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PIV MEASUREMENTS AT THE BLOWDOWN PIPE OUTLET

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April 2013

Abstract

This report summarizes the findings of the PIV measurement tests carried out in January – February 2013 with the scaled down PPOOLEX test facility at LUT. The main objective of the tests was to find out the operational limits of the PIV system regarding suitable test conditions and correct values of different adjustable PIV parameters. An additional objective was to gather CFD grade data for verification/validation of numerical models. Both water and steam injection tests were carried out. PIV measurements with cold water injection succeeded well. Raw images were of high quality, averaging over the whole measurement period could be done and flow fields close to the blowdown pipe outlet could be determined. In the warm water injection cases the obtained averaged velocity field images were harder to interpret, especially if the blowdown pipe was also filled with warm water in the beginning of the measurement period. The absolute values of the velocity vectors seemed to be smaller than in the cold water injection cases. With very small steam flow rates the steam/water interface was inside the blowdown pipe and quite stable in nature. The raw images were of good quality but due to some fluctuation in the velocity field averaging of the velocity images over the whole measured period couldn't be done. Condensation of steam in the vicinity of the pipe exit probably caused these fluctuations. A constant outflow was usually followed by a constant inflow towards the pipe exit. Vector field images corresponding to a certain phase of the test could be extracted and averaged but this would require a very careful analysis so that the images could be correctly categorized. With higher steam flow rates rapid condensation of large steam bubbles created small gas bubbles which were in front of the measurement area of the PIV system. They disturbed the measurements by reflecting laser light like seeding particles and therefore the raw images were of poor quality and they couldn't be processed correctly. Experiments in the PPOOLEX facility form a very challenging environment for the use of the PIV measurement system. Some observations regarding the suitability of the system for different kind of flow situations can be made on the basis of the tests reported here. However, the full capacity of the system must be determined later on the basis of a more comprehensive experiment series

Key words
Resilience engineering, adjustment, work practice, maintenance, outage, field operators, organizational core task, safety culture, trade-offs

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Summary

This report summarizes the findings of the PIV measurement tests carried out in January – February 2013 with the scaled down PPOOLEX test facility at LUT. The tests could not be done according to the original timetable because severe problems with the PC controlling the PIV measurement system were encountered. The problems were solved only at the end of 2012 and therefore the tests had to be carried out quite fast and in somewhat reduced scope.

The main objective of the tests was to find out the operational limits of the PIV system regarding suitable test conditions and correct values of different adjustable PIV parameters. An additional objective was to gather CFD grade data for verification/validation of numerical models. Both water and steam injection tests were carried out.

PIV measurements with cold water injection succeeded well. Raw images were of high quality, averaging over the whole measurement period could be done and flow fields close to the blowdown pipe outlet could be determined.

In the warm water injection cases the obtained averaged velocity field images were harder to interpret, especially if the blowdown pipe was also filled with warm water in the beginning of the measurement period. The absolute values of the velocity vectors seemed to be smaller than in the cold water injection cases.

With very small steam flow rates the steam/water interface was inside the blowdown pipe and quite stable in nature. The raw images were of good quality but due to some fluctuation in the velocity field averaging of the velocity images over the whole measured period couldn't be done. Condensation of steam in the vicinity of the pipe exit probably caused these fluctuations. A constant outflow was usually followed by a constant inflow towards the pipe exit. Vector field images corresponding to a certain phase of the test could be extracted and averaged but this would require a very careful analysis so that the images could be correctly categorized.

With higher steam flow rates rapid condensation of large steam bubbles created small gas bubbles which were in front of the measurement area of the PIV system. They disturbed the measurements by reflecting laser light like seeding particles and therefore the raw images were of poor quality and they couldn't be processed correctly.

Experiments in the PPOOLEX facility form a very challenging environment for the use of the PIV measurement system. Some observations regarding the suitability of the system for different kind of flow situations can be made on the basis of the tests reported here. However, the full capacity of the system must be determined later on the basis of a more comprehensive experiment series.

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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 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 dry well and wet well 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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CONTENTS

NOMENCLATURE

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
EHS	effective heat source
EMS	effective momentum source
EXCOP	experimental studies on containment phenomena project
GOTHIC	general purpose thermal-hydraulic code
KTH	Kungliga Tekniska Högskolan
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
PIV	particle image velocimetry
POOLEX	condensation pool experiments project
PPOOLEX	pressurized condensation pool experiments project
SAFIR	Safety of Nuclear Power Plants - Finnish National Research Programme
SLR	steam line rupture
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

1 INTRODUCTION

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

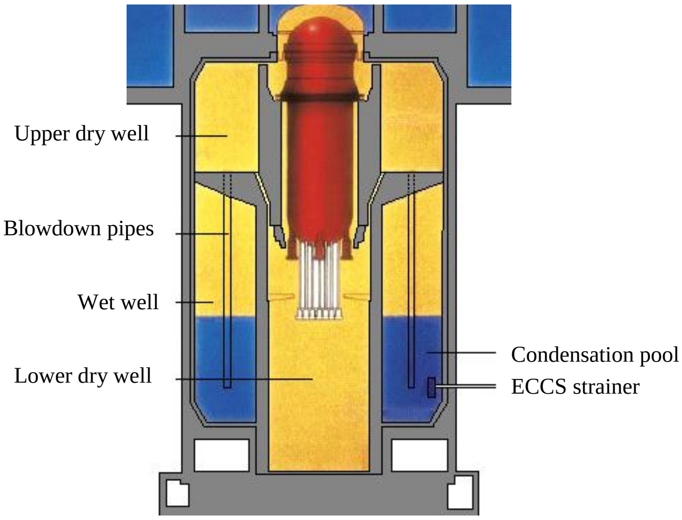

Figure 1. Schematic of the Olkiluoto type BWR containment.

The main objective of the EXCOP 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 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 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 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 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. In December 2008 and January 2009 a test series focusing on steam condensation in the dry well 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 wet well pool and the interaction of parallel blowdown pipes were investigated further in 2010 [8], [9]. In January–February 2011 a second test series 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]. For supporting the development of the Effective Momentum Source (EMS) and Effective Heat Source (EHS) models to be implemented in GOTHIC code by KTH an additional series of thermal stratification and mixing experiments (MIX series) was conducted in June–October 2012 [12, 13].

Work with the PPOOLEX facility continued in January–February 2013 with experiments focusing on PIV measurements of the DCC phenomenon (labeled as DCC-01…02). The main purpose of the experiments was to find out how well the PIV measurement system suits for different flow conditions in the PPOOLEX facility and to generate data for the code developers. In this report, the results of the DCC 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 PIV measurement system is presented in chapter three. The test programme is introduced in chapter four. The test results are presented and discussed in chapter five. Chapter six 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. It was replaced with a more versatile PPOOLEX facility in the end of 2006. The PPOOLEX facility is described in more detail in reference [14]. However, the main features of the facility and its instrumentation are introduced below.

2.1 TEST VESSEL

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

The main component of the facility is the ~31 m^3 cylindrical test vessel, 7.45 m in height and 2.4 m in diameter. It is constructed from three plate cylinder segments and two dome segments. The test facility is able to withstand considerable structural loads caused by rapid condensation of steam. The dry and wet well sections are volumetrically scaled according to the compartment volumes of the Olkiluoto containment (ratio approximately1:320). Inlet plenum for injection of steam penetrates through the side wall of the dry well compartment. The inlet plenum is 2.0 m long and its inner diameter is 214.1 mm. There are several windows for visual observation in both compartments. A DN100 (∅ 114.3 x 2.5 mm) drain pipe with a manual valve is connected to the vessel bottom. A relief valve connection is mounted on the vessel head. The removable vessel head and a man hole (DN500) in the wet well compartment wall provide access to the interior of the vessel for maintenance and modifications of internals and instrumentation. The dry well 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.

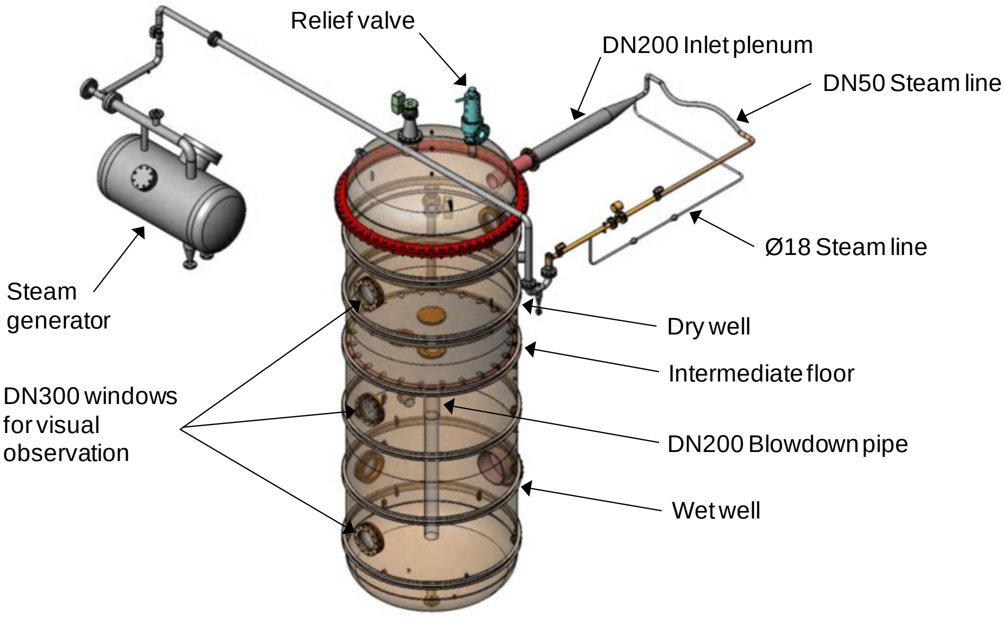

Figure 2. PPOOLEX test vessel.

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
Dry well volume [m^3]	13.3	4350
Wet well volume [m^3]	17.8	5725
Nominal water volume in the suppression pool [m^3]	8.38*	2700
Nominal water level in the suppression pool [m]	2.14*	9.5
Pipes submerged [m]	1.05	6.5
A_{pipes}/A_{pool}x100%	0.8 / 1.6**	1.6

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

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 [15] test facility, which has a core section of 1 MW heating power and three horizontal steam generators. Steam is led through a thermally insulated steam line, made of sections of standard DN80 (Ø88.9x3.2) and DN50 (Ø60.3x3.9) 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.

2.3 BLOWDOWN PIPE

The DN200 blowdown pipe is positioned inside the pool in a non-axisymmetric location, i.e. the pipe is 300 mm away from the centre of the condensation pool. The total length of the blowdown pipe is 3209 mm. The pipe is made from austenitic stainless steel AISI 304L (Ø219.1x2.5).

2.4 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 dry well, inside the blowdown pipes, at the condensation pool bottom and in the gas phase of the wet well. 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 valve position sensors. For the preceding thermal stratification and mixing experiments an extensive net of temperature measurements (thermocouples TC1–TC15) were installed in the blowdown pipe to accurately record the frequency and amplitude of steam/water-interface oscillations. These measurements were available also in the DCC test series. Appendix 1 presents the PPOOLEX measurements during the DCC series in more detail.

2.5 CCTV SYSTEM

Standard video cameras and digital videocassette recorders were used for visual observation of the test vessel interior during the test series. A Phantom v9.1 high speed camera was used for capturing the behaviour at the blowdown pipe outlet.

2.6 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 [16].

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

3 PIV MEASUREMENT SYSTEM

Particle image velocimetry (PIV) is a way to visualize and measure flow velocity properties in three dimensions. The PIV measurement system for the PPOOLEX facility was purchased from LaVisionUK Ltd. The following chapters present some general information of the system. For more detailed information see reference [17].

3.1 LASER

The system's laser is a Neodym-YAG double-cavity laser. The two pulsed lasers are mounted on a single baseplate. The lasers emit the beam in infrared range at 1064 nm and they are polarization combined. A second harmonic generator is used to convert the beam to visible range at 532 nm. Dichroic mirrors separate the visible light from the residual infrared light and direct the beam to the experiment. The delay between two pulses can be controlled with an external trigger source. The specification of the lasers is presented in Table 2.

Table 2. Performance values of lasers used in the PIV system [18]

Laser characteristics	Performance value
Beam diameter	6.35 mm
Pulse width	7-9 ns
Energy stability	±2% RMS
Energy @ 532 nm	180 mJ
Repetition rate	0-15 Hz
Divergence, full angle for 90% of output energy	< 0.8 mrad
Beam pointing stability	< 100 µrad
M^2 value	≈ 3.5
Power supply	1x650 W

3.2 LIGHT SHEET OPTICS

System's light sheet optics uses a combination of two spherical lenses and one cylindrical divergence lens [19].The arrangement is presented in Figure 3.

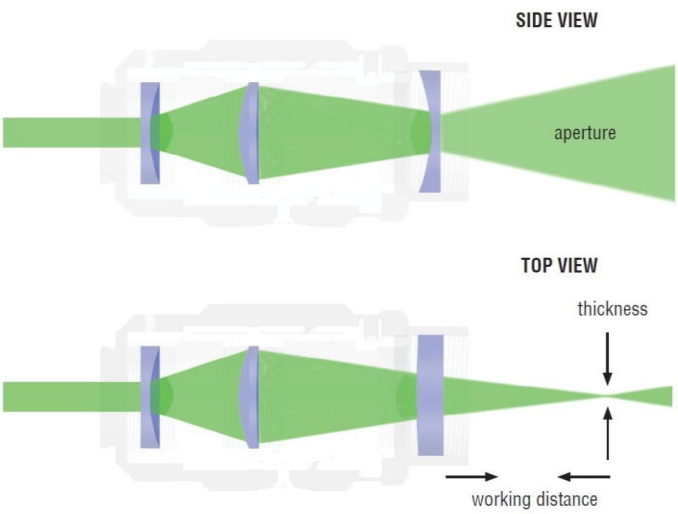

Figure 3. Light sheet optics arrangement of the PIV system.

The appropriate thickness of the light sheet is achieved with the two spherical lenses. The aperture and the height of the light sheet are controlled by the focal length of the divergence lens and the diameter of the laser.

3.3 CAMERAS

The system's cameras are Imager Pro X 4M CCD cameras [20].The camera type has progressive-scan technology with a dual frame-technique for cross correlation. The CCD sensors are cooled with Peltier element to +10°C to reduce background noise. General specifications of the camera are presented in Table 3.

Table 3. General system specifications of Imager Pro X 4M CCD camera

Camera characteristics	Performance value
Double shutter	two images with 115 ns min. interframing time
Dynamic range A/D	14 bit
Number of pixels	2048x2048 pixels
Pixel size	7.4 x 7.4 μm^2
Frame rate	14 frames/s
Camera memory	4 GB
Spectral range	290-1100 nm
Maximum quantum efficiency	yield point 55% at 500 nm
Full well capacity	40000 e-
Size of the camera head	84x66x175 mm^3

3.4 CAMERA ACCESSORIES

For faster use a Camera Link is included in the system. The Camera Link allows a faster download of taken images and they are transferable to a system computer in real time. With remote controlled focus rings the focus and aperture of the camera lenses can be controlled with computer software. Depending on the lens where the remote controlled focus ring is used, the focus can be adjusted in more than 106 steps and the aperture in more than 105 steps. The system has also a remote controlled Scheimpflug mount which allows all areas of the image plane to be in focus. Scheimpflug mount is used in stereo-PIV imaging. Lenses for the cameras are 50 mm in focal length and the luminous intensity (maximum aperture) is 1.4 [21].

3.5 SYSTEM COMPUTER AND SOFTWARE

For collecting PIV recording and other data the equipment has a system computer. The system computer is part of the PIV system whereas data analyzing can be done in separate computers. The system includes three separate "floating" style analysis licenses meaning that analyzing can be done in any three computers at the same time. At the moment the analysis software is, however, implemented only to the system computer. For speeding up analyzing, the system includes three graphics processing units that utilize parallel data processing. Graphics processing units speed up the PIV calculation by factor of ten or more [21].

The system utilizes DaVis software solution for image acquisition and analysis of flow fields in both 2D and 3D cases. DaVis software is written in a fully integrated macro programming language (CL) which is similar in syntax to C++. It allows modifying and adding capabilities of the DaVis software. User can also create completely new macros and add unique and customized functions to the software. DaVis software supports following file types: bmp, jpg, tif, dat, txt and

PostScript. DaVis software also supports data interface to LabView, MathCAD, Matlab, Techplot and common CFD softwares [21].

3.6 POSITIONING OF PIV SYSTEM INTO PPOOLEX

The main purpose of using the PIV system in PPOOLEX is to obtain information about flow fields induced by collapsing steam bubbles during rapid condensation. The test results will be used for validating CFD data obtained with computer simulations. The positioning of the system is important for obtaining the best possible data from the measurements. The ultimate goal in positioning the PIV system is to achieve the best possible lighting conditions. For obtaining the out-of-plane vector component the position arrangement is done with two cameras.

The biggest limitation for fully free positioning of the system is the fact that the PPOOLEX test facility is on one side close to the wall of the laboratory. There is not enough space for the laser and cameras to be mounted between the PPOOLEX and the wall. Due to this only one option of the possible three blowdown pipe positions can be used in the PIV experiments.

3.7 PROBLEMS WITH THE PC CONROLLING THE PIV SYSTEM

Some problems were encountered with the PC used for running the control and measurement programs of the PIV system when the experiments were about to start. The PC was sent to Germany for fault detection and repair. No distinctive reason for the unwanted behavior of the system was found there. The operating system of the PC was reinstalled at LUT, but some problems appeared again when it was tested. Finally some loose wires were found inside the PC and by connecting them the problems disappeared. This episode took several months and the experiments were therefore very much delayed from the original timetable.

4 TEST PROGRAM

An extensive test series on DCC, where the potential of the PIV system and of the new high speed camera for capturing the details of DCC related phenomena can be comprehensively utilized, was to be carried out in the PPOOLEX test facility in 2012. CFD grade data for verification/validation of numerical models were to be recorded. Flow fields in the pool volume and particularly around the blowdown pipe outlet were supposed to be determined.

As explained at the end of the previous chapter the problems with the PC controlling the PIV measurement system wrecked these plans. Due to the limited time left for the experiment series only some tests with water injection and a couple of trials with steam injection could be done.

The arrangement of the cameras and the laser were done in forward-forward-scattering manner to obtain stereo-PIV. Before the tests the calibration plate was mounted with a special device close to the exit mouth of the blowdown pipe. After installing of the calibration plate the PPOOLEX facility was filled with water so that the actual calibration of the system could be performed. For seeding glass hollow spheres were used. Different values for the important PIV parameters were tried during the tests. The used range of the parameters is presented in Table 4.

Table 4. PIV parameters in the tests

Parameter	Value
Seeding particles	Glass hollow spheres
Mean diameter of the seeding particles	11 µm
Density of seeding material	1,10 g/cm^3
Laser sheet thickness	7 mm
Field of view	300x300x7 mm x mm x mm
Frequency between image pairs	1-7 Hz
Time delay between laser pulses	5000-67000 µs
Image pairs for one camera per measurement	50-100
Scheimpflug angle for camera 1	2.5° - 3.0°
Scheimpflug angle for camera 2	-2.0° - -2.5°
Laser pulse energy for laser 1	50 %
Laser pulse energy for laser 2	20-61 %

In the water injection tests the wet well pool was filled with isothermal water (11–14 °C) to the level of ~2.14 m i.e. the blowdown pipe outlet was submerged by ~1.0 m. Water injection through the blowdown pipe was taken directly from the tap in the laboratory. Both cold (~ 11 °C) and warm (~ 54 °C) water was injected. The flow was kept constant during each recorded test.

In the steam injection tests the pool water temperature varied from 15 to 55 °C. The initial water level was ~2.1 m. Steam was generated with the nearby PACTEL facility. The initial air content of the dry well compartment was first blown to the wet well pool with a relatively high steam discharge rate. At the same time the dry well structures heated up. During the actual measurement periods steam flow rate into the PPOOLEX vessel was controlled with the help of the remote-operated control valve in the steam line. The flow rate was kept constant throughout each recorded measurement series. The main parameters of the DCC tests are listed in Table 5.

Table 5. Thermal hydraulic parameters in the DCC tests

Experiment	Water level [m]	Water temperature at pipe outlet elevation [°C]	Water injection [l/min]	Steam injection [g/s]	Comments
DCC-0-test1	2.14	11	24.0 (cold)	-	
DCC-0-test2	2.16	11	24.0 (cold)	-	
DCC-0-test3	2.18	11	13.2 (cold)	-	
DCC-0-test4	2.19	11	23.8 (warm)	-	
DCC-0-test5	2.20	11	23.8 (warm)	-	
DCC-0-test6	2.21	11	13.0 (warm)	-	
DCC-0-test7	2.22	11	13.0 (warm)	-	
DCC-0-test8	2.24	11	13.0 (warm)	-	
DCC-00-test1	2.14	14	24.0 (cold)	-	
DCC-00-test2	2.16	14	13.0 (cold)		
DCC-00-test3	2.17	14	24.0 (warm)		
DCC-00-test4	2.19	14	13.0 (warm)		
DCC-01-test1	2.14	~ 20	-	~ 250	
DCC-01-test2	2.15	~ 21	-	~ 250	
DCC-01-test3	2.17	~ 30	-	~ 400	
DCC-01-test4	2.22	~ 50	-	~ 220	
DCC-01-test5	2.26	~ 52	-	~ 370	
DCC-01-test6	2.28	~ 54	-	~ 160	
DCC-01-test7	2.29	~ 55	-	~ 160	
DCC-02-test1	2.13	~ 15	-	~ 120	
DCC-02-test2	2.14	~ 19	-	~ 75	
DCC-02-test3	2.14	~ 20	-	~ 75	
DCC-02-test4	2.19	~ 32	-	~ 285	

Some observations regarding the suitability of the PIV measurement system for different kind of flow situations can be made on the basis of these tests. However, the full capacity of the system must be determined later on the basis of a more comprehensive experiment series.

5 EXPERIMENT RESULTS

The following chapters present some findings regarding the use of the PIV measurement system during water and steam injection conditions in the PPOOLEX facility.

5.1 INJECTION OF COLD WATER

At first, injection of cold water through the blowdown pipe was performed and the resulting flow fields below the pipe outlet were measured with the PIV system. The flow conditions below the blowdown pipe remained quite constant during the whole injection period and therefore averaging, for example, over 100 velocity field images can be done. In Figure 4 the result of such averaging from a cold water injection case (24.0 l/min) is presented. The reference vector with the value of 0.1 m/s is shown in the top left corner. The background color refers to the out-of-plane velocity component and the scale is on the right side of the figure.

The flow below the blowdown pipe is first downwards but turns towards the outer edge of the blowdown pipe (left and right hand sides) within maximum vertical distance of about 90-100 mm. Very close to the edge of the pipe the flow turns from downwards direction to horizontal and then upwards direction within a distance of about 10 mm. The division line between the left and right direction is close to the center axis of the pipe. The velocities in the averaged image are very small, between 0.001 m/s and 0.01 m/s. Velocities in the direction of the z-axis (out-of-plane component) are also largest just below the pipe exit and are close to zero in the lower half of the image.

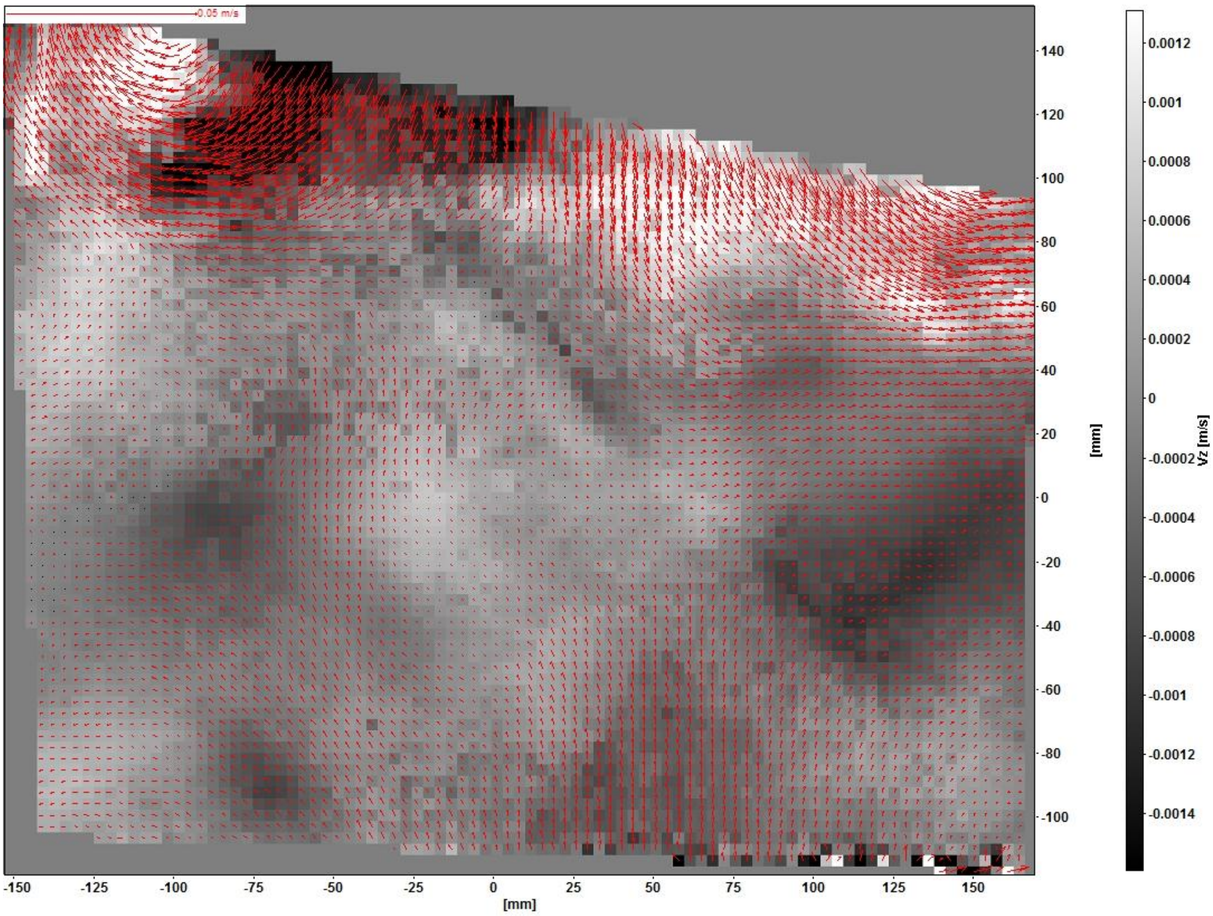

Figure 4. Averaged velocity field image from a cold water injection case.

5.2 INJECTION OF WARM WATER

In the warm water injection cases the pool was filled with 10-14 °C water. The submerged part of the blowdown pipe was either filled with cold (10-14 °C) water or with water in the same temperature as the injected water (54 °C). Figure 5 shows the development of temperature profile inside the blowdown pipe (TC01-TC15) and the temperature below the pipe outlet (T5) during a warm water injection (23.8 l/min) case, where the blowdown pipe was originally filled with cold water.

The PIV results of this case are very much like those of the cold water injection case, because cold water inside the blowdown pipe is barely replaced by injected warm water during the 100 second measurement period. Water flowing out of the pipe exit is therefore at the same temperature as pool water. Only at the end of the measurement period the lowest temperature measurement in the pipe indicates some increase in the temperature of injected water. Due to this the averaged velocity field image is almost a copy of the image from the cold water injection case.

When the blowdown pipe was already totally filled with warm water in the beginning of the measurement period, but the pool water was still at about 11 °C, the situation changed. Water flowing out of the pipe exit was warm from the beginning of the measurement period (Figure 6).

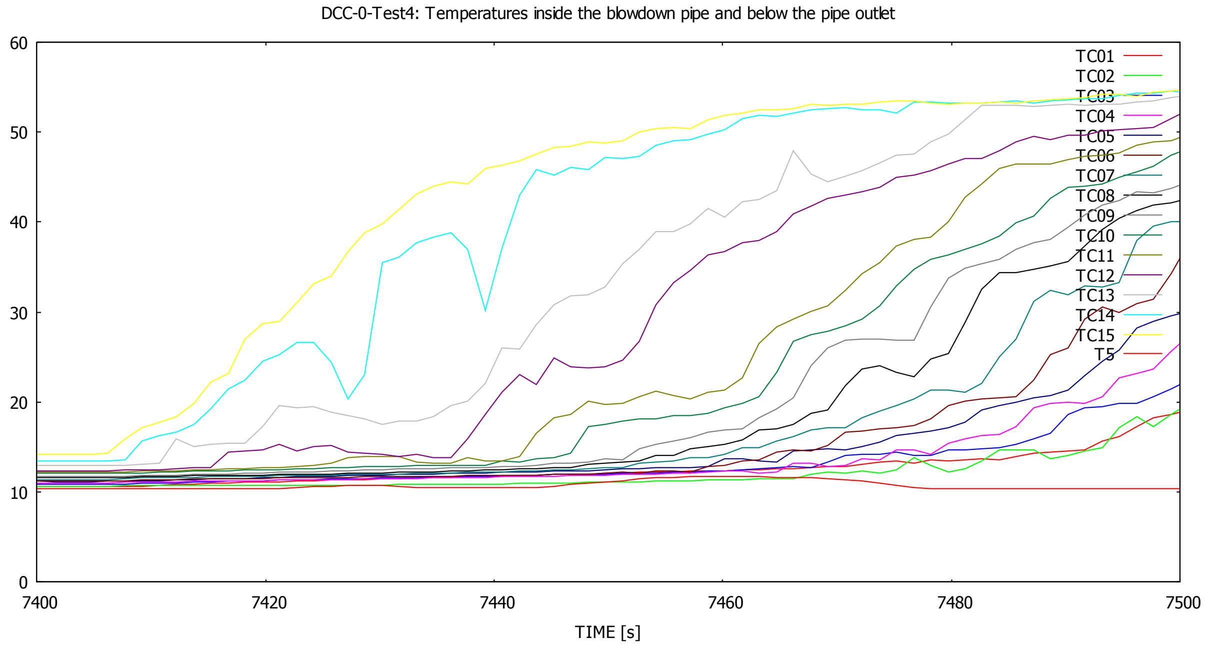

Figure 5. Development of temperature profile inside the blowdown pipe and temperature below the pipe exit when the pipe is originally filled with cold water.

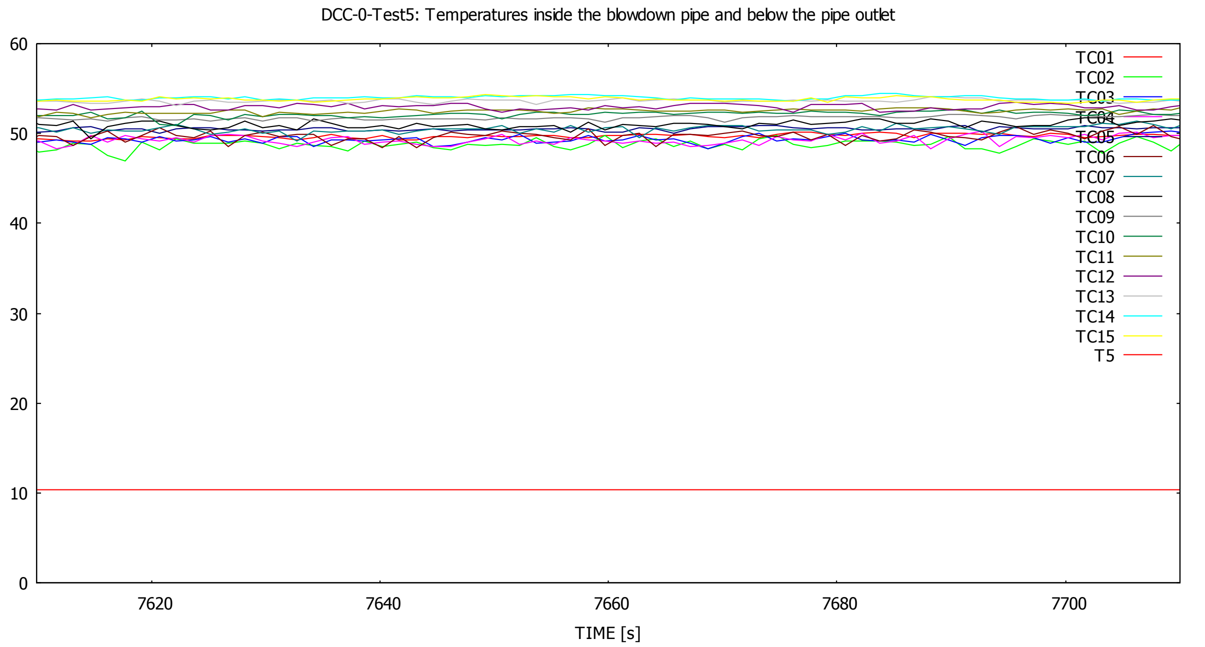

Figure 6. Temperatures in the blowdown pipe (TC01-TC15) and below the pipe outlet (T5) during a warm water injection case where the pipe is already filled with warm water.

The PIV results are different compared to those cases where out flowing water was cold. Again, averaging of the velocity field images can be done since the flow conditions below the pipe outlet don't change too much. Figure 7 presents the obtained averaged velocity field from the case where warm water injection was used and the pipe was initially filled with warm water. The injection rate (23.8 l/min) corresponds to that of the cold water case presented in chapter 5.1.

On the left hand side close to the pipe edge the flow direction seems to be upwards toward the pipe. In the center section the flow direction is towards the outer edge of the pipe. The right hand upper corner is outside the field of view (FOV) and no velocity information is available from there. Therefore it is impossible to determine whether the strongest flow out of the pipe is there or elsewhere (outside the measurement volume covered by the laser sheet). Again the velocities are very small (from 0.001 m/s to 0.01 m/s). In the direction of the z-axis the velocities in the lower half of the image seem to be slightly larger than in the cold water case.

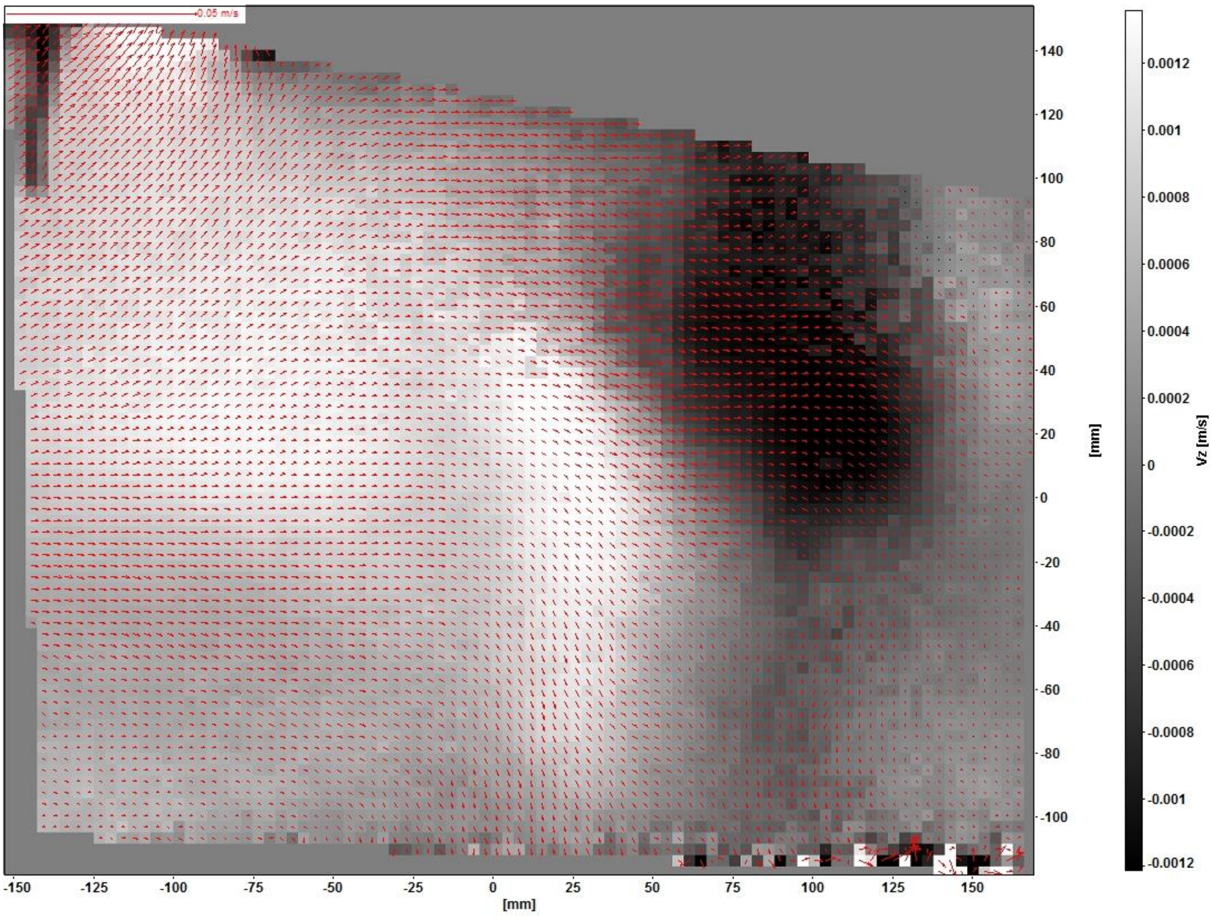

Figure 7. Averaged velocity field image from a warm water injection case where the pipe is originally filled with warm water.

5.3 INJECTION OF STEAM

Steam was injected trough the blowdown pipe with flow rates ranging from about 75 g/s to almost 400 g/s. In the very small flow rate cases the steam/water interface was inside the blowdown pipe and quite stable in nature. With higher flow rates formation and collapse of steam bubbles as well as upwards and downwards movement of the interface in the blowdown pipe could be observed. The dominating condensation modes were then *steam condensation within vents or blowdown pipes* and *chugging* [22].

5.3.1 Small steam flow rate with stable steam/water interface

In the measurements it was found out that there is some fluctuation in the velocity field although the steam/water interface is stable at the exit of the blowdown pipe. Condensation of steam in the vicinity of the pipe exit probably causes these fluctuations. A constant outflow is usually followed by a constant inflow towards the pipe exit. Between these two phases the velocity field is rather stable and the movement is from the centerline of the pipe exit towards the outer edge. In this middle phase the velocities are relatively small compared to the stronger outflow and inflow phases.

Due to the changes in flow direction averaging of the velocity images over the whole measured period is impossible even in this low steam flow rate case. Vector field images corresponding to a certain phase of the experiment could be extracted from the whole series of vector field images and averaged. This would, however, require a very careful analysis of the vector field images so that they could be correctly categorized. In many cases the velocities would either be too small or there would be no continuous pattern in the velocity field. The series of not averaged vector field images in Figure 8 presents how the direction of flow below the blowdown pipe exit changes (from inflow to outflow). There are spurious vectors in the bottom of the vector field images because the lighting conditions aren't sufficient in the bottom part. The most important data from the vicinity of the blowdown pipe is, however, obtained. Also the velocities in the bottom are small or almost non-existent.

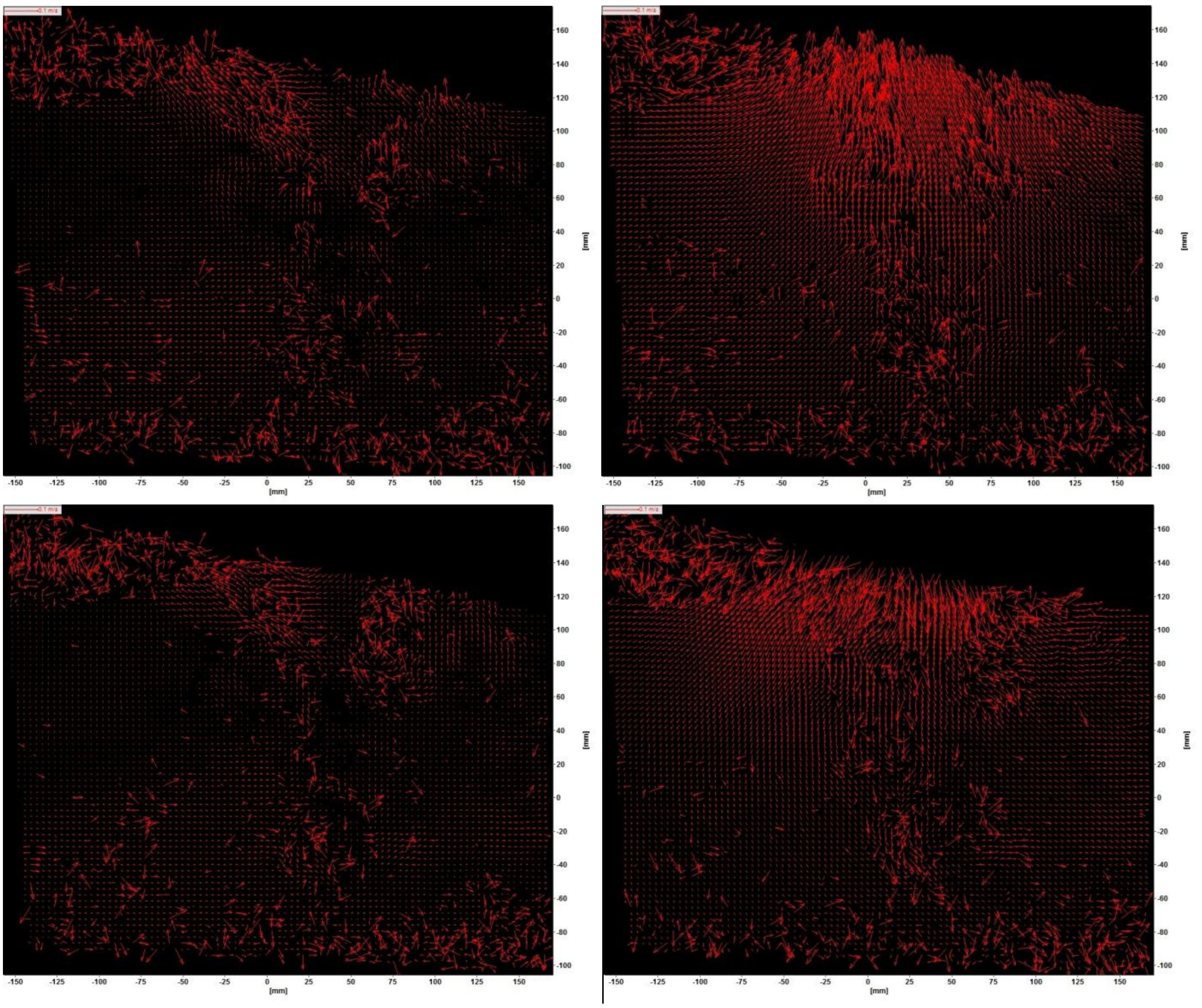

Figure 8. Change of flow direction from inflow to outflow in the stable interface case.

5.3.2 High flow rate with bubble formation and rapid condensation

In the higher steam flow rate cases round and toroidal steam bubbles form at the blowdown pipe outlet and then break up or collapse rapidly causing a strong backflow of pool water into the pipe. As a result the steam/water interface first moves upwards in the blowdown pipe and then again downwards to begin a new cycle (Figure 9). This oscillatory up and down motion of the interface inside the pipe is typical for the chugging condensation mode.

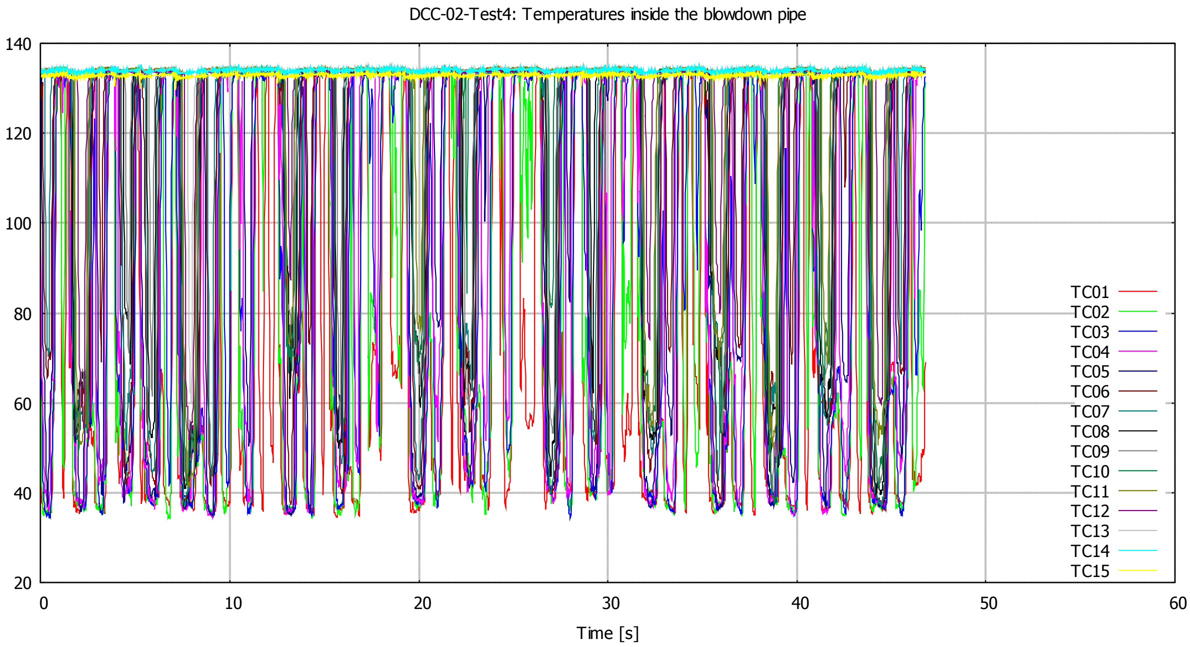

Figure 9. Movement of steam/water interface inside the blowdown pipe in a high steam flow rate test as registered by thermocouples in the pipe along a length of 1 m upwards from the outlet.

The rapid condensation process creates small non-condensable gas (and uncondensed steam) bubbles which stay at the vicinity of the blowdown pipe outlet for some time. When these small bubbles are in front of the measurement area of the PIV system they cause severe problems. The bubbles reflect laser light like seeding particles and disturb the PIV measurement system because it can’t distinguish the bubbles and seeding particles from each other. Therefore images taken from the measurement area can’t be interpreted correctly and reliable results can’t be obtained. Figure 10 shows a poor quality raw image from a high steam flow rate case (on the left) and a good quality raw image from a low steam flow rate (stable steam/water interface) case (on the right).

It is important to use the maximum aperture for the cameras to obtain a depth-of-field thickness close to the laser sheet thickness. As a result the depth-of-field is shallow and all the bubbles in front of it become blurry. Thus small bubbles in front of the laser sheet are big in size and almost completely fill a single interrogation window which mixes up the vector field analytics. Obtaining vector fields from such situations is nearly impossible.

If fluorescent particles and long-pass filters for cameras are used all laser light can be cut out. This will eliminate, in principle, all the reflections out of the bubbles. Using fluorescent particles and long-pass filters might solve this problem but this needs to be studied more in future. In addition, every bubble in the laser sheet creates a tracer particle free volume in the field-of-view. This phenomenon will be studied also more when preliminary testing of the long-pass filters begins. Measuring bubbly flows with PIV is challenging in any case. Fluctuations of the flow are also problematic as they make averaging series of vector field images difficult.

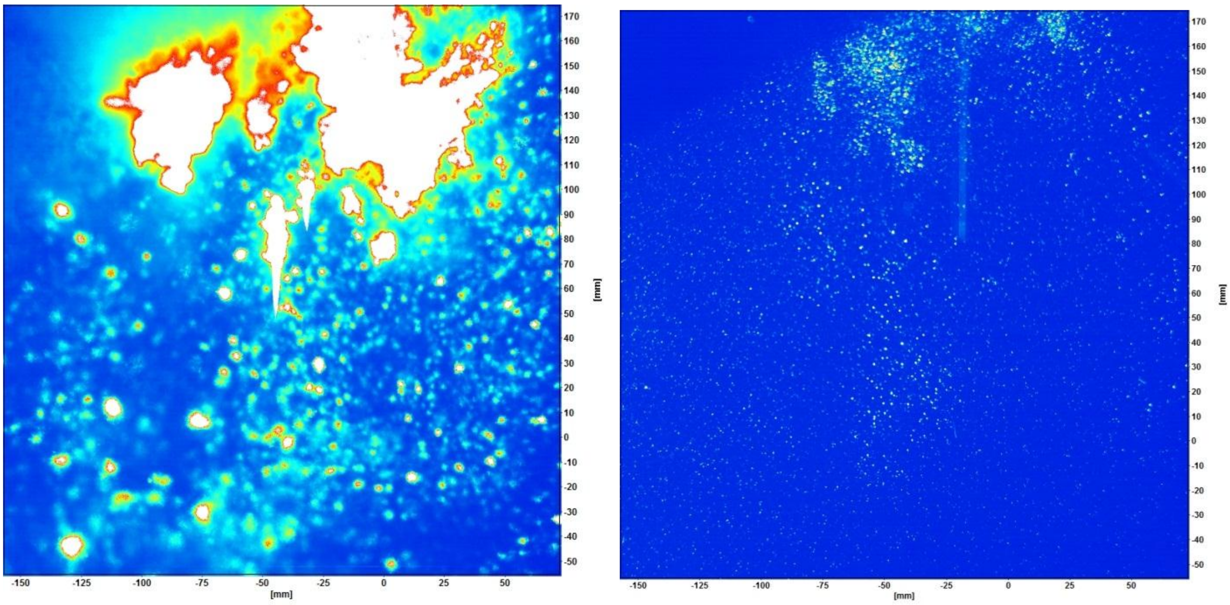

Figure 10. Poor and high quality raw images from steam injection tests with different flow rates.

The above said is true for the immediate vicinity of the blowdown pipe outlet where most of the small bubbles are. In forthcoming experiments the measurement area of the PIV system could be selected from further down where the fraction of disturbing bubbles is smaller but valuable information of flow velocities associated with the formation and collapse of large steam bubbles at the blowdown pipe exit could still be obtained. Furthermore, the use of laser-induced fluorescence (LIF) seeding particles with appropriate camera filters could improve the situation even more.

Another option would be to try to measure velocity fields above the blowdown pipe outlet elevation and close to the outer surface of the pipe. These could be of interest in the small steam flow rate cases where a film or tongue of warm water spreads upwards along the pipe outer wall.

6 SUMMARY AND CONCLUSIONS

This report summarizes the findings of the PIV measurement tests carried out in January – February 2013 with the scaled down PPOOLEX test facility designed and constructed at Lappeenranta University of Technology. The tests could not be done according to the original timetable because severe problems with the PC controlling the PIV measurement system were encountered. The problems were solved only at the end of 2012 and therefore the tests had to be carried out quite fast with somewhat reduced objectives.

The test facility is a closed stainless steel vessel divided into two compartments, dry well and wet well. Between the compartments there is vertical blowdown pipe. The PIV measurement system was acquired for determining flow fields at the blowdown pipe outlet during water/gas/steam injection.

The main objective of the tests was to find the operational limits for the PIV system regarding suitable test conditions and correct values of different adjustable parameters of the system. An additional objective was to gather CFD grade data for verification/validation of numerical models.

In the water injection tests the wet well pool was filled with isothermal water (11–14 °C) to the level of ~2.14 m i.e. the blowdown pipe outlet was submerged by ~1.0 m. Both cold (~ 11 °C) and warm (~ 54 °C) water was injected. The flow was kept constant during each recorded test.

In the steam injection tests the pool water temperature varied from 15 to 55 °C. The initial water level was again ~2.1 m. Steam was generated with the nearby PACTEL facility. The initial air content of the dry well compartment was first blown to the wet well pool. During the actual measurement periods steam flow rate was kept constant with the help of the remote-operated control valve in the steam line.

The PIV measurements with cold water injection succeeded well. The raw images are of high quality, averaging over the whole measurement period can be done and the flow fields close to the blowdown pipe outlet can be determined. Examination of the velocity field images reveals that there are large distinctive areas where the flow is mainly either downwards, upwards or sideways.

Also in the warm water injection cases averaging of the velocity field images can be done since the flow conditions below the pipe outlet don’t change too much during the test. When also the blowdown pipe is filled with warm water in the beginning of the measurement period the obtained averaged velocity field images are harder to interpret. The absolute values of the velocity vectors are smaller than in the cold water injection case and there seems to be no such large areas where the velocity vectors would clearly point to one direction only.

In the steam injection cases with very small flow rate the steam/water interface was inside the blowdown pipe and quite stable in nature. The raw images are of good quality but due to some fluctuation in the velocity field averaging of the velocity images over the whole measured period can’t be done. Condensation of steam in the vicinity of the pipe exit probably causes these fluctuations. A constant outflow is usually followed by a constant inflow towards the pipe exit. Between these two phases the velocity field is rather stable and the movement is from the centerline of the pipe exit towards the outer edge. Vector field images corresponding to a certain phase of the experiment could be extracted and averaged but this would require a very careful analysis so that the images would be correctly categorized.

With higher steam flow rates formation and collapse of steam bubbles as well as upwards and downwards movement of the interface in the blowdown pipe can be observed. The rapid condensation process creates small gas bubbles (steam and non-condensable gas) which stay at the vicinity of the blowdown pipe outlet for some time. When these small bubbles are in front of the measurement area of the PIV system they disturb the measurements by reflecting laser light like seeding particles. Sometimes the outer edge of the blowdown pipe also causes a reflection which is not profitable for PIV processing. Due to the above mentioned reasons the raw images of the higher flow rate cases are of poor quality and they can’t be processed and interpreted correctly.

In forthcoming experiments the measurement area of the PIV system could be selected from further down where the fraction of disturbing bubbles is smaller but valuable information of flow velocities could still be obtained. Furthermore, the use of laser-induced fluorescence with appropriate camera filters could improve the situation even more. With such arrangements PIV measurements of high steam flow rate experiments might be successful.

Experiments in the PPOOLEX facility form a very challenging environment for the use of the PIV measurement system. Some observations regarding the suitability of the system for different kind of flow situations can be made on the basis of the tests reported here. However, the full capacity of the system must be determined later on the basis of a more comprehensive experiment series.

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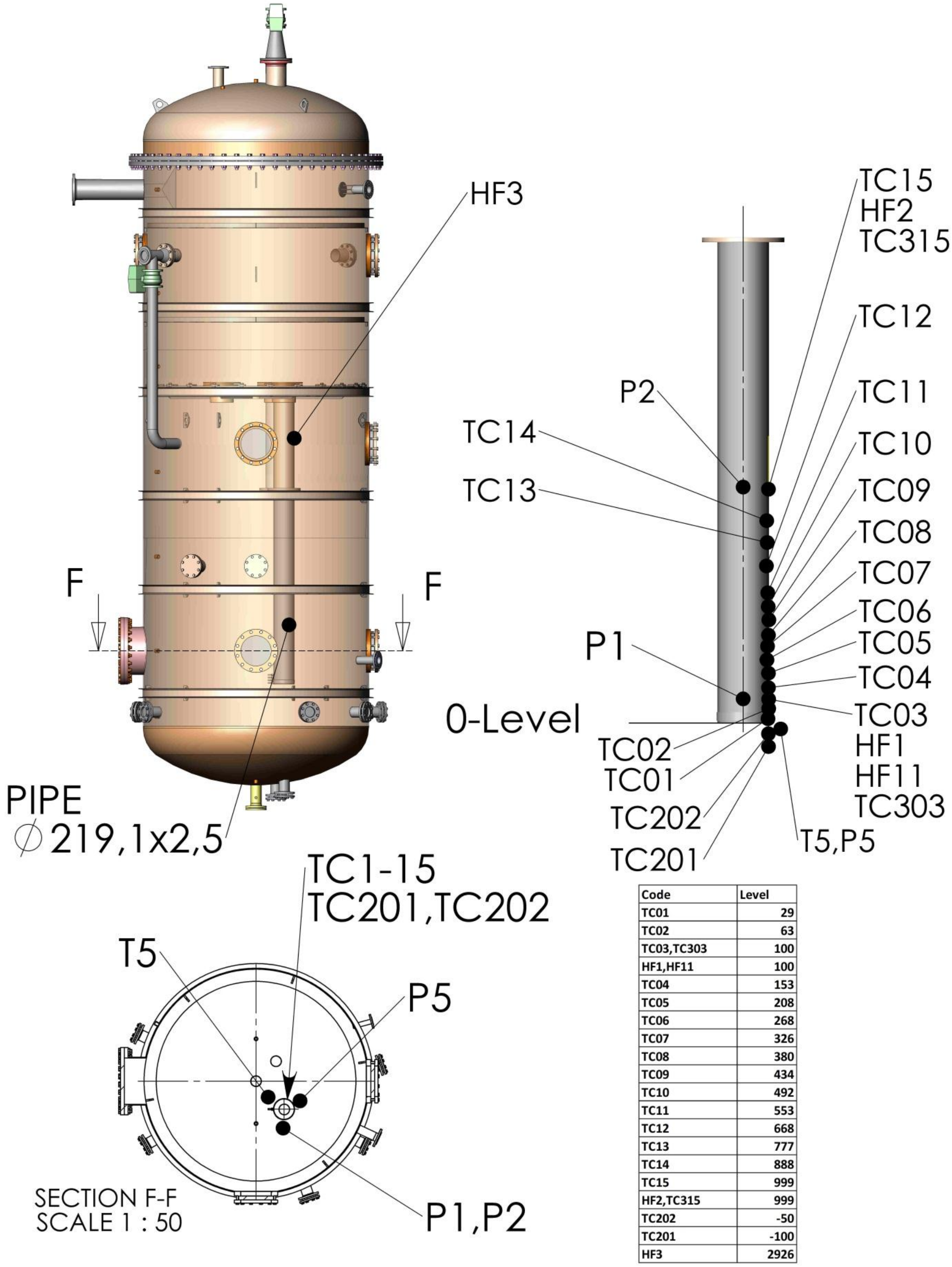
APPENDIX 1: PPOOLEX INSTRUMENTATION



Code	Level
TC01	29
TC02	63
TC03,TC303	100
HF1,HF11	100
TC04	153
TC05	208
TC06	268
TC07	326
TC08	380
TC09	434
TC10	492
TC11	553
TC12	668
TC13	777
TC14	888
TC15	999
HF2,TC315	999
TC202	-50
TC201	-100
HF3	2926

Blowdown pipe measurements.

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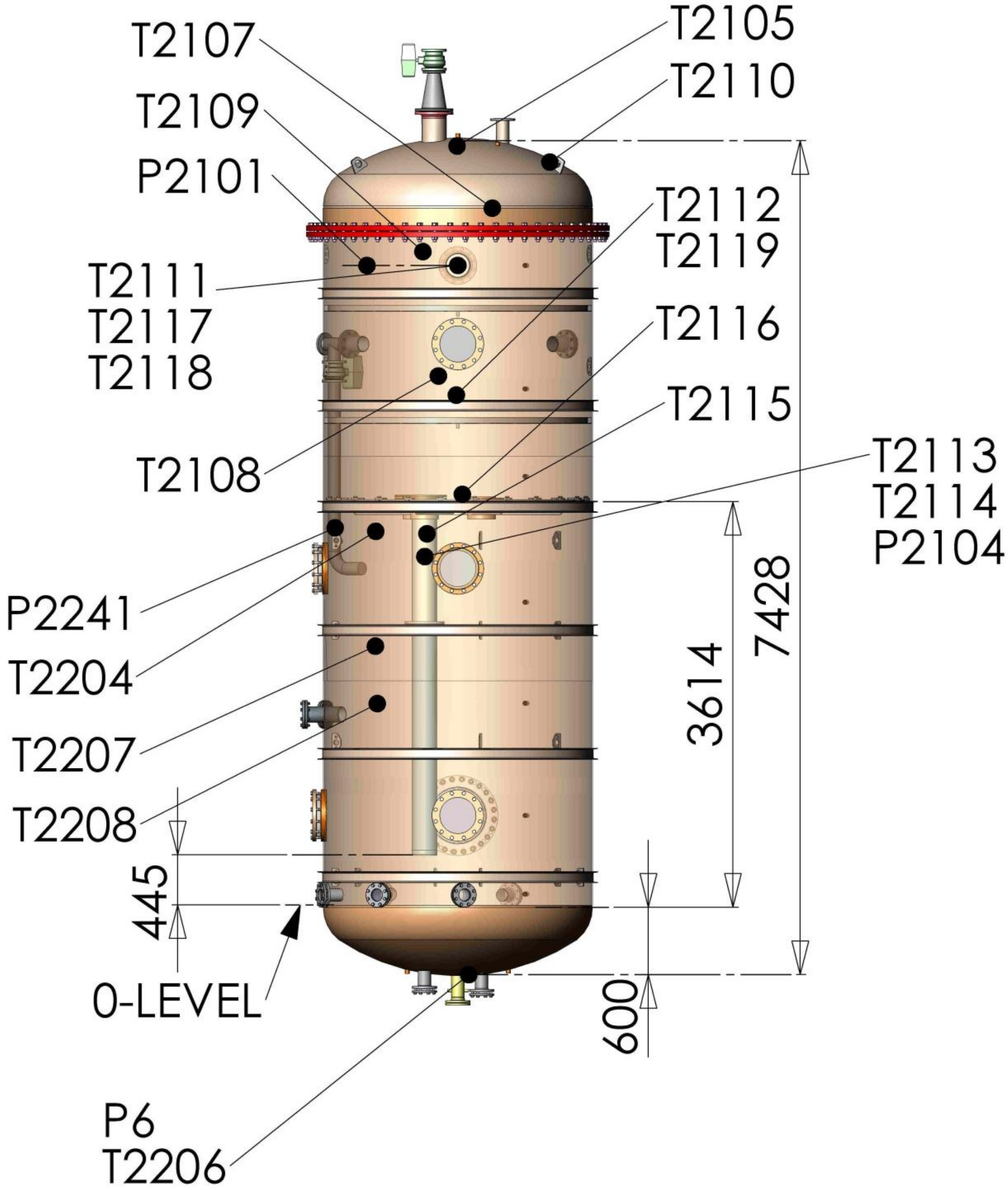
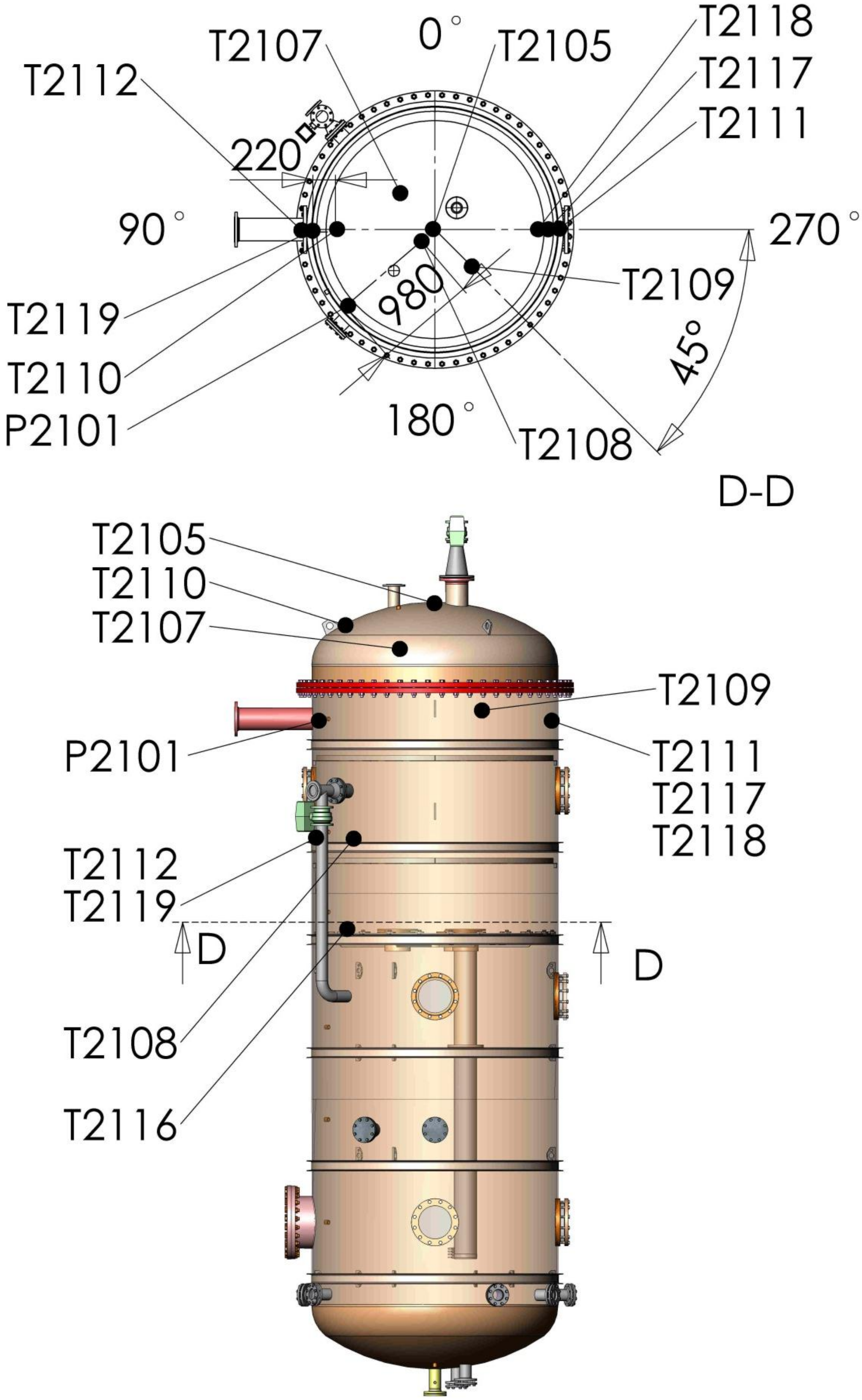
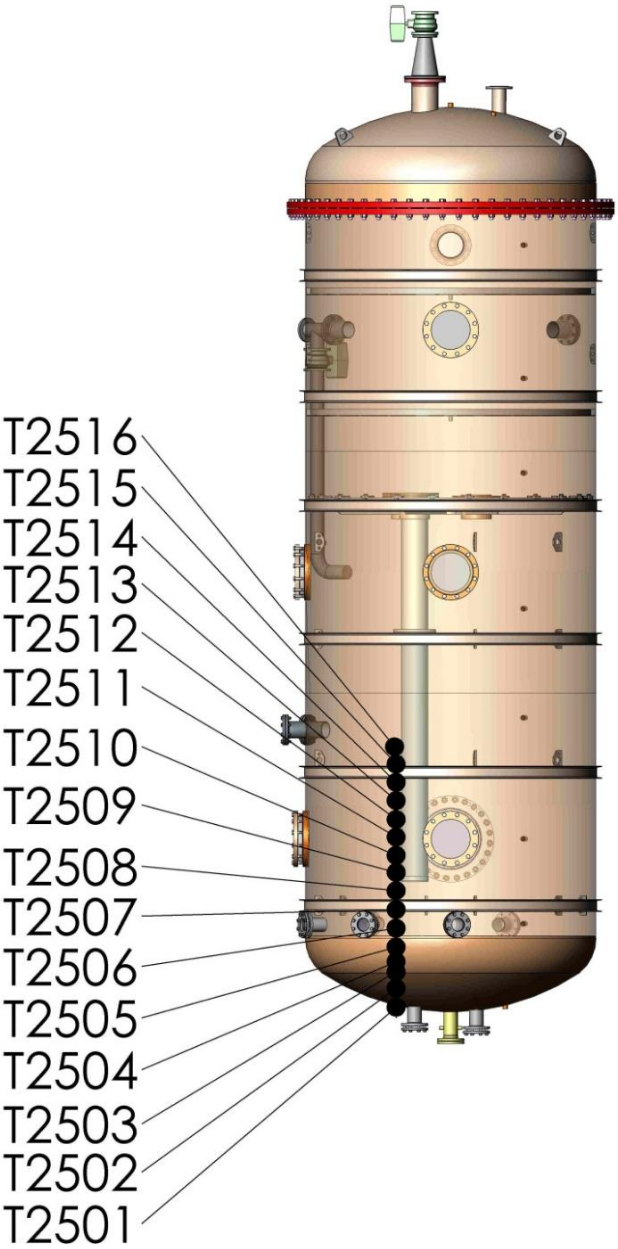


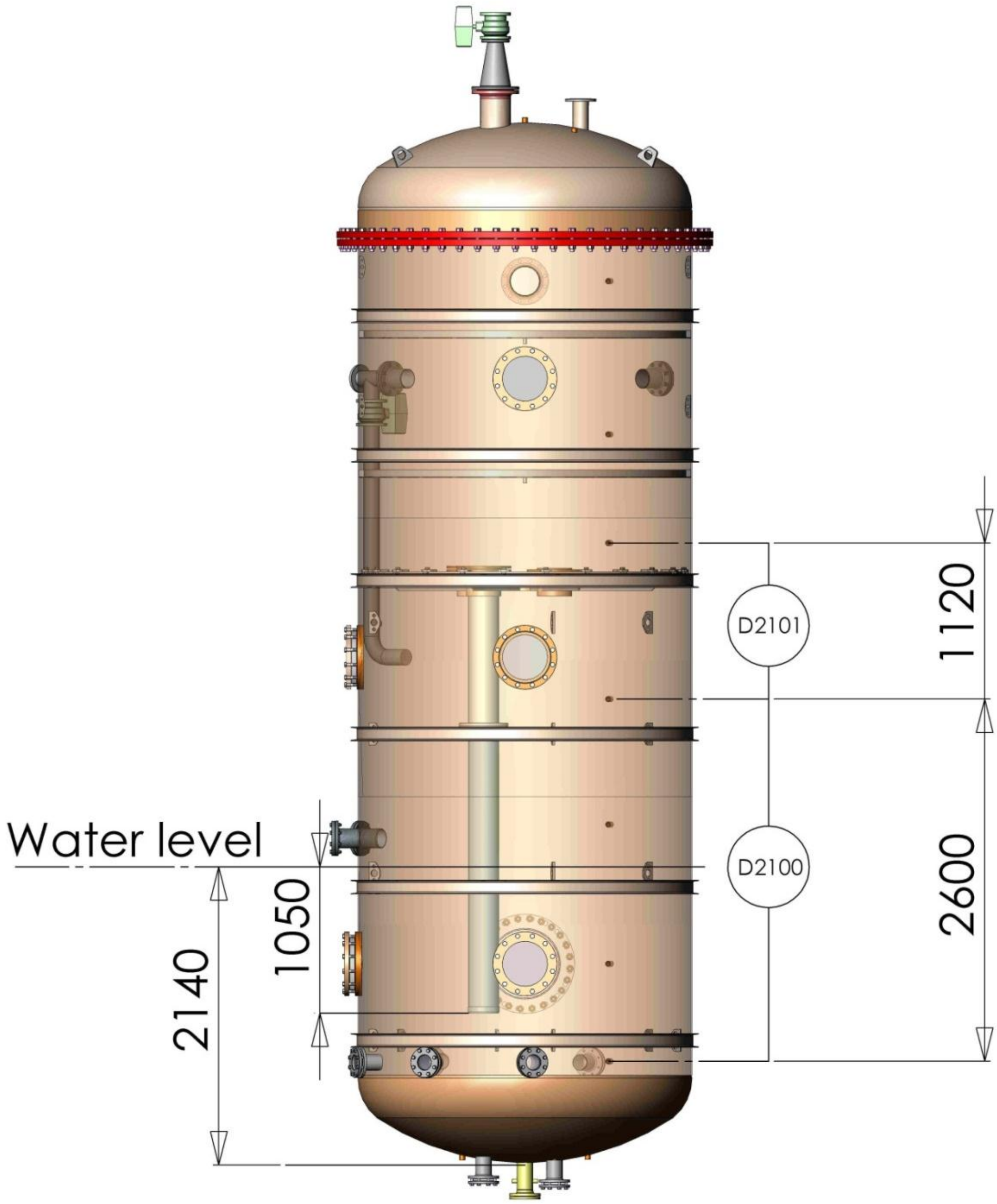
Test vessel measurements.



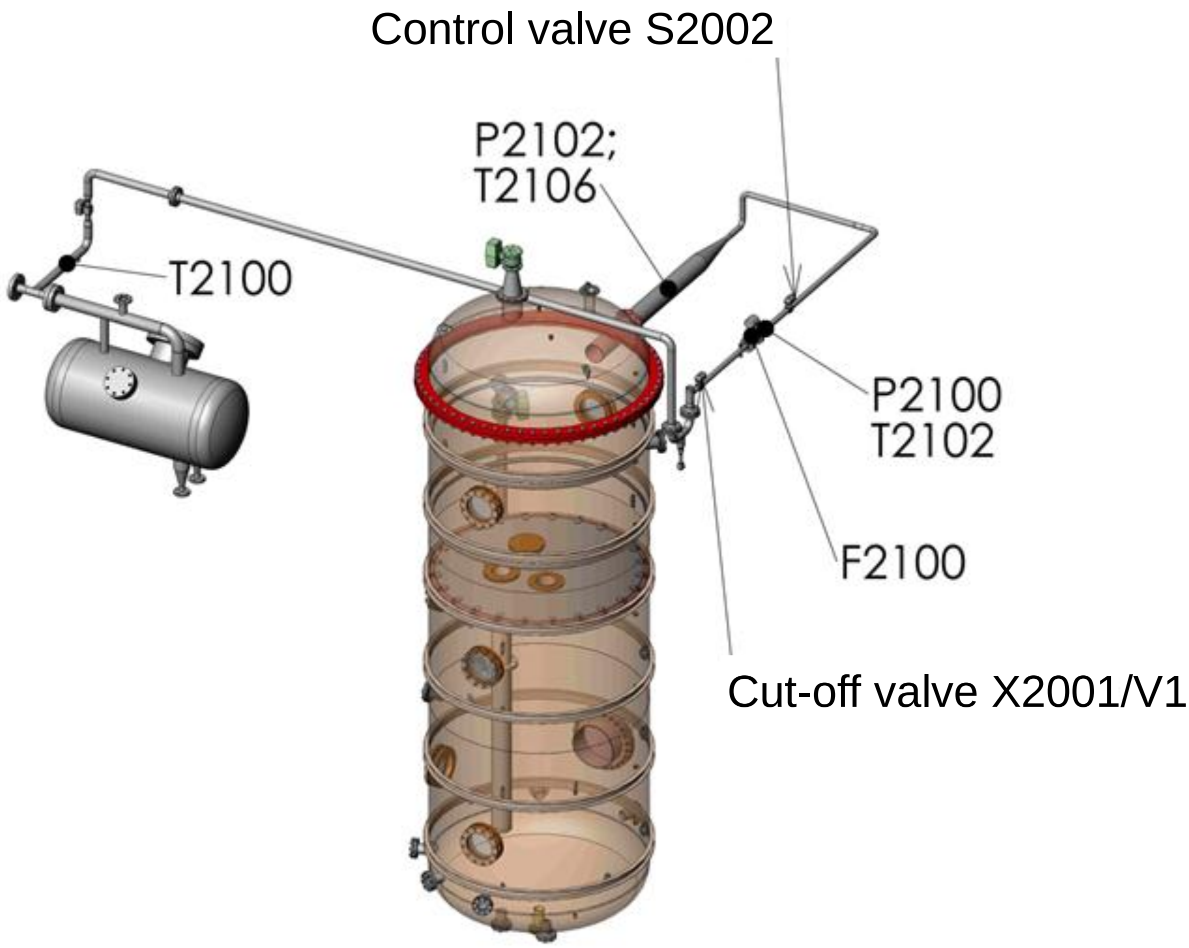
Dry well measurements.



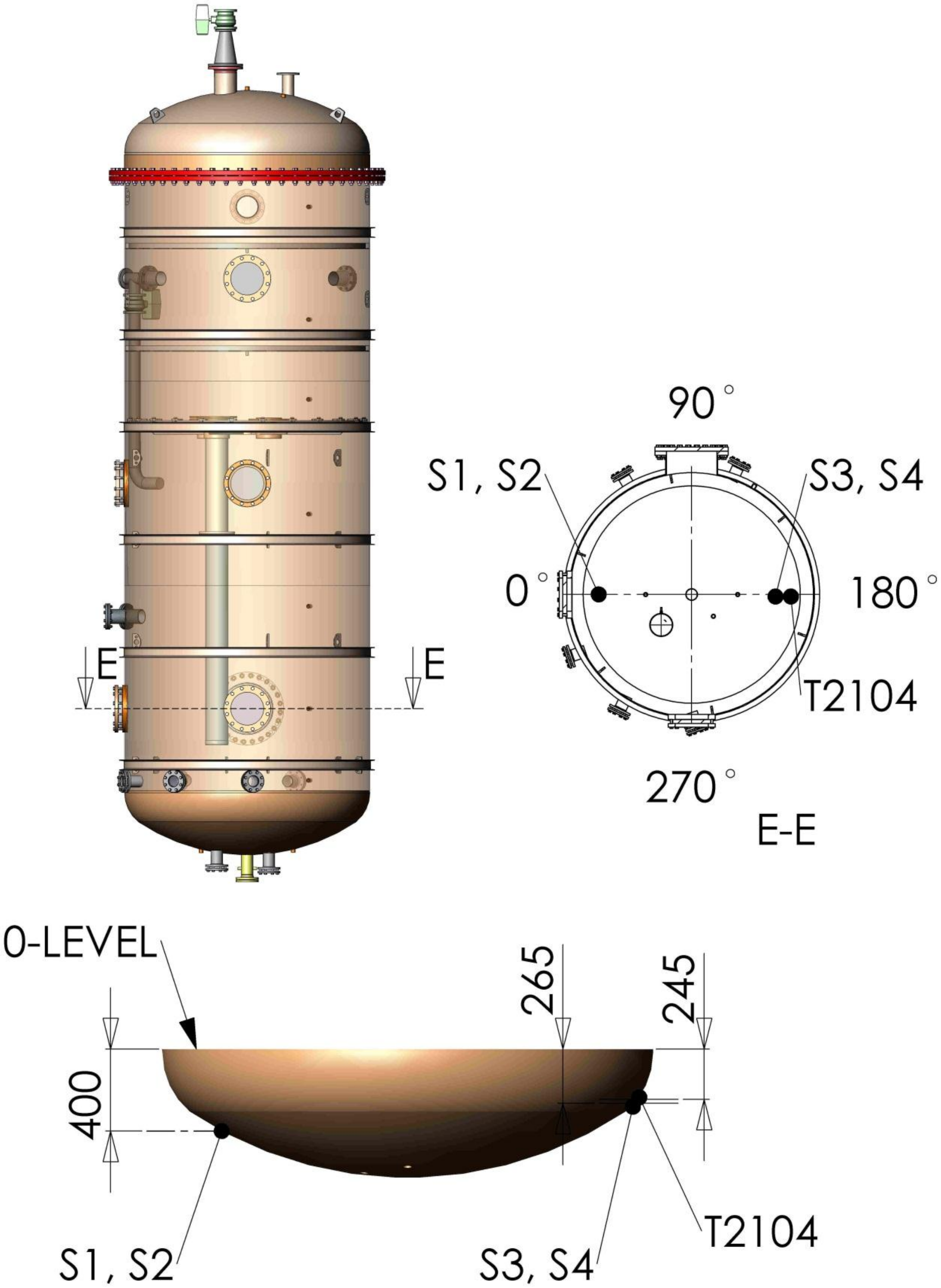
Temperature measurements in the wet well pool for the detection of possible thermal stratification.



Pressure difference measurements in the test vessel. Nominal water level is 2.14 m.



Steam line measurements.



Strain gauges and thermocouple T2104 on the outer wall of the pool bottom.

Measurement	Code	Elevation	Location	Error estimation	Measurement software
Camera trigger	C1	-	Wet well	Not defined	LabView
Pressure difference	D2100	100–2700	Wet well	±0.06 m	FieldPoint
Pressure difference	D2101	2700–3820	Across the floor	±0.09 bar	FieldPoint
Heat flux	HF1	545	Blowdown pipe	Not defined	LabView
Heat flux	HF2	1444	Blowdown pipe	Not defined	LabView
Heat flux	HF3	3400	Blowdown pipe	Not defined	LabView
Heat flux	HF11	545	Blowdown pipe	Not defined	LabView
Flow rate	F2100	-	Steam line	±4.9 l/s	FieldPoint
Pressure	P1	545	Blowdown pipe	±0.7 bar	LabView
Pressure	P2	1445	Blowdown pipe	±0.7 bar	LabView
Pressure	P5	395	Blowdown pipe outlet	±0.7 bar	LabView
Pressure	P6	-615	Wet well bottom	±0.5 bar	LabView
Pressure	P2100	-	Steam line	±0.5 bar	FieldPoint
Pressure	P2101	5700	Dry well	±0.06 bar	FieldPoint
Pressure	P2102	-	Inlet plenum	±0.06 bar	FieldPoint
Pressure	P2104	3400	Blowdown pipe	±0.06 bar	FieldPoint
Pressure	P2241	3600	Wet well gas space	±0.1 bar	FieldPoint
Control valve position	S0035/ S2002	-	Steam line	Not defined	FieldPoint
Strain	S1	-400	Bottom segment	Not defined	LabView
Strain	S2	-400	Bottom segment	Not defined	LabView
Strain	S3	-265	Bottom segment	Not defined	LabView
Strain	S4	-265	Bottom segment	Not defined	LabView
Temperature	T5	395	Blowdown pipe outlet	±1.8 °C	LabView
Temperature	T1279	-3860	Laboratory	±1.8 °C	FieldPoint
Temperature	T1280	-1860	Laboratory	±1.8 °C	FieldPoint
Temperature	T1281	140	Laboratory	±1.8 °C	FieldPoint
Temperature	T1282	2140	Laboratory	±1.8 °C	FieldPoint
Temperature	T1283	4140	Laboratory	±1.8 °C	FieldPoint
Temperature	T1284	6140	Laboratory	±1.8 °C	FieldPoint
Temperature	T1285	8140	Laboratory	±1.8 °C	FieldPoint
Temperature	T2100	-	Steam line beginning	±3.5 °C	FieldPoint
Temperature	T2102	-	Steam line	±3.5 °C	FieldPoint
Temperature	T2104	-245	Wet well outer wall	±1.8 °C	FieldPoint
Temperature	T2105	6780	Dry well top	±1.8 °C	FieldPoint
Temperature	T2106	-	Inlet plenum	±1.8 °C	FieldPoint
Temperature	T2107	6085	Dry well middle	±1.8 °C	FieldPoint
Temperature	T2108	4600	Dry well bottom	±1.8 °C	FieldPoint
Temperature	T2109	5790	Dry well lower middle	±1.8 °C	FieldPoint
Temperature	T2110	6550	Dry well outer wall	±1.8 °C	FieldPoint
Temperature	T2111	5700	Dry well outer wall	±1.8 °C	FieldPoint
Temperature	T2112	4600	Dry well outer wall	±1.8 °C	FieldPoint
Temperature	T2113	3400	Blowdown pipe	±1.8 °C	LabView
Temperature	T2114	3400	Blowdown pipe	±1.8 °C	FieldPoint
Temperature	T2115	3550	Blowdown pipe	±1.8 °C	FieldPoint
Temperature	T2116	3600	Dry well floor	±1.8 °C	FieldPoint
Temperature	T2117	5700	Dry well inner wall	±1.8 °C	FieldPoint
Temperature	T2118	5700	Dry well, 10 mm from the wall	±1.8 °C	FieldPoint

Temperature	T2119	4600	Dry well inner wall	±1.8 °C	FieldPoint
Temperature	T2204	3410	Wet well gas space	±1.8 °C	FieldPoint
Temperature	T2206	-615	Wet well bottom	±1.8 °C	FieldPoint
Temperature	T2207	2585	Wet well gas space	±1.8 °C	FieldPoint
Temperature	T2208	1760	Wet well gas space	±1.8 °C	FieldPoint
Temperature	T2501	-530	Wet well	±1.8 °C	FieldPoint
Temperature	T2502	-390	Wet well	±1.8 °C	FieldPoint
Temperature	T2503	-260	Wet well	±1.8 °C	FieldPoint
Temperature	T2504	-125	Wet well	±1.8 °C	FieldPoint
Temperature	T2505	10	Wet well	±1.8 °C	FieldPoint
Temperature	T2506	150	Wet well	±1.8 °C	FieldPoint
Temperature	T2507	287	Wet well	±1.8 °C	FieldPoint
Temperature	T2508	427	Wet well	±1.8 °C	FieldPoint
Temperature	T2509	560	Wet well	±1.8 °C	FieldPoint
Temperature	T2510	695	Wet well	±1.8 °C	FieldPoint
Temperature	T2511	830	Wet well	±1.8 °C	FieldPoint
Temperature	T2512	965	Wet well	±1.8 °C	FieldPoint
Temperature	T2513	1103	Wet well	±1.8 °C	FieldPoint
Temperature	T2514	1236	Wet well	±1.8 °C	FieldPoint
Temperature	T2515	1369	Wet well	±1.8 °C	FieldPoint
Temperature	T2516	1505	Wet well	±1.8 °C	FieldPoint
Temperature	TC01	474	Blowdown pipe	±1.8 °C	LabView
Temperature	TC02	508	Blowdown pipe	±1.8 °C	LabView
Temperature	TC03	545	Blowdown pipe	±1.8 °C	LabView
Temperature	TC04	598	Blowdown pipe	±1.8 °C	LabView
Temperature	TC05	653	Blowdown pipe	±1.8 °C	LabView
Temperature	TC06	713	Blowdown pipe	±1.8 °C	LabView
Temperature	TC07	771	Blowdown pipe	±1.8 °C	LabView
Temperature	TC08	825	Blowdown pipe	±1.8 °C	LabView
Temperature	TC09	879	Blowdown pipe	±1.8 °C	LabView
Temperature	TC10	937	Blowdown pipe	±1.8 °C	LabView
Temperature	TC11	998	Blowdown pipe	±1.8 °C	LabView
Temperature	TC12	1113	Blowdown pipe	±1.8 °C	LabView
Temperature	TC13	1222	Blowdown pipe	±1.8 °C	LabView
Temperature	TC14	1333	Blowdown pipe	±1.8 °C	LabView
Temperature	TC15	1444	Blowdown pipe	±1.8 °C	LabView
Temperature	TC201	-100	Below blowdown pipe	±1.8 °C	LabView
Temperature	TC202	-50	Below blowdown pipe	±1.8 °C	LabView
Temperature	TC303	545	Blowdown pipe outer surface	±1.8 °C	LabView
Temperature	TC315	1444	Blowdown pipe outer surface	±1.8 °C	LabView
Cut-off valve position	V1	-	Steam line	Not defined	LabView
Cut-off valve position	X2100	-	Steam line	Not defined	FieldPoint
Steam partial pressure	X2102	4600	Dry well	Not defined	FieldPoint

Measurements of the PPOOLEX facility in the DCC test series.

APPENDIX 2: PPOOLEX TEST FACILITY PHOTOGRAPHS

Mineral wool insulated dry well compartment and steam line.

PIV system camera installed outside the purpose-built viewing window of the PPOOLEX facility.

Title	PIV MEASUREMENTS AT THE BLOWDOWN PIPE OUTLET
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Abstract

This report summarizes the findings of the PIV measurement tests carried out in January – February 2013 with the scaled down PPOOLEX test facility at LUT. The main objective of the tests was to find out the operational limits of the PIV system regarding suitable test conditions and correct values of different adjustable PIV parameters. An additional objective was to gather CFD grade data for verification/validation of numerical models. Both water and steam injection tests were carried out. PIV measurements with cold water injection succeeded well. Raw images were of high quality, averaging over the whole measurement period could be done and flow fields close to the blowdown pipe outlet could be determined. In the warm water injection cases the obtained averaged velocity field images were harder to interpret, especially if the blowdown pipe was also filled with warm water in the beginning of the measurement period. The absolute values of the velocity vectors seemed to be smaller than in the cold water injection cases. With very small steam flow rates the steam/water interface was inside the blowdown pipe and quite stable in nature. The raw images were of good quality but due to some fluctuation in the velocity field averaging of the velocity images over the whole measured period couldn't be done. Condensation of steam in the vicinity of the pipe exit probably caused these fluctuations. A constant outflow was usually followed by a constant inflow towards the pipe exit. Vector field images corresponding to a certain phase of the test could be extracted and averaged but this would require a very careful analysis so that the images could be correctly categorized. With higher steam flow rates rapid condensation of large steam bubbles created small gas bubbles which were in front of the measurement area of the PIV system. They disturbed the measurements by reflecting laser light like seeding particles and therefore the raw images were of poor quality and they couldn't be processed correctly. Experiments in the PPOOLEX facility form a very challenging environment for the use of the PIV measurement system. Some observations regarding the suitability of the system for different kind of flow situations can be made on the basis of the tests reported here. However, the full capacity of the system must be determined later on the basis of a more comprehensive experiment series

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

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