NKS-334
ISBN 978-87-7893-416-1

# PPOOLEX Experiments with a Sparger

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April 2015

## Abstract

This report summarizes the results of the sparger experiments carried out with the scaled down PPOOLEX test facility designed and constructed at Lappeenranta University of Technology. 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 experiments was to obtain verification data for the development of the Effective Momentum Source (EMS) and Effective Heat Source (EHS) models to be implemented in GOTHIC code by KTH. A detailed test matrix and procedure put together on the basis of the pre-test calculations was provided by KTH.

Altogether five experiments were carried out. The experiments consisted of two stratification periods and two mixing periods.

During the first stratification period a 120–130 g/s steam flow rate was used. With this flow rate steam flowed through the injection holes of the sparger head as small jets and condensed mainly outside the sparger pipe. As a result temperatures remained constant below the blowdown pipe outlet but increased towards the pool surface layers indicating strong thermal stratification of the wetwell pool water. In the end of the first stratification period the temperature difference between the pool bottom and surface was 18–26 ºC depending on the test in question. In the second stratification period a 70–97 g/s steam flow rate was used. In the end of this period the temperature difference between the pool bottom and surface was 20–31 ºC.

During the mixing periods I and II the steam flow rate was increased rapidly to 130–260 g/s or decreased to 40–70 g/s to mix the pool water inventory. Total mixing of the pool was not obtained in every experiment. Mixing efficiency depended on the flow mode in question i.e. on the used steam mass flow rate and on the pool bulk temperature. Enough turbulence to mix the pool could be created either with high steam flow rates causing strong internal circulation in the pool or with quite small steam flow rates (in the range of 70 g/s) causing external chugging phenomenon at the sparger head. With the intermediate flow rates only the elevations above and a short distance below the sparger head could be mixed. When the flow rate was very low (in the range of 40 g/s) condensation took place inside the sparger pipe and there was no mixing effect at all.



## Key words

condensation pool, steam blowdown, sparger, mixing

NKS-334
ISBN 978-87-7893-416-1
Electronic report, April 2015
NKS Secretariat
P.O. Box 49
DK - 4000 Roskilde, Denmark
Phone +45 4677 4041
www.nks.org
e-mail nks@nks.org

Research Report
Lappeenranta University of Technology
Nuclear Safety Research Unit

EXCOP 1/2014

# PPOOLEX EXPERIMENTS WITH A SPARGER

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Lappeenranta, 25.2.2015

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| **Project title and reference code** | **Report identification & Pages** | **Date** |
| SAFIR2014-EXCOP<br>NKS-ENPOOL | EXCOP 1/2014<br>20 p. + app. 17 p. | 25.2.2015 |

**Report title and author(s)**

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Altogether five experiments were carried out. The experiments consisted of two stratification periods and two mixing periods. The steam line was heated up before the first stratification period was initiated. The initial water bulk temperature in the condensation pool was 14–19 °C.

During the first stratification period a 120–130 g/s steam flow rate (corresponding to the mass flux of about 80 kg/m$^2$s) was used. With this flow rate steam flowed through the injection holes of the sparger head as small jets and condensed mainly outside the sparger pipe. As a result temperatures remained constant below the blowdown pipe outlet but increased towards the pool surface layers indicating strong thermal stratification of the wetwell pool water. In the end of the first stratification period the temperature difference between the pool bottom and surface was 18–26 ºC depending on the test in question. In the second stratification period a 70–97 g/s steam flow rate (round 60 kg/m$^2$s) was used. In the end of this period the temperature difference between the pool bottom and surface was 20–31 ºC.

During the mixing periods I and II the steam flow rate was increased rapidly to 130–260 g/s (about 80-165 kg/m$^2$s) or decreased to 40–70 g/s (about 25-43 kg/m$^2$s) to mix the pool water inventory. Total mixing of the pool was not obtained in every experiment. Mixing efficiency depended on the flow mode in question i.e. on the used steam mass flow rate and on the pool bulk temperature. Enough turbulence to mix the pool could be created either with high steam flow rates causing strong internal circulation in the pool or with quite small steam flow rates (in the range of 70 g/s) causing external chugging phenomenon (alternating steam jets and water ingress backwards) at the sparger head. With the intermediate flow rates only the elevations above and a short distance below the sparger head could be mixed. When the flow rate was very low (in the range of 40 g/s) condensation took place inside the sparger pipe and there was no mixing effect at all.

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| Principal author or Project manager | Reviewed by |
|---|---|
| Jani Laine, Research Scientist | Vesa Riikonen, Senior Research Scientist |
| **Approved by** | **Availability statement** |
| Heikki Purhonen, Research Director | SAFIR2014 limitations |

# Acknowledgement

NKS conveys its gratitude to all organisations and persons who by means of financial support or contributions in kind have made the work presented in this report possible.

# Disclaimer

# PREFACE

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

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

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

A new research project called Experimental Studies on Containment Phenomena (EXCOP) started in 2011 within the national nuclear power plant safety research programme SAFIR2014. The EXCOP project focuses on gathering an extensive experiment database on condensation dynamics, heat transfer and structural loads, which can be used for testing and developing computational methods used for nuclear safety analysis. To achieve the above mentioned goals sophisticated measuring solutions i.e. a Particle Image Velocimetry (PIV) system and a modern high speed camera have been installed to the PPOOLEX facility in 2011. Networking among international research organizations is enhanced via participation in the NORTHNET framework and NKS/ENPOOL project. Analytical and numerical work of Kungliga Tekniska Högskolan (KTH) is combined to EXCOP, ELAINE, NUMPOOL and ESA projects of SAFIR2014. The studies are funded by the VYR, NKS and NORTHNET.

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# NOMENCLATURE

| | |
|---|---|
| v | velocity |

**Greek symbols**

| | |
|---|---|
| Δ | change |

**Abbreviations**

| | |
|---|---|
| BWR | boiling water reactor |
| CCTV | closed circuit television |
| CFD | computational fluid dynamics |
| CONDEX | Condensation experiments |
| DCC | direct contact condensation |
| DYN | experiment series focusing on dynamic loading |
| ECCS | emergency core cooling system |
| EMS | effective momentum source |
| EXCOP | experimental studies on containment phenomena project |
| KTH | Kungliga Tekniska Högskolan |
| LRR | load reduction ring |
| LOCA | loss-of-coolant accident |
| LUT | Lappeenranta University of Technology |
| MSLB | main steam line break |
| MIX | mixing experiment series |
| NKS | Nordic nuclear safety research |
| PACTEL | parallel channel test loop |
| PAR | experiment series with parallel blowdown pipes |
| POOLEX | condensation pool experiments project |
| PPOOLEX | pressurized condensation pool experiments project |
| PWR | pressurized water reactor |
| SAFIR | Safety of Nuclear Power Plants - Finnish National Research Programme |
| SLR | steam line rupture |
| SPA | sparger experiment series |
| SRV | safety/relief valve |
| TC | thermocouple |
| TRA | experiment series with transparent blowdown pipes |
| TVO | Teollisuuden Voima Oyj |
| VTT | Technical Research Centre of Finland |
| VYR | State Nuclear Waste Management Fund |

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# 1 INTRODUCTION

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

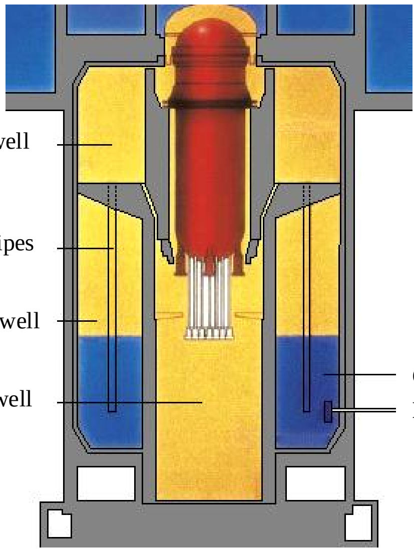


*Figure 1. Schematic of the Olkiluoto type BWR containment.*

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

To achieve the project objectives, a combined experimental/analytical/computational study programme is being carried out. Experimental part at LUT is responsible for the development of a database on condensation pool dynamics and heat transfer at well controlled conditions. Analytical/computational part at VTT, KTH and LUT use the developed experiment database for the improvement and validation of models and numerical methods including CFD and system codes. Also analytical support is provided for the experimental part by pre- and post-calculations of the experiments. Furthermore, the (one-directional or bi-directional) coupling of CFD and structural analysis codes in solving fluid-structure interactions can be facilitated with the aid of load measurements of the steam blowdown experiments.

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

Experiments with the PPOOLEX facility started in 2007 by running characterizing tests where the general behaviour of the facility was observed and instrumentation and the proper operation of automation, control and safety systems was tested [1]. The SLR series focused on the initial period of a postulated MSLB accident inside the containment [2]. Air was used as the flowing substance in these experiments. The research program continued in 2008 with a series of thermal stratification and mixing experiments [3]. Stratification in the water volume of the wetwell during small steam discharge was of special interest. In December 2008 and January 2009 a test series focusing on steam condensation in the drywell compartment was carried out [4]. Experiments to study the effect of the Forsmark type blowdown pipe outlet collar design on loads caused by chugging phenomena were also done in 2009 [5]. Then the research programme continued with eleven experiments (TRA and PAR series) studying the effect of the number of blowdown pipes (one or two) on loads caused by chugging phenomenon [6]. In January 2010, experiments focusing on dynamic loading (DYN series) during steam discharge were carried out [7]. Stratification and mixing in the wetwell pool and the interaction of parallel blowdown pipes were investigated further in 2010 [8], [9]. In January–February 2011 a second series of the experiments with the Forsmark type blowdown pipe outlet collar was carried out [10]. First tests with the new PIV measurement system were executed at the end of 2011 [11].

In June–October 2012 a series of thermal stratification and mixing experiments (labeled as MIX-01…06) were carried out [12]. For the test series additional thermocouples were installed inside the blowdown pipe to get accurate information of the movement of steam/water-interface inside the pipe during the mixing period. The main purpose of the experiments was to generate data for the development of the Effective Momentum Source (EMS) and Effective Heat Source (EHS) models to be implemented in GOTHIC code by KTH [13].

To generate more data for the development of the EMS and EHS models a second series of thermal stratification and mixing experiments was carried out in October–November 2013 (labeled as MIX-07…12) [14].

Work with the PPOOLEX facility continued in November–December 2014 with a series of experiments focusing on the behaviour of a safety relief valve sparger (labelled as SPA-T2…T6). For the test series an extensive net of thermocouples were installed inside the condensation pool. In this report, the results of the SPA experiments are presented. First, chapter two gives a short description of the test facility and its measurements as well as of the data acquisition system used. The test programme is introduced in chapter three. The test results are presented and discussed in chapter four. Chapter five summarizes the findings of the experiment series.

# 2 PPOOLEX TEST FACILITY

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 experiments 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 [15]. 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 experiments 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 2. Table 1 lists the main dimensions of the test facility compared to the conditions in the Olkiluoto plant.

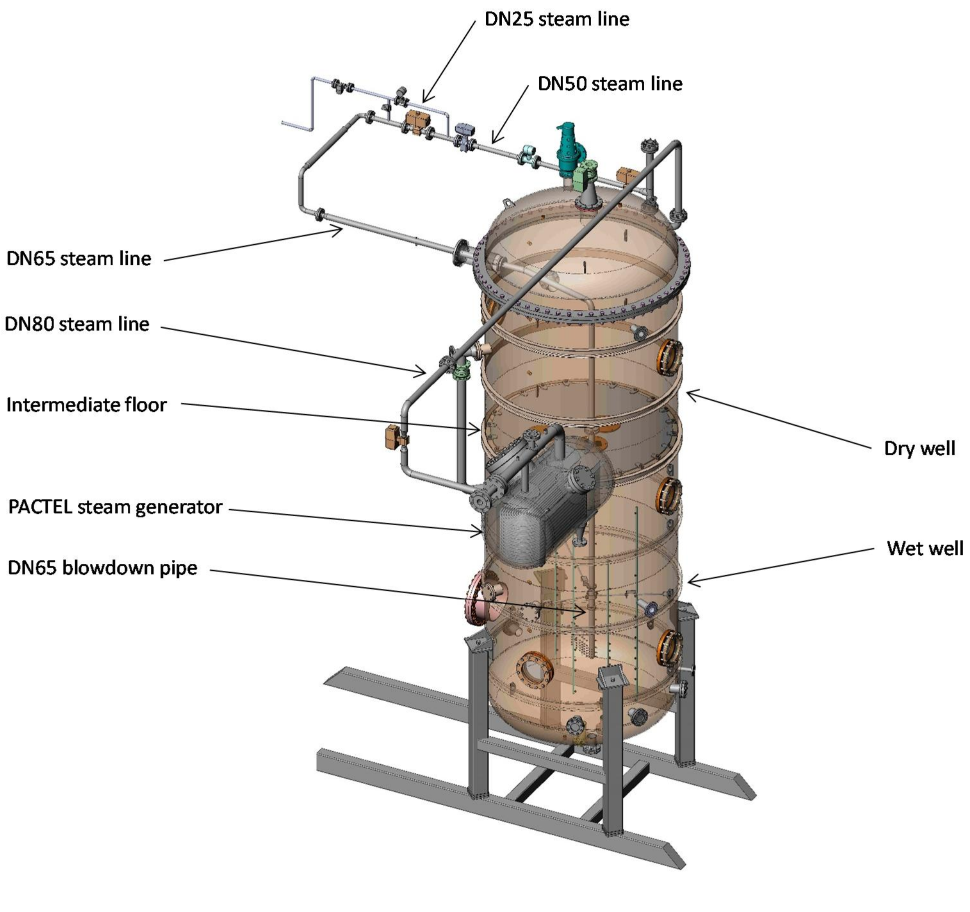


*Figure 2. PPOOLEX test vessel.*

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

| | PPOOLEX test facility | Olkiluoto 1 and 2 |
|---|---|---|
| Number of blowdown pipes | 1-2 | 16 |
| Inner diameter of the blowdown pipe [mm] | 214.1 | 600 |
| Suppression pool cross-sectional area [m$^2$] | 4.45 | 287.5 |
| 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 experiments is generated with the nearby PACTEL [16] 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 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). There is a load reduction ring (LRR) 700 mm above the pipe outlet with 8 axially drilled Ø8 mm holes. However, during the actual sparger experiments all the LRR holes were plugged.

## 2.4 AIR REMOVAL SYSTEM

For the sparger experiments 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. With the help of the air removal system oxygen content of PPOOLEX water could be decreased from 6 mg/l to 3 mg/l during the preparation period for the experiments. However, the system was not used in all experiments because it was still being tested.

## 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 experiments 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…T4113, T4200…T4219, T4300…T4319 and T4400…T4413) were installed in the pool below the water level for detecting vertical temperature distribution. The 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 2011. The data acquisition system is discussed in more detail in reference [17].

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

The used measurement frequency of LabView was 1 kHz for pressures and strains and 20 Hz for temperatures. The rest of the measurements (for example temperature, pressure and flow rate in the steam line) were recorded by the self-made software with the frequency of 0.67 Hz.

# 3 TEST PROGRAM

The test program in November – December 2014 consisted of five experiments (labeled from SPA-T2 to SPA-T6). Before the actual experiments a characterization test (SPA-T0) was carried out. The main purpose of the SPA experiment series was to obtain additional data for the development of the EMS and EHS models to be implemented in GOTHIC code by KTH. A detailed test matrix and procedure put together on the basis of pre-test calculations was provided by KTH before the experiments [18]. During the experimental campaign the test parameters for the next test were updated on the basis of an initial analysis of the results of the previous tests. All the experiments had two stratification periods and two mixing periods.

Before the experiments, the wetwell pool was filled with isothermal water (15–20 °C) 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 experiments 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 rapidly increasing or decreasing (depending on the test specifications) steam flow rate into the test vessel after the predetermined temperature difference between the bottom and surface layers of the pool had been reached. The second stratification process with a small steam flow rate was initiated after a uniform temperature distribution or otherwise determined condition 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.

For SPA-T2 and SPA-T6, 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.

The main parameters of the SPA-T0 and SPA-T2…T6 experiments are listed in Table 2 and 3, correspondingly. The path of each experiment 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 3. In the map steam mass flux is determined as flow rate through the injection holes of the sparger head divided by the cross-sectional area of the holes.

*Table 2. Parameter values of the characterization test SPA-T0.*

| Exp. | Initial water level [m] | Steam source pressure [MPa] | Period I | | Period II | |
|---|---|---|---|---|---|---|
| | | | Initial water temperature [°C] | Steam flow rate [g/s] | Initial water temperature [°C] | Steam flow rate [g/s] |
| SPA-T0 | 3.0 | 0.6 | 20 | 30–300 | 60 | 30–310 |

*Table 3. Parameter values of the sparger test series in 2014 SPA-T2…T6.*

| Exp. | Initial water level [m] | Initial water temperature [°C] | Steam source pressure [MPa] | Steam flow rate [g/s] | | | |
|---|---|---|---|---|---|---|---|
| | | | | Stratification I | Mixing I | Stratification II | Mixing II |
| SPA-T2 | 3.0 | 14 | 0.6 | 130 | 70 | 70 | 200 |
| SPA-T3 | 3.0 | 19 | 0.6 | 120 | 260 | 95 | 250 |
| SPA-T4 | 3.0 | 16 | 0.6 | 130 | 175 | 93 | 130 |
| SPA-T5 | 3.0 | 15 | 0.6 | 123 | 208 | 97 | 150 |
| SPA-T6 | 3.0 | 15 | 0.6 | 130 | 150 | 90 | 40 |

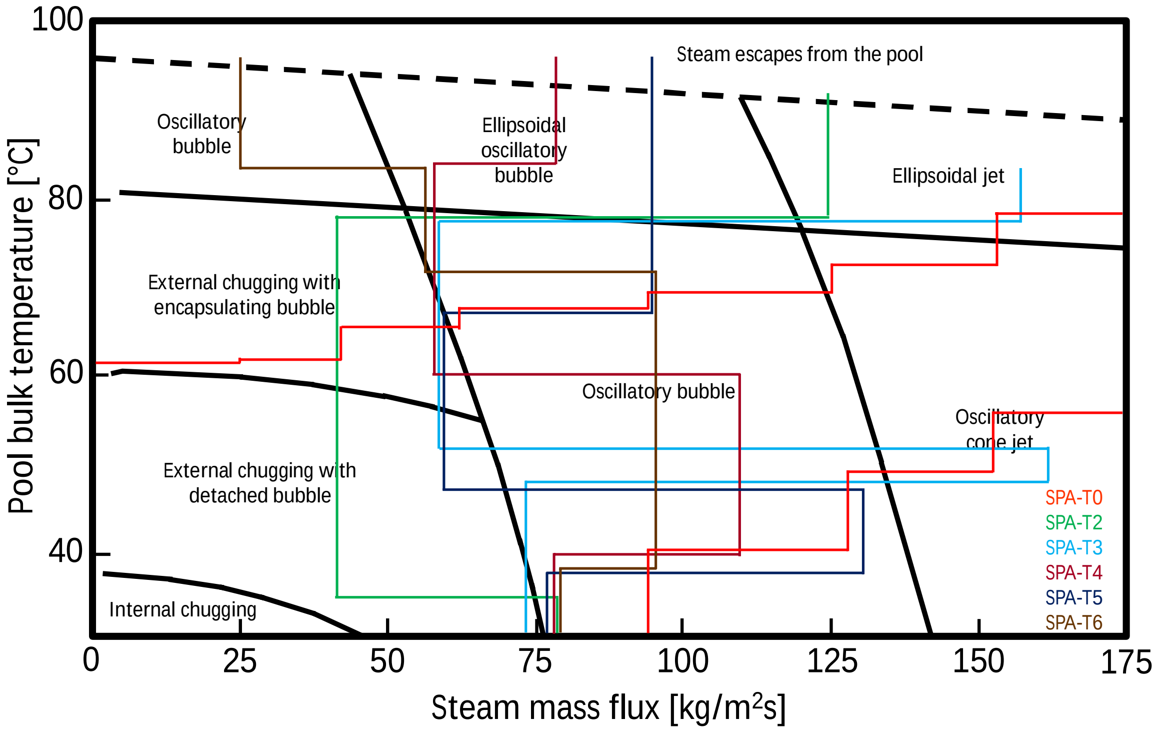


*Figure 3. Paths of the SPA experiments marked on the direct condensation mode map for pure steam discharge of Chan and Lee [19].*

# 4 EXPERIMENT RESULTS

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

## 4.1 HEAT UP PERIOD

The SPA experiments consisted of five parts; a heat up period, two thermal stratification periods and two mixing periods. First, the steam flow rate was set to 220–240 g/s to remove air from the steam line as well as to heat up the piping, Table 4. The pool bulk temperature rose approximately 2 °C during the heat up period, which lasted for about 200 seconds in every experiment.

*Table 4. Parameters of the heat-up periods of the SPA 2014 experiments.*

| Exp. | Time period [s] | Steam flow rate [g/s] | Pool water temperature increase [°C] |
|---|---|---|---|
| SPA-T2 | 28–228 | ~230 | 14→16 |
| SPA-T3 | 35–235 | ~220 | 19→21 |
| SPA-T4 | 27–226 | ~230 | 16→18 |
| SPA-T5 | 35–236 | ~240 | 15→17 |
| SPA-T6 | 15–214 | ~240 | 15→17 |

## 4.2 STATIFICATION AND MIXING

### 4.2.1 Stratification period I

After the steam line had been heated up the steam flow rate was rapidly decreased to the level of 120–130 g/s (corresponding to the mass flux of about 80 kg/m$^2$s) in order to start the first stratification period. With this kind of mass fluxes steam flowed through the injection holes of the sparger head 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. As a result temperatures below the sparger pipe outlet remained constant while they rose towards the pool surface layers indicating strong thermal stratification of the wetwell pool water, Figure 4 and Figure 5. 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. The stratification period was continued as long as the temperature difference between the pool bottom (measured by thermocouple T4100) and surface (T4111, T4113 in SPA-T2 and SPA-T6) had reached the target value given by KTH i.e. 15–30 ºC depending of the test, Table 5.

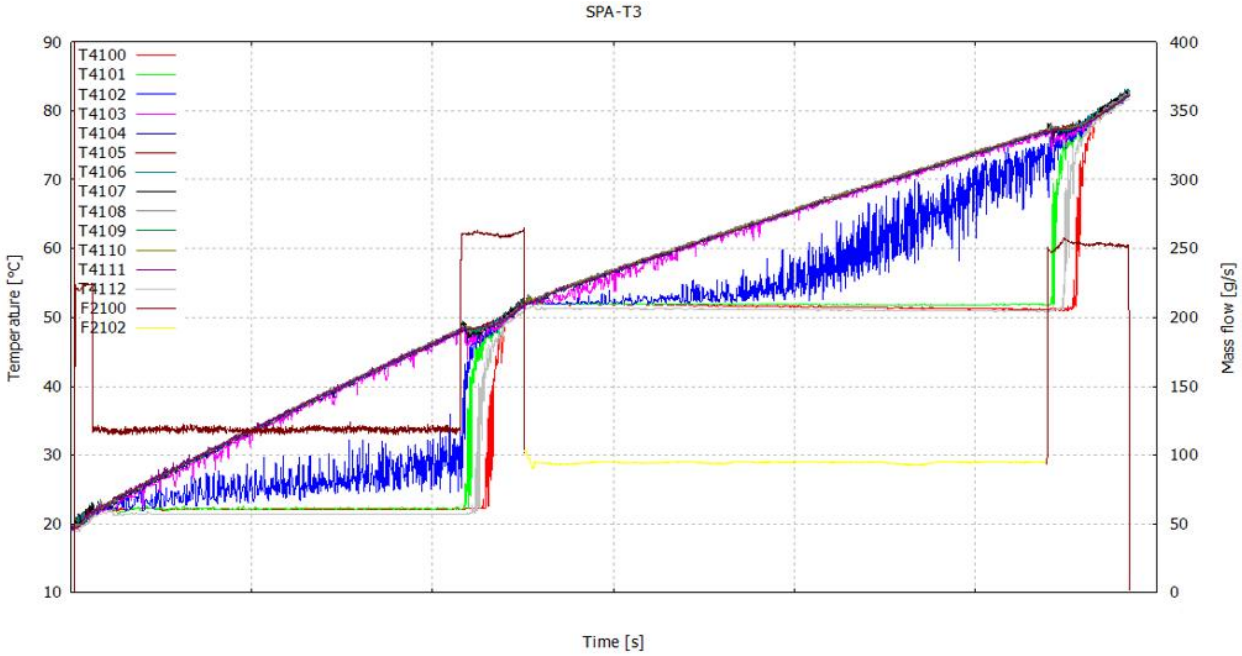


*Figure 4. Vertical temperature distribution in wetwell water (T4100–T4112) and steam flow rate (F2100 and F2102) in SPA-T3.*

From Figure 5 one can see that the vertical distance, where the stratification occurs, is very narrow compared to the previous stratification/mixing experiments in PPOOLEX with a straight blowdown pipe. Outside the stratification zone the curves are almost straight vertical lines indicating constant water temperature at a given moment of time. The transition zones below and above the stratification zone are also very narrow because the angles of the curves are almost 90° indicating a very sharp change of temperature.

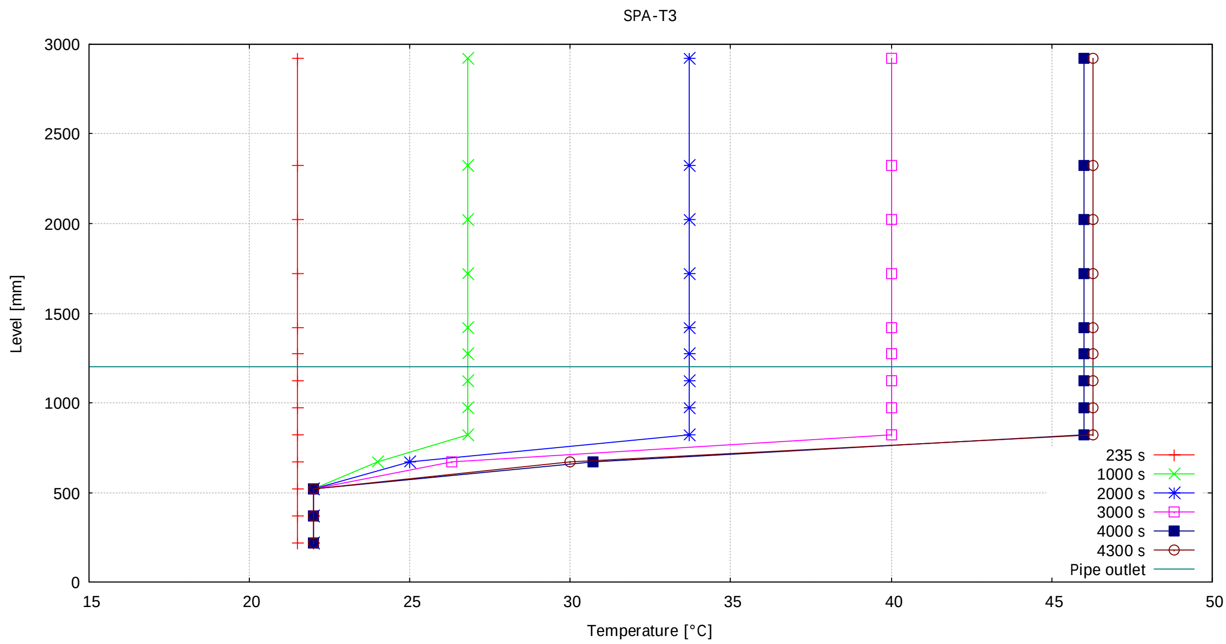


*Figure 5. Development of vertical temperature profile of pool water in SPA-T3 during stratification period I.*

*Table 5. Stratification period I related observations of the SPA 2014 experiments.*

| Exp. | Time period [s] | Initial water temperature [°C] | Steam flow rate [g/s] | Stratification time [s] | Final water temperature T4100 / T4111 [°C] | Final temperature difference between T4100 and T4111 [°C] |
|---|---|---|---|---|---|---|
| SPA-T2 | 228–2755 | 16 | 130 | 2527 | 17/35 | 18 |
| SPA-T3 | 235–4303 | 21 | 120 | 4068 | 22/48 | 26 |
| SPA-T4 | 226–3162 | 18 | 129 | 2936 | 19/39 | 20 |
| SPA-T5 | 236–3352 | 17 | 123 | 3116 | 18/38 | 20 |
| SPA-T6 | 214–3210 | 17 | 130 | 2996 | 18/39 | 21 |

### 4.2.2 Mixing period I

After the desired temperature difference between the pool bottom and surface was attained the steam mass flow rate was rapidly increased up to 150–260 g/s (about 95-165 $kg/m^2s$) to create turbulence in the pool with the help of the steam jets and thus to mix the condensation pool water inventory totally, Table 6. In SPA-T2 the steam flow rate for the first mixing period was decreased to 70 g/s (about 43 $kg/m^2s$) to find out if the pool water inventory can be mixed with the external chugging condensation mode, Figure 3 and Figure 6. In this mode the steam/water interface moves up and down inside the sparger pipe because water suction into the sparger head through the injection holes and steam discharge out of the head alternate thus creating a mixing effect. With the highest used flow rates as well as with the 70 g/s flow rate enough turbulence was created to mix the pool water volume completely. Depending of the used steam flow rate and initial pool water temperature it took 500–2950 s to achieve total mixing of the pool water volume. With the intermediate flow rate (150 g/s in SPA-06) mixing was observed only along a small distance below the sparger head outlet elevation and when the first mixing period was terminated after about 5400 s the temperature difference between the pool bottom and surface had increased from 21 °C to 55 °C. The elevations above the sparger head outlet were, however, well mixed.

*Table 6. Mixing period I related observations of the SPA 2014 experiments.*

| Exp. | Time period [s] | Steam flow rate [g/s] | Mixing time [s] | Final temperature [°C] |
|---|---|---|---|---|
| SPA-T2 | 2755–5155 | 70 | ~2400 | 39 |
| SPA-T3 | 4303–5005 | 260 | ~500 | 52 |
| SPA-T4 | 3162–6108 | 175 | ~2950 | 60 |
| SPA-T5 | 3352–4605 | 208 | ~660 | 42 |
| SPA-T6 | 3210–8602 | 150 | No mixing | 18 (bottom), 73 (top) |

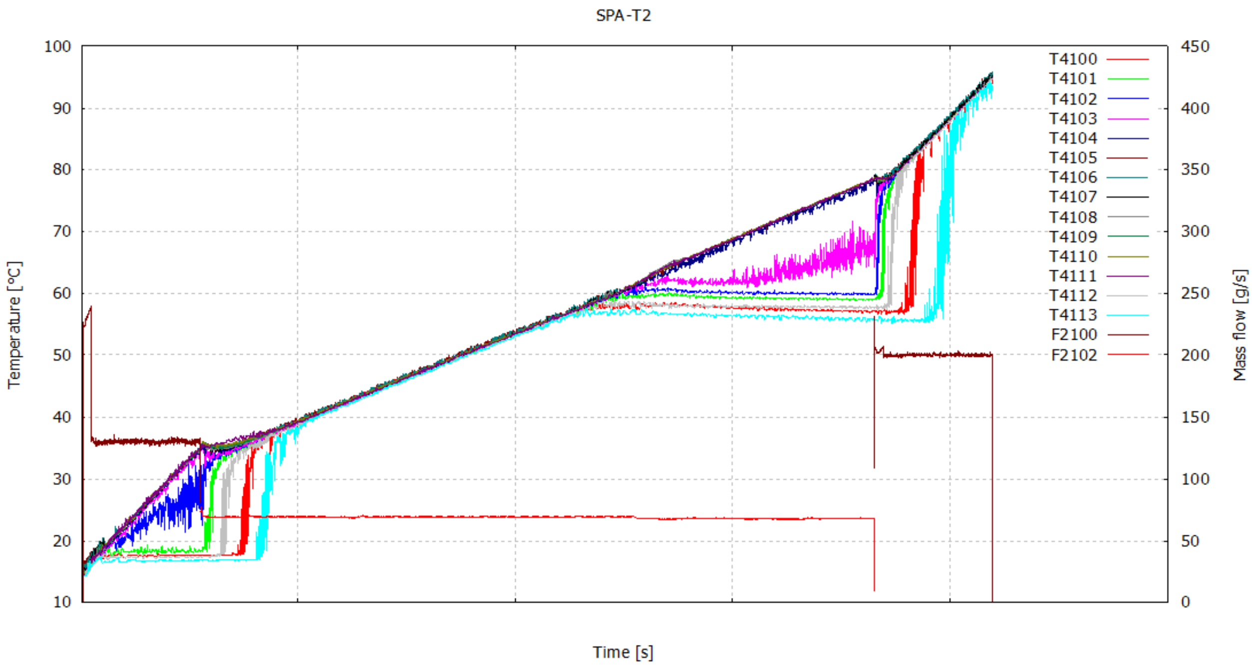


*Figure 6. Vertical temperature distribution in wetwell water (T4100–T4113) and steam flow rate (F2100 and F2102) in SPA-T2.*

### 4.2.3 Stratification period II

The first mixing period was terminated and the second stratification period initiated by decreasing the steam flow rate to the level of 90–97 g/s (round 60 kg/m$^2$s), Table 7. With this flow rate steam condensed again mainly outside the sparger pipe thus creating suitable conditions for thermal stratification to occur. Because the pool water bulk temperature was 20–40 ℃ higher than in the beginning of the first stratification period a smaller steam flow rate could be used without the risk of ending up in the chugging region of the condensation map, see Figure 3. The second stratification period was continued as long as the temperature difference between the pool bottom (measured by thermocouple T4100) and surface (T4111, T4113 in SPA-T2 and SPA-T6) had reached the target value 20–30 °C depending of the test.

In SPA-T2, the same steam flow rate was used in the second stratification period as during the first mixing period; 70 g/s (about 43 kg/m$^2$s). With this flow rate a 22 °C temperature difference was created during stratification period II.

In SPA-T6, the initial temperature difference between the pool bottom and water surface was 55 °. During the second stratification period the temperature difference increased to the value of 65 °C.

*Table 7. Stratification period II related observations of the SPA 2014 experiments.*

| Exp. | Time period [s] | Initial water temperature [°C] | Steam flow rate [g/s] | Stratification time [s] | Final water temperature T4100 / T4111 [°C] | Final temperature difference between T4100 and T4111 [°C] |
|---|---|---|---|---|---|---|
| SPA-T2 | 11300–18252 | 39 | 70 | 6952 | 56/78 | 22 |
| SPA-T3 | 5005–10793 | 52 | 95 | 5788 | 51/77 | 26 |
| SPA-T4 | 6108–12202 | 60 | 93 | 6094 | 53/84 | 31 |
| SPA-T5 | 4605–8902 | 47 | 97 | 4297 | 47/67 | 20 |
| SPA-T6 | 8602–11605 | 18–72 | 90 | 3003 | 19/84 | 65 |

### 4.2.4 Mixing period II

After the desired temperature difference between the pool bottom and surface was attained the second mixing period was initiated by increasing the steam flow rate rapidly to the level of 130–250 g/s (about 80-160 kg/m$^2$s), Table 8. Total mixing of the pool water inventory was achieved only in SPA-T2 and SPA-T3 with the 200 and 250 g/s steam flow rate, correspondingly. In SPA-T2 it took 2250 s and in SPA-T3 530 s before the pool water was mixed totally.

In SPA-T4 and SPA-T5 total mixing of the pool water volume was not achieved. When the second mixing period was terminated the temperature difference between the pool bottom and surface had increased from 31 °C to 44 °C in SPA-T4 and from 20 °C to 30 °C in SPA-T5.

In SPA-T6 the steam flow rate was decreased to 40 g/s (round 25 kg/m$^2$s) for the second mixing period in order to find out if the pool water inventory could be mixed with oscillatory bubble condensation mode, Figure 3 and Figure 7. However, with this flow rate the temperature difference between the pool bottom and surface increased from 65 °C to 72 °C because condensation took place inside the sparger pipe and there was no mixing effect at all.

*Table 8. Mixing period II related observations of the SPA 2014 experiments.*

| Exp. | Time period [s] | Steam flow rate [g/s] | Mixing time [s] | Final temperature [°C] |
|---|---|---|---|---|
| SPA-T2 | 18252–20980 | 200 | ~2250 | 92 |
| SPA-T3 | 10793–11701 | 250 | ~530 | 79 |
| SPA-T4 | 12202–14502 | 130 | No mixing | 52–96 |
| SPA-T5 | 8902–13995 | 150 | No mixing | 65–95 |
| SPA-T6 | 11605–18430 | 40 | No mixing | 23–95 |

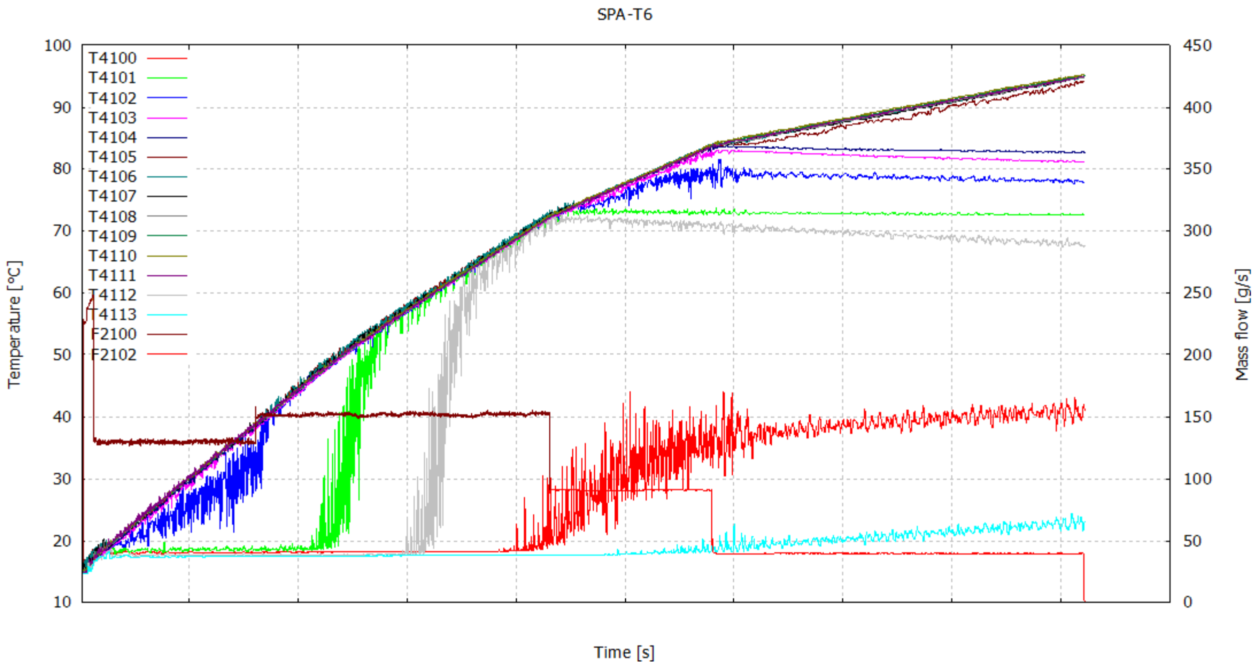


*Figure 7. Vertical temperature distribution in wetwell water (T4100–T4113) and steam flow rate (F2100 and F2102) in SPA-T6.*

# 5 SUMMARY AND CONCLUSIONS

This report summarizes the results of the sparger experiments (SPA test series) in 2014 with the scaled down PPOOLEX test facility designed and constructed at Lappeenranta University of Technology. The test facility is a closed stainless steel vessel divided into two compartments, drywell and wetwell. In the SPA series 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 experiments was to obtain verification data for the development of the Effective Momentum Source (EMS) and Effective Heat Source (EHS) models to be implemented in GOTHIC code by KTH.

Altogether five experiments were carried out according to a test plan written by KTH. The experiments consisted of two small steam flow rate stratification periods and of two higher (or lower) flow rate mixing periods. In the beginning of the experiments air was removed from the steam line and the piping structures were heated up with a steam mass flow rate of 220…240 g/s. The initial water bulk temperature in the condensation pool was 14–19 °C.

During the first stratification period a 120–130 g/s steam flow rate was used. With this flow rate steam flowed through the injection holes of the sparger head as small jets and condensed mainly outside the sparger pipe. No chugging kind of phenomenon existed and the steam jets were too weak to create turbulence in the pool. As a result temperatures remained constant below the sparger pipe outlet but increased towards the pool surface layers indicating strong thermal stratification of the wetwell pool water. In the end of the first stratification period the temperature difference between the pool bottom and surface was 18–26 °C depending on the test in question. In the second

stratification period a 70–97 g/s steam flow rate was used. In the end of this period the temperature difference between the pool bottom and surface was 20–31 ºC.
During the mixing periods I and II the steam flow rate was increased rapidly to 130–260 g/s or decreased to 40–70 g/s to mix the pool water inventory. Total mixing of the pool was not obtained in every experiment. Mixing efficiency depended on the flow mode in question i.e. on the used steam mass flow rate and on the pool bulk temperature. With the highest used flow rates (from 175 to 260 g/s) complete mixing was achieved. Complete mixing was also achieved with the 70 g/s flow rate used in the first mixing period of SPA-T2. With the used intermediate flow rates (130 and 150 g/s) and with the lowest used flow rate (40 g/s) mixing was incomplete. One reason for this kind of behavior is the horizontal direction of the injection holes in the sparger head. When the flow rate is very low (in the range of 40 g/s) condensation takes place inside the sparger pipe and there is no mixing effect at all. When the flow rate is in the region of 70 g/s the flow mode is external chugging, where discharge of steam out of the sparger head through the injection holes and water suction into the sparger head alternate. This creates enough turbulence in the pool so that also the water volume below the sparger pipe outlet is finally mixed. With the intermediate and high flow rates steam jets through the injection holes prevail and there is no water ingress back into the sparger head. In the high flow rate cases the momentum created by the horizontal steam jets is so strong that the resulting internal circulation hits the pool wall and partly turns downwards thus mixing also the elevations far below the sparger head. In the intermediate flow rate cases the created momentum is sufficient to cause mixing only along a small distance below the sparger head outlet elevation. In both cases the elevations above the sparger head outlet were, however, well mixed.

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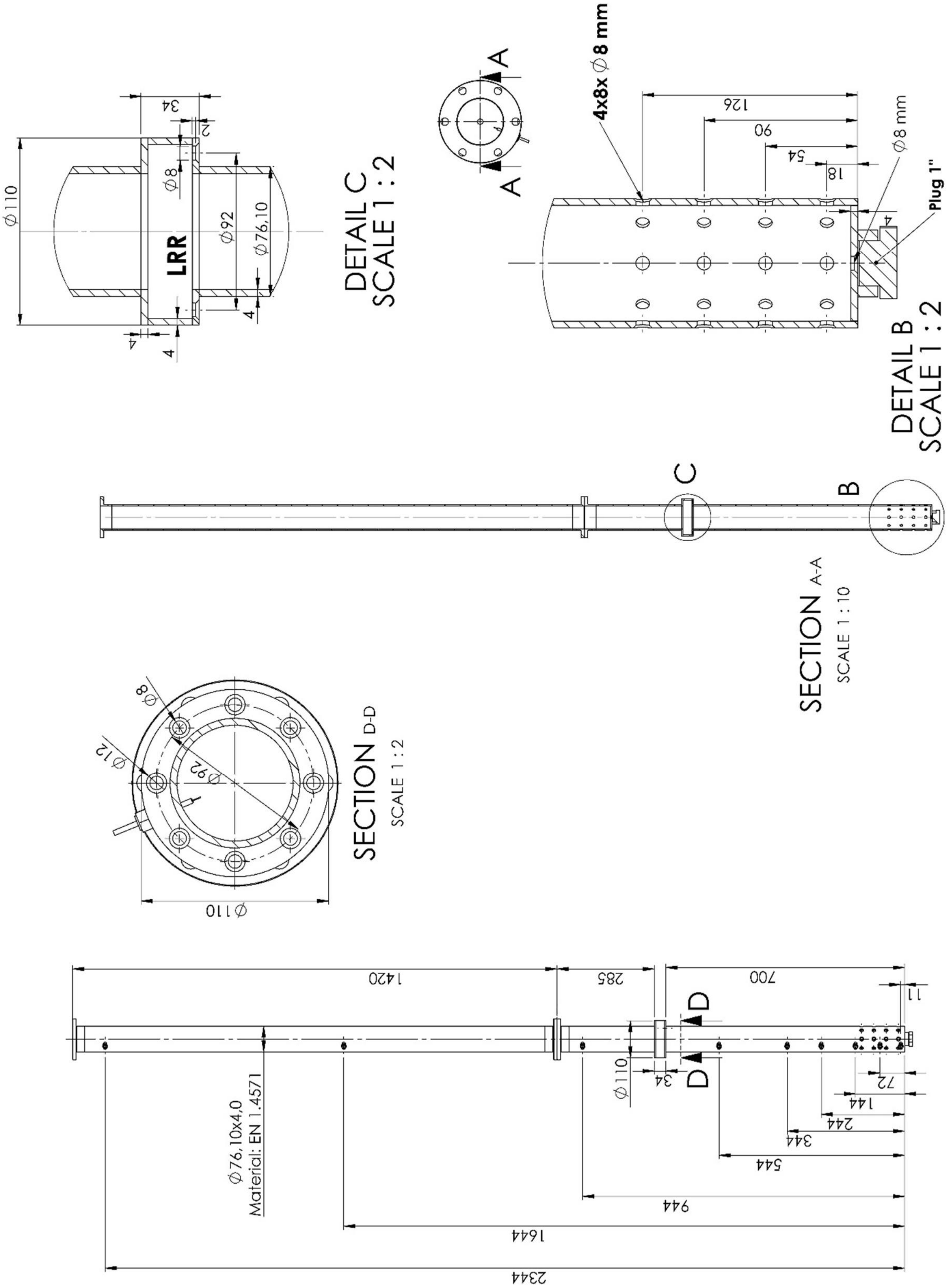
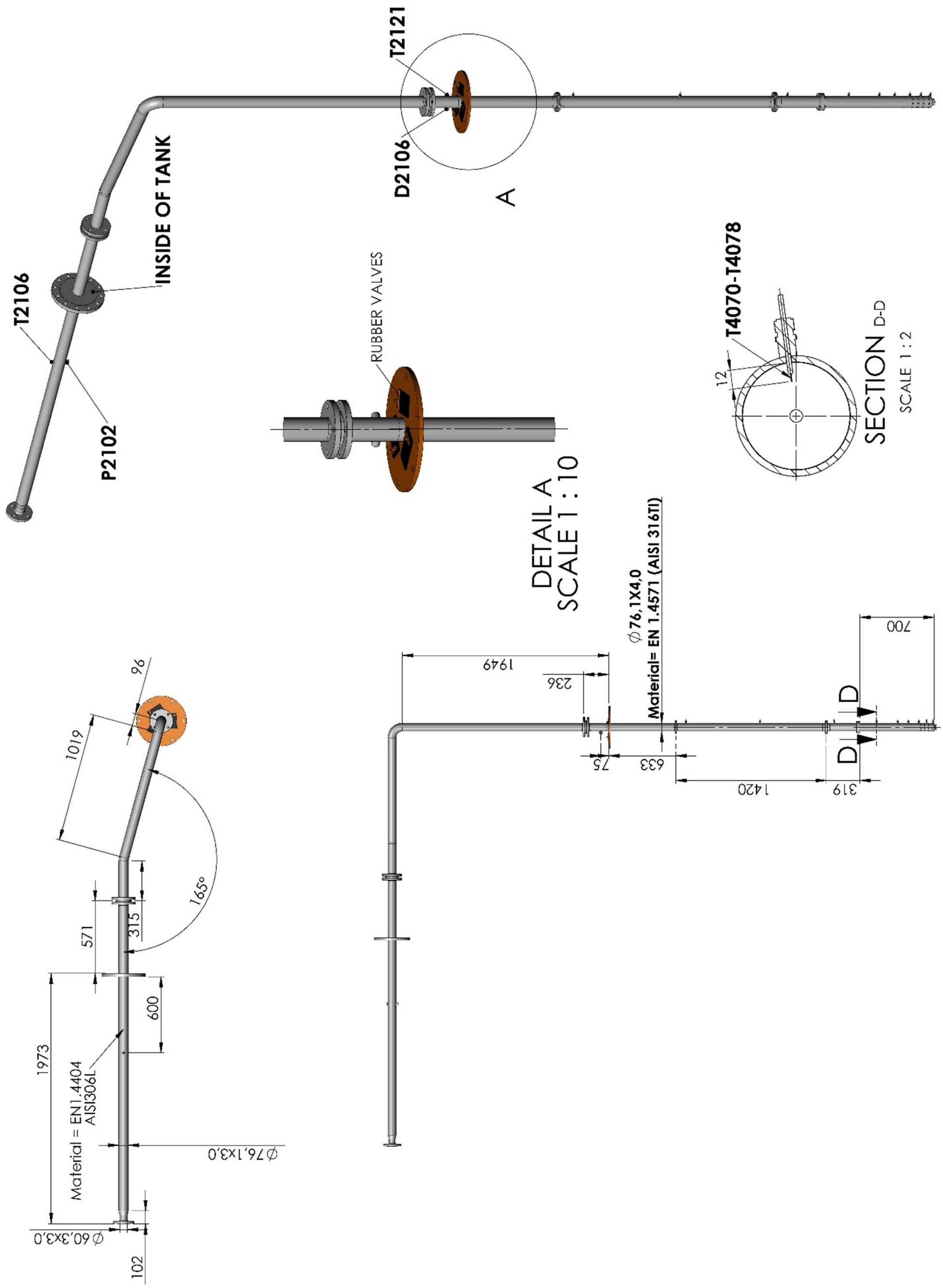
# APPENDIX 1: PPOOLEX DRAWINGS

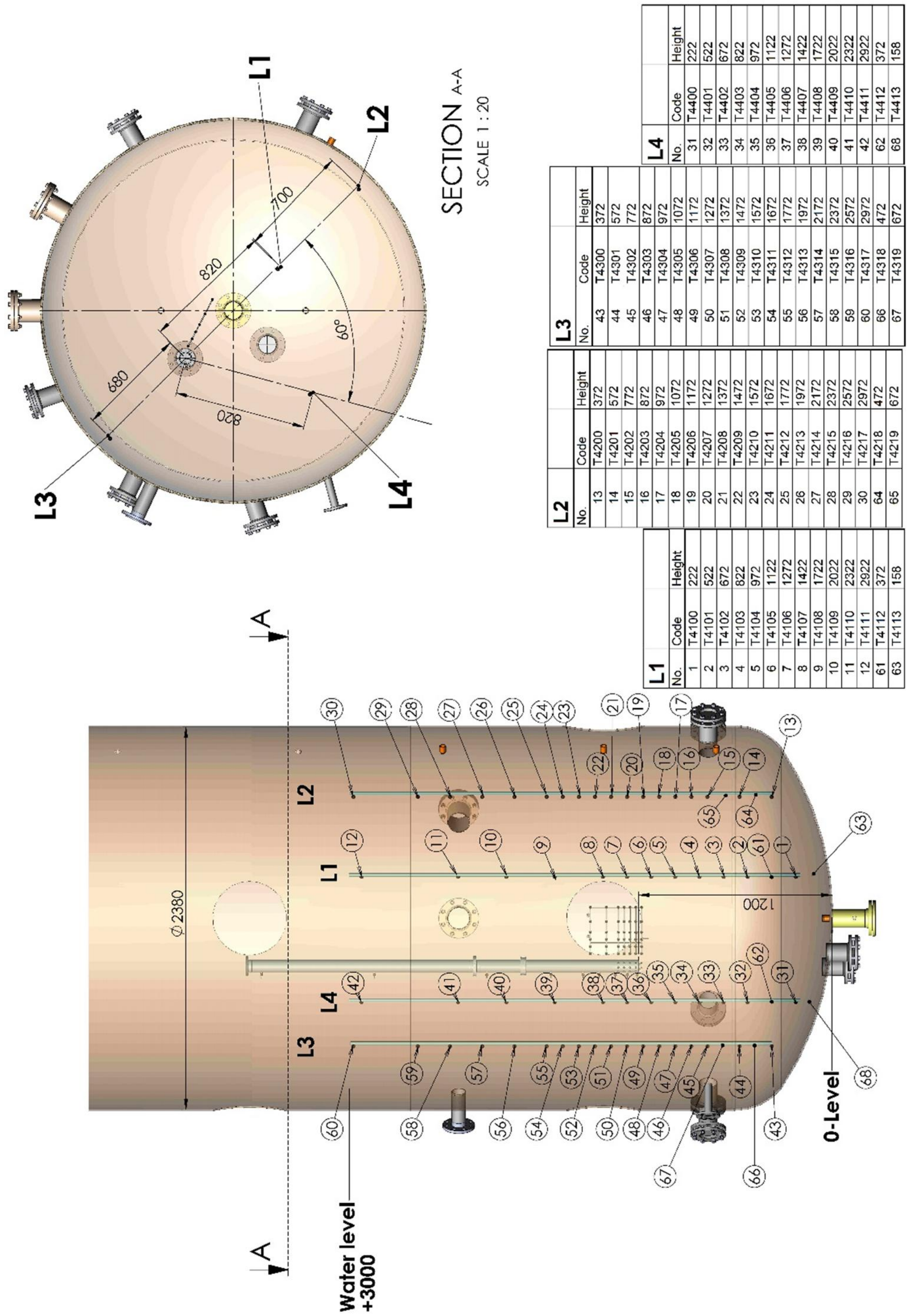



*DN65 sparger pipe.*




*DN65 steam line.*

# APPENDIX 2: PPOOLEX INSTRUMENTATION




**L1**

| No. | Code | Height |
|---|---|---|
| 1 | T4100 | 222 |
| 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**

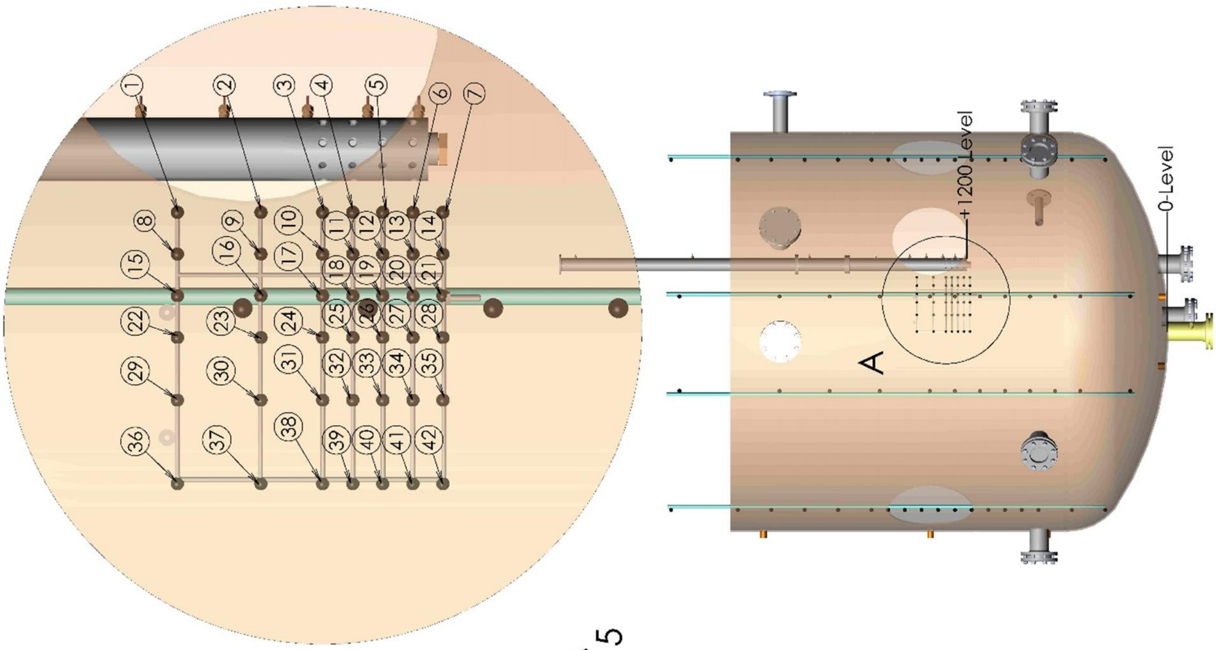
| No. | Code | Height |
|---|---|---|
| 43 | T4300 | 372 |
| 44 | T4301 | 572 |
| 45 | T4302 | 772 |
| 46 | T4303 | 872 |
| 47 | T4304 | 972 |
| 48 | T4305 | 1072 |
| 49 | T4306 | 1172 |
| 50 | T4307 | 1272 |
| 51 | T4308 | 1372 |
| 52 | T4309 | 1472 |
| 53 | T4310 | 1572 |
| 54 | T4311 | 1672 |
| 55 | 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 |
|---|---|---|
| 31 | T4400 | 222 |
| 32 | T4401 | 522 |
| 33 | T4402 | 672 |
| 34 | T4403 | 822 |
| 35 | T4404 | 972 |
| 36 | T4405 | 1122 |
| 37 | T4406 | 1272 |
| 38 | T4407 | 1422 |
| 39 | T4408 | 1722 |
| 40 | T4409 | 2022 |
| 41 | T4410 | 2322 |
| 42 | T4411 | 2922 |
| 62 | T4412 | 372 |
| 68 | T4413 | 158 |

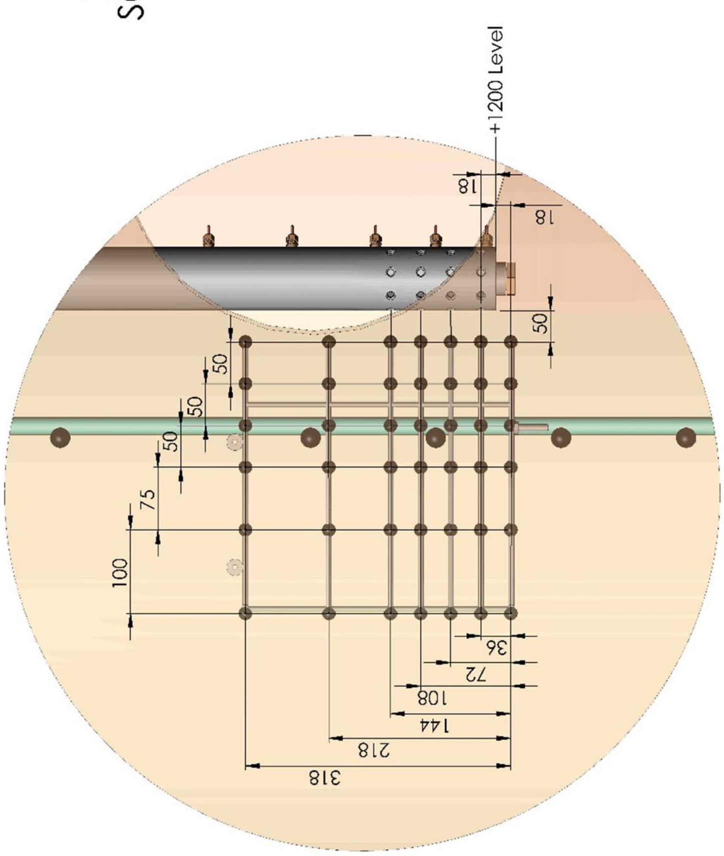
*Four trains of temperature measurements in the wetwell.*

Open your mind. LUT.
Lappeenranta University of Technology

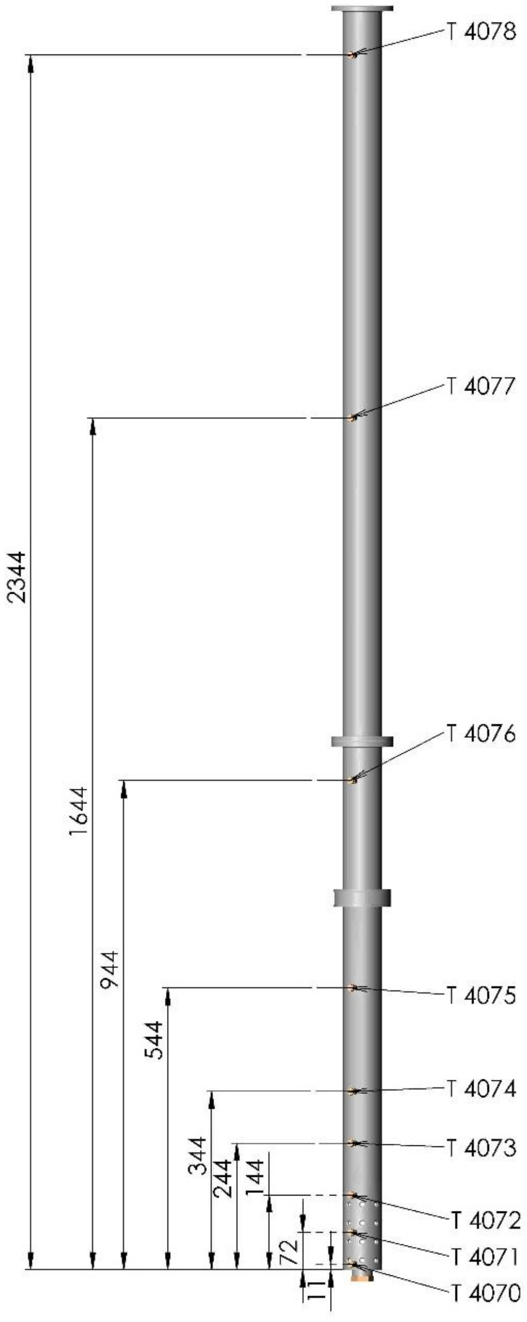



DETAIL A
SCALE 1 : 5

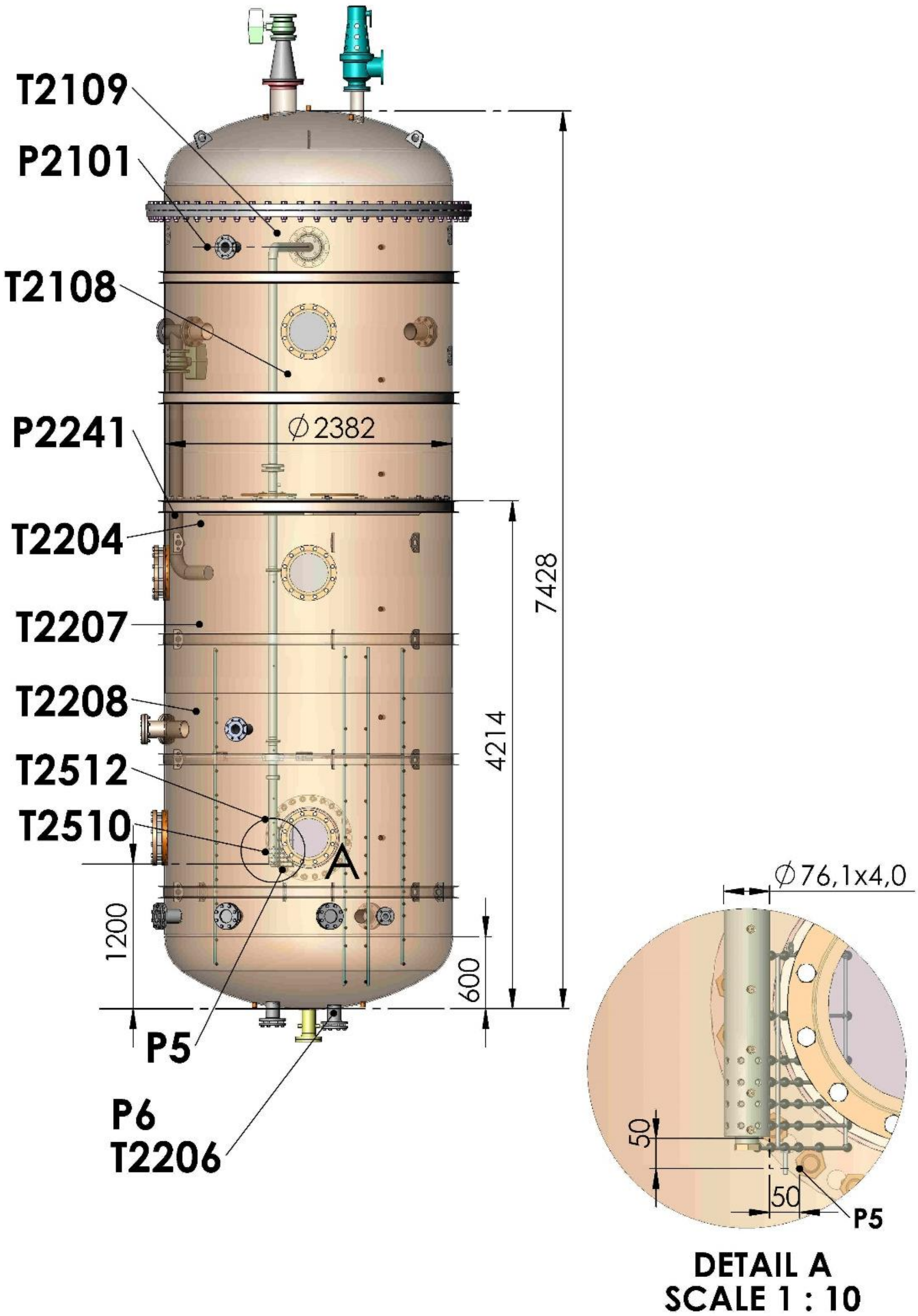
| No. | Code | No. | Code | No. | Code |
|---|---|---|---|---|---|
| 1 | T4000 | 16 | T4021 | 31 | T4042 |
| 2 | T4001 | 17 | T4022 | 32 | T4043 |
| 3 | T4002 | 18 | T4023 | 33 | T4044 |
| 4 | T4003 | 19 | T4024 | 34 | T4045 |
| 5 | T4004 | 20 | T4025 | 35 | T4046 |
| 6 | T4005 | 21 | T4026 | 36 | T4050 |
| 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 |
| 12 | T4014 | 27 | T4035 | 42 | T4056 |
| 13 | T4015 | 28 | T4036 | | |
| 14 | T4016 | 29 | T4040 | | |
| 15 | T4020 | 30 | T4041 | | |



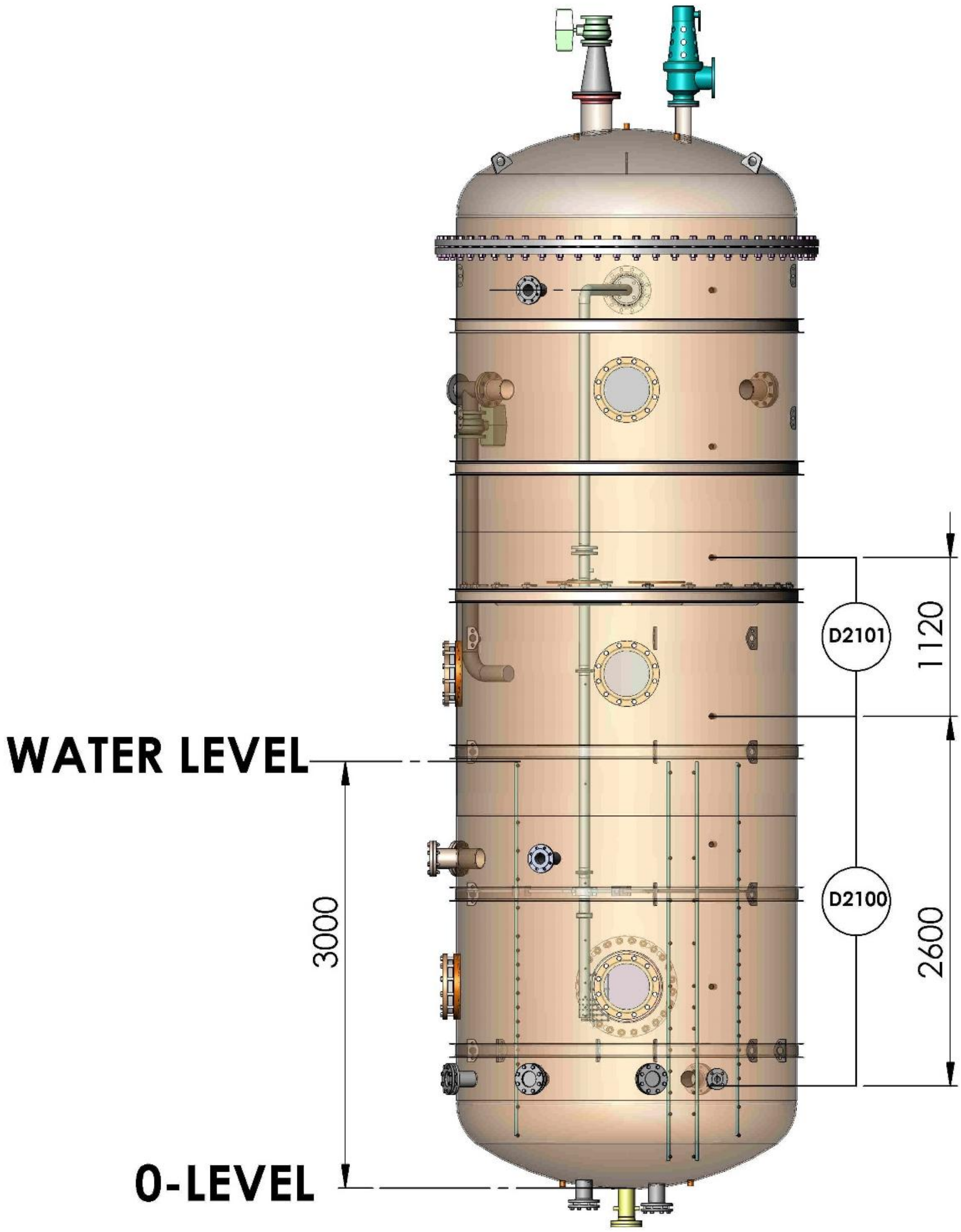

*6x7 grid of temperature measurements in the wetwell.*



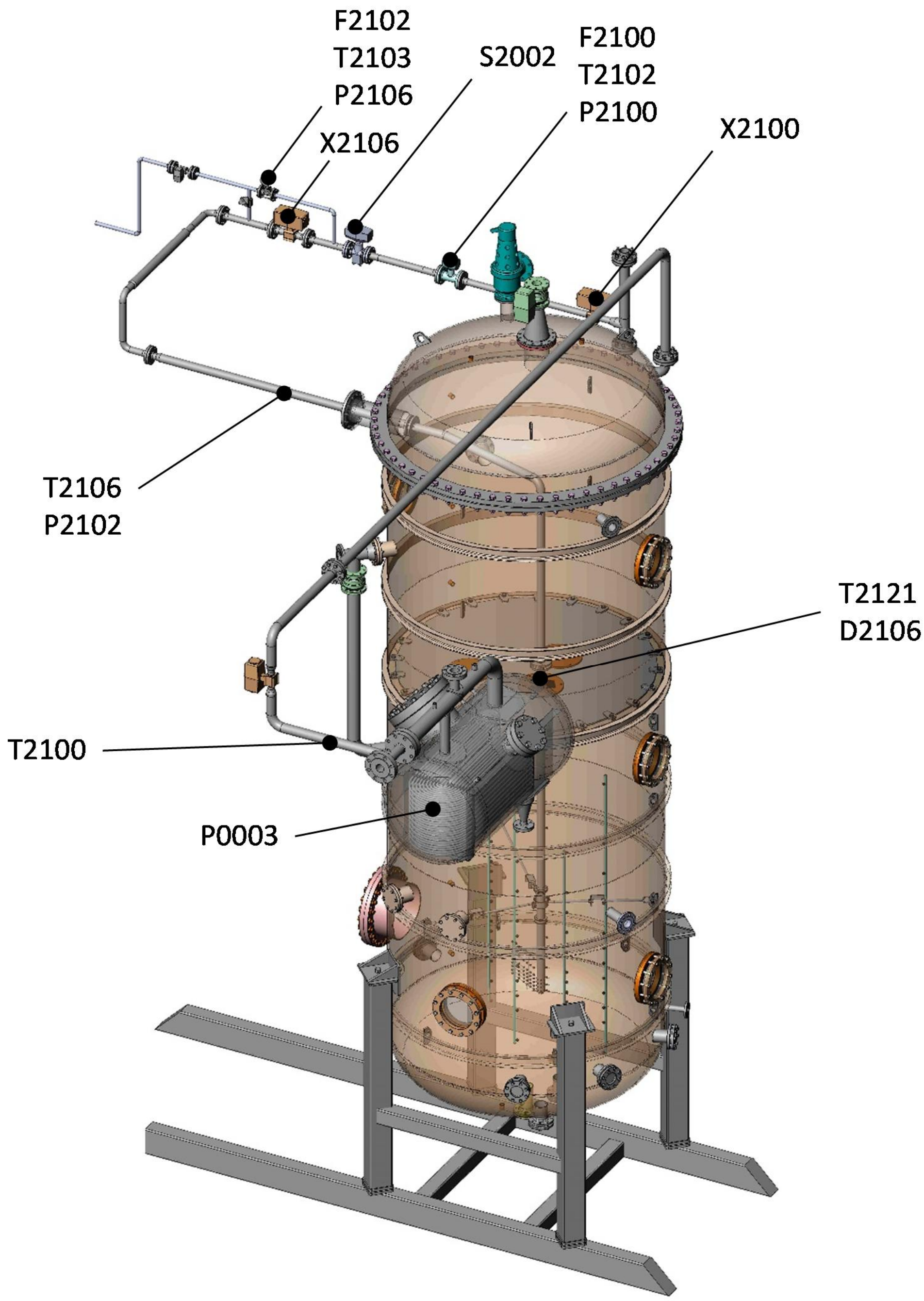

*Temperature measurements inside the sparger pipe.*



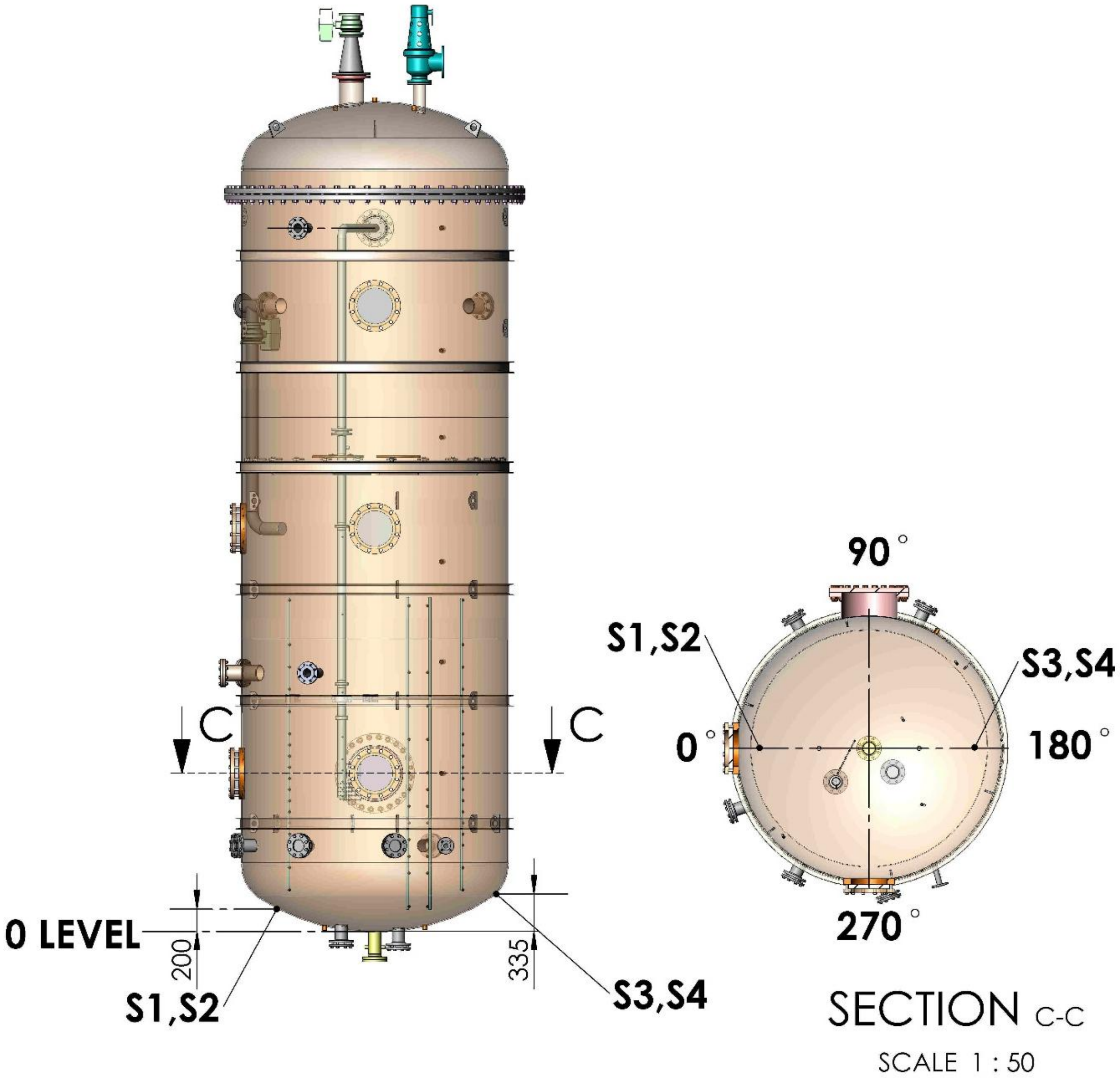

*Test vessel measurements.*




*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 | 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 | T4209 | 1472 | Wetwell | ±2 °C | FieldPoint |
| Temperature | T4210 | 1572 | Wetwell | ±2 °C | FieldPoint |
| Temperature | T4211 | 1672 | 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 | 29712 | 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 | T4309 | 1472 | Wetwell | ±2 °C | FieldPoint |
| Temperature | T4310 | 1572 | Wetwell | ±2 °C | FieldPoint |
| Temperature | T4311 | 1672 | 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 | 29712 | 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 |

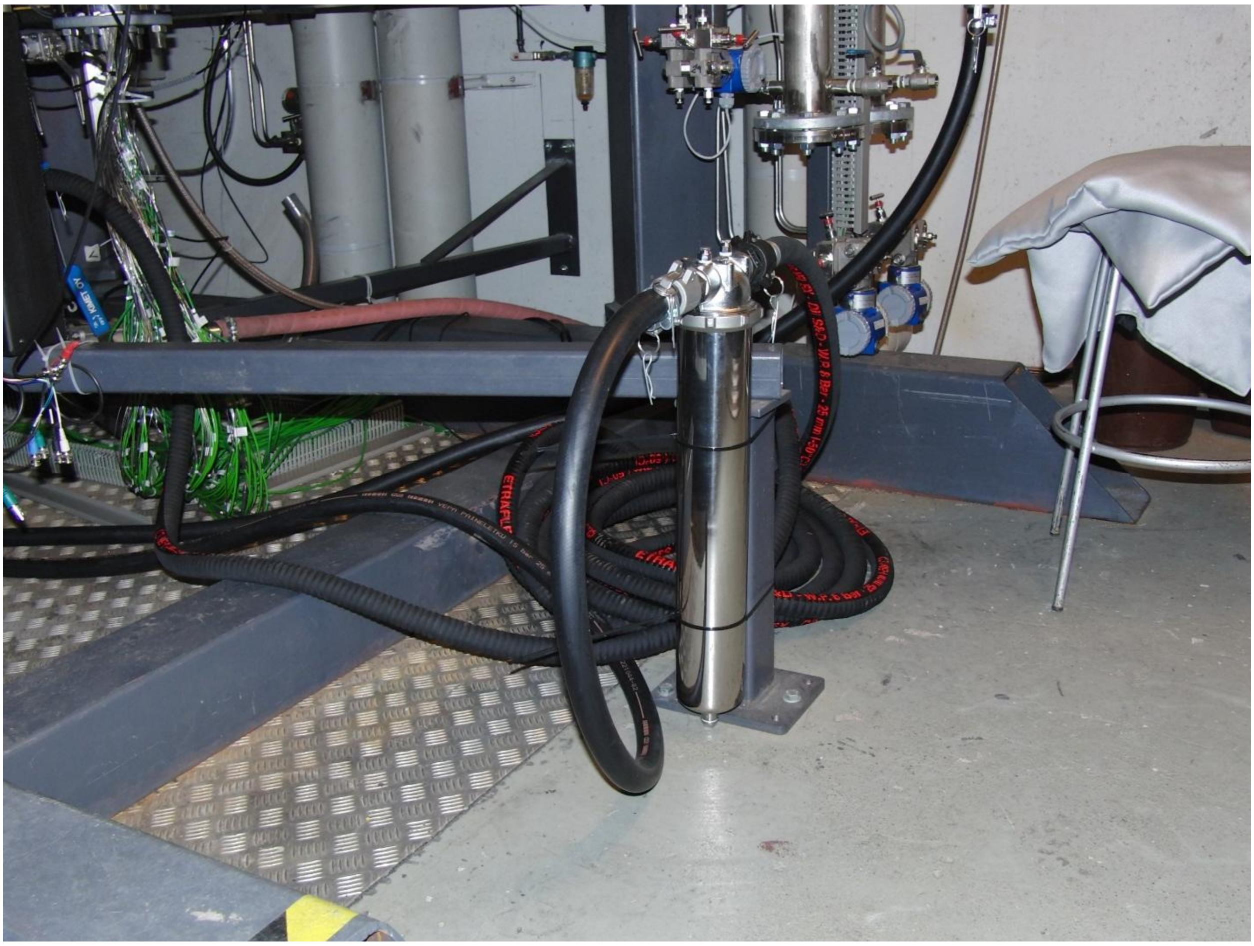
| | | | | | |
|---|---|---|---|---|---|
| Temperature | T4410 | 2322 | Wetwell | ±2 °C | FieldPoint |
| Temperature | T4411 | 2922 | Wetwell | ±2 °C | FieldPoint |
| Temperature | T4412 | 372 | Wetwell | ±2 °C | FieldPoint |
| Cut-off valve position | V1 | - | DN50 Steam line | Not defined | LabView |
| 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.*



*Filter unit of the air removal system.*


*Air removal device.*

**Bibliographic Data Sheet** **NKS-334**

| | |
|---|---|
| Title | PPOOLEX Experiments with a Sparger |
| Author(s) | Jani Laine, Markku Puustinen, Antti Räsänen |
| Affiliation(s) | Lappeenranta University of Technology, Nuclear Safety Research Unit, Finland |
| ISBN | 978-87-7893-416-1 |
| Date | April 2015 |
| Project | NKS-R / ENPOOL |
| No. of pages | 19 p. + app. 17 p. |
| No. of tables | 8 |
| No. of illustrations | 7 + 9 |
| No. of references | 19 |

Abstract
max. 2000 characters

This report summarizes the results of the sparger experiments carried out with the scaled down PPOOLEX test facility designed and constructed at Lappeenranta University of Technology. 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 experiments was to obtain verification data for the development of the Effective Momentum Source (EMS) and Effective Heat Source (EHS) models to be implemented in GOTHIC code by KTH. A detailed test matrix and procedure put together on the basis of the pre-test calculations was provided by KTH.

Altogether five experiments were carried out. The experiments consisted of two stratification periods and two mixing periods.

During the first stratification period a 120–130 g/s steam flow rate was used. With this flow rate steam flowed through the injection holes of the sparger head as small jets and condensed mainly outside the sparger pipe. As a result temperatures remained constant below the blowdown pipe outlet but increased towards the pool surface layers indicating strong thermal stratification of the wetwell pool water. In the end of the first stratification period the temperature difference between the pool bottom and surface was 18–26 ºC depending on the test in question. In the second stratification period a 70–97 g/s steam flow rate was used. In the end of this period the temperature difference between the pool bottom and surface was 20–31 ºC.

During the mixing periods I and II the steam flow rate was increased rapidly to 130–260 g/s or decreased to 40–70 g/s to mix the pool water inventory. Total mixing of the pool was not obtained in every experiment. Mixing efficiency depended on the flow mode in question i.e. on the used steam mass flow rate and on the pool bulk temperature. Enough turbulence to mix the pool could be created either with high steam flow rates causing strong internal circulation in the pool or with quite small steam flow rates (in the range of 70 g/s) causing external chugging phenomenon at the sparger head. With the intermediate flow rates only the elevations above and a short distance below the sparger head could be mixed. When the flow rate was very low (in the range of 40 g/s) condensation took place inside the sparger pipe and there was no mixing effect at all.

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

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