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PPOOLEX Experiments on Wall Condensation

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Abstract

This report summarizes the results of the wall condensation experiments carried out in December 2008 and January 2009 with the scaled down PPOOLEX test facility designed and constructed at Lappeenranta University of Technology. Steam was blown into the dry well compartment and from there through a DN200 blowdown pipe to the condensation pool. Altogether five experiments, each consisting of several blows, were carried out.

The main purpose of the experiment series was to study wall condensation phenomenon inside the dry well compartment while steam is discharged through it into the condensation pool and to produce comparison data for CFD calculations at VTT.

The PPOOLEX test facility is a closed stainless steel vessel divided into two compartments, dry well and wet well. For the wall condensation experiments the test facility was equipped with a system for collecting and measuring the amount of condensate from four different wall segments of the dry well compartment. A thermo graphic camera was used in a couple of experiments for filming the outside surface of the dry well wall.

The effect of the initial temperature level of the dry well structures and of the steam flow rate for the accumulation of condensate was studied. The initial temperature level of the dry well structures varied from 23 to 99 C. The steam flow rate varied from 90 to 690 g/s and the temperature of incoming steam from 115 to 160 C.

During the initial phase of steam discharge the accumulation of condensate was strongly controlled by the temperature level of the dry well structures; the lower the initial temperature level was the more condensate was accumulated. As the dry well structural temperatures increased the condensation process slowed down. Most of the condensate usually accumulated during the first 200 seconds of the discharge. However, the condensation process never completely stopped because a small temperature difference remained between the dry well atmosphere and inner wall even in the case of an extended steam discharge period.

More condensate was collected from the two upper wall segments than from the two lower segments. In addition, more condensate was collected from the segments opposite to the inlet plenum than from the segment on the same side as the inlet plenum.

Key words

condensation pool, steam/air blowdown, wall condensation

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PREFACE

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

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

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

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Appendix 2: Test facility photographs

NOMENCLATURE

p	pressure
Q	volumetric flow rate
q_m	mass flow rate
T	temperature

Greek symbols

Δ	change
ε	strain

Abbreviations

BWR	boiling water reactor
CFD	computational fluid dynamics
CONDEX	Condensation experiments
DCC	direct contact condensation
ECCS	emergency core cooling system
LOCA	loss-of-coolant accident
LUT	Lappeenranta University of Technology
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
PWR	pressurized water reactor
SAFIR	Safety of Nuclear Power Plants – Finnish National Research Programme
SLR	steam line rupture
SRV	safety/relief valve
TVO	Teollisuuden Voima Oyj
VTT	Technical Research Centre of Finland
VYR	State Nuclear Waste Management Fund
VVER	Vodo Vodjanyi Energetitseskij Reaktor

1 INTRODUCTION

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

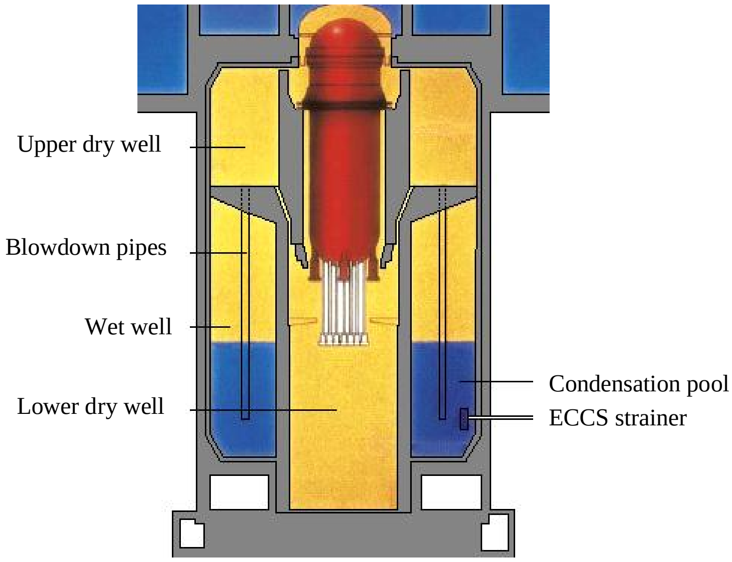

Figure 1. Schematic of the Olkiluoto type BWR containment.

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

To achieve the project objectives, a combined experimental/analytical/computational study programme is being carried out. Experimental part at LUT is responsible for the development of a database on condensation pool dynamics and heat transfer at well controlled conditions. Analytical/computational part at VTT, KTH and LUT use the developed experimental database for the improvement and validation of models and numerical methods including CFD and system codes. Also analytical support is provided for the experimental part by pre- and post-calculations of the experiments. Furthermore, the (one-directional or bi-directional) coupling of CFD and structural analysis codes in solving fluid-structure interactions can be facilitated with the aid of load measurements of the steam blowdown experiments. Some of the bubble dynamics models are applicable also outside the BWR scenarios, e.g. for the quench tank operation in the pressurizer vent line of a Pressurized Water Reactor (PWR), for the bubble condenser in a VVER-440/213 reactor system, or in case of a submerged steam generator pipe break.

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

Experiments with the new PPOOLEX facility started in 2007 by running a series of characterizing tests [1]. They focused on observing the general behaviour of the facility, on testing instrumentation and the proper operation of the automation, control and safety systems. The next five experiments (SLR series) focused on the initial phase of a postulated MSLB accident inside the containment [2]. Air was used as the flowing substance in these experiments. The research program continued in 2008 with a series of thermal stratification and mixing experiments [3]. Stratification in the water volume of the wet well during small steam discharge was of special interest.

The research programme continued in December 2008 and January 2009 with five experiments (WLL series) focusing on steam condensation in dry well compartment. In this report, the results of these experiments are presented. First, chapter two gives a short description of the test facility and its measurements as well as of the data acquisition system used. The test programme of the WLL experiment series is introduced in chapter three. The test results are presented and shortly discussed in chapter four. Chapter five summarizes the findings of the experiment series.

2 PPOOLEX TEST FACILITY

Condensation studies at LUT started with an open pool test facility (POOLEX) modelling the suppression pool of the BWR containment. During the years 2002-2006, the facility had several modifications and enhancements as well as improvements of instrumentation before it was replaced with a more versatile PPOOLEX facility in the end of 2006. The PPOOLEX facility is described in more detail in reference [4]. However, the main features of the facility and its instrumentation are introduced below. Some test facility photographs are shown in Appendix 2.

2.1 TEST VESSEL

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

The main component of the facility is the ~31 m^3 cylindrical test vessel, 7.45 m in height and 2.4 m in diameter. The vessel is constructed from three separate plate cylinder segments and from two dome segments. The test facility is able to withstand considerable structural loads caused by rapid condensation of steam. The vessel sections modelling dry well and wet well are volumetrically scaled according to the compartment volumes of the Olkiluoto containment buildings (ratio approximately 1:320). The DN200 (∅ 219.1 x 2.5 mm) blowdown pipe is positioned inside the pool in a non-axisymmetric location, i.e. 300 mm away from the centre of the condensation pool. Horizontal piping (inlet plenum) for injection of gas and steam penetrates through the side wall of the dry well compartment. The length of the inlet plenum is 2.0 m and the inner diameter 214.1 mm. There are several windows for visual observation in the walls of both compartments. A DN100 (∅ 114.3 x 2.5 mm) drain pipe with a manual valve is connected to the bottom of the vessel. A relief valve connection is mounted on the vessel head. The large removable vessel head and a man hole (DN500) in the wet well compartment wall provide access to the interior of the vessel for maintenance and modifications of internals and instrumentation. The test vessel is not thermally insulated. A sketch of the test vessel is presented in Figure 2. Table 1 lists the main dimensions of the test facility compared to the conditions in the Olkiluoto plant.

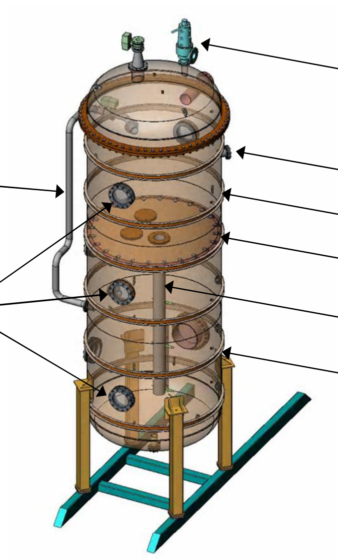

Figure 2. PPOOLEX test vessel.

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

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

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

2.2 PIPING

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

Steam needed in the experiments is produced with the nearby PACTEL [5] 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 (Ø88.9x2.0) and DN50 (Ø60.3x2.0) pipes, from the PACTEL steam generators towards the test vessel. The steam line is connected to the DN200 inlet plenum with a 0.47 m long cone section. Accumulators connected to the compressed air network of the lab can be used for providing non-condensable gas injection. A schematic illustration of the air and steam line piping is presented in Figure 3.

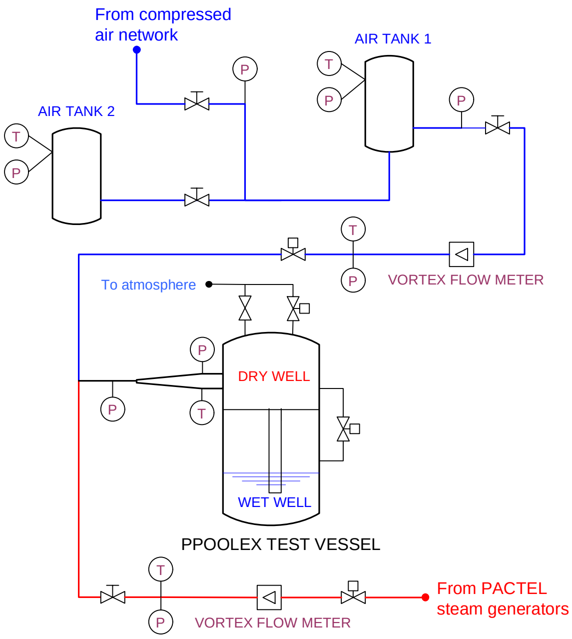

Figure 3. Arrangement of air and steam supply in the PPOOLEX facility.

2.3 CONDENSATE COLLECTION SYSTEM

During the experiments condensate is collected from four different wall segments of the dry well compartment. The collection system consists of two drain gutters, piping and four condensate tanks with water level measurements, see photographs in Appendix 2. Drain gutters are installed around the inner wall of the dry well compartment on two different elevations. Condensate is collected from four different wall segments. Two of the segments are located on the opposite half of the dry well in relation to the inlet plenum and the other two on the same side. Condensate is not collected from a 0.45 m high wall segment below the lower drain gutter, from the separating floor and from the vessel head. The total area of the four wall segments is 14.6 m^2 and the total volume of the condensate tanks 30 litres, Table 2.

Table 2. Condensate collection system.

Condensate tank	Drain gutter	Wall segment	Wall segment area [m^2]	Tank capacity [l]
1	Upper	Opposite to the inlet plenum	2.07	7.5
2	Lower	Opposite to the inlet plenum	5.25	7.5
3	Upper	Same side as inlet plenum	2.04	7.5
4	Lower	Same side as inlet plenum	5.25	7.5
		Total	14.6	30

2.4 MEASUREMENT INSRUMENTATION

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

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

For WLL experiments additional thermocouples were installed on the inner and outer surface of the dry well on two locations. A list of different types of measurements of the PPOOLEX facility during the WLL experiments is presented in Table 3. The figures in Appendix 1 show the exact locations of the measurements and the table in Appendix 1 lists the identification codes and error estimations of the measurements. The error estimations are calculated on the basis of variance analysis. The results agree with normal distributed data with 95 % confidence interval.

Table 3. Instrumentation of the PPOOLEX test facility.

Quantity measured		No.	Range	Accuracy
Pressure	Dry well	1	0–6 bar	0.06 bar
	Wet well	5	0–6/0–10 bar	0.4/0.5 bar
	Blowdown pipe	3	0–10 bar	0.7 bar
	Inlet plenum	1	0–6 bar	0.06 bar
	Steam line	1	1–51	0.5 bar
	Air line	2	0–6/1–11 bar	0.06/0.1 bar
	Air tanks 1&2	2	0–16/0–11 bar	0.15/0.11 bar
Temperature	Dry well	5	-40–200 °C	±3.2 °C
	Wet well gas space	3	0–250 °C	±2.0 °C
	Wet well water volume	2	0–250 °C	±2.0 °C
	Blowdown pipe	6	0–250 °C	±2.0 °C
	Inlet plenum	1	-40–200 °C	±3.2 °C
	Steam line	2	0–400 °C	±3.6 °C
	Air line	1	-20–100 °C	±2.8 °C
	Air tanks 1&2	2	-20–100/200 °C	±2.8/3.1 °C
	Structures	7	0–200 °C	±2.6 °C
Mass flow rate	Steam line	1	0–285 l/s	±4.9 l/s
	Gas line	1	0–575 m^3/h	±18 g/s
Water level in the wet well and condensate tanks		5	0–30000/0-15000 Pa	0.06/0.03 m
Pressure difference across the floor		1	-499–505 kPa	± 9.7 kPa
Loads on structures		4	N/A	N/A
Vertical movement of the pool bottom		1	N/A	N/A
Vertical acceleration of the pool bottom		1	N/A	N/A

In the wall condensation experiments, standard video cameras, digital videocassette recorders and a quad processor were used for visual observation of the test vessel interior. With a digital colour quad processor it is possible to divide the TV screen into four equal size parts and look at the view of four cameras on the same screen (Figure 4). The digital high-speed video camera was not used in these experiments. In a couple of WLL experiments, Therma CAM™ PM965 thermo graphic camera was used for filming the outer wall of the dry well compartment at the location where the steam jet hits to the wall.

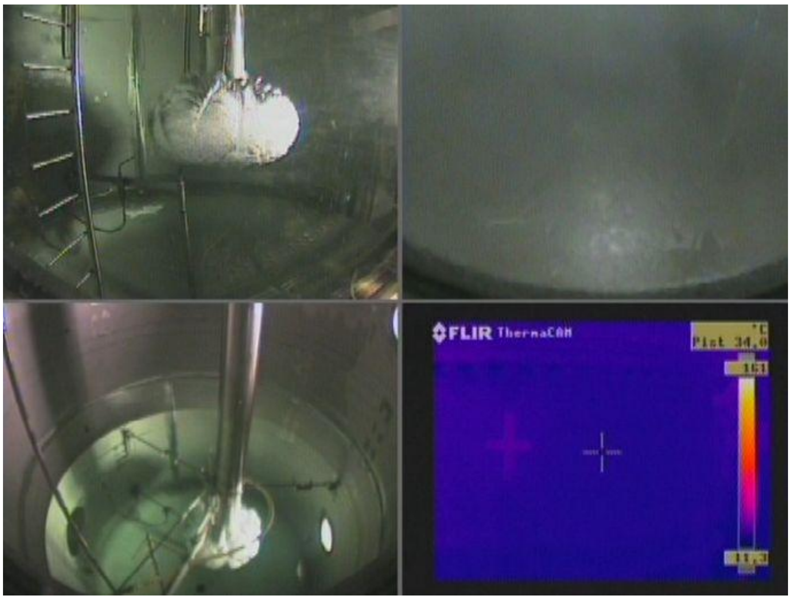

Figure 4. Typical camera views from the WLL experiments. Views are from the beginning of the test WLL-05-1.

2.5 DATA ACQUISITION

National Instruments PCI-PXI-SCXI PC-driven measurement system is used for data acquisition. The system enables high-speed multi-channel measurements. The maximum number of measurement channels is 96 with additional eight channels for strain gauge measurements. The maximum recording speed depends on the number of measurements and is in the region of three hundred thousand samples per second. Measurement software is LabView 8.6. The data acquisition system is discussed in more detail in reference [7]. Figure 5 shows monitoring of the WLL experiments with LabView software.

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

In the wall condensation experiments, the used data recording frequency of LabView was 1 kHz. For the temperature measurements the data recording frequency was 10 Hz. The temperature measurements are therefore averaged of 100 measured points. The rest of the measurements (for example temperature, pressure and flow rate in the steam line) were recorded by FieldPoint software with the frequency of 0.67 Hz.

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

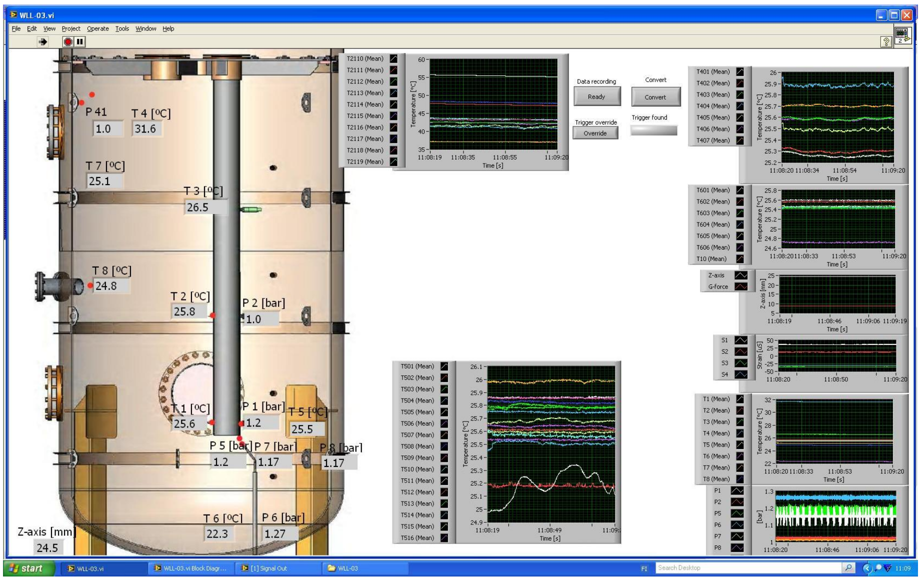

Figure 5. Monitoring of a WLL experiment with LabView software.

3 TEST PROGRAMME

The wall condensation test program with steam discharge in December 2008 and January 2009 focused on the initial phase of a postulated steam line rupture accident inside BWR containment and consisted of five experiments (labelled from WLL-01 to WLL-05). The objective was to study wall condensation in the dry well compartment as well as to get comparison data for CFD simulations at VTT. Each experiment included two to six blows (tests) of steam. The experiments were carried out by using a DN200 blowdown pipe.

Before each experiment the condensation pool was filled with approximately 20 °C water to the level of 2.14 m i.e. the blowdown pipe outlet was submerged by 1.05 m. This air/water distribution corresponds to the scaled gas and liquid volumes in the containment of the reference plant. The steam generator initial pressure ranged from 0.2 to 0.8 MPa.

Initially, the dry well compartment was filled with air at atmospheric pressure. Pre-heating of the wall segments was executed with steam. After pre-heating (and between individual tests) the test vessel was shortly ventilated with compressed air before the initiation of the actual test discharge to dry the wall surfaces and to clear the windows. After the correct initial pressure level in the steam generators had been achieved the remote-controlled shut-off valve in the steam line was opened. As a result, the dry well compartment was filled with steam that mixed there with the initial air content. Pressure build-up in the dry well then pushed water in the blowdown pipe downwards and after a while the pipe cleared and flow into the wet well compartment began. Table 4 shows the main parameters of the wall condensation experiments.

Table 4. Initial parameter values of the WLL experiments in the PPOOLEX facility.

Experiment	Steam source pressure [MPa]	Initial water level [m]	Initial water temperature [°C]
WLL-01	0.2–0.5	2.14	20
WLL-02	0.25–0.8	2.14	20
WLL-03	0.25–0.4	2.14	20
WLL-04	0.55	2.14	20
WLL-05	0.65	2.14	20

4 ANALYSIS OF THE EXPERIMENTS

The following chapters give a more detailed description of the experiment program and present the observed phenomena. Table 5 summarizes the values of the main parameters during the individual blows of the WLL experiment series.

Table 5. Main parameters during WLL experiments.

Test	Initial steam source pressure [MPa]	Steam flow rate[1] [g/s]	Temperature of incoming steam [°C]	Blow duration [s]	Initial temperature of dry well inner wall[2] [°C]	Final temperature of dry well inner wall[2] [°C]	Mass of cumulated condensate [kg]
WLL-01-1	0.2	90…140	115…120	238	75	115	14
WLL-01-2	0.3	180…210	126…131	395	88	125	18
WLL-01-3	0.4	270…290	136…140	606	94	126	19
WLL-01-4	0.5	320…360	142…146	798	99	127	19
WLL-02-1	0.25	200…220	120	60	81	98	4.5
WLL-02-2	0.25	150…220	119…123	200	81	118	14
WLL-02-3	0.4	320…350	131…134	61	94	107	3
WLL-02-4	0.4	320…360	132…135	409	88	125	18
WLL-02-5	0.8	580…660	153…159	61	99	118	4.5
WLL-02-6	0.8	460…690	150…160	735	97	127	17
WLL-03-1	0.25	190…220	120	61	46	83	8
WLL-03-2	0.25	120…220	118…126	319	44	124	>30[3]
WLL-03-3	0.4	340…360	133…135	59	50	90	9
WLL-03-4	0.4	320…360	133…139	624	41	131	>30[3]
WLL-04-1	0.55	440…480	142…146	55	23	78	13.5
WLL-04-2	0.55	430…480	142…146	182	41	125	>30[3]
WLL-04-3	0.55	420…480	142…146	271	68	128	23
WLL-05-1	0.65	500…560	147…152	120	26	115	28
WLL-05-2	0.65	470…550	146…151	240	62	129	25.5

4.1 WLL-02-6

WLL-02-6 is an example of an extended steam discharge test. During the steam discharge, whose duration was 735 seconds, the steam flow rate ranged from 460 to 690 g/s and the temperature of incoming steam from 150 to 160 °C, Figure 6. Pre-heating of the dry well structures was used.

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[1] The steam mass flow rate was calculated on the basis of the volumetric flow rate (measured by F2100) and density of steam, which in turn was determined on the basis of the steam pressure measurement (measured by P2100) by assuming saturated steam flow.
[2] An average value of temperatures measured by thermocouples T2117 and T2119.
[3] All four condensate tanks were completely filled.

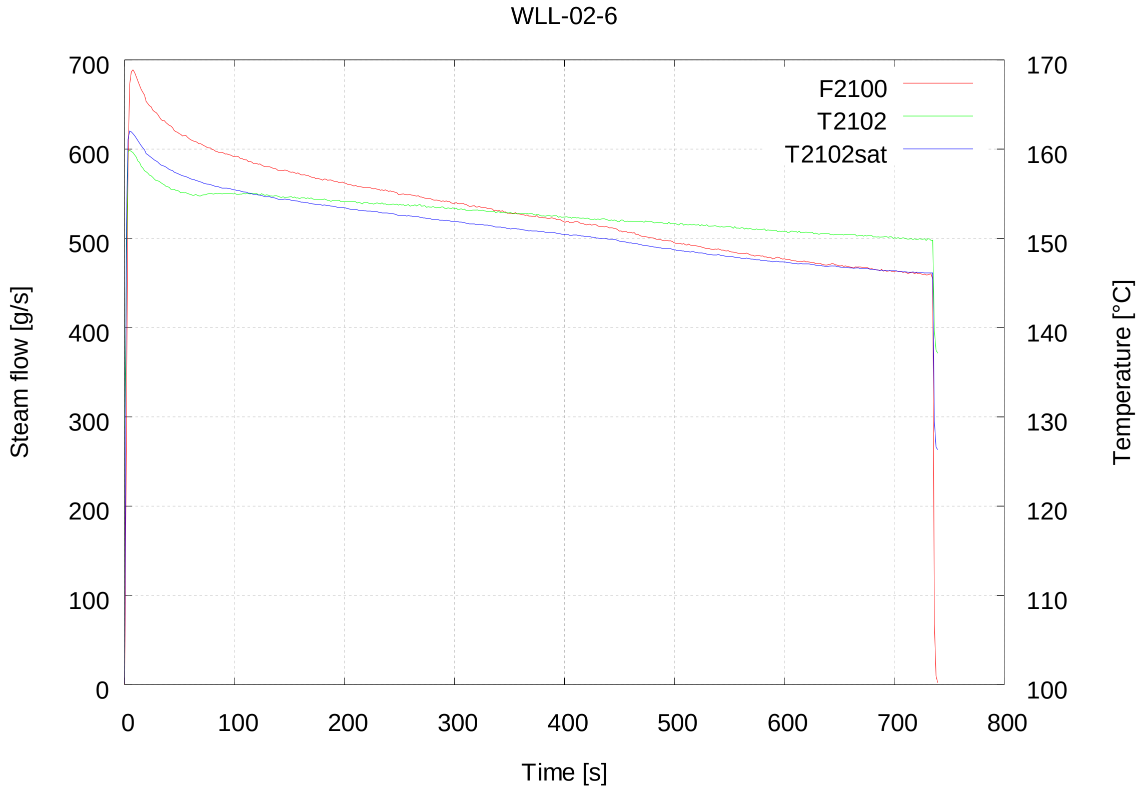


Figure 6. Flow rate (F2100) and temperature of incoming steam (T2102) in WLL-02-6. T2102sat is the saturated steam temperature at the flow meter.

Figure 6 shows, that at first the temperature of incoming steam at the flow meter is below the saturation temperature. However, the conditions in the steam line slightly change during the initial phase of the test. The pressure decreases and therefore the saturation temperature also decrease. At about 100 seconds into the test, steam becomes superheated at the flow meter. Because saturated conditions are assumed while performing the conversion from volumetric steam flow rate to mass flow rate, a small underestimation in the steam mass flow rate during the first hundred seconds is possible.

During the test a small temperature difference developed between the dry well atmosphere and inner wall, Figure 7. The difference got smaller along the test. For instance, at 200 seconds the difference was approximately 9 °C but had decreased to a value of about 7 °C when the steam discharge was terminated.

Figure 7 also shows the total accumulation of condensate. One can see that there is a small delay in the measured amount of the condensate in the beginning of the test due to the piping from the drain gutters to the tanks. During the first 200 seconds the condensation process is the strongest. It then slows down due to the wall heat up and follows an almost straight line for the rest of the steam discharge period.

A clear temperature difference also developed between the inner and outer wall of the dry well compartment during the wall heat up period of the test, Figure 8. From 150 seconds onwards this temperature difference remained at the level of approximately 2 °C until the steam discharge was terminated.

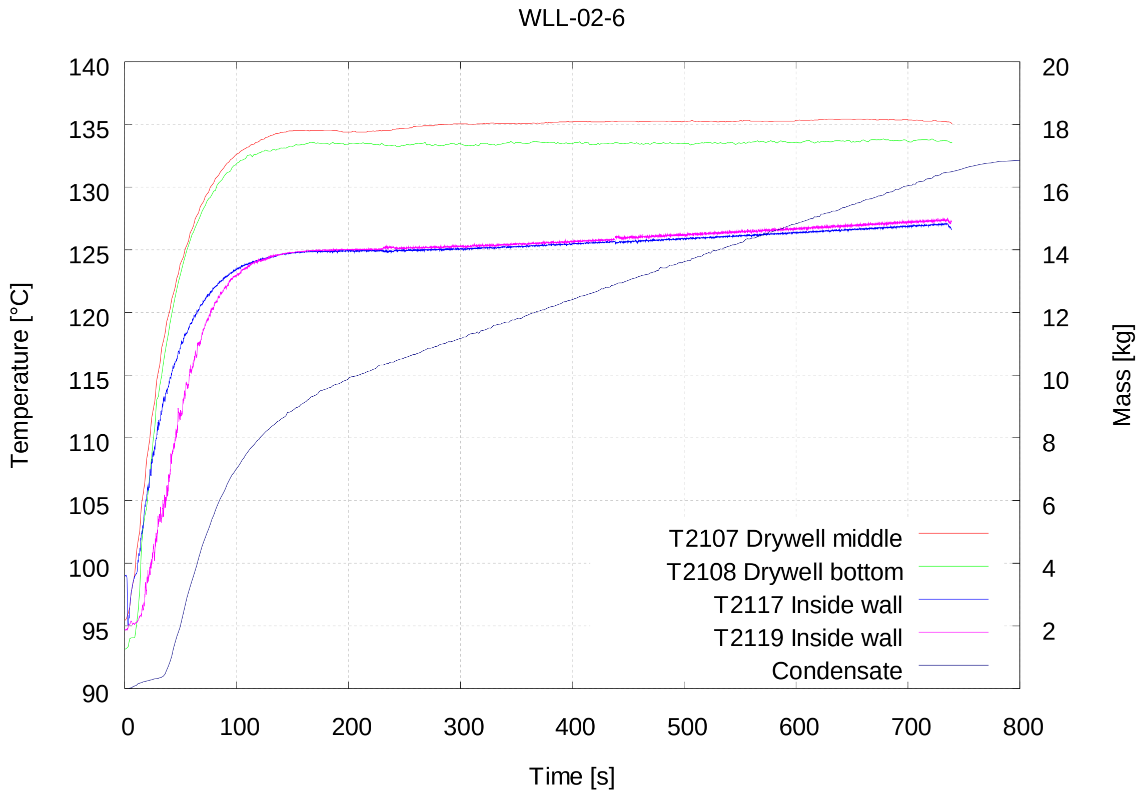


Figure 7. Temperatures in the atmosphere (T2107 and T2108) and on the inside wall (T2117 and T2119) of the dry well and accumulation of condensate in WLL-02-6.

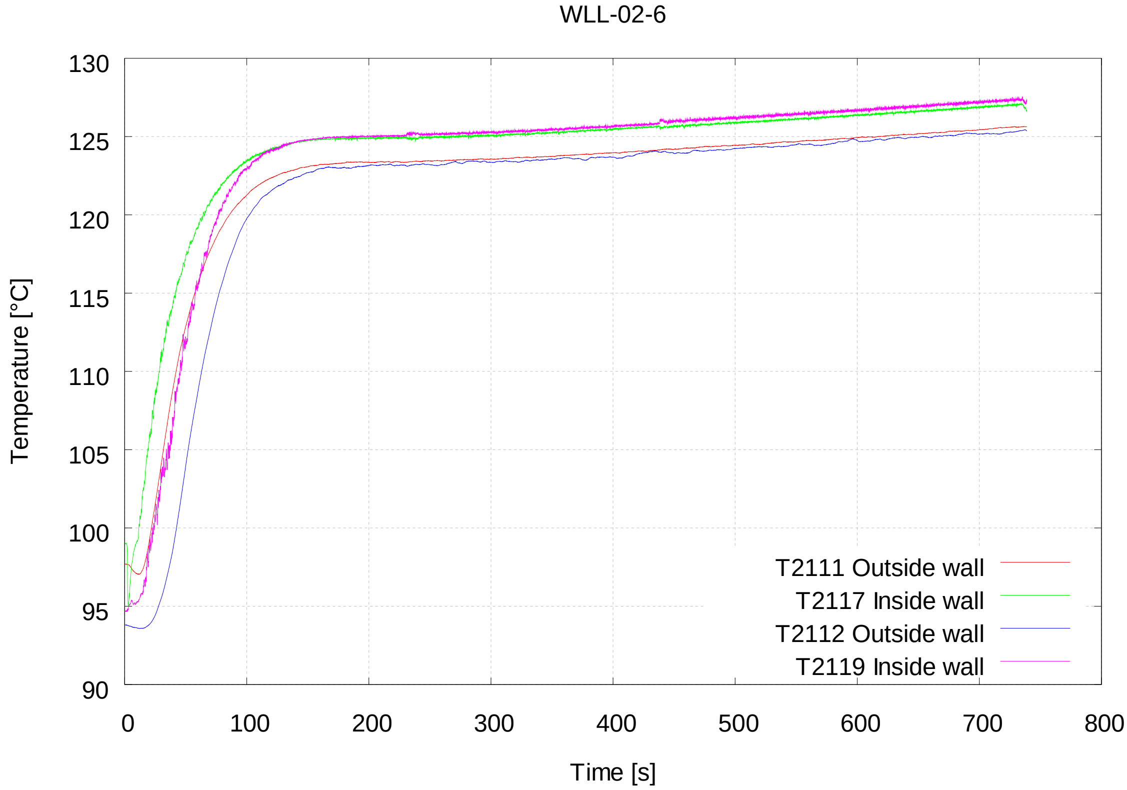


Figure 8. Temperatures on the outside and inside wall of the dry well in WLL-02-6.

4.2 WLL-04

The effect of pre-heating level of the dry well structures on the accumulation of condensate was studied in experiment WLL-04. The experiment consisted of three separate steam blowdowns with different initial dry well structural temperature levels. In all three tests, the initial pressure level of the steam source and the position of the steam line valve were the same. Therefore, during the first 55 seconds that are examined here, the steam flow rate and the temperature of the incoming steam were practically the same in all three tests, Figure 9. The dry well atmosphere is a mixture of non-condensable gas and steam during the examined period, since it usually takes a couple of hundred seconds to get to the pure steam discharge phase of the tests.

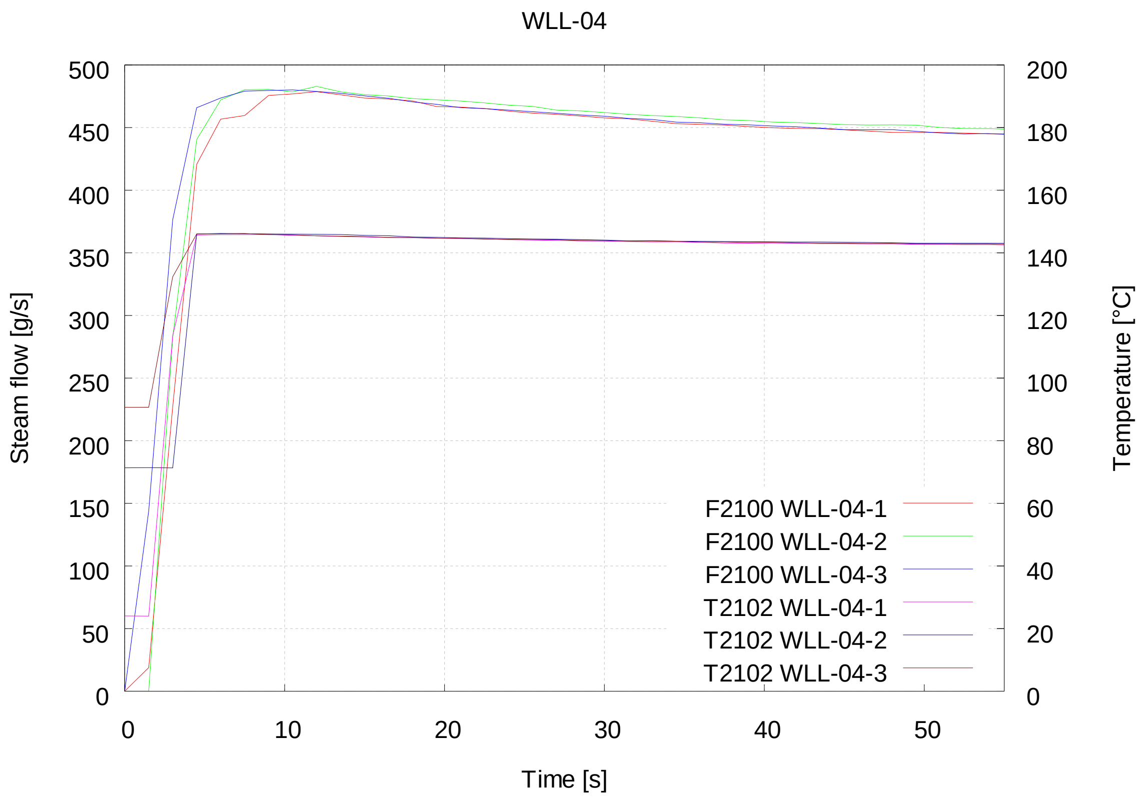


Figure 9. Steam mass flow rate (F2100) and temperature of incoming steam (T2102) in WLL-04 tests between 0…55 seconds.

The accumulation of condensate is clearly controlled by the initial temperature level of the dry well structures. The largest amount of condensate (5.8 kg) was measured in WLL-04-1, where the initial temperature of the dry well structures was the lowest (approximately 23 °C), Figure 10. However, in WLL-04-2 almost the same amount of condensate (5.5 kg) accumulated despite of the higher initial structural temperature (41 °C). In WLL-04-3, where the initial structural temperature was 68 °C, only 4.0 kg of condensate accumulated during the first 55 seconds.

Figure 11 shows how the collected amount of condensate in the four tanks in WLL-04-1 differed from each other. More condensate was collected from the two upper segments than from the two lower segments (tank 1 vs. tank 2 and tank 3 vs. tank 4). In addition, more condensate was collected from the wall segments opposite to the inlet plenum than from the wall segments on the same side as the inlet plenum (tank 1 vs. tank 3 and tank 2 vs. tank 4).

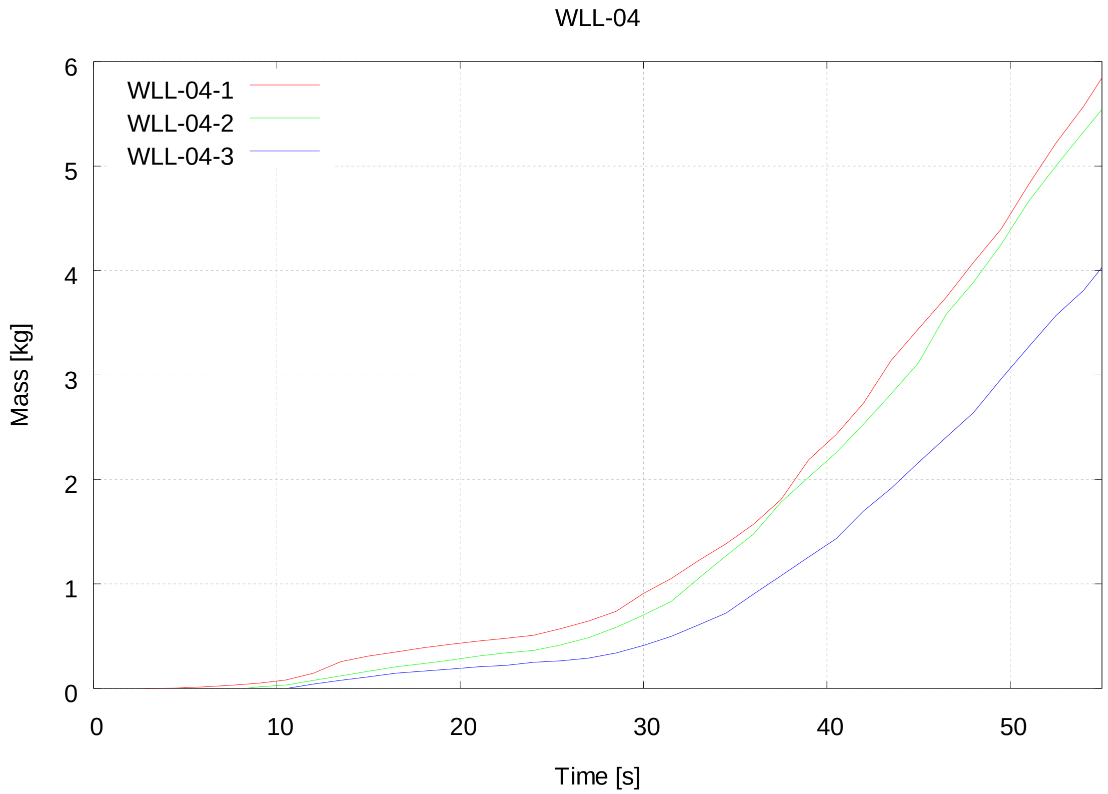


Figure 10. Accumulation of condensate in WLL-04 tests between 0…55 seconds.

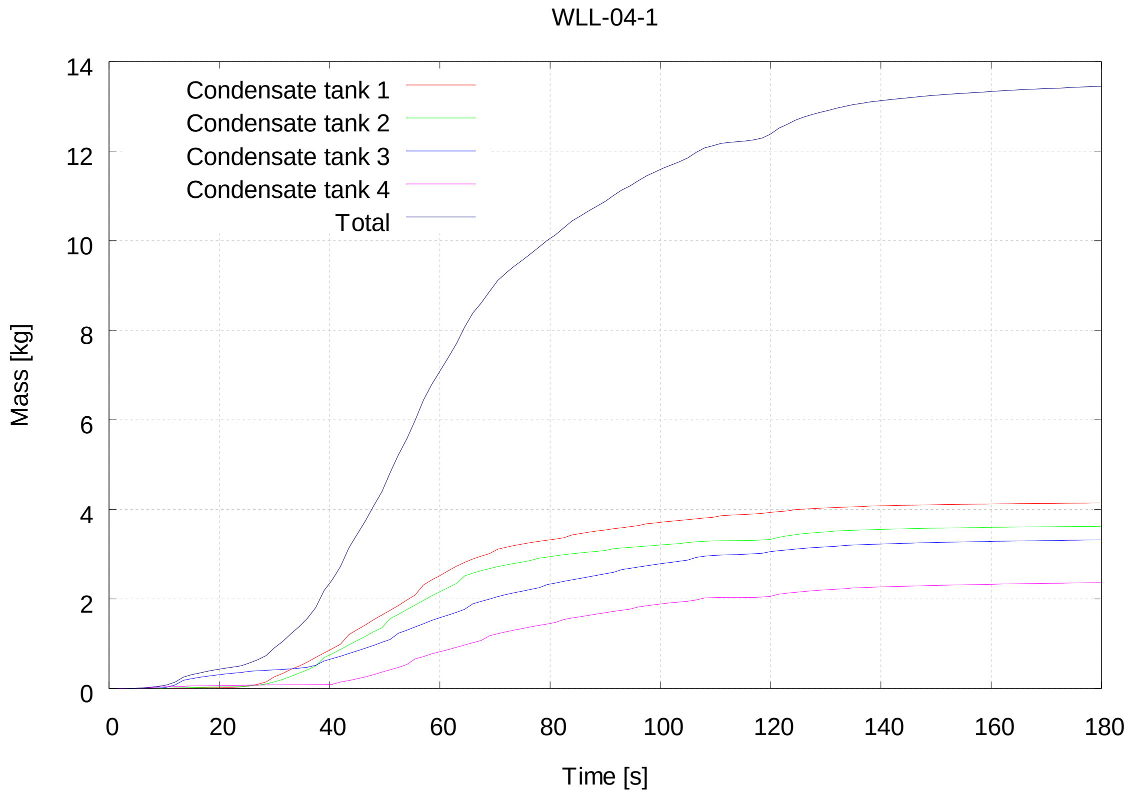


Figure 11. Accumulation of condensate in WLL-04-1.

4.3 WLL-05-1

A thermo graphic camera was used during the experiments WLL-04 and WLL-05 for viewing the temperature distribution on the outer wall of the dry well compartment. The camera filmed the wall segment opposite to the inlet plenum. Due to the limited amount of space between the test vessel and the laboratory wall, the camera had to be positioned diagonally to the axis of the inlet plenum, see photographs in Appendix 2.

In WLL-05-1, steam was discharged into the pool for 120 seconds, Figure 12. The flow rate ranged from 500 to 560 g/s and the temperature of incoming steam (at the flow meter) from 147 to 152 °C. The dry well structures were not pre-heated i.e. they were initially at the temperature of 26 °C. Figure 13 shows views captured from the recording of the thermo graphic camera. They reveal that the wall temperature increases first, as expected, on the right edge of the views where the steam flow hits to the inside surface of the dry well wall. The maximum temperature difference between the hot spot and the colder part of the wall during the test can be estimated to be about 20-30 °C. It occurs at about 50-60 seconds from the beginning of the steam discharge. After that, the wall temperatures start to equalize and become almost uniform at the end of the discharge (see the last views in Figure 13). This observation is confirmed by the shape of the measured wall temperature curves. They tend to turn horizontal towards the end of the test (Figure 12). In vertical direction, one can see only a small temperature difference in the camera views. Wall temperatures are slightly higher at the lower edge of the view than at the top. This indicates that the steam jet probably bends downwards before it hits the wall.

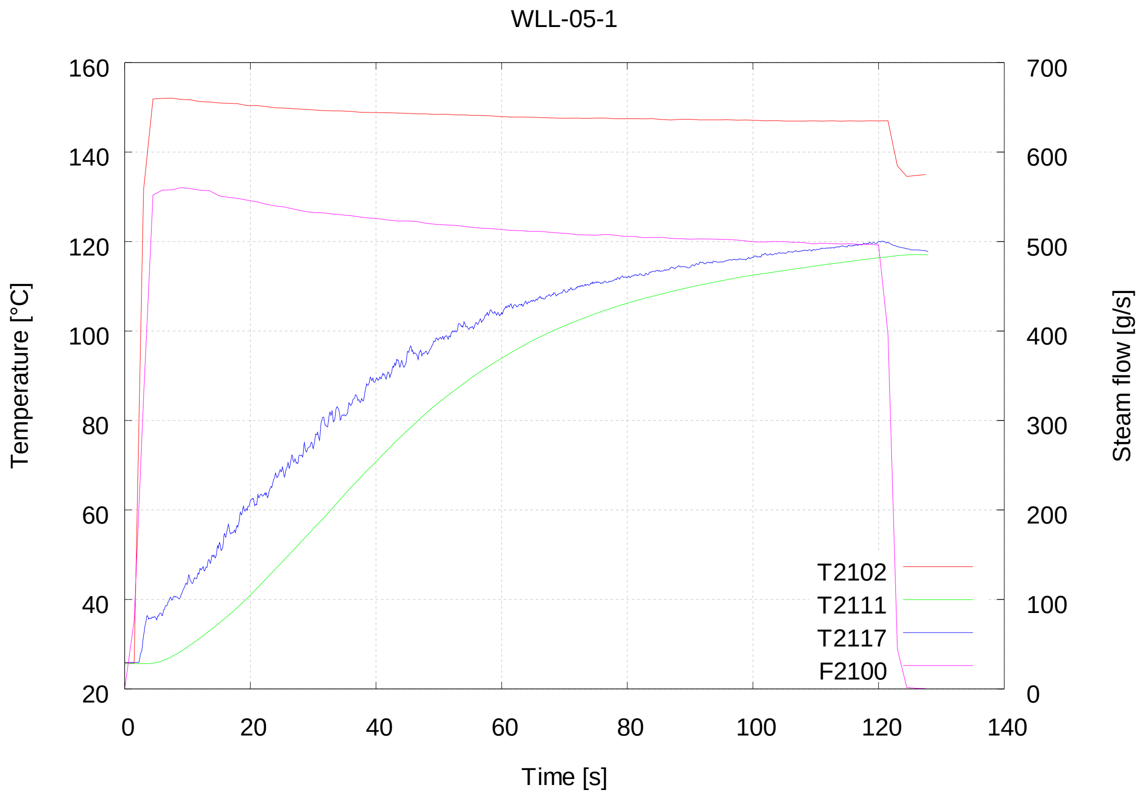
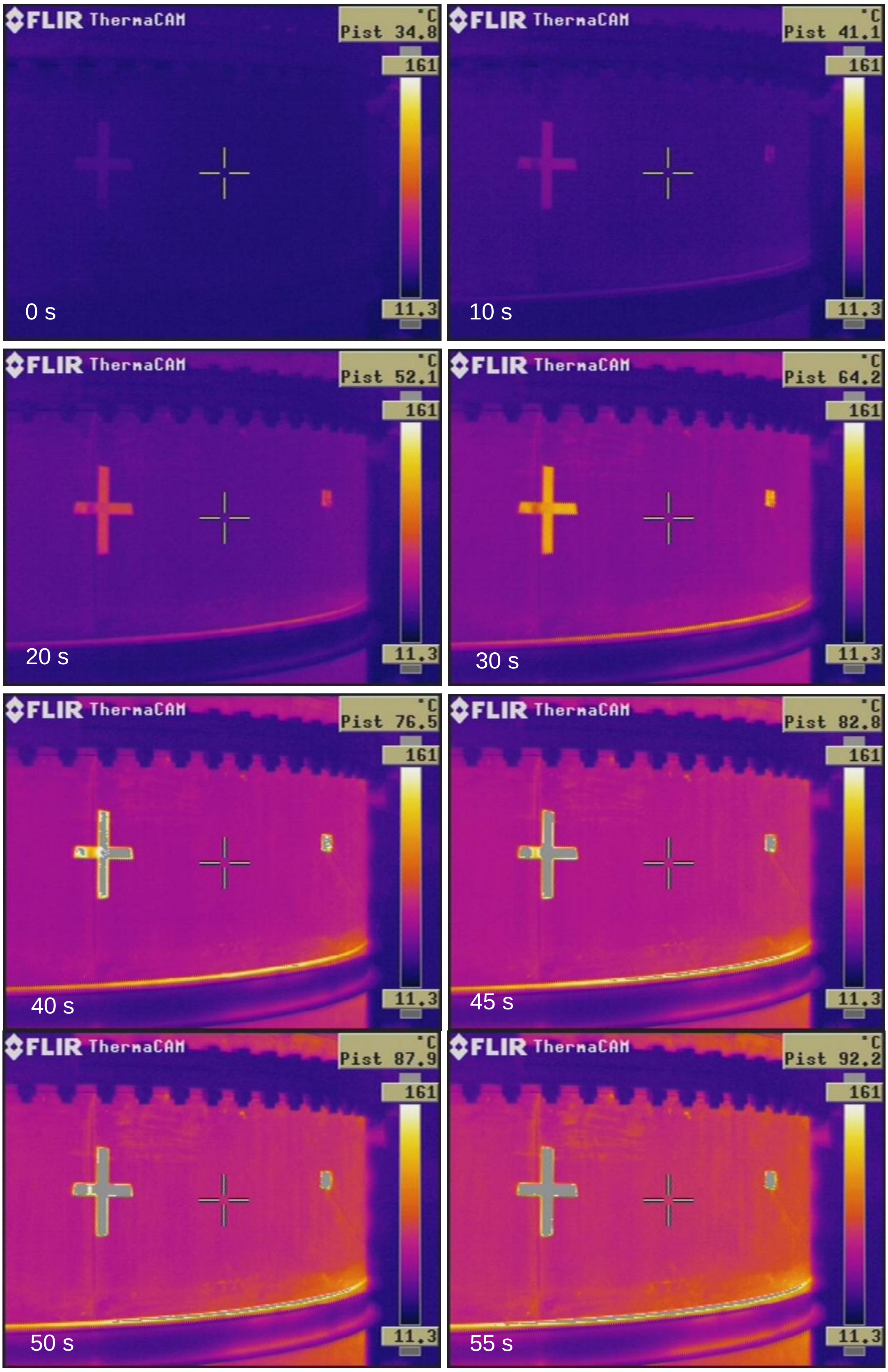


Figure 12. Mass flow rate (F2100) and temperature (T2102) of incoming steam and temperatures on the outer (T2111) and inner (T2117) wall of the dry well opposite to the inlet plenum in WLL-05-1.


FLIR ThermaCAM
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Pist 34,8
161
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FLIR ThermaCAM
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Pist 41,1
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11,3
20 s
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Pist 64,2
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11,3
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°C
Pist 76,5
161
11,3
40 s
FLIR ThermaCAM
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Pist 82,8
161
11,3
45 s
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11,3
50 s
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11,3
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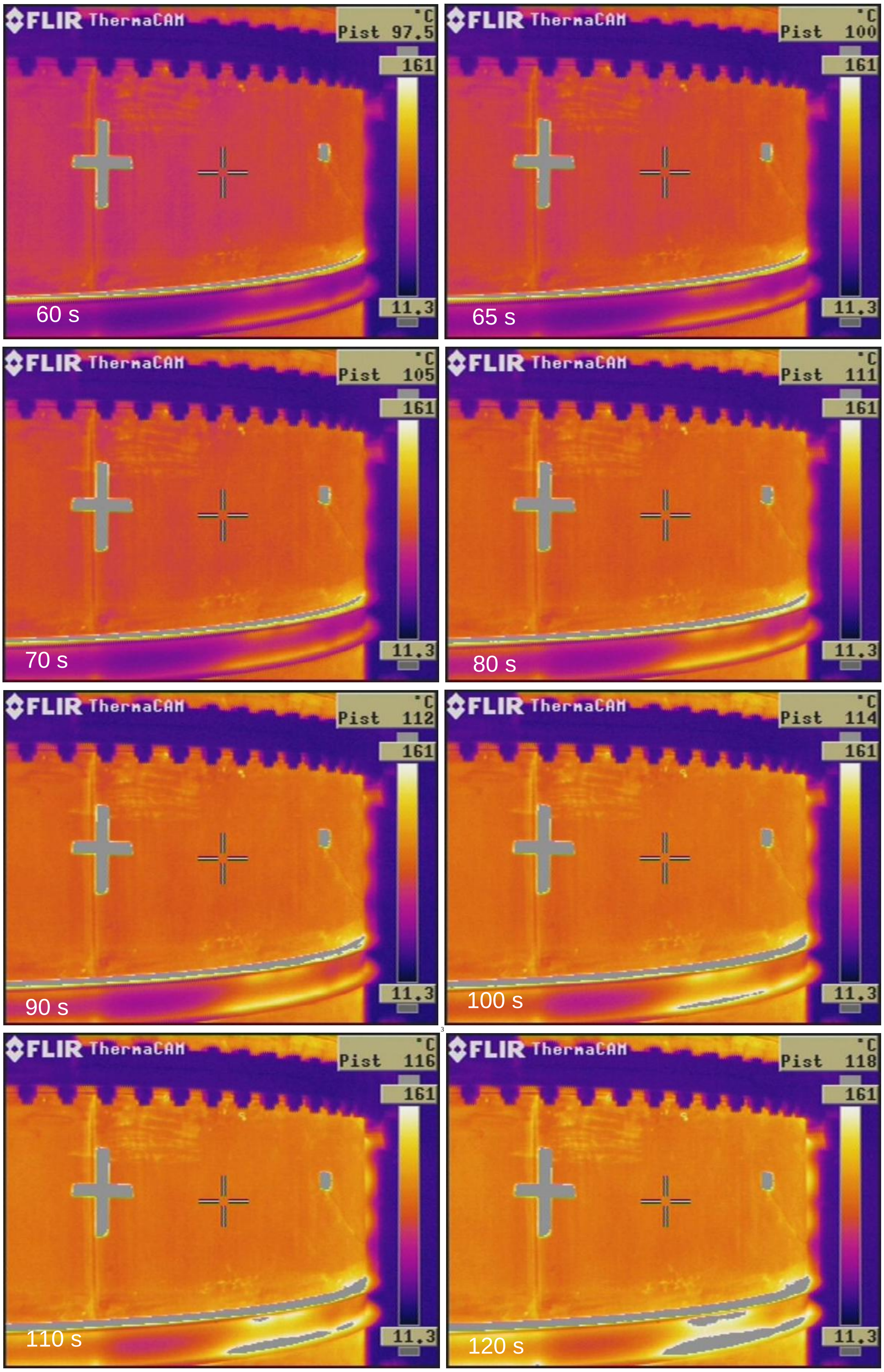

Figure 13. Frame captures of thermo graphic camera from WLL-05-1. See the positioning of the camera from photographs in Appendix 2.

5 SUMMARY AND CONCLUSIONS

This report summarizes the results of the wall condensation experiments carried out in December 2008 and January 2009 with the scaled down PPOOLEX test facility designed and constructed at Lappeenranta University of Technology. The main purpose of the experiment series was to study wall condensation phenomenon inside the dry well compartment while steam is discharged through it into the condensation pool as well as to get comparison data for CFD simulations at VTT.

The test facility is a closed stainless steel vessel divided into two compartments, dry well and wet well. The test facility was equipped with a system for collecting and measuring the amount of condensate from four different wall segments of the dry well compartment. In addition, a thermo graphic camera was used in a couple of experiments for measuring the temperature distribution on the outside surface of the dry well wall.

In the experiments, steam was blown into the dry well compartment and from there through a DN200 (∅219.1x2.5) blowdown pipe down to the condensation pool filled with water. Before each experiment the condensation pool was filled with approximately 20 °C water to the level of 2.14 m i.e. the blowdown pipe outlet was submerged by 1.05 m. Altogether five successful experiments, each consisting of several steam blows, were carried out.

In the experiments, the initial temperature level the dry well structures varied from 23 to 99 °C. Pre-heating of the structures was used in all but two tests. The range of the steam flow rate was from 90 to 690 g/s and the temperature of incoming steam from 115 to 160 °C.

During the initial phase of steam discharge the condensation process was strongly controlled by the temperature level of the dry well structures. As the structural temperatures increased the accumulation of condensate slowed down. This means that most of the condensate usually accumulated during the first 200 seconds of the discharge. However, the condensation process never terminated, because a temperature difference of a few degrees remained between the atmosphere and the inner wall of the dry well as long as steam was blown into the pool (max. 800 s).

The collected amount of condensate from the four wall segments differed from each other. More condensate was collected from the two upper segments than from the two lower segments. In addition, more condensate was collected from the wall segments opposite to the inlet plenum than from the wall segments on the same side as the inlet plenum.

According to a recording of the thermo graphic camera from the opposite wall of the inlet plenum a temperature difference of about 20-30 °C develops between the hot spot and the colder part of the wall during the initial phase of the tests. A small temperature difference also in vertical direction of the camera views indicates that the steam jet probably bends downwards before it hits the wall.

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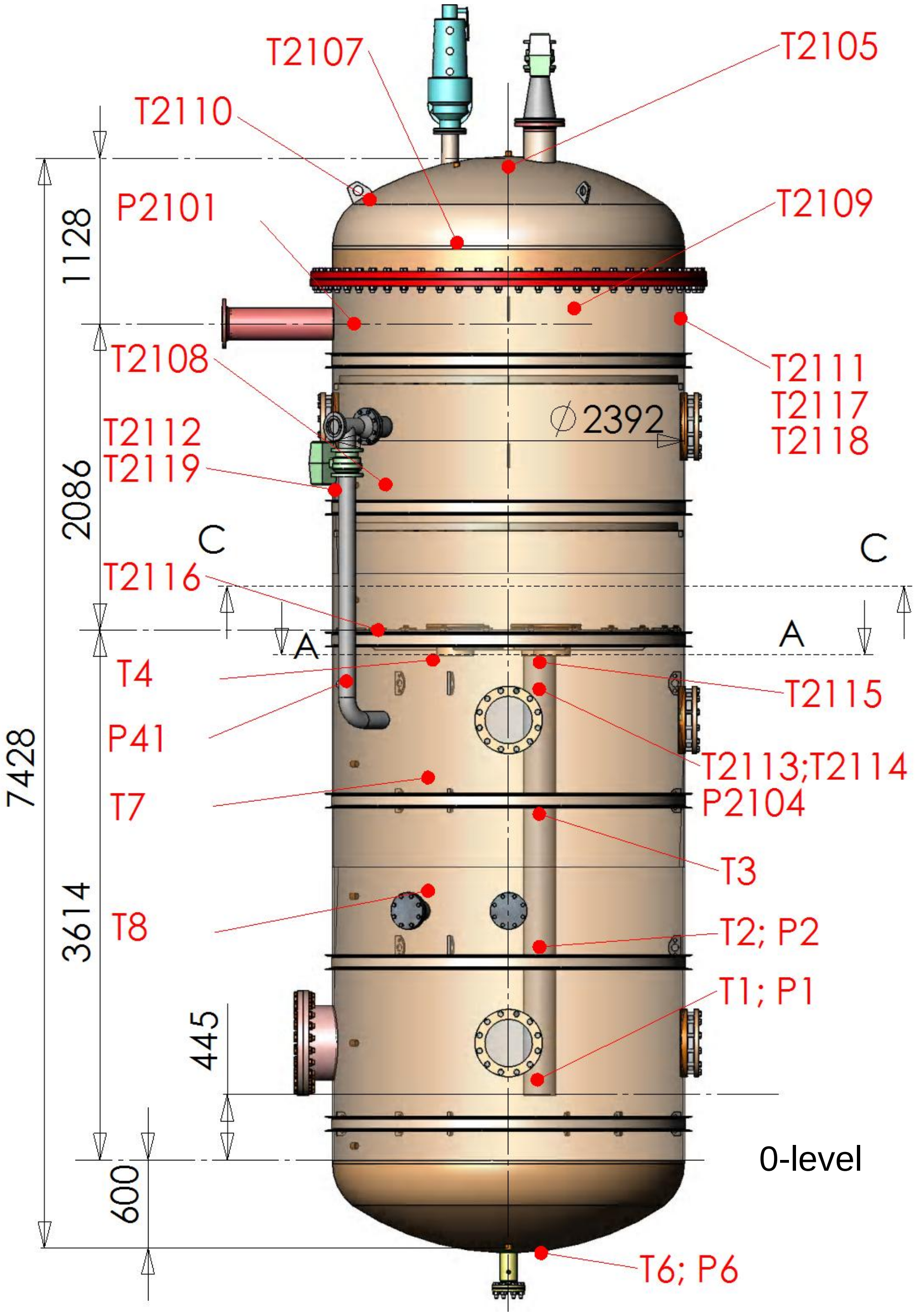
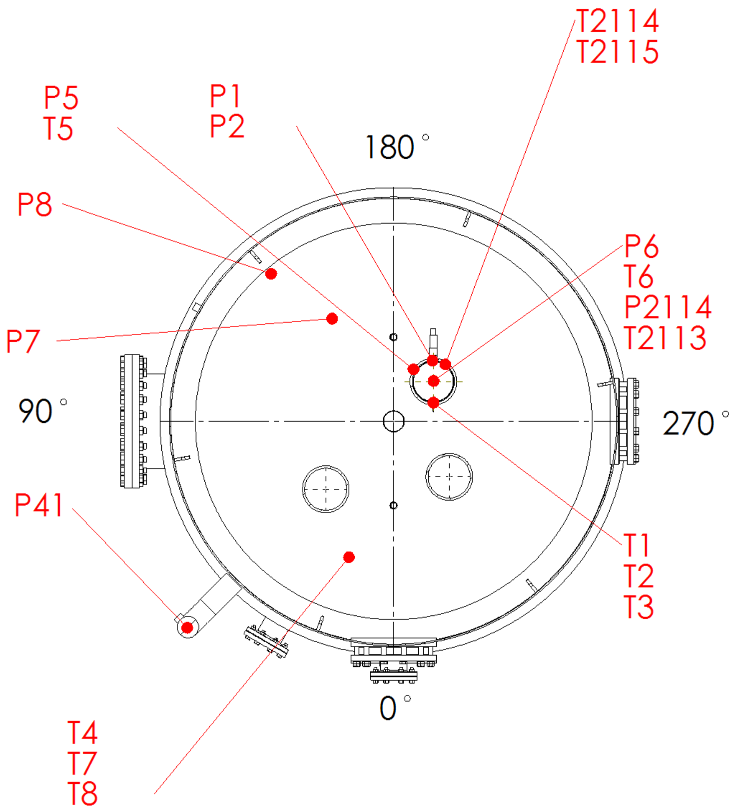
LAPPEENRANTA
UNIVERSITY OF TECHNOLOGY

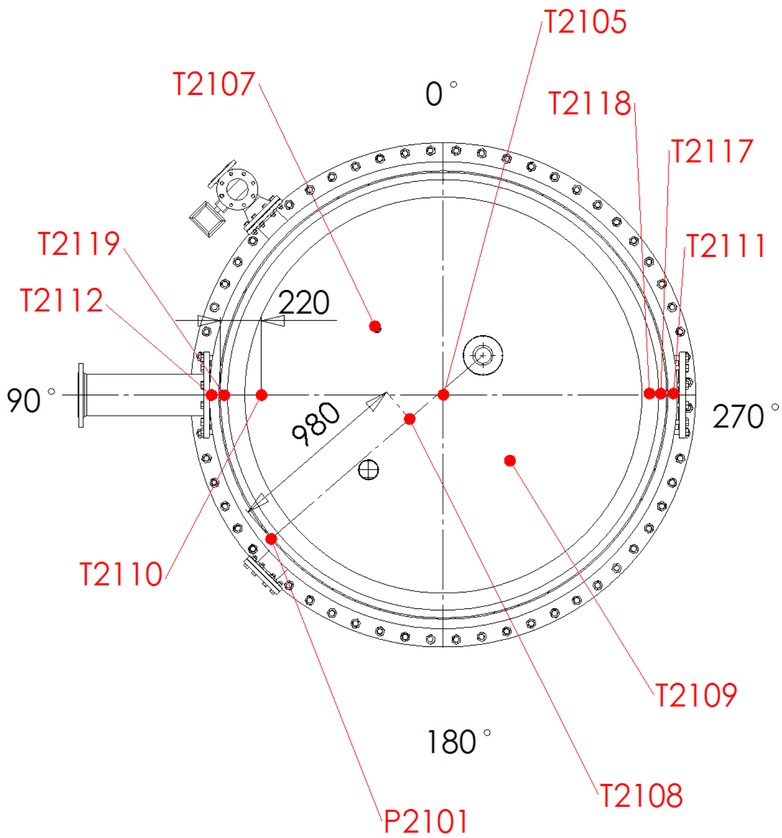
APPENDIX 1: INSTRUMENTATION OF THE PPOOLEX TEST FACILITY



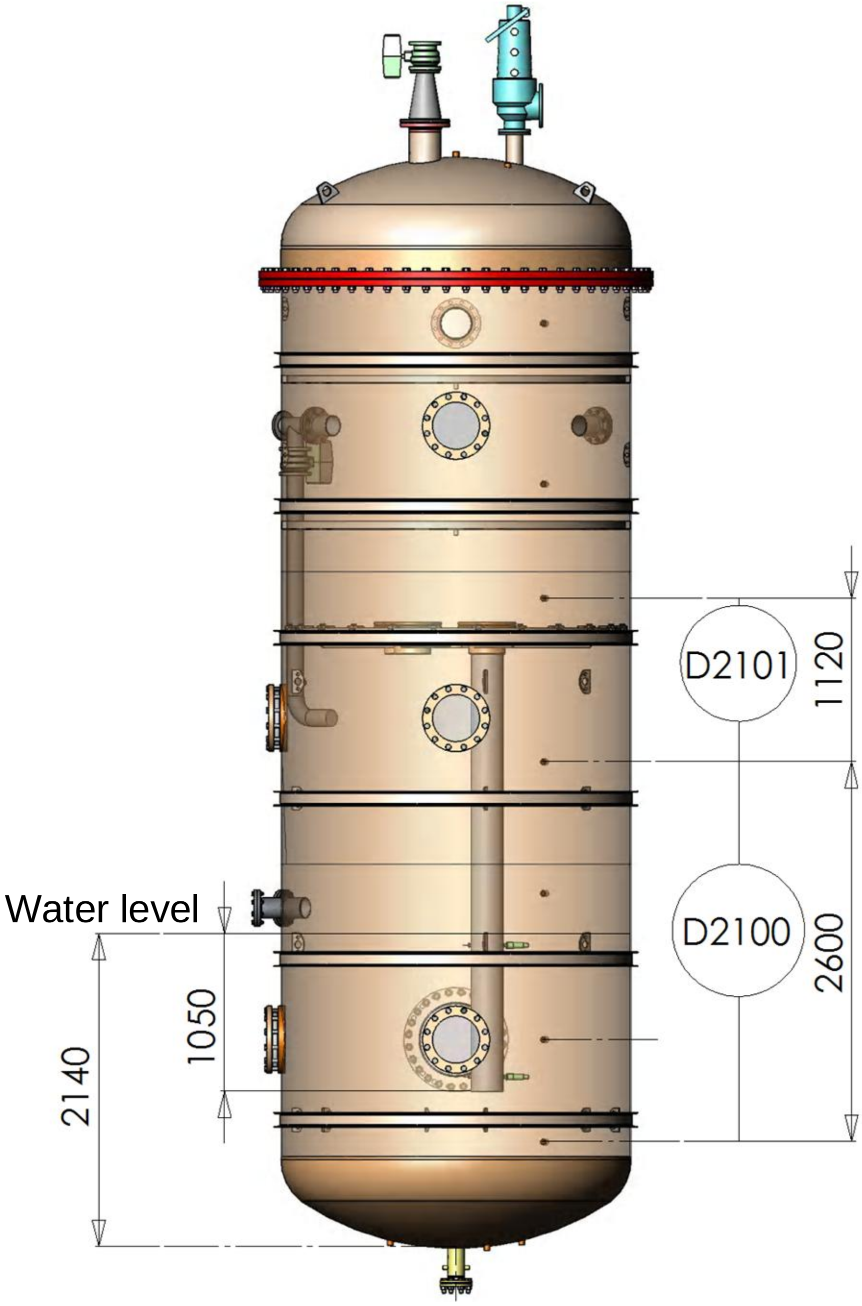
Test vessel measurements.



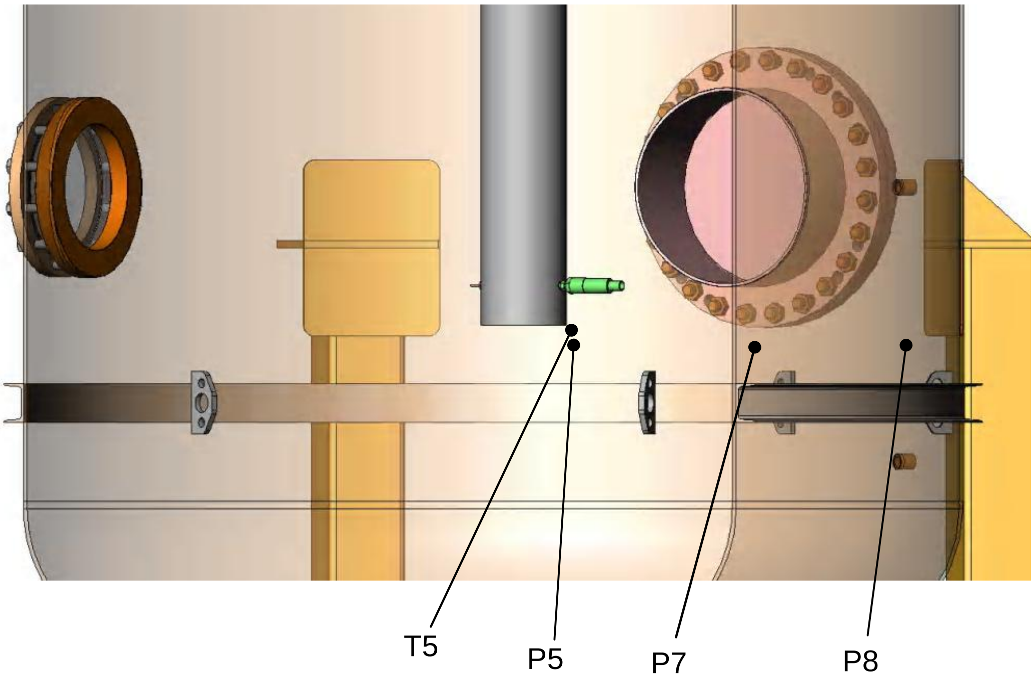
Cross-section A-A.



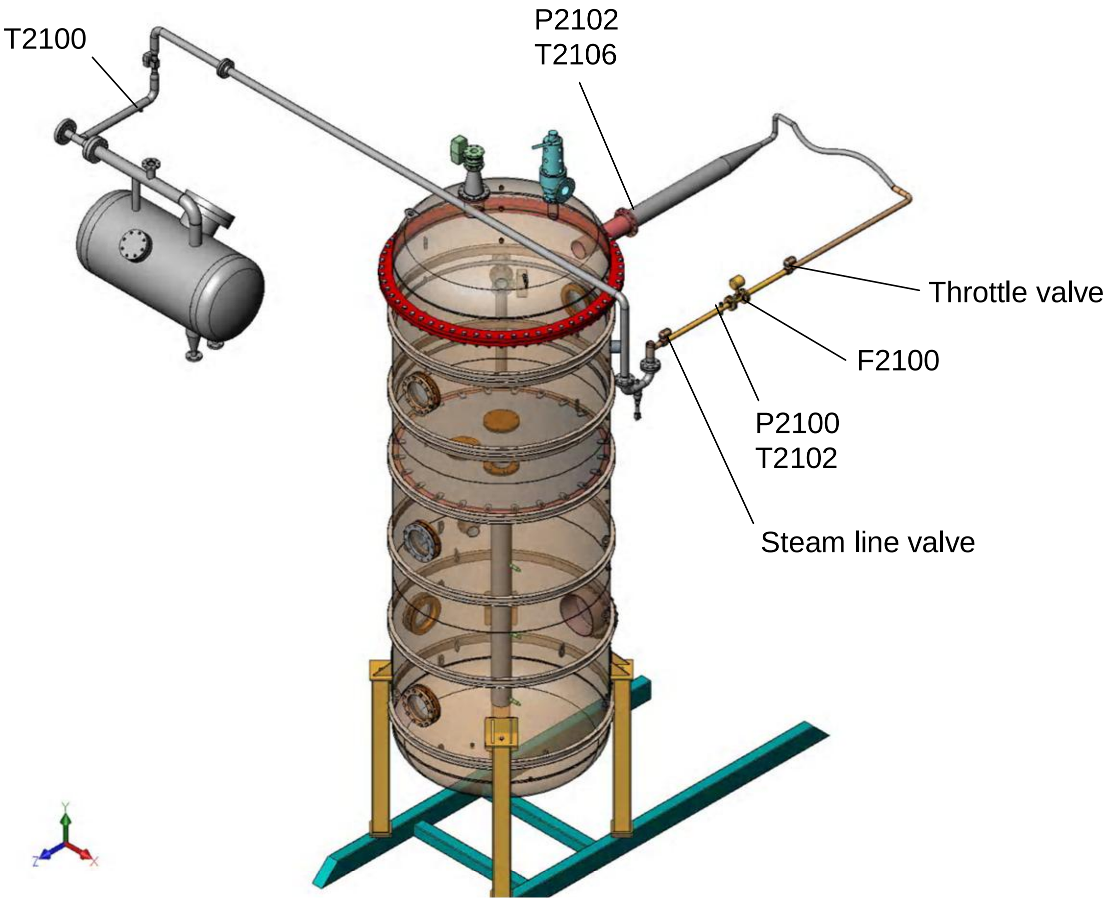
Cross-section C-C.



Test vessel measurements.



Pressure and temperature measurements at the blowdown pipe outlet.



Measurements in the steam line.

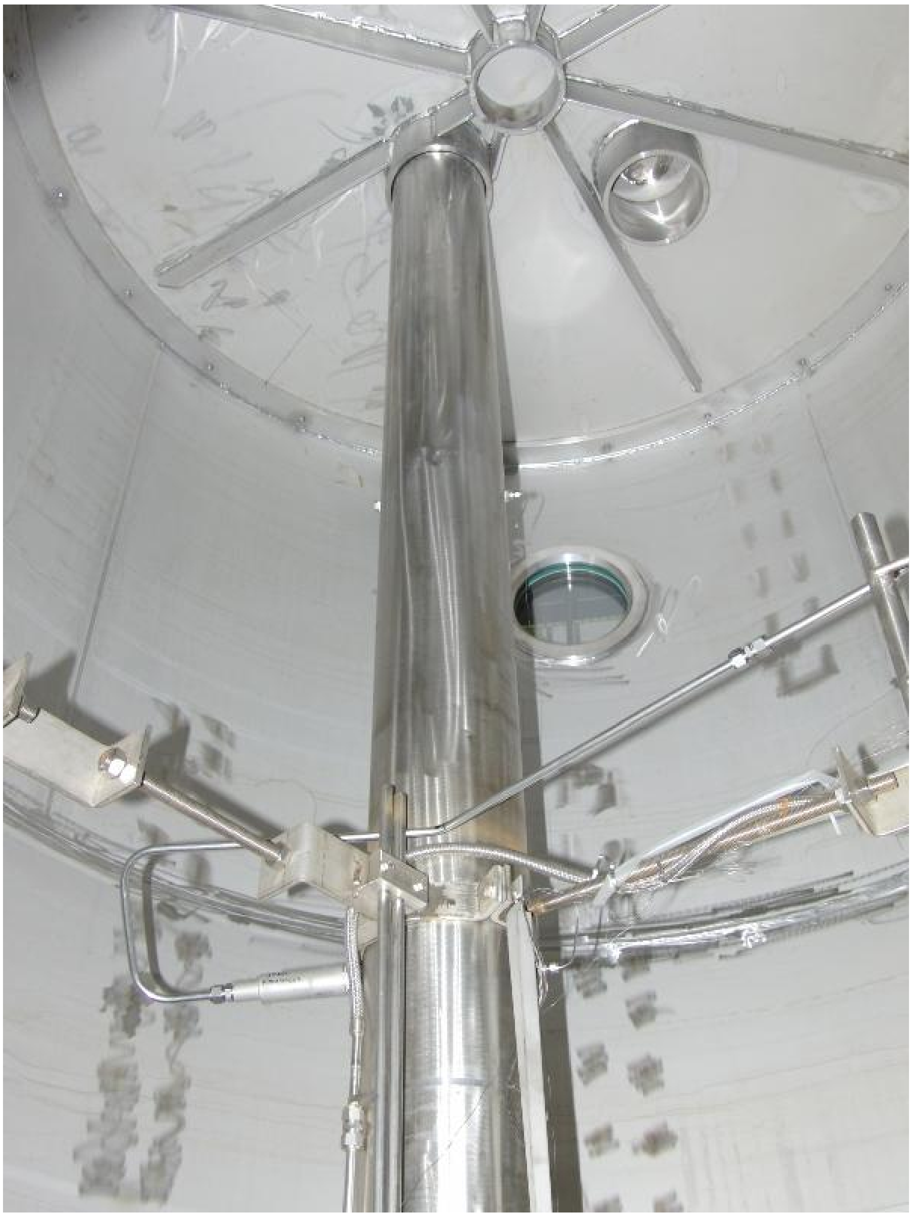
Measurement	Code	Elevation	Angle	Location	Error estimation
Pressure	P1	545	214	Blowdown pipe	±0.7 bar
Temperature	T1	545	245	Blowdown pipe	±1.8 °C
Pressure	P2	1445	214	Blowdown pipe	±0.7 bar
Temperature	T2	1445	245	Blowdown pipe	±1.8 °C
Temperature	T3	2345	245	Blowdown pipe	±1.8 °C
Temperature	T4	3410	20	Wet well gas space	±1.8 °C
Pressure	P5	395	198	Blowdown pipe outlet	±0.7 bar
Temperature	T5	420	198	Blowdown pipe outlet	±1.8 °C
Pressure	P6	-1060	225	Wet well bottom	±0.5 bar
Temperature	T6	-1060	225	Wet well bottom	±1.8 °C
Pressure	P7	395	135	Wet well	±0.4 bar
Temperature	T7	2585	20	Wet well	±1.8 °C
Pressure	P8	395	135	Wet well	±0.4 bar
Temperature	T8	1760	20	Wet well	±1.8 °C
Pressure	P41	3600	45	Wet well gas space	±0.1 bar
Flow rate	F2100	-	-	Steam line	±4.9 l/s
Pressure	P2100	-	-	Steam line	±0.5 bar
Temperature	T2100	-	-	Steam line beginning	±3.5 °C
Pressure	P2101	5700	90	Dry well	±0.06 bar
Pressure	P2102	-	-	Inlet plenum	±0.06 bar
Temperature	T2102	-	-	Steam line	±3.5 °C
Pressure	P2104	3400	225	Blowdown pipe	±0.06 bar
Temperature	T2104	-245	180	Wet well outer wall	±2.9 °C
Temperature	T2105	6780	-	Dry well top	±3.1 °C
Temperature	T2106	-	-	Inlet plenum	±3.1 °C
Temperature	T2107	6085	45	Dry well middle	±1.9 °C
Temperature	T2108	4600	120	Dry well bottom	±3.1 °C
Temperature	T2109	5790	225	Dry well lower middle	±9.9 °C
Temperature	T2110	6550	90	Dry well outer wall	±1.8 °C
Temperature	T2111	5700	270	Dry well outer wall	±1.8 °C
Temperature	T2112	4600	90	Dry well outer wall	±1.8 °C
Temperature	T2113	3400	225	Blowdown pipe	±1.8 °C
Temperature	T2114	3400	220	Blowdown pipe	±1.8 °C
Temperature	T2115	3250	220	Blowdown pipe	±1.8 °C
Temperature	T2116	3600	135	Dry well floor	±1.8 °C
Temperature	T2117	5700	270	Dry well inner wall	±1.8 °C
Temperature	T2118	5700	270	Dry well, 10 mm from the wall	±1.8 °C
Temperature	T2119	4600	90	Dry well inner wall	±1.8 °C
Pressure diff.	D2100	100–2700	120	Wet well	±0.06 m
Pressure diff.	D2101	2700–3820	120	Across the floor	±0.09 bar
Pressure diff.	D2102	-	-	Condensate water tank 1	±0.03 m
Pressure diff.	D2103	-	-	Condensate water tank 2	±0.03 m

Pressure diff.	D2104	-	-	Condensate water tank 3	±0.03 m
Pressure diff.	D2105	-	-	Condensate water tank 4	±0.03 m
Strain	S1	-400	0	Bottom segment	Not defined
Strain	S2	-400	0	Bottom segment	Not defined
Strain	S3	-265	180	Bottom segment	Not defined
Strain	S4	-265	180	Bottom segment	Not defined
Vertical pool movement	Z-axis	892	180	Below pool bottom	Not defined
Pool bottom acceleration	G-force	892	180	Pool bottom	Not defined
Valve position	X1100	-	-	Steam line	Not defined

Measurements in the PPOOLEX facility for WLL experiments.

APPENDIX 2: TEST FACILITY PHOTOGRAPHS

Dry well compartment, relief valves and inlet plenum.



Inside view of the wet well compartment: blowdown pipe and intermediate floor.

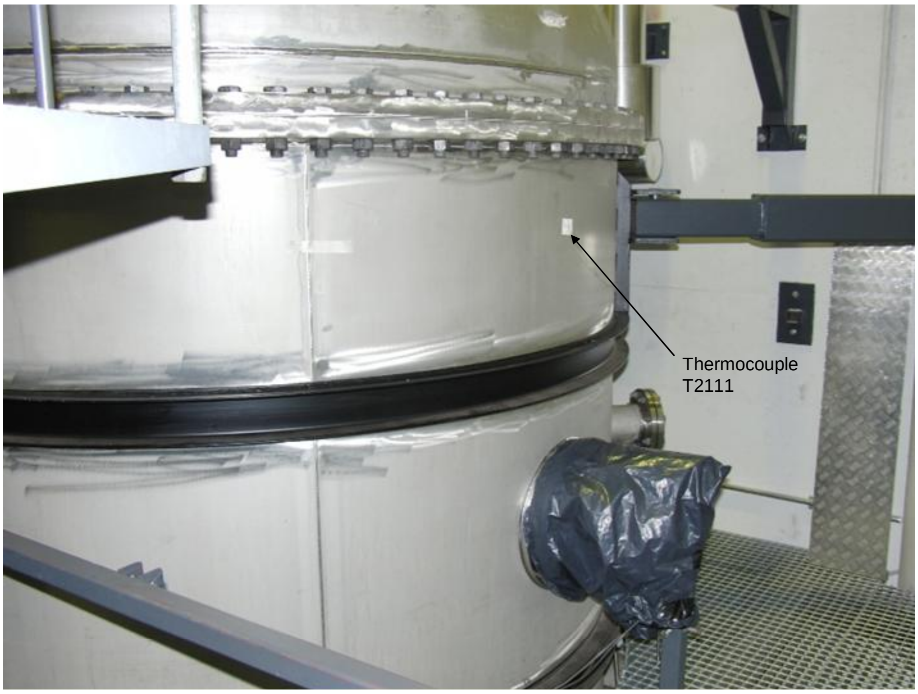
Pressure (P1, P5, P7 and P8) and temperature (T1 and T5) measurements at the blowdown pipe outlet.

Drain gutters on the dry well inner wall on two elevations.

Piping system for condensate collection tanks 3 and 4.

Condensate collection tanks 1 and 2 (left) and tanks 3 and 4 (right).

A thermo graphic camera in a filming position.



A view from the filming position of the thermo graphic camera.

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Affiliation(s)	Lappeenranta University of Technology, Finland Nuclear Safety Research Unit
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No. of tables	5 + 1
No. of illustrations	13 + 14
No. of references	7

Abstract

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The PPOOLEX test facility is a closed stainless steel vessel divided into two compartments, dry well and wet well. For the wall condensation experiments the test facility was equipped with a system for collecting and measuring the amount of condensate from four different wall segments of the dry well compartment. A thermo graphic camera was used in a couple of experiments for filming the outside surface of the dry well wall.

The effect of the initial temperature level of the dry well structures and of the steam flow rate for the accumulation of condensate was studied. The initial temperature level of the dry well structures varied from 23 to 99 C. The steam flow rate varied from 90 to 690 g/s and the temperature of incoming steam from 115 to 160 C.

During the initial phase of steam discharge the accumulation of condensate was strongly controlled by the temperature level of the dry well structures; the lower the initial temperature level was the more condensate was accumulated. As the dry well structural temperatures increased the condensation process slowed down. Most of the condensate usually accumulated during the first 200 seconds of the discharge. However, the condensation process never completely stopped because a small temperature difference remained between the dry well atmosphere and inner wall even in the case of an extended steam discharge period.

More condensate was collected from the two upper wall segments than from the two lower segments. In addition, more condensate was collected from the segments opposite to the inlet plenum than from the segment on the same side as the inlet plenum.

Key words condensation pool, steam/air blowdown, wall condensation

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