both of the tests defined by steam mass flux and pool bulk temperature is marked on the condensation mode map for a sparger of Chan and Lee [19] in Figure 2. In the map steam mass flux is determined as the flow rate through the injection holes of the sparger head divided by the cross-sectional area of the holes. In SPA-T1, the steam mass flux exceeds the right hand edge of the map during both mixing periods and therefore the two peak values of the mass flux are marked on the map.

Table 2. Parameter values of the sparger tests SPA-T1 and SPA-T7.

Test	Initial water level [m]	Initial water temperature [°C]	Steam flow rate [g/s]				
			Stratification I	Mixing I	Stratification II	Mixing II	Stratification III
SPA-T1	3.0	~12	~30	120-125	~45	~100	~34
SPA-T7	3.0	~16	30-35	~48	~30	~49	-

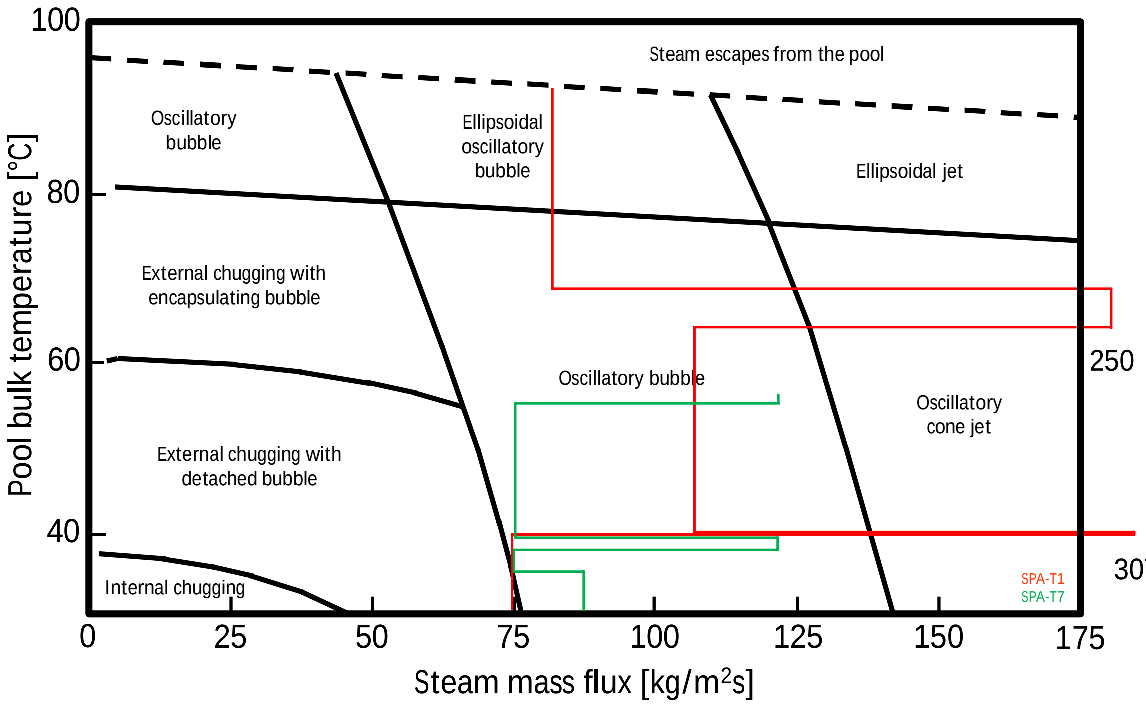

Figure 2. Paths of the SPA-T1 and SPA-T7 tests marked on the direct condensation mode map for pure steam discharge of Chan and Lee [19].

4 TEST RESULTS

The following chapters give a more detailed description of the two sparger tests and present the observed phenomena.

4.1 HEAT UP PERIOD

In the beginning of both of the tests there was a short heat up period in order to remove air from the steam line as well as to heat up the piping from the PACTEL steam generators to the PPOOLEX vessel. For this period the steam flow rate was set to about 200 g/s, Table 3. The pool bulk temperature rose approximately 2-3 °C during the heat up period, which lasted for about 200 seconds in both tests.

Table 3. Parameters of the heat-up periods of the SPA-T1 and SPA-T7 tests.

Exp.	Time period [s]	Steam flow rate [g/s]	Pool water temperature increase [°C]
SPA-T1	30–250	~200	13→16
SPA-T7	75–275	~206	16→18

4.2 HORIZONTAL VS. VERTICAL INJECTION

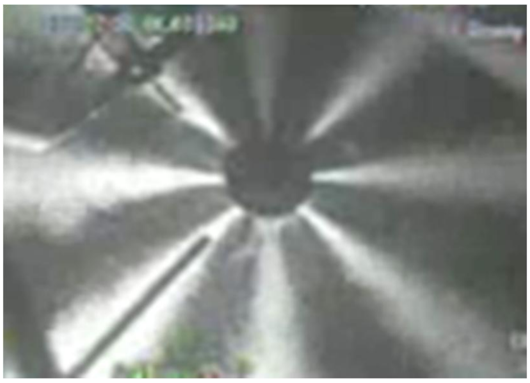

Figure 3. Eight steam jets at the sparger head in SPA-T1 (photo captured from video recording).

Two different kind of flow conditions could be detected in the wetwell pool of the PPOOLEX facility in the SPA-T1 and SPA-T7 tests. When steam injection was through the lowest ring of holes at the sparger head (SPA-T1) eight horizontal and radially directed steam jets developed around the lower end of the sparger pipe (Figure 3). In this case water was expelled out of the sparger pipe in the beginning of the test and the pipe was practically full of steam during the rest of the test. This can be seen from the temperature curves measured from inside the sparger pipe (Figure 4). Only the measurement T4070, which is 7 mm below the elevation of the lowest ring of injection holes, shows slightly lower temperatures than the temperature of incoming steam. The two mixing periods can be seen in the curves as steps with slightly increased steam temperatures.

When steam injection was through the eight holes of the LRR (SPA-T7) the steam jets pointed downwards. Since all the injection holes of the sparger head were blocked, there was no route for water to escape and as a result the section of the sparger pipe below the LRR was full of water during the whole duration of the test. Therefore only the three temperature measurements above the LRR elevation inside the sparger pipe indicate temperatures of incoming steam and the rest of the measurements show slowly increasing temperatures of the pool water (Figure 5).

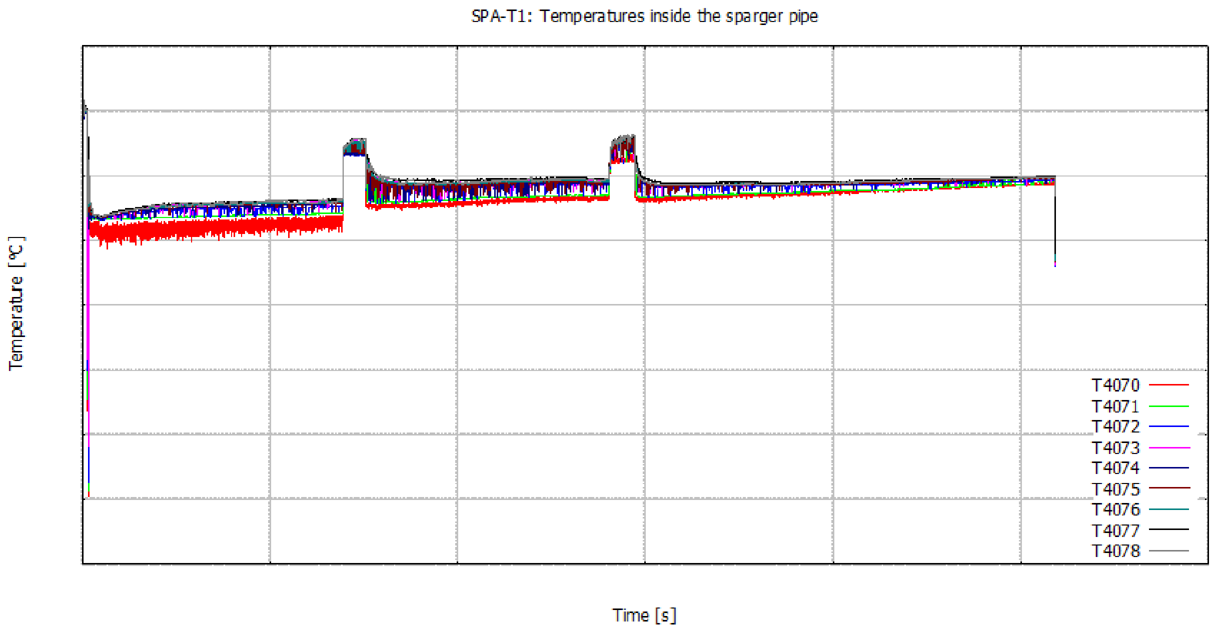

Figure 4. Temperatures inside the sparger pipe in the SPA-T1 test.

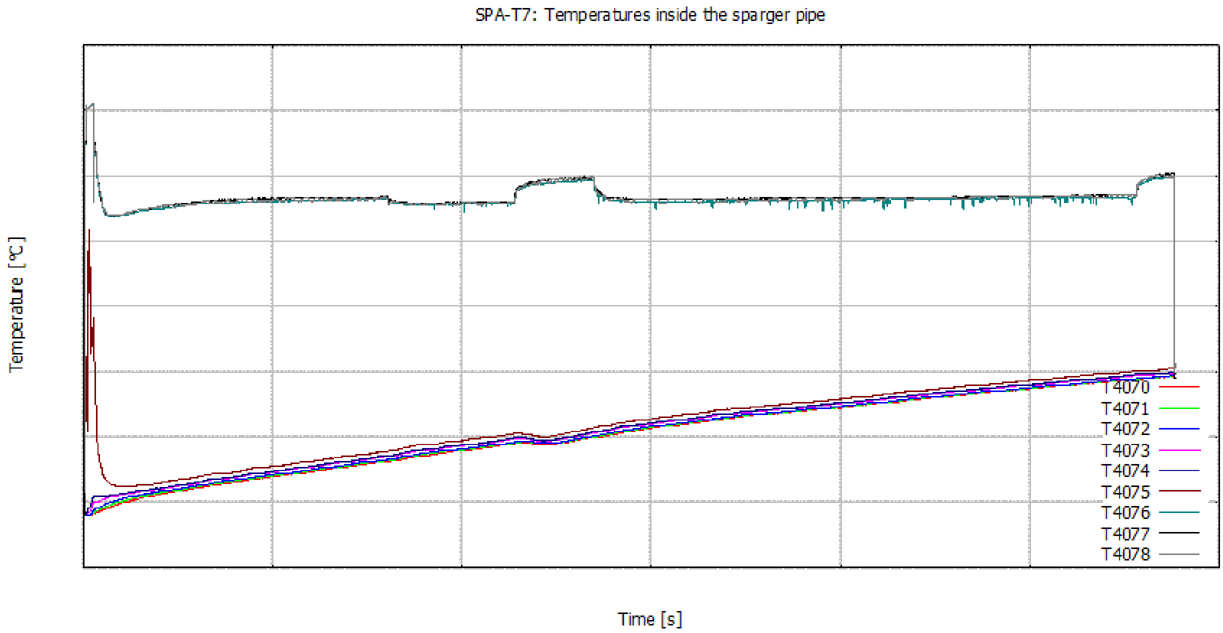

Figure 5. Temperatures inside the sparger pipe in the SPA-T7 test.

4.3 STATIFICATION AND MIXING

4.3.1 Stratification period I

After the steam line had been heated up the steam flow rate was rapidly decreased to the predetermined level of 30 g/s in SPA-T1 (corresponding to the mass flux of about 75 kg/m^{2}s) and 35 g/s in SPA-T7 (corresponding to the mass flux of about 87 kg/m^{2}s) in order to start the first stratification period. In SPA-T7, the flow rate was later at 8100 seconds decreased to 30 g/s because it looked like the transition region between the cold and warm pool water would be closer to the pool bottom than expected with the 35 g/s flow rate.

With this kind of mass fluxes steam flowed through the injection holes of the sparger as small jets and condensed mainly outside the sparger pipe. Because no chugging kind of phenomenon existed and the steam jets were too weak to create much turbulence in the pool, suitable conditions for thermal stratification to occur prevailed.

In SPA-T1, where the steam injection was horizontal, the transition region between the cold and warm pool water was set a short distance below the lower end of the sparger pipe during the first stratification period. Temperature measurement T4104, roughly 200 mm below the lower end of the sparger, indicated a slight increase in temperature while all other TCs below the 1000 mm elevation did not register rising temperatures. Temperatures rose towards the pool surface layers indicating strong thermal stratification of the wetwell pool water, Figure 6 and Figure 7. The heat-up process was driven by flow of warm condensed water upwards from the sparger outlet as well as by conduction through the pipe wall.

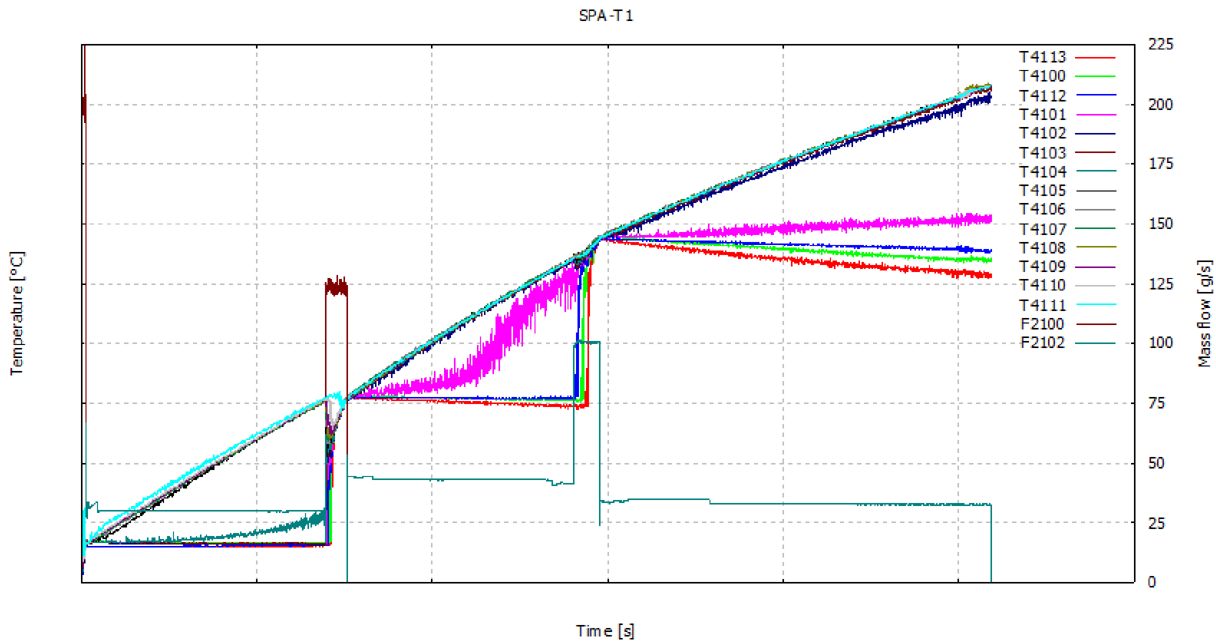

Figure 6. Vertical temperature distribution in wetwell water (T4100–T4113) and steam flow rate (F2100 and F2102) in SPA-T1.

From Figure 7 one can see that the vertical length of the transition region, where the shift from cold to warm pool water occurs, is very small compared to the previous stratification/mixing experiments in PPOOLEX with a straight blowdown pipe. Furthermore, the lower and upper boundary of the transition region are also quite sharp. This can be concluded from the almost 90° angles in the curves. Outside the transition region the curves are almost straight vertical lines indicating rather constant water temperature at a given moment of time.

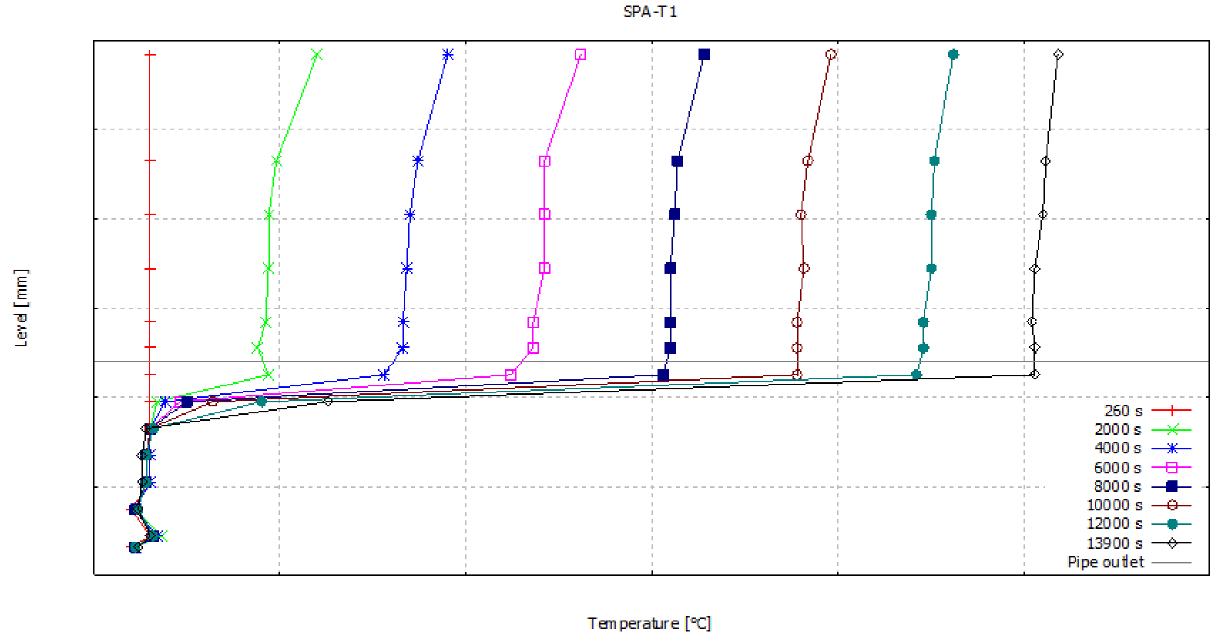

Figure 7. Development of vertical temperature profile of pool water in SPA-T1 during stratification period I.

In SPA-T7, where the steam injection was vertically downwards from the LRR, the transition region between the cold and warm pool water was much deeper in the pool during the first stratification period than in SPA-T1. This means that also temperatures below the sparger pipe outlet rose except at the elevations very close to the pool bottom, Figure 8 and 9. The situation changed somewhat when the steam injection flow rate was decreased from 35 g/s to 30 g/s at 8100 seconds. After that the transition region between cold and warm pool water was set to the elevation of about 700 mm i.e. about 500 mm below the sparger pipe outlet.

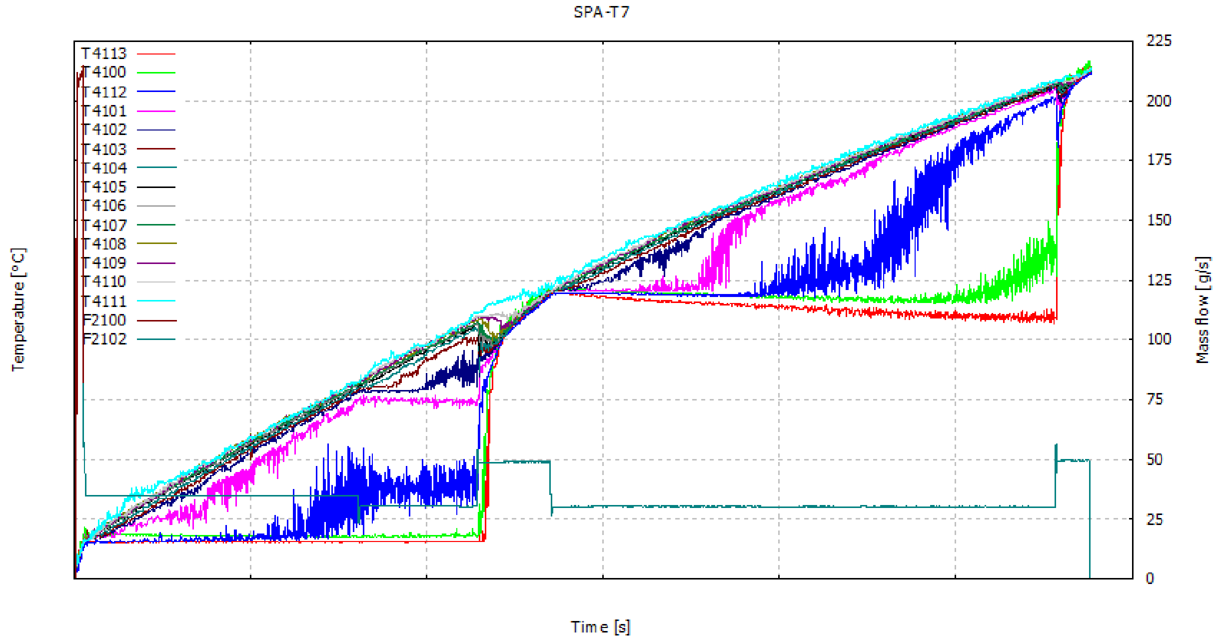

Figure 8. Vertical temperature distribution in wetwell water (T4100–T4113) and steam flow rate (F2100 and F2102) in SPA-T7.

From Figure 9 one can see that the vertical length of the transition region was in SPA-T7 much longer than in SPA-T1. The boundary layers at the edges of the transition region aren't as sharp as in SPA-T1 either. Towards the end of the first stratification period the curve of the temperature profile above the sparger pipe outlet elevation gets slightly more tilted than in SPA-T1 (Figure 9).

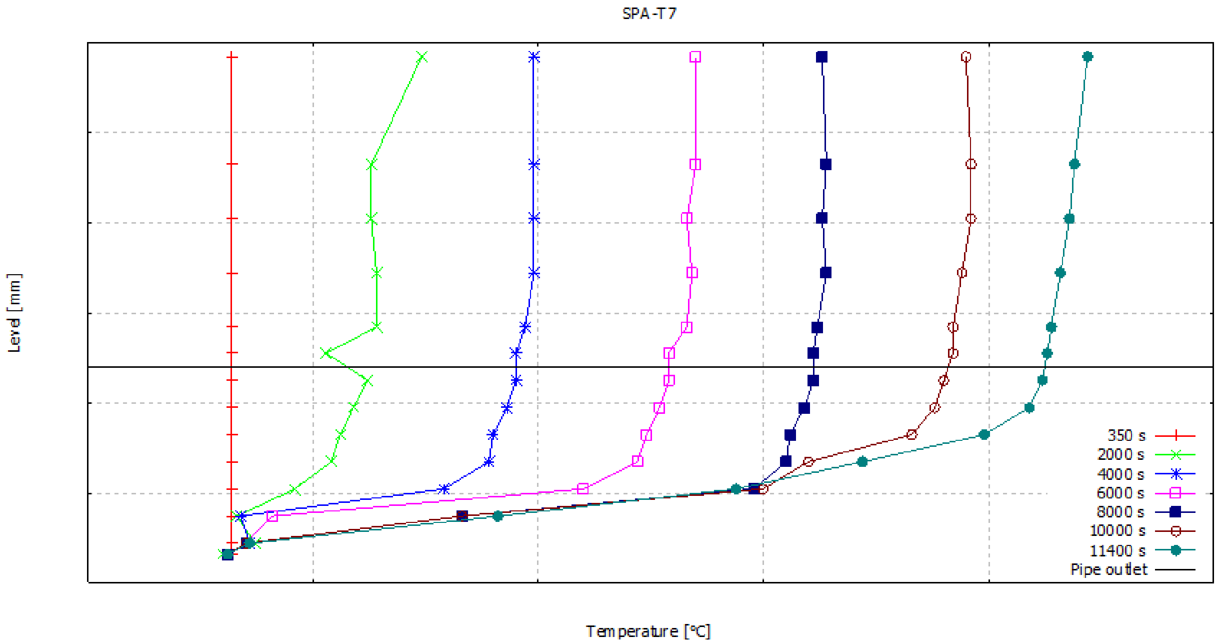

Figure 9. Development of vertical temperature profile of pool water in SPA-T7 during stratification period I.

The stratification period was continued as long as the temperature difference between the pool bottom (measured by thermocouple T4113) and surface (measured by thermocouple T4111) had reached the target value given by KTH i.e. 20–25 °C depending of the test, Table 4.

Table 4. Stratification period I related observations of the SPA-T1 and SPA-T7 tests

Test	Time period [s]	Initial water temperature [°C]	Steam flow rate [g/s]	Stratification time [s]	Final water temp. T4113 / T4111 [°C]	Final temp. difference between T4113 / T4111 [°C]
SPA-T1	250–13900	~17	~30	13650	~16/41	~25
SPA-T7	275–11420	~18	~30-35	11145	~18/37	~19

4.3.2 Mixing period I

The first mixing period was started by adjusting the steam flow rate to the target value determined on the basis of pre-test analysis (about 120 g/s in SPA-T1 and about 50 g/s in SPA-T7). The aim was to create turbulence in the pool with the help of steam escaping through the injection holes and thus to mix the condensation pool water inventory completely, Table 5.

Table 5. Mixing period I related observations of the SPA-T1 and SPA-T7 tests

Test	Time period [s]	Steam flow rate [g/s]	Mixing time [s]	Final pool water temperature [°C]
SPA-T1	13900–15150	~123	~1240	~41
SPA-T7	11420–13500	~49	~2080	~39

In SPA-T1, the steam flow rate for the first mixing period was set to 120-125 g/s (about 298-310 kg/m^{2}s) to find out how well the pool water inventory can be mixed with the oscillatory cone jet mode, Figures 2, 6 and 10. In SPA-T1, the mixing effect was created by horizontal steam jets spurting from the injection holes of the sparger head. Strong internal circulation developed in the pool and the pool water mixed completely in about 1240 seconds.

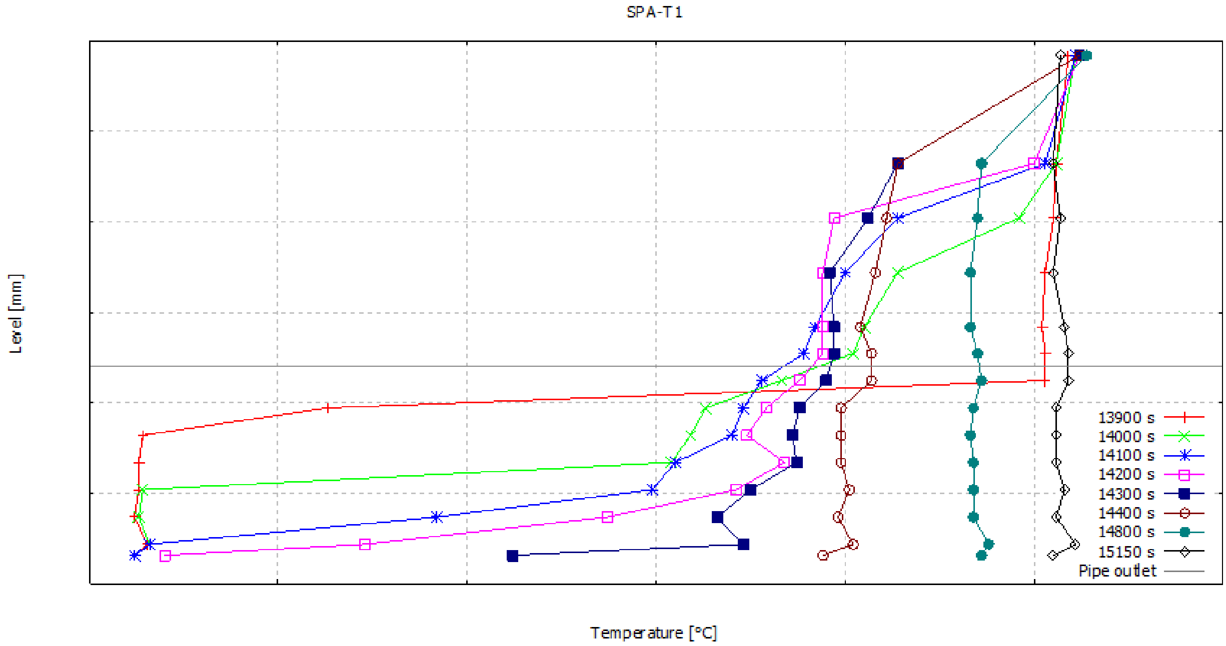

Figure 10. Progression of mixing in pool water in SPA-T1 during the first mixing period.

In the beginning of the mixing process water temperatures decreased ~3-7 °C above the sparger head elevation except at the pool surface (Figure 11). As the mixing process continued temperatures on these elevations started to rise again and finally reached the temperature of 41 °C, which prevailed at the pool surface during the whole mixing period. Below the sparger head elevation temperatures practically had an increasing trend for the whole mixing period.

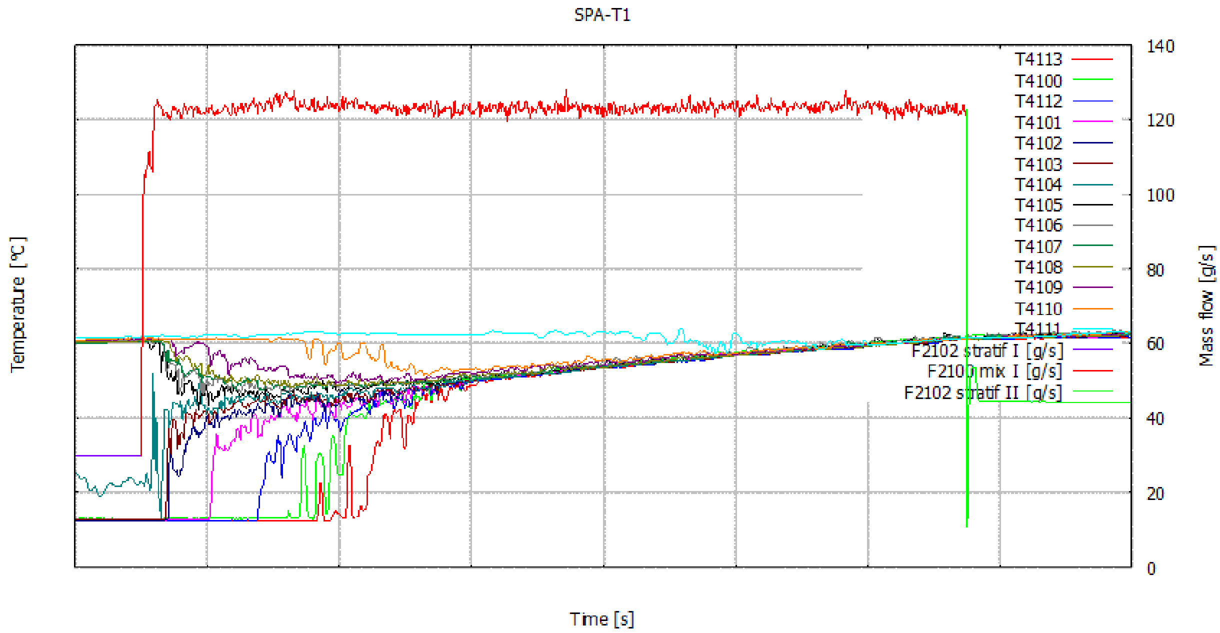

Figure 11. Development of pool water temperatures during the first mixing period in SPA-T1.

For comparison it can be noted that in the earlier tests with all the injection holes of the sparger head unblocked a flow rate of 150 g/s was not enough to mix the pool. The flow mode was then somewhere in the threshold region of the external chugging and oscillatory bubble modes and mixing was observed only above the sparger head outlet elevation and along a short distance below the sparger head outlet elevation.

In SPA-T7, the actual mixing flow rate was 49 g/s and corresponding mass flux about 122 kg/m^{2}s. According to the direct condensation mode map for pure steam discharge of Chan and Lee the dominant flow mode is then oscillatory bubble, Figure 2. Now the direction of the steam jets was downwards because in SPA-T7 the injection was through the LRR. Although the downwards directed jets could be expected to reach the pool bottom easier and thus increase the mixing effect, the lower mixing injection flow rate than in SPA-T1 partly canceled this effect. Less turbulence and internal circulation was created and as a result complete mixing took about 2080 seconds despite the fact that the temperature difference between the pool bottom and surface in the beginning of the mixing process was less in SPA-T7 than in SPA-T1, Figures 8 and 12.

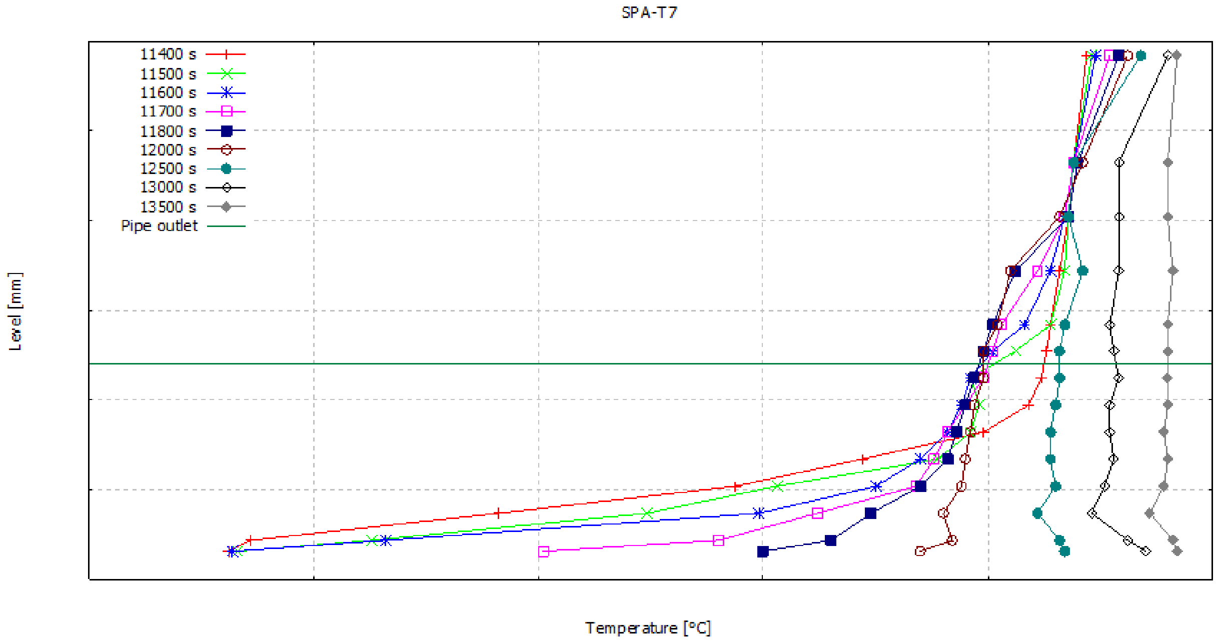

Figure 12. Progression of mixing in pool water in SPA-T7 during the first mixing period.

The mixing process was somewhat different in SPA-T7 compared to SPA-T1. In the beginning there was only about a 2 °C temperature decrease between the 1000 mm and 2000 mm elevations before the temperatures started to rise again (Figure 13). From the 2000 mm elevation upwards the pool was quite isothermal during the whole mixing process but the temperature increased about 2 °C before the pool was completely mixed as opposed to the almost constant pool surface temperature in SPA-T1. The different thermal hydraulic state of the pool in the beginning of the mixing process in SPA-T7 as well as the downward direction of the steam jets are the main reasons for the different kind of development of the mixing process.

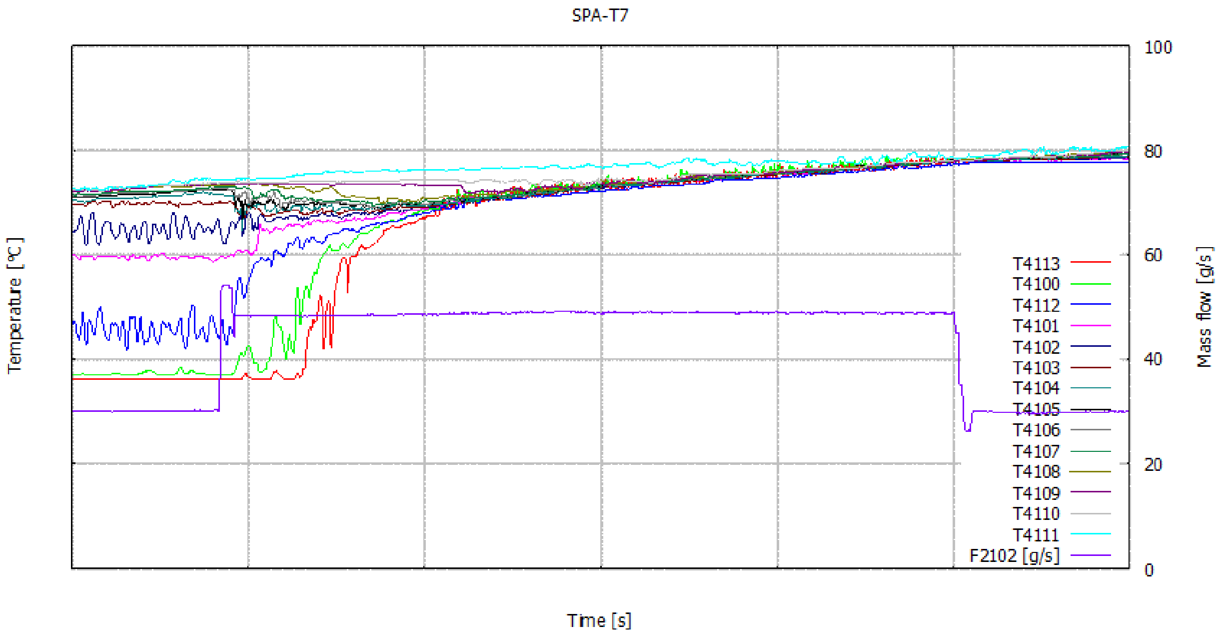

Figure 13. Development of pool water temperatures during the first mixing period in SPA-T7.

4.3.3 Stratification period II

The first mixing period was terminated and the second stratification period initiated by decreasing the steam flow rate in SPA-T1 to the level of 45 g/s (round 112 kg/m^{2}s) and in SPA-T7 to 30 g/s (round 75 kg/m^{2}s), Table 6.

Table 6. Stratification period II related observations of the SPA-T1 and SPA-T7 tests

Test	Time period [s]	Initial water temperature [°C]	Steam flow rate [g/s]	Stratification time [s]	Final water temp. T4113 / T4111 [°C]	Final temp. difference between T4113 / T4111 [°C]
SPA-T1	15150–28100	~41	~45	12950	~39/64	~25
SPA-T7	13500–27830	~39	~30	14330	~37/57	~20

With these flow rates no chugging kind of phenomenon existed and steam condensed mainly outside the sparger pipe thus creating again suitable conditions for thermal stratification to occur. The second stratification period was continued as long as the temperature difference between the pool bottom and surface had reached the target value of 25 °C (in SPA-T1) and 20 °C (in SPA-T7).

In SPA-T1, the transition region between the cold and warm pool water was now set just below the T4101 measurement point at the 522 mm elevation, see Figure 4. This is about 700 mm below the lower end of the sparger pipe as opposed to the about 200 mm distance during the first stratification period. The reason for this deeper location of the transition region is the larger steam injection flow rate during the second stratification period. It creates stronger internal circulation in the pool thus shifting the location of the transition region downwards. Above this transition region all the temperature curves had the same kind of increasing trend indicating a rather constant pool water temperature at a given moment of time.

In SPA-T7, where the steam injection was vertically downwards from the LRR, the second stratification period was slightly longer than the first one despite the fact that the same criteria for a 20 °C temperature difference between the pool bottom and surface was used. As the stratification process proceeded the transition region between the cold and warm pool water moved downwards being just about 200 mm above the pool bottom when the period was terminated. At the end of the second stratification period the transition from cold to warm pool water happens along the vertical distance covering only two measurement elevations (T4100 and T4112). This means that the length of the transition region is then less than 200 mm. This is still somewhat more than in SPA-T1 during the second stratification period but the difference between the two tests is now smaller than during the first stratification period.

4.3.4 Mixing period II

The second mixing period was started by increasing the steam flow rate to the target value determined on the basis of pre-test analysis (100 g/s in SPA-T1 and 50 g/s in SPA-T7), Table 7.

Table 7. Mixing period II related observations of the SPA-T1 and SPA-T7 tests

Test	Time period [s]	Steam flow rate [g/s]	Mixing time [s]	Final pool water temperature [°C]
SPA-T1	28100–29500	~100	~1400	~67
SPA-T7	27830–28500	~50	~670	~57

The actual measured flow rate during the second mixing period in SPA-T1 ranged from about 99 g/s to 101 g/s (about 246-251 kg/m^{2}s). The prevailing flow mode should then be the oscillatory cone jet mode as was also during the first mixing period, Figure 3. Although the mixing flow rate was smaller than in the first mixing period enough internal circulation again developed in the pool for complete mixing to take place in about 1400 seconds.

In the beginning of the second mixing period there was not such slight decrease in the pool water temperature as during the first mixing period after the start-up of the mixing process. This was due to the fact that after the second stratification period the amount of cold water in the pool bottom was very small and the transition region was deep below the sparger pipe outlet. The mixing process proceeded now somewhat differently by slowly eroding the layers of cold water rather than mixing them through internal circulation as was the case during the first mixing period (Figure 14).

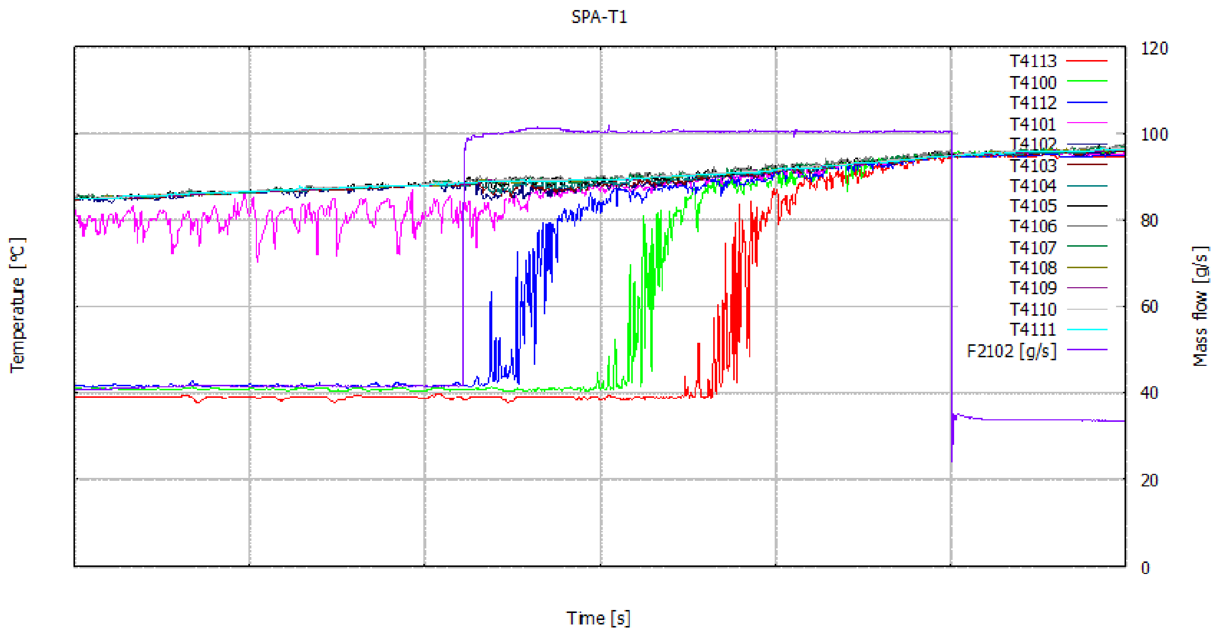

Figure 14. Development of pool water temperatures during the second mixing period in SPA-T1.

In SPA-T7, the measured flow rate during the second mixing period was between 49 and 50 g/s, which correspond to a mass flux of about 122-124 kg/m^{2}s. As during the first mixing period the dominant flow mode was oscillatory bubble, Figure 2.

The time needed for complete mixing during the second mixing period was only about one third of that in the first mixing period despite of the same flow rate and initial temperature difference. The different ratio of cold and warm water after the second stratification period compared to the situation after the first stratification period can be considered to be the main reason for the shorter mixing time. Because the transition region between the cold and warm pool water was deeper after the second stratification period the 1-2 °C temperature decrease in the beginning of the mixing process was now experienced at the elevation range of 400-800 mm as opposed to the range of 1000-2000 mm in the beginning of the first mixing period (Figure 15).

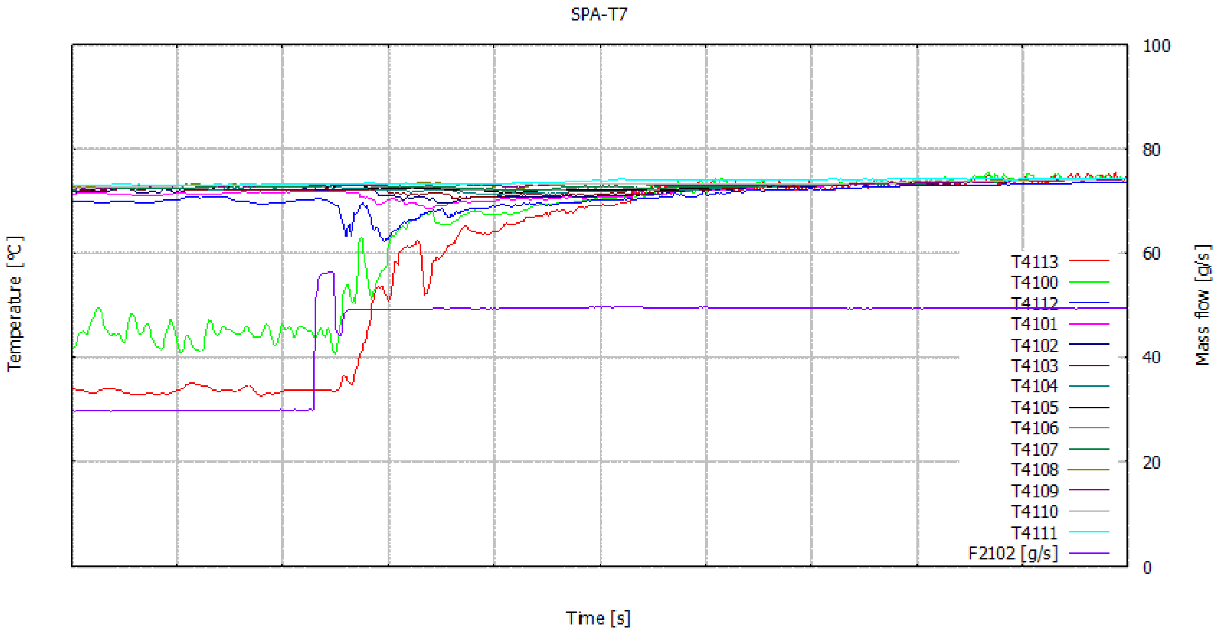

Figure 15. Development of pool water temperatures during the second mixing period in SPA-T7.

4.3.5 Stratification period III

In SPA-T1, a third stratification period was initiated after the second mixing period. It was continued until the pool surface temperature reached the value of 95 °C. The used steam mass flow rate was about 34 g/s (~85 kg/m^{2}s). According to the direct condensation mode map for pure steam discharge of Chan and Lee the dominant flow mode is then first oscillatory bubble and ellipsoidal oscillatory bubble after the pool water temperature exceeds 80 °C, Figure 2.

The transition region between the cold and warm pool water was now set slightly above the 500 mm elevation, which is a little higher than during the second stratification period, see Figure 6. The contributing factor here is the weaker internal circulation in the pool due to the smaller steam injection flow rate during the third stratification period. Above this transition region all the temperature curves had the same kind of increasing trend indicating almost constant pool water temperature at a given moment of time.

5 SUMMARY AND CONCLUSIONS

This report summarizes the results of the two sparger pipe tests (SPA-T1 and SPA-T7) carried out in the PPOOLEX facility at LUT in 2015. The test facility is a closed stainless steel vessel divided into two compartments, drywell and wetwell. In the SPA tests the drywell compartment was bypassed i.e. the sparger pipe in the wetwell was connected directly to the steam line coming from the PACTEL facility which acted as a steam source. During the experiments, the test facility was equipped with extra temperature measurements in the wetwell compartment for capturing different aspects of the investigated phenomena.

The main objective of the tests was to obtain additional data for the development of the Effective Momentum Source (EMS) and Effective Heat Source (EHS) models to be implemented in GOTHIC code by KTH. The test parameters were selected by KTH on the basis of pre-test simulations and analysis of the results of the earlier sparger tests in PPOOLEX. In these earlier tests the injection holes of the load reduction ring (LRR) were blocked and steam injection into the pool was thus only through the holes at the sparger head (32 holes in four rows). These holes point to horizontal direction. In order to extend the EMS and EHS models to cover also situations where steam injection into the pool is directed vertically downwards these two additional tests were carried out. In SPA-T1, the holes of the LRR were still blocked and in addition three rows of the holes at the sparger head were blocked, too. Steam injection was thus only through the eight holes in the lowest row at the sparger head. In SPA-T7, all holes at the sparger head were blocked but the eight holes of the LRR were open. Flow was then only through these vertically downwards pointing holes. Both tests had two stratification periods and two mixing periods. In addition SPA-T1 had an extra stratification period at the end of the test.

During the stratification periods the used steam injection flow rate was in the range of 30-45 g/s (75-112 kg/m^{2}s). With this kind of mass fluxes steam flowed through the injection holes of the sparger as small jets and condensed mainly outside the sparger pipe. Because no chugging kind of phenomenon existed and the steam jets were too weak to create much turbulence in the pool, suitable conditions for thermal stratification to occur prevailed.

The transition region, where the shift from cold to warm pool water occurred, was practically just below the sparger head elevation when steam injection was through the sparger head (SPA-T1). Furthermore, the vertical length of the region was very short and temperatures below that elevation remained almost at their initial value.

When the steam injection was vertically downwards from the LRR (SPA-T7), the transition region between the cold and warm pool water was much deeper in the pool and only a small amount of water close to the pool bottom remained at its initial temperature. The vertical length of the transition region was also longer in the LRR case.

The larger used steam injection flow rate during the second stratification period in SPA-T1 created stronger internal circulation in the pool. As a result, the location of the transition region moved about 500 mm downwards compared to the first stratification period. Above this transition region all the temperature curves had the same kind of increasing trend indicating a rather constant pool water temperature at a given moment of time.

Oscillatory cone jet mode was the prevailing flow mode during both mixing periods in the SPA-T1 test, where steam was injected horizontally through the single unblocked row of holes at the sparger head. In the first mixing period the momentum created by the horizontal steam jets was so strong that the resulting internal circulation hit the pool wall and partly turned downwards thus mixing also the water volume far below the sparger head elevation. In the second mixing period the flow rate was slightly smaller and therefore the mixing process proceeded somewhat differently by slowly eroding the layers of cold water rather than mixing them through internal circulation. For comparison it can be noted that in the earlier tests with all the injection holes of the sparger head unblocked a considerably larger flow rate was not enough to mix the pool. Then the flow mode was different and mixing was observed only above and a short distance below the sparger head outlet elevation.

A smaller injection flow rate was used during both mixing periods in SPA-T7 than in SPA-T1. Therefore, the dominant flow mode during the mixing periods of the SPA-T7 test was the oscillatory bubble mode. Less turbulence and internal circulation than in SPA-T1 was created and, as a result, complete mixing took a much longer time. However, the downwards direction of the steam jets in SPA-T7 increased the mixing effect.

These additional sparger tests in PPOOLEX verified that the existing flow mode of injected steam is a crucial factor in the success of a mixing process of a thermally stratified water pool. Mixing with a larger absolute flow rate can be less successful than with a smaller flow rate if the flow mode after dividing the flow to smaller jets in a sparger head is such that not enough momentum and internal circulation is created in the pool for complete mixing to take place.

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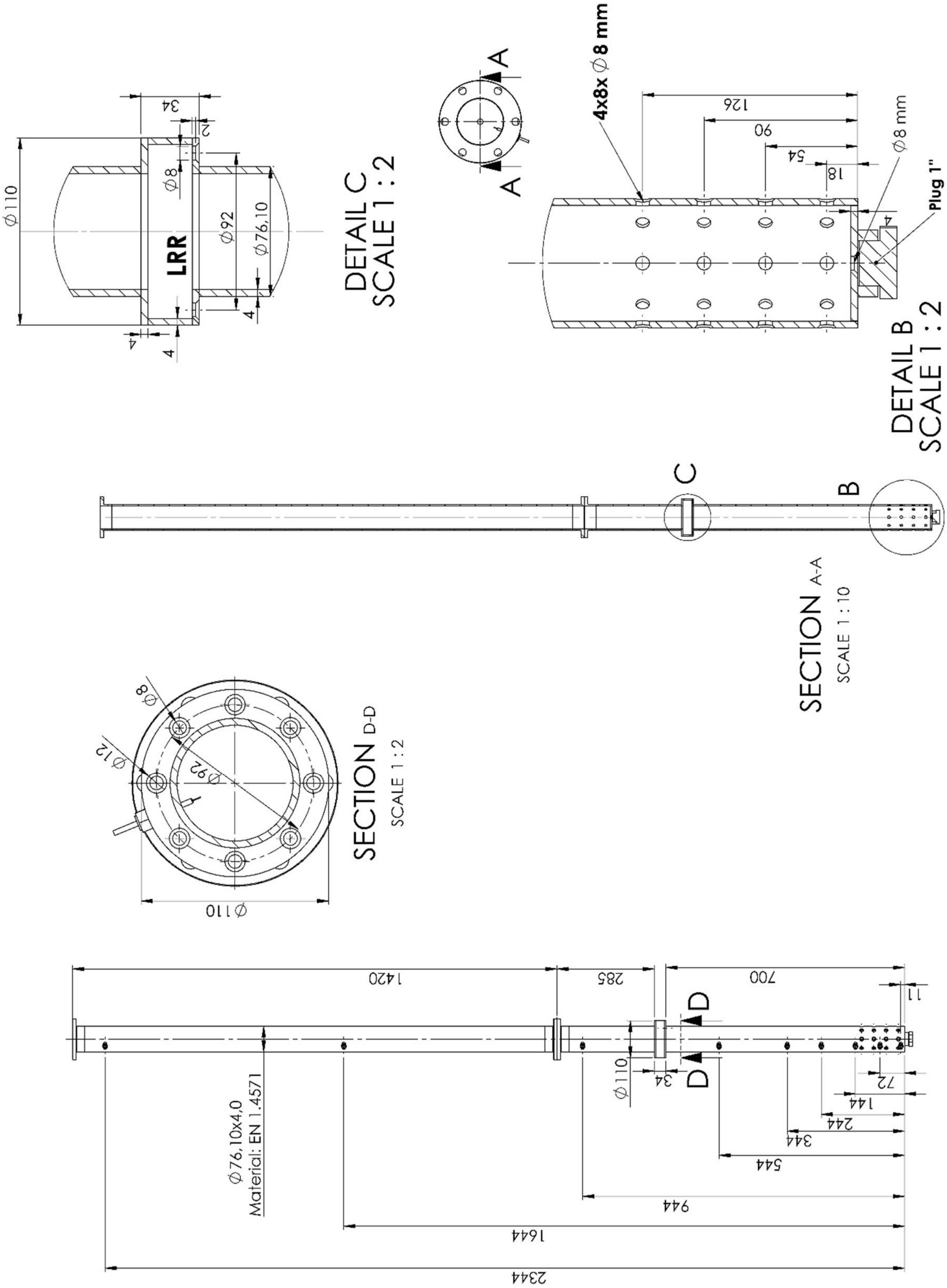
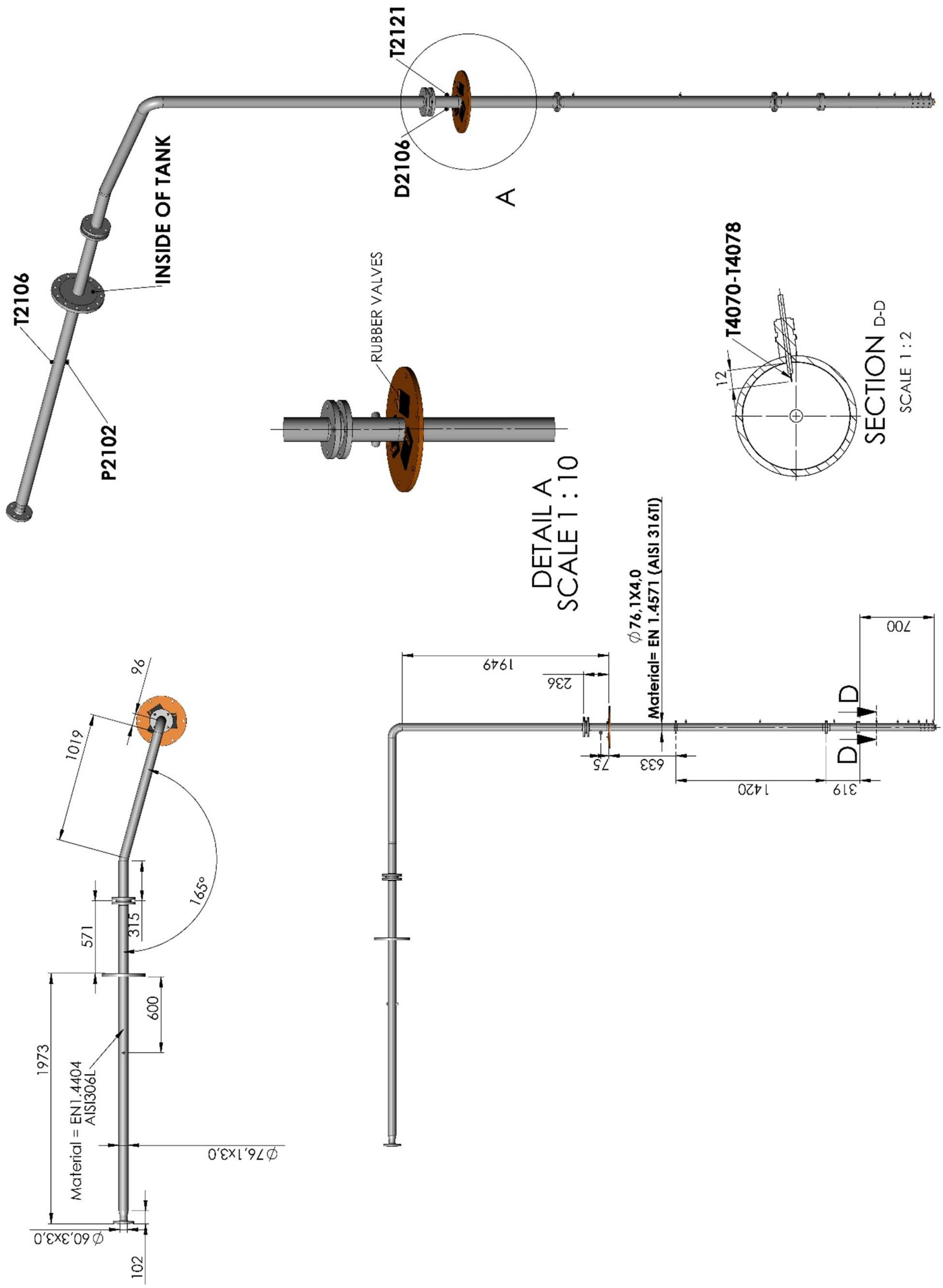
APPENDIX 1: PPOOLEX DRAWINGS

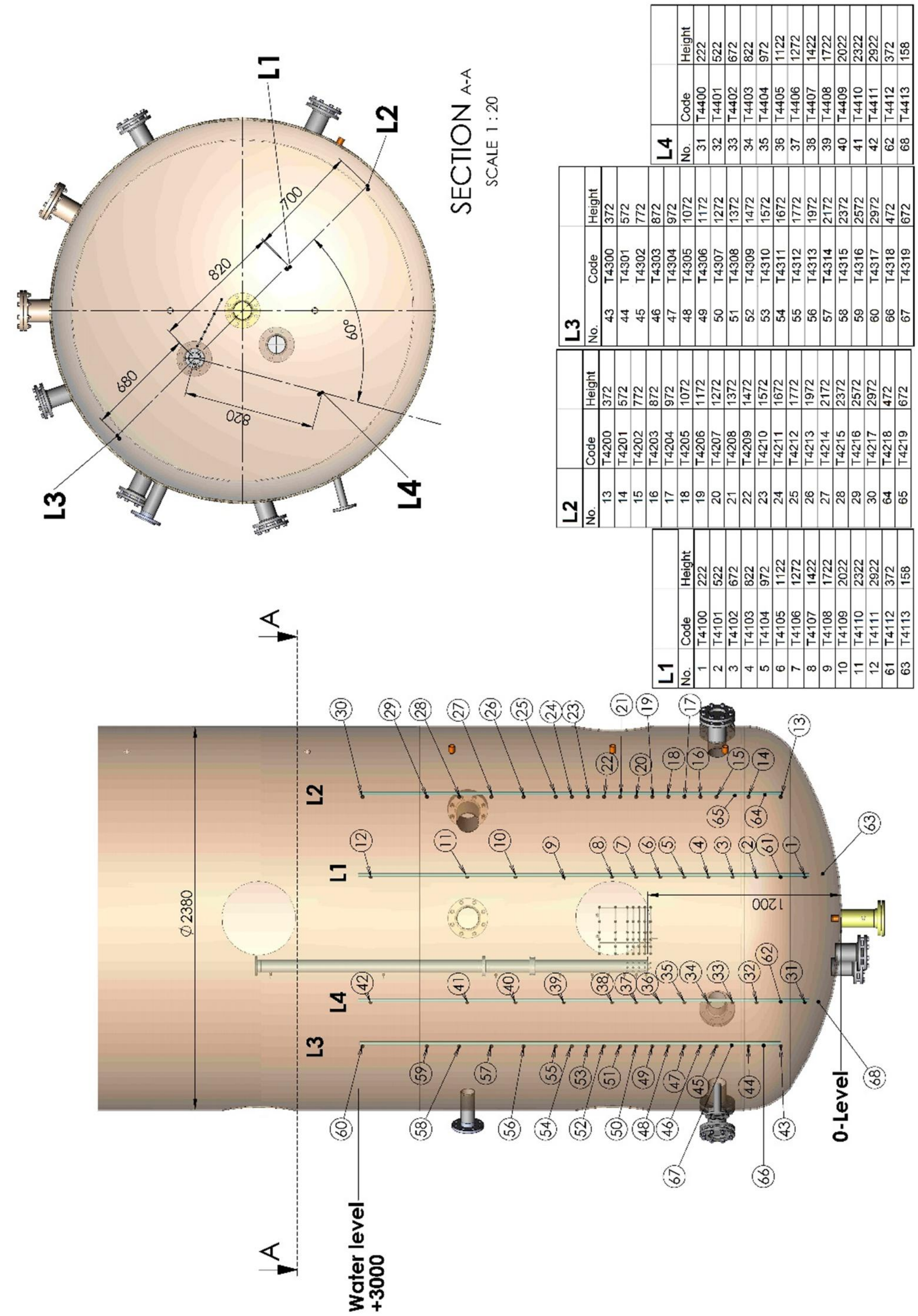


DN65 sparger pipe.



DN65 steam line.

APPENDIX 2: PPOOLEX INSTRUMENTATION



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2	T4101	522
3	T4102	672
4	T4103	822
5	T4104	972
6	T4105	1122
7	T4106	1272
8	T4107	1422
9	T4108	1722
10	T4109	2022
11	T4110	2322
12	T4111	2922
61	T4112	372
63	T4113	158

L2 No.	Code	Height
13	T4200	372
14	T4201	572
15	T4202	772
16	T4203	872
17	T4204	972
18	T4205	1072
19	T4206	1172
20	T4207	1272
21	T4208	1372
22	T4209	1472
23	T4210	1572
24	T4211	1672
25	T4212	1772
26	T4213	1972
27	T4214	2172
28	T4215	2372
29	T4216	2572
30	T4217	2972
64	T4218	472
65	T4219	672

L3 No.	Code	Height
43	T4300	372
44	T4301	572
45	T4302	772
46	T4303	872
47	T4304	972
48	T4305	1072
49	T4306	1172
50	T4307	1272
51	T4308	1372
52	T4309	1472
53	T4310	1572
54	T4311	1672
55	T4312	1772
56	T4313	1972
57	T4314	2172
58	T4315	2372
59	T4316	2572
60	T4317	2972
66	T4318	472
67	T4319	672

L4 No.	Code	Height
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32	T4401	522
33	T4402	672
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35	T4404	972
36	T4405	1122
37	T4406	1272
38	T4407	1422
39	T4408	1722
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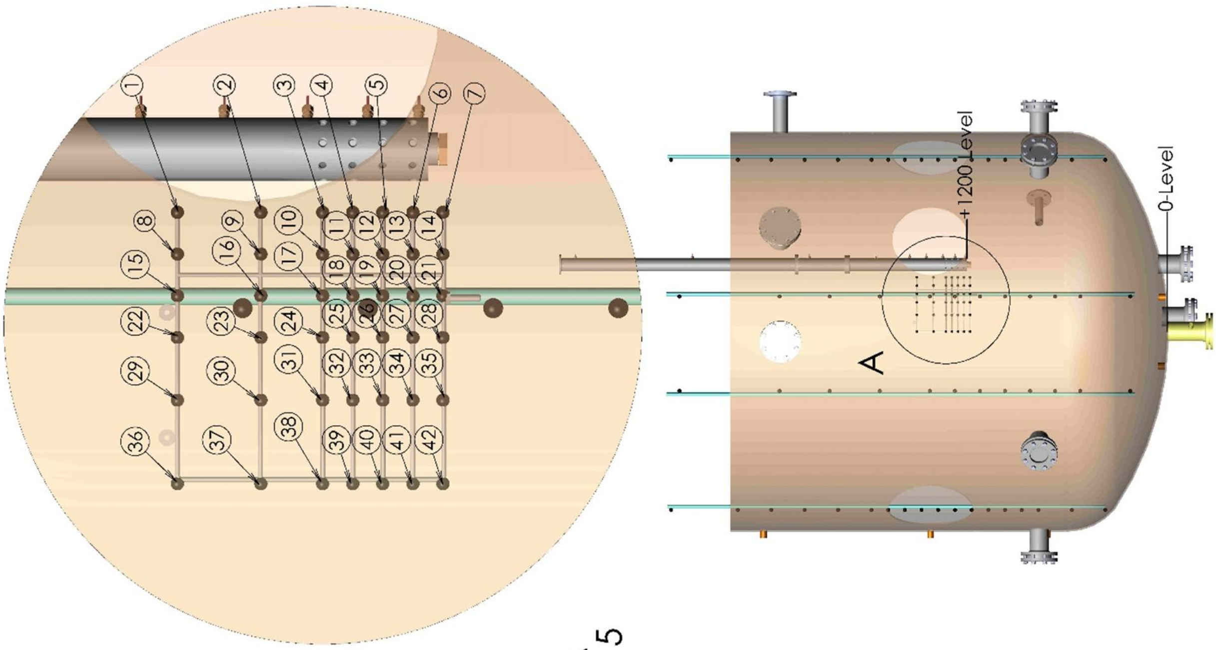
41	T4410	2322
42	T4411	2922
62	T4412	372
68	T4413	158

Four trains of temperature measurements in the wetwell.



DETAIL A
SCALE 1 : 5

No.	Code	No.	Code	No.	Code
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2	T4001	17	T4022	32	T4043
3	T4002	18	T4023	33	T4044
4	T4003	19	T4024	34	T4045
5	T4004	20	T4025	35	T4046
6	T4005	21	T4026	36	T4050
7	T4006	22	T4030	37	T4051
8	T4010	23	T4031	38	T4052
9	T4011	24	T4032	39	T4053
10	T4012	25	T4033	40	T4054
11	T4013	26	T4034	41	T4055
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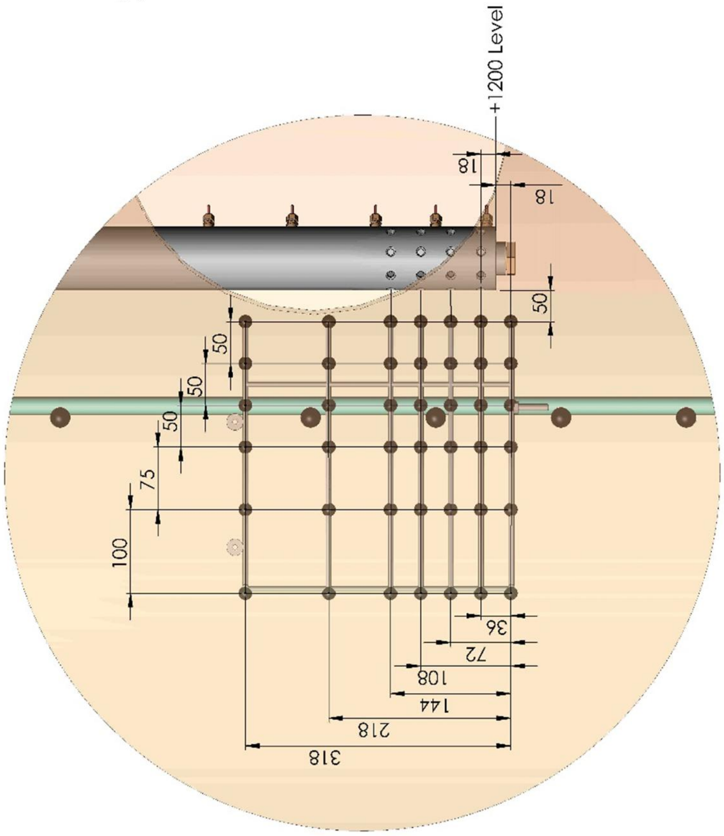
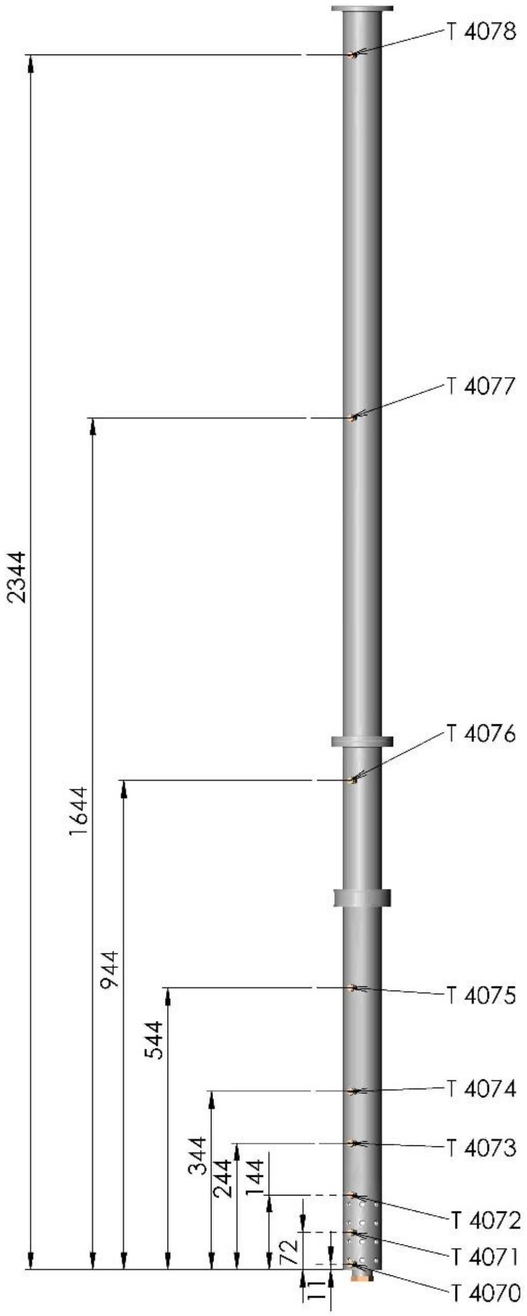
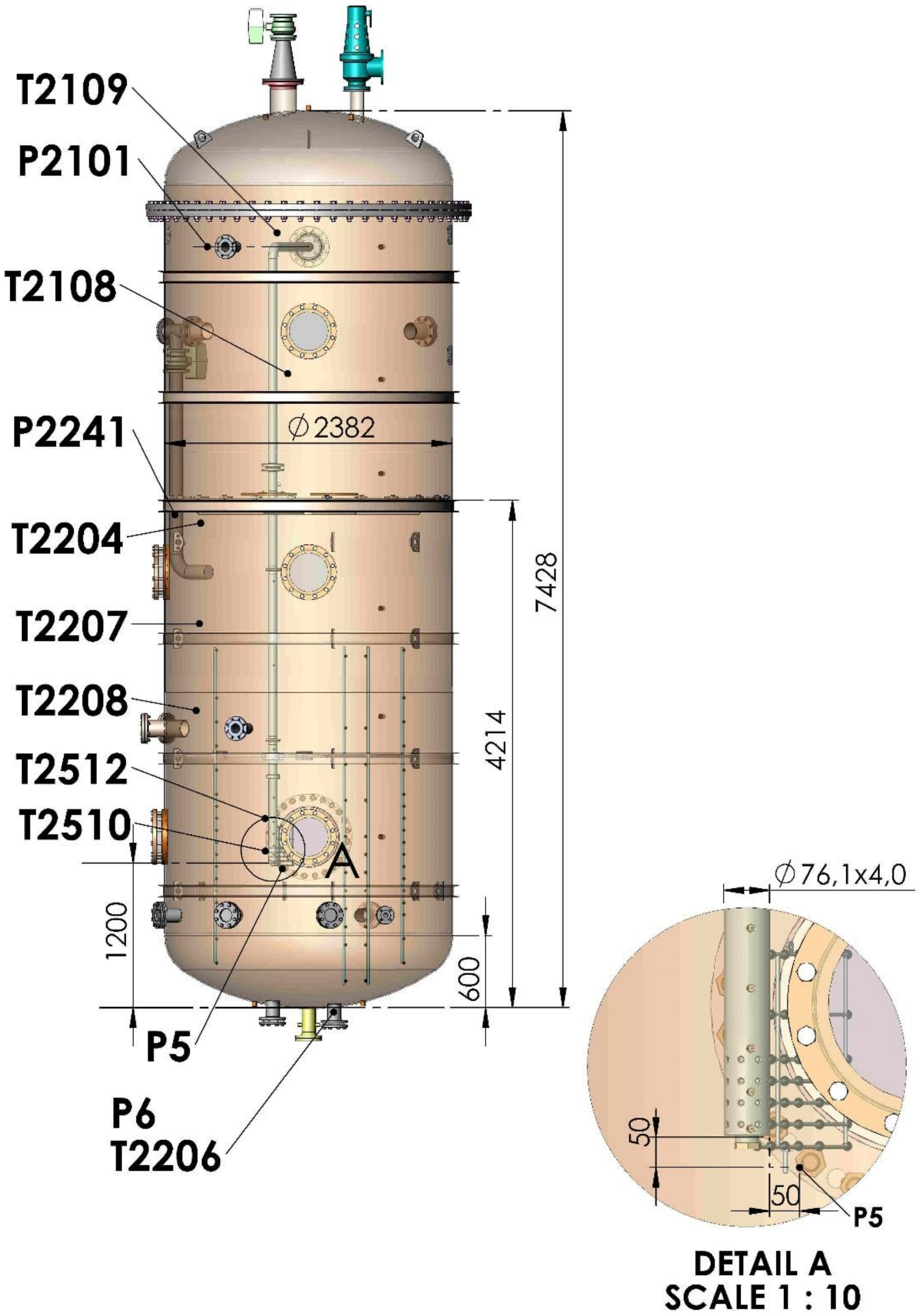


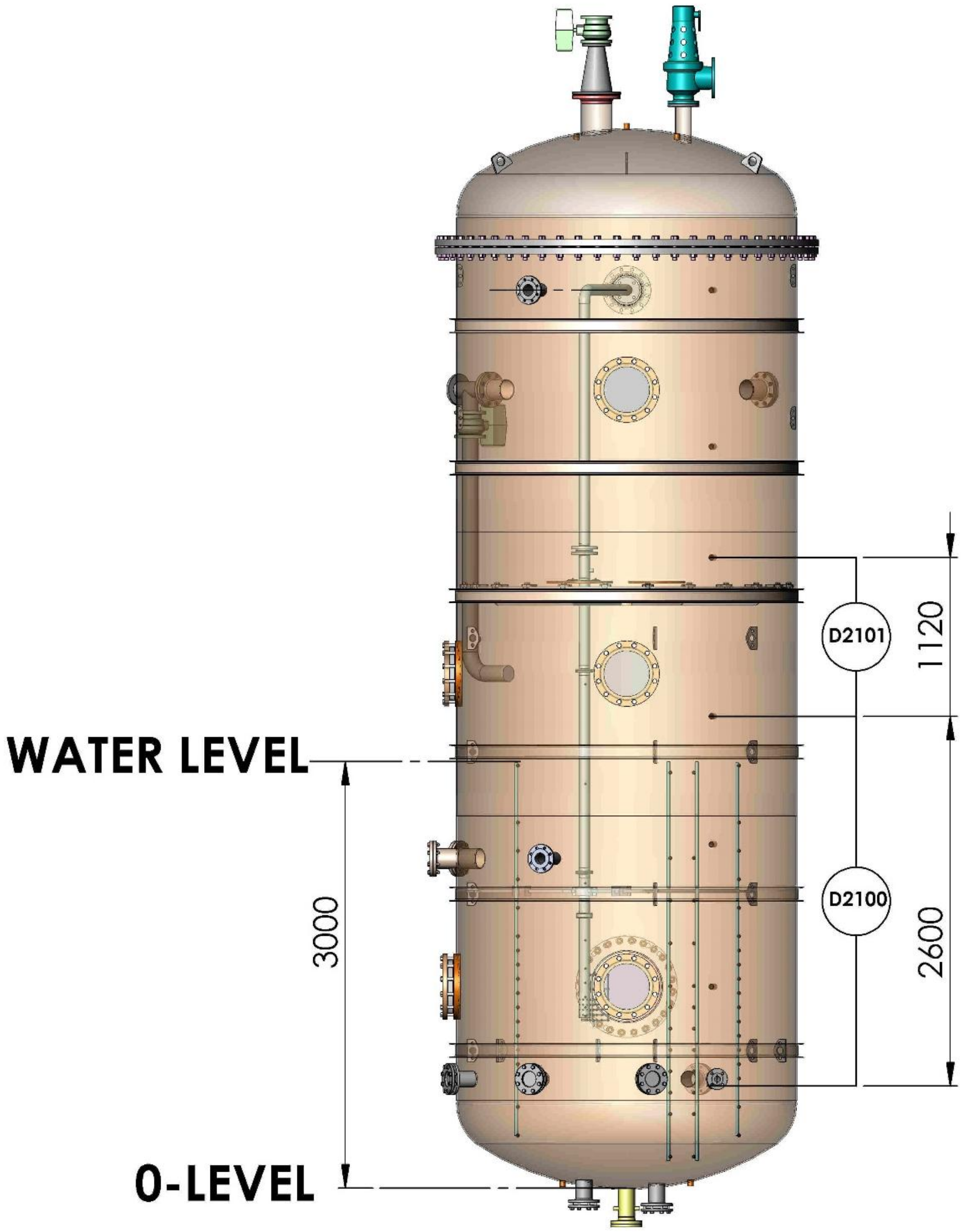
6x7 grid of temperature measurements in the wetwell.



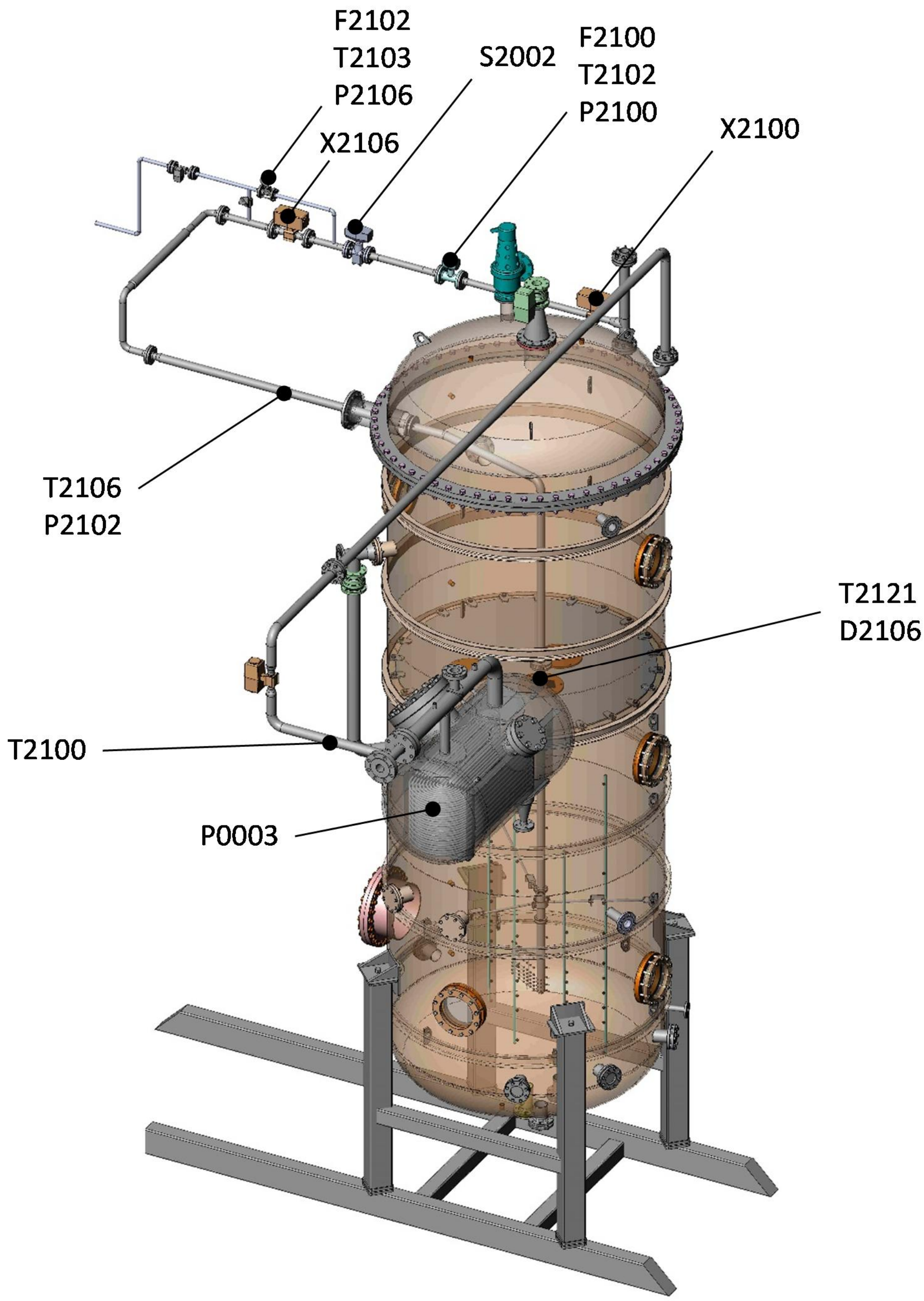
Temperature measurements inside the sparger pipe.



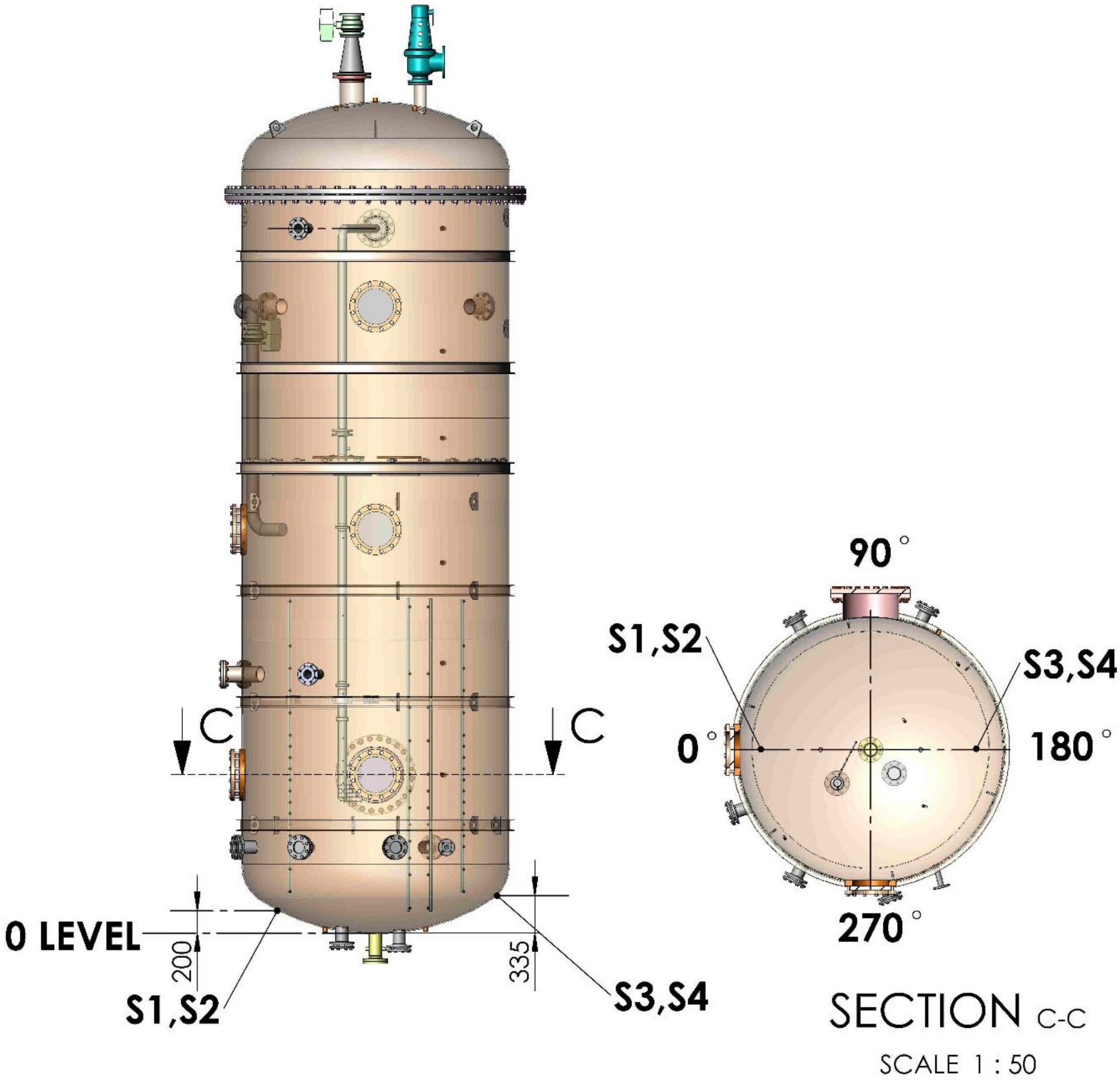
Test vessel measurements.



Pressure difference measurements. Nominal water level is 3.0 m.



Measurements in the steam line.



Strain gauges on the outer wall of the pool bottom.

Measurement	Code	Elevation	Location	Error estimation	Measurement software
Camera trigger	C1	-	Wetwell	Not defined	LabView
Pressure difference	D2100	700–3300	Wetwell	±0.05 m	FieldPoint
Pressure difference	D2101	3300–4420	Wetwell–drywell	±4 000 Pa	FieldPoint
Pressure difference	D2106	4347	Blowdown pipe–drywell	±3 000 Pa	FieldPoint
Flow rate	F2100	-	DN50 steam line	±5 l/s	FieldPoint
Flow rate	F2102	-	DN25 steam line	±0.7 l/s	FieldPoint
Pressure	P0003	-	Steam generator 1	±0.3 bar	FieldPoint
Pressure	P0004	-	Steam generator 2	±0.3 bar	FieldPoint
Pressure	P0005	-	Steam generator 3	±0.3 bar	FieldPoint
Pressure	P5	1150	Blowdown pipe outlet	±0.7 bar	LabView
Pressure	P6	-15	Wetwell bottom	±0.5 bar	LabView
Pressure	P2100	-	DN50 steam line	±0.2 bar	FieldPoint
Pressure	P2101	6300	Drywell	±0.03 bar	FieldPoint
Pressure	P2102	-	Inlet plenum	±0.03 bar	FieldPoint
Pressure	P2106	-	DN25 steam line	±0.06 bar	FieldPoint
Pressure	P2241	4200	Wetwell gas space	±0.05 bar	FieldPoint
Control valve position	S2002	-	DN50 Steam line	Not defined	FieldPoint
Strain	S1	200	Bottom segment	Not defined	LabView
Strain	S2	200	Bottom segment	Not defined	LabView
Strain	S3	335	Bottom segment	Not defined	LabView
Strain	S4	335	Bottom segment	Not defined	LabView
Temperature	T1279	-3260	Laboratory	±0.1 °C	FieldPoint
Temperature	T1280	-1260	Laboratory	±0.1 °C	FieldPoint
Temperature	T1281	740	Laboratory	±1.8 °C	FieldPoint
Temperature	T1282	2740	Laboratory	±0.1 °C	FieldPoint
Temperature	T1283	4740	Laboratory	±0.1 °C	FieldPoint
Temperature	T1284	6740	Laboratory	±0.1 °C	FieldPoint
Temperature	T1285	8740	Laboratory	±0.1 °C	FieldPoint
Temperature	T2100	-	DN80 steam line	±3 °C	FieldPoint
Temperature	T2102	-	DN50 steam line	±2 °C	FieldPoint
Temperature	T2103	-	DN25 steam line	±2 °C	FieldPoint
Temperature	T2106	-	Inlet plenum	±2 °C	FieldPoint
Temperature	T2108	5200	Drywell	±2 °C	FieldPoint
Temperature	T2109	6390	Drywell	±2 °C	FieldPoint
Temperature	T2121	4347	Blowdown pipe	±2 °C	FieldPoint
Temperature	T2204	4010	Wetwell gas space	±2 °C	FieldPoint
Temperature	T2206	-15	Wetwell bottom	±2 °C	FieldPoint
Temperature	T2207	3185	Wetwell gas space	±2 °C	FieldPoint
Temperature	T2208	2360	Wetwell gas space	±2 °C	FieldPoint
Temperature	T2510	1295	Wetwell	±2 °C	FieldPoint
Temperature	T2512	1565	Wetwell	±2 °C	FieldPoint
Temperature	T4000	1500	Wetwell	±2 °C	FieldPoint
Temperature	T4001	1400	Wetwell	±2 °C	LabView
Temperature	T4002	1326	Wetwell	±2 °C	LabView
Temperature	T4003	1290	Wetwell	±2 °C	LabView
Temperature	T4004	1254	Wetwell	±2 °C	LabView
Temperature	T4005	1218	Wetwell	±2 °C	LabView

Temperature	T4006	1182	Wetwell	±2 °C	LabView
Temperature	T4010	1500	Wetwell	±2 °C	FieldPoint
Temperature	T4011	1400	Wetwell	±2 °C	LabView
Temperature	T4012	1326	Wetwell	±2 °C	LabView
Temperature	T4013	1290	Wetwell	±2 °C	LabView
Temperature	T4014	1254	Wetwell	±2 °C	LabView
Temperature	T4015	1218	Wetwell	±2 °C	LabView
Temperature	T4016	1182	Wetwell	±2 °C	LabView
Temperature	T4020	1500	Wetwell	±2 °C	LabView
Temperature	T4021	1400	Wetwell	±2 °C	LabView
Temperature	T4022	1326	Wetwell	±2 °C	LabView
Temperature	T4023	1290	Wetwell	±2 °C	LabView
Temperature	T4024	1254	Wetwell	±2 °C	LabView
Temperature	T4025	1218	Wetwell	±2 °C	LabView
Temperature	T4026	1182	Wetwell	±2 °C	LabView
Temperature	T4030	1500	Wetwell	±2 °C	LabView
Temperature	T4031	1400	Wetwell	±2 °C	LabView
Temperature	T4032	1326	Wetwell	±2 °C	LabView
Temperature	T4033	1290	Wetwell	±2 °C	LabView
Temperature	T4034	1254	Wetwell	±2 °C	LabView
Temperature	T4035	1218	Wetwell	±2 °C	LabView
Temperature	T4036	1182	Wetwell	±2 °C	LabView
Temperature	T4040	1500	Wetwell	±2 °C	FieldPoint
Temperature	T4041	1400	Wetwell	±2 °C	LabView
Temperature	T4042	1326	Wetwell	±2 °C	LabView
Temperature	T4043	1290	Wetwell	±2 °C	LabView
Temperature	T4044	1254	Wetwell	±2 °C	LabView
Temperature	T4045	1218	Wetwell	±2 °C	LabView
Temperature	T4046	1182	Wetwell	±2 °C	LabView
Temperature	T4050	1500	Wetwell	±2 °C	FieldPoint
Temperature	T4051	1400	Wetwell	±2 °C	FieldPoint
Temperature	T4052	1326	Wetwell	±2 °C	FieldPoint
Temperature	T4053	1290	Wetwell	±2 °C	FieldPoint
Temperature	T4054	1254	Wetwell	±2 °C	FieldPoint
Temperature	T4055	1218	Wetwell	±2 °C	FieldPoint
Temperature	T4056	1182	Wetwell	±2 °C	FieldPoint
Temperature	T4070	1211	Blowdown pipe	±2 °C	FieldPoint
Temperature	T4071	1272	Blowdown pipe	±2 °C	FieldPoint
Temperature	T4072	1344	Blowdown pipe	±2 °C	FieldPoint
Temperature	T4073	1444	Blowdown pipe	±2 °C	FieldPoint
Temperature	T4074	1544	Blowdown pipe	±2 °C	FieldPoint
Temperature	T4075	1744	Blowdown pipe	±2 °C	FieldPoint
Temperature	T4076	2144	Blowdown pipe	±2 °C	FieldPoint
Temperature	T4077	2844	Blowdown pipe	±2 °C	FieldPoint
Temperature	T4078	3544	Blowdown pipe	±2 °C	FieldPoint
Temperature	T4100	222	Wetwell	±2 °C	FieldPoint
Temperature	T4101	522	Wetwell	±2 °C	FieldPoint
Temperature	T4102	672	Wetwell	±2 °C	FieldPoint
Temperature	T4103	822	Wetwell	±2 °C	FieldPoint
Temperature	T4104	972	Wetwell	±2 °C	FieldPoint
Temperature	T4105	1122	Wetwell	±2 °C	FieldPoint
Temperature	T4106	1272	Wetwell	±2 °C	FieldPoint

Temperature	T4107	1422	Wetwell	±2 °C	FieldPoint
Temperature	T4108	1722	Wetwell	±2 °C	FieldPoint
Temperature	T4109	2022	Wetwell	±2 °C	FieldPoint
Temperature	T4110	2322	Wetwell	±2 °C	FieldPoint
Temperature	T4111	2922	Wetwell	±2 °C	FieldPoint
Temperature	T4112	372	Wetwell	±2 °C	FieldPoint
Temperature	T4113	158	Wetwell	±2 °C	FieldPoint
Temperature	T4200	372	Wetwell	±2 °C	FieldPoint
Temperature	T4201	572	Wetwell	±2 °C	FieldPoint
Temperature	T4202	772	Wetwell	±2 °C	FieldPoint
Temperature	T4203	872	Wetwell	±2 °C	FieldPoint
Temperature	T4204	972	Wetwell	±2 °C	FieldPoint
Temperature	T4205	1072	Wetwell	±2 °C	FieldPoint
Temperature	T4206	1172	Wetwell	±2 °C	FieldPoint
Temperature	T4207	1272	Wetwell	±2 °C	FieldPoint
Temperature	T4208	1372	Wetwell	±2 °C	FieldPoint
Temperature	T4210	1572	Wetwell	±2 °C	FieldPoint
Temperature	T4212	1772	Wetwell	±2 °C	FieldPoint
Temperature	T4213	1972	Wetwell	±2 °C	FieldPoint
Temperature	T4214	2172	Wetwell	±2 °C	FieldPoint
Temperature	T4215	2372	Wetwell	±2 °C	FieldPoint
Temperature	T4216	2572	Wetwell	±2 °C	FieldPoint
Temperature	T4217	2972	Wetwell	±2 °C	FieldPoint
Temperature	T4218	472	Wetwell	±2 °C	FieldPoint
Temperature	T4219	672	Wetwell	±2 °C	FieldPoint
Temperature	T4300	372	Wetwell	±2 °C	FieldPoint
Temperature	T4301	572	Wetwell	±2 °C	FieldPoint
Temperature	T4302	772	Wetwell	±2 °C	FieldPoint
Temperature	T4303	872	Wetwell	±2 °C	FieldPoint
Temperature	T4304	972	Wetwell	±2 °C	FieldPoint
Temperature	T4305	1072	Wetwell	±2 °C	FieldPoint
Temperature	T4306	1172	Wetwell	±2 °C	FieldPoint
Temperature	T4307	1272	Wetwell	±2 °C	FieldPoint
Temperature	T4308	1372	Wetwell	±2 °C	FieldPoint
Temperature	T4310	1572	Wetwell	±2 °C	FieldPoint
Temperature	T4312	1772	Wetwell	±2 °C	FieldPoint
Temperature	T4313	1972	Wetwell	±2 °C	FieldPoint
Temperature	T4314	2172	Wetwell	±2 °C	FieldPoint
Temperature	T4315	2372	Wetwell	±2 °C	FieldPoint
Temperature	T4316	2572	Wetwell	±2 °C	FieldPoint
Temperature	T4317	2972	Wetwell	±2 °C	FieldPoint
Temperature	T4318	472	Wetwell	±2 °C	FieldPoint
Temperature	T4319	672	Wetwell	±2 °C	FieldPoint
Temperature	T4400	222	Wetwell	±2 °C	FieldPoint
Temperature	T4401	522	Wetwell	±2 °C	FieldPoint
Temperature	T4402	672	Wetwell	±2 °C	FieldPoint
Temperature	T4403	822	Wetwell	±2 °C	FieldPoint
Temperature	T4404	972	Wetwell	±2 °C	FieldPoint
Temperature	T4405	1122	Wetwell	±2 °C	FieldPoint
Temperature	T4406	1272	Wetwell	±2 °C	FieldPoint
Temperature	T4407	1422	Wetwell	±2 °C	FieldPoint
Temperature	T4408	1722	Wetwell	±2 °C	FieldPoint

Temperature	T4409	2022	Wetwell	±2 °C	FieldPoint
Temperature	T4410	2322	Wetwell	±2 °C	FieldPoint
Temperature	T4411	2922	Wetwell	±2 °C	FieldPoint
Temperature	T4412	372	Wetwell	±2 °C	FieldPoint
Temperature	T4413	158	Wetwell	±2 °C	FieldPoint
Cut-off valve position	V1	-	DN50 Steam line	Not defined	LabView
Cut-off valve position	X2100	-	DN50 Steam line	Not defined	FieldPoint
Steam partial pressure	X2102	5200	Drywell	Not defined	FieldPoint
Cut-off valve position	X2106	-	DN50 Steam line	Not defined	FieldPoint

Measurements of the PPOOLEX facility in the SPA experiment series.

APPENDIX 3: PPOOLEX TEST FACILITY PHOTOGRAPHS

Interior of the try well compartment and DN65 steam line.

Lower part of the sparger pipe.

Bibliographic Data Sheet **NKS-364**

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Abstract
max. 2000 characters

This report summarizes the results of the two sparger pipe tests (SPA-T1 and SPA-T7) carried out in the PPOOLEX test facility at LUT in 2015. Steam was blown through the vertical DN65 sparger type blowdown pipe to the condensation pool filled with sub-cooled water.

The main objective of the tests was to obtain additional data for the development of the Effective Momentum Source (EMS) and Effective Heat Source (EHS) models to be implemented in GOTHIC code by KTH. The test parameters were selected by KTH on the basis of pre-test simulations and analysis of the results of the earlier sparger tests in PPOOLEX. As opposed to the earlier tests only one row of injection holes at the sparger head (SPA-T1) or the holes of the load reduction ring (SPA-T7) were now used for steam injection. Both tests had two stratification periods and two mixing periods. In addition SPA T1 had an extra stratification period at the end of the test.

During the stratification periods the used steam injection flow rate was in the range of 30-45 g/s (75-112 kg/m2s). With these kind of mass fluxes steam flowed through the injection holes of the sparger as small jets and condensed mainly outside the sparger pipe. Because no chugging kind of phenomenon existed and the steam jets were too weak to create much turbulence in the pool, suitable conditions for thermal stratification to occur prevailed.

When the steam injection was vertically downwards from the LRR the transition region between the cold and warm pool water was deeper in the pool than in the horizontal injection case. The vertical length of the transition region was also longer in the LRR case.

Complete mixing was achieved with both tested flow modes, oscillatory cone jet mode (SPA-T1) and oscillatory bubble mode (SPA-T7). In the earlier tests with all the injection holes of the sparger head unblocked a considerably larger flow rate was not enough to mix the pool. Then the flow mode was different and not enough momentum and internal circulation were created for complete mixing to happen. Mixing was observed only above and a short distance below the sparger head outlet elevation.

Key words: condensation pool, steam blowdown, sparger, mixing