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CFD Simulation of Air Discharge Tests in the PPOOLEX Facility

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Key words

condensation pool, air discharge, non-condensable gas, CFD simulation

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PREFACE

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

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

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

CONTENTS

NOMENCLATURE

A	area
c_p	specific heat capacity at constant pressure
D_h	hydraulic diameter
F	flow rate
g	acceleration of gravity
G	mass flux
I	turbulence intensity
k	turbulence kinetic energy
P	pressure
q_m	mass flow rate
S	strain
T	temperature
T_{tot}	total temperature
Z	vertical movement

Greek symbols

α	volume fraction
ε	turbulence dissipation rate
λ	thermal conductivity
μ	dynamic viscosity
ρ	density

Abbreviations

AVI	audio video interleave
BWR	boiling water reactor
CCTV	closed circuit television
CFD	computational fluid dynamics
CHAR	characterizing experiment
CONDEX	condensation experiments with PPOOLEX facility project
DCC	direct contact condensation
ECCS	emergency core cooling system
FINNUS	Finnish Research Programme on Nuclear Power Plant Safety
fps	frames per second
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 test facility, condensation pool experiments project
PPOOLEX	containment test facility
PWR	pressurized water reactor

RAM	random access memory
SAFIR	Safety of Nuclear Power Plants – Finnish National Research Program
SAFIR2010	The Finnish Research Programme on Nuclear Power Plant Safety 2007 – 2010
SIMPLEC	Semi-Implicit Method for Pressure-Linked Equations, Consistent
TVO	Teollisuuden Voima Oy
UDF	user defined function
USB	universal serial bus
VOF	Volume of Fluid
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 drywell to the condensation pool through the blowdown pipes in the Olkiluoto type BWRs. 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.

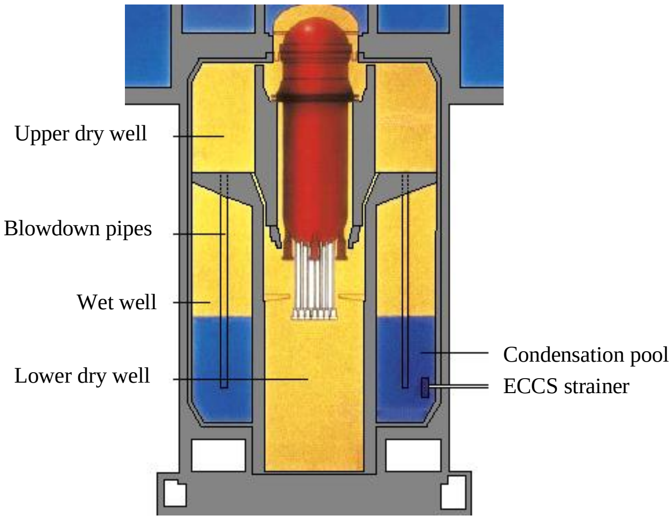


Figure 1. Schematic of the Olkiluoto type BWR containment.

The main objective of the CONDEX project is to increase the understanding of different phenomena inside the dry well and wet well compartments of a BWR containment during a steam line break accident. These phenomena could be connected to bubble dynamics issues, thermal stratification and mixing, wall condensation, interaction of parallel blowdown pipes etc. Steam bubbles interact with pool water by heat transfer, condensation and momentum exchange via buoyancy and drag forces. Pressure oscillations due to rapid condensation occur frequently. The investigation of the gas/steam injection phenomenon requires high-grade measuring techniques. For example, to estimate the loads on the pool structures by condensation pressure oscillations the frequency and the amplitude of the oscillations have to be measured. Experience of needed and suitable instrumentation, data acquisition and visualization equipment was achieved already during the preceding projects dealing with condensation pool issues.

Experiment results of the CONDEX project can be used for the validation of different numerical methods for simulating gas/steam injection through a blowdown pipe into liquid. Experimental studies on the process of formation, detachment and break-up and the simultaneous direct contact condensation (DCC) of large steam bubbles as well as on the stratification and mixing phenomena in the pool are still sparse. However, the improvement of models is necessary for the reduction of uncertainties in predicting containment behaviour during gas/steam injection. 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.

The development work of 3D two-phase flow models for CFD codes can be assisted by the CONDEX 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, 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 were started in 2007 by running a series of characterizing tests. Two of these tests were selected to be modelled with the Fluent CFD code. In this report, the results of those CFD simulations 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. Chapter three presents the tests selected for simulation shortly. The simulation model is introduced in chapter four. The simulation results are presented and shortly discussed in chapter five. Chapter six summarizes the findings of the simulation exercise.

2 PPOOLEX TEST FACILITY

Condensation studies at LUT started with an open cylindrical pool test facility (POOLEX) modeling the suppression pool of the BWR containment. During the years 2002-2006, the facility had several modifications and enhancements as well as improvements of instrumentation before it was replaced with a more versatile PPOOLEX facility in the end of 2006. The PPOOLEX facility is described in more detail in reference [1]. 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. The vessel is made of three separate plate cylinder segments and of two dome segments. The test facility is able to withstand considerable structural loads caused by rapid condensation of steam. The vessel sections modeling dry and wet well are volumetrically scaled according to the volumes of the Olkiluoto 1 and 2 containment compartments. The DN200 (Ø 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 inner diameter 214.1 mm. There are several windows for visual observation in the vessel wall. A DN100 (Ø 114.3 x 2.5 mm) drain pipe with a manual valve is connected to the bottom of the vessel. A relief valve connection is mounted on the vessel head. The large removable vessel head and a man hole (DN500) in the wet well compartment wall provide access to the interior of the vessel for maintenance and modifications of internals and instrumentation. A sketch of the test vessel is presented in Figure 2. Table 1 lists the main dimensions of the test facility compared to the conditions in the Olkiluoto plant.

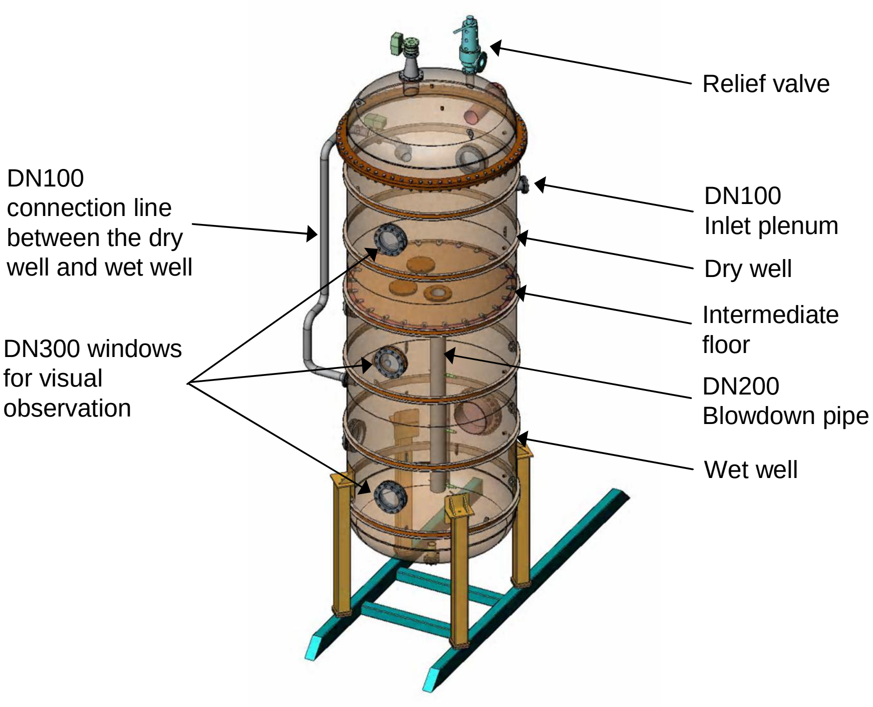


Figure 2. PPOOLEX test vessel.

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

	PPOOLEX facility	Olkiluoto 1 and 2
Number of blowdown pipes	1	16
Inner diameter of 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 suppression pool [m^3]	8.38*	2700
Nominal water level in 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 well and wet well compartments in order to keep the pressure in the wet well compartment in all possible accident situations less than 0.05 MPa above the dry well pressure In the PPOOLEX test facility, pressure difference between the compartments is regulated through a connection line (Ø 114.3 x 2.5 mm) installed between the dry well and the gas volume of the wet well. A remotely operated valve in the connection line can be programmed to open with a desired pressure difference according to test specifications. However, the pressure difference across the separating 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 [2] test facility, which has a core section of 1 MW heating power and three steam generators. Steam is led through a thermally insulated steam line, made of sections of standard DN80 (Ø 88.9 x 2.0 mm) and DN50 (Ø 60.3 x 2.0 mm) pipes, from the PACTEL steam generators towards the test vessel. The steam line is connected to the DN200 inlet plenum with a 0.47 m long cone section. Accumulators connected to the compressed air network of the laboratory can be used for providing non-condensable gas injection. A schematic illustration of the air and steam line piping is presented in Figure 3.

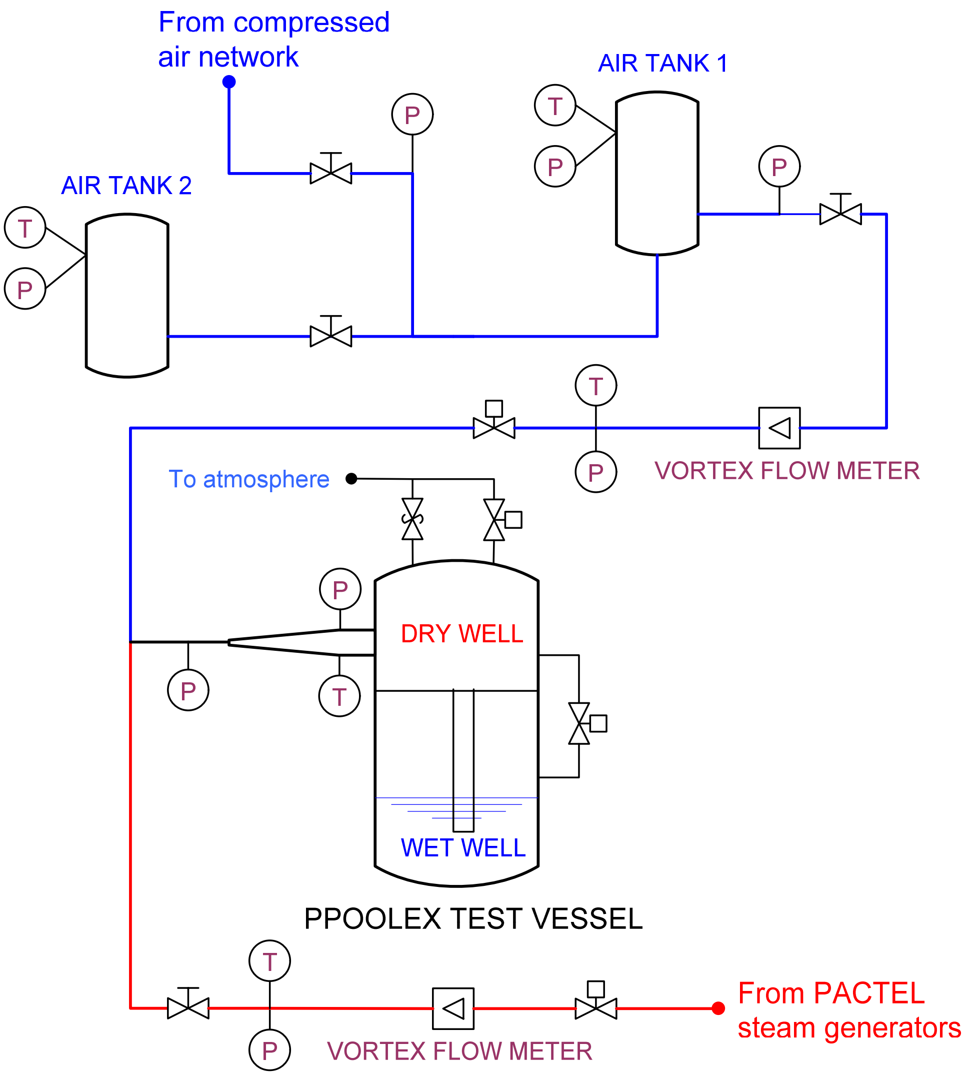


Figure 3. Arrangement of air and steam supply in the PPOOLEX facility.

2.3 MEASUREMENT INSRUMENTATION

The applied instrumentation depends on the experiments in question. Normally, the test facility is equipped with several thermocouples (T) for measuring air/steam and pool water temperatures and with pressure transducers (P) for observing pressure behavior in the dry well, inside the blowdown pipe, at the condensation pool bottom and in the gas phase of the wet well. Steam and air flow rates are measured with vortex flow meters (F) in the steam and air lines. TORBAR measurement in the inlet plenum provides another mean to estimate the injection flow rate. 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. A list of different types of basic measurements in the PPOOLEX test facility is presented in Table 2. The figures in Appendix 1 show the exact locations of the measurements and the table in Appendix 1 lists the identification codes. Part of the instrumentation listed in the table and shown in the figures in Appendix 1 were added late in the characterizing experiment series and were therefore not present during the tests selected for the simulation exercise discussed in this report.

Table 2. Instrumentation of the PPOOLEX test facility

Quantity measured		No.	Range	Accuracy
Pressure	Dry well	1	0-6 bar	±0.06 bar
	Wet well	3	0-6/0-10 bar	±0.4/0.5 bar
	Blowdown pipe	1	0-10 bar	±0.7 bar
	Inlet plenum	1	0-6 bar	±0.06 bar
	Steam line	1	1-51 bar	±0.5 bar
	Air line	2	0-6/1-11 bar	±0.06/0.1 bar
	Air tanks 1&2	2	0-16/0-11 bar	±0.15/0.11 bar
Temperature	Dry well	4	-40-200 °C	±3.2 °C
	Wet well	5	0-250 °C	±2.0 °C
	Pool water	1	0-200 °C	±2.6 °C
	Blowdown pipe	3	0-250 °C	±2.0 °C
	Inlet plenum	1	-40-200 °C	±3.2 °C
	Steam line	1	0-400 °C	±3.6 °C
	Air line	1	-20-100 °C	±2.8 °C
	Air tanks 1&2	2	-20-100/200 °C	±2.8/3.1 °C
	Vessel wall	1	0-200 °C	±2.9 °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
	Inlet plenum*	1	0.002-0.018 bar	±99 g/s
Water level in wet well		1	0-30000 Pa	0.06 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		1	N/A	N/A

* TORBAR (used only occasionally as a supplementary measurement)

2.4 CCTV SYSTEM

For more accurate observation of air/steam bubbles at the blowdown pipe outlet, the test facility is furnished with a Citius Imaging digital high-speed video camera (model C10) [3].

The camera is controlled with a PC. The PC is also used for displaying and storing of video data. The camera is a single unit and it is connected to the PC through a USB bus.

The high-speed video recording is at first stored to the RAM-memory in the camera (in AVI-format). From there it is transferred to the PC hard disk. The camera is furnished with the largest possible amount of memory; 2 GB. The camera can achieve over 10000 frames/second (fps) recording speed and up to 652 x 496 pixels resolution with 256 shades of gray. However, speed and maximum recording time depend on the resolution used.

Standard video cameras, digital videocassette recorders and a quad processor supplement the visual observation system. By using a digital color quad processor it is possible to divide the TV screen into four equal size parts and look at the view of four cameras on the same screen.

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 measurements. The maximum recording speed depends on the number of measurements and is in the region of 300 thousand samples per second. Measurement software is LabView 7.1. The data acquisition system is discussed in more detail in reference [4].

Separate HPVee based 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. The voltage readings are converted to engineering units by using special conversion software.

In the characterizing tests, the used data recording frequency of LabView was 1 kHz except for temperature measurements. For them the data recording frequency was 50 Hz. The temperature measurements are therefore averages of 20 measured points. The rest of the measurements (for example in the air/steam lines) are recorded by HPVee software with the frequency of 2 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 HPVee and LabView record the channel.

A separate measurement channel is also used for the digital high-speed video camera triggering. When the camera gets a signal from the trigger, it starts to record. Depending on the adjustment, the camera records the events either from the triggering moment towards the future or from the past until the triggering moment.

3 CHAR-09-1 AND CHAR-09-3 TESTS

Tests CHAR-09-1 and CHAR-09-3 from the characterizing test program were selected for the simulation exercise [5]. In both tests, only pure air was used. Air accumulators, filled with the help of the compressed air network of the laboratory, served as air source in the experiments.

The initial pressure of the accumulators was 0.8 MPa in both tests. The tests were carried out by using the DN200 blowdown pipe.

Before the tests the condensation pool (wet well) was filled with water to the level of 2.14 m i.e. the blowdown pipe outlet was submerged by 1.05 m. Pool water bulk temperature was about 24 °C. The position of the throttle valve in the air line was adjusted before each test so that the desired flow rate would be achieved.

After the correct initial pressure level in the air accumulators had been achieved the remote-controlled shut-off valve in the air line was opened. As a result, the inlet plenum was filled with air that immediately pushed its way to the dry well compartment and mixed there with the initial air content. Pressure build-up in the dry well then pushed water in the blowdown pipe downwards and after a while the pipe cleared and air flow into the wet well compartments started. Table 3 shows the initial parameters of the CHAR-09-1 and CHAR-09-3 tests.

Table 3. Initial parameters of characterizing tests CHAR-09-1 and CHAR-09-3

Experiment	Air accumulator initial pressure [MPa]	Initial pool water level [m]	Air flow rate [g/s]	Pool water temperature [°C]
CHAR-09-1	0.8	2.14	10-170	~ 24
CHAR-09-3	0.8	2.14	10-600	~ 24

During the recorded blows the mass flow rate of air decreased as the pressure difference between the air accumulators and the test vessel decreased. Figure 4 illustrates how the pressure difference between the air accumulators and the test vessel disappeared.

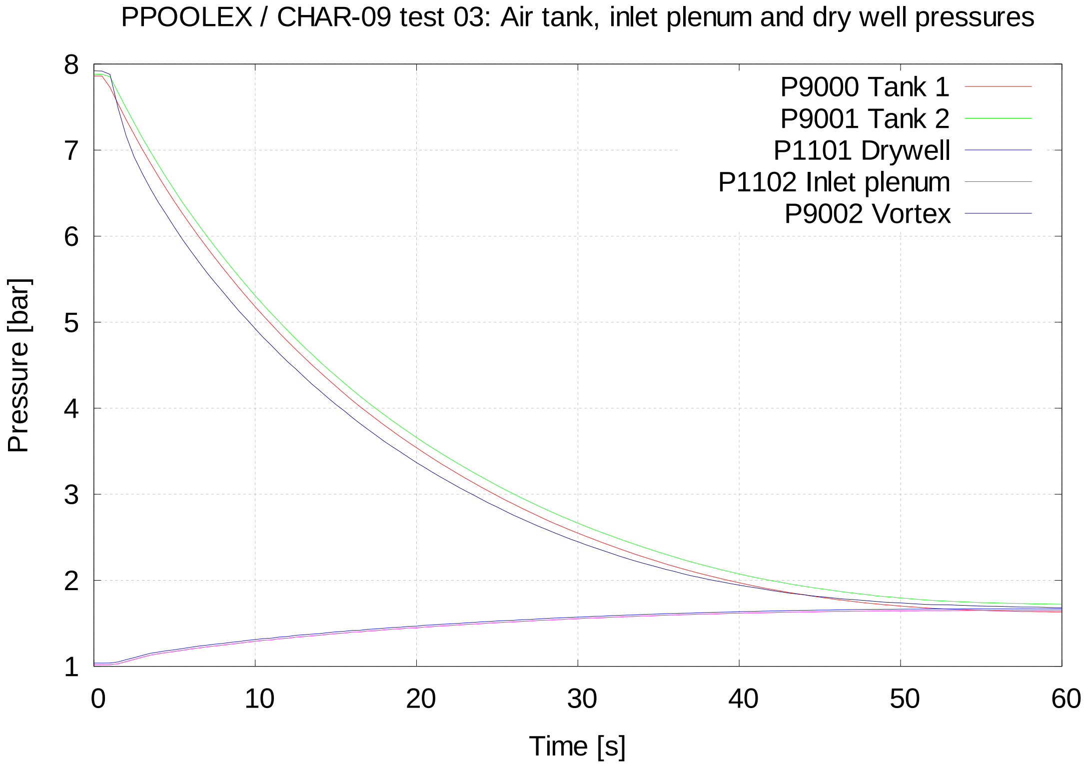


Figure 4. Disappearing pressure difference between the air accumulators and the test vessel in air discharge test CHAR-09-3.

The initial gas atmosphere in the dry well compartment and in the gas space of the wet well heated-up due to compression after air discharge from the accumulators had started. As temperatures in the gas space of the wet well compartment increased, they also stratified. The temperature measurement just above the pool water level indicated an increase of only few degrees while the measurement close to the top of the compartment registered a rise even over 20 °C, when the test vessel pressure was let to increase to about 0.18 MPa (from the initial pressure of 0.1 MPa). Cold structures near the water surface elevation and the cold water itself prevented more extensive heat-up in the lowest measurement point. In Figure 5, the development from a uniform initial temperature of the compartment to a strongly stratified situation can be clearly seen.

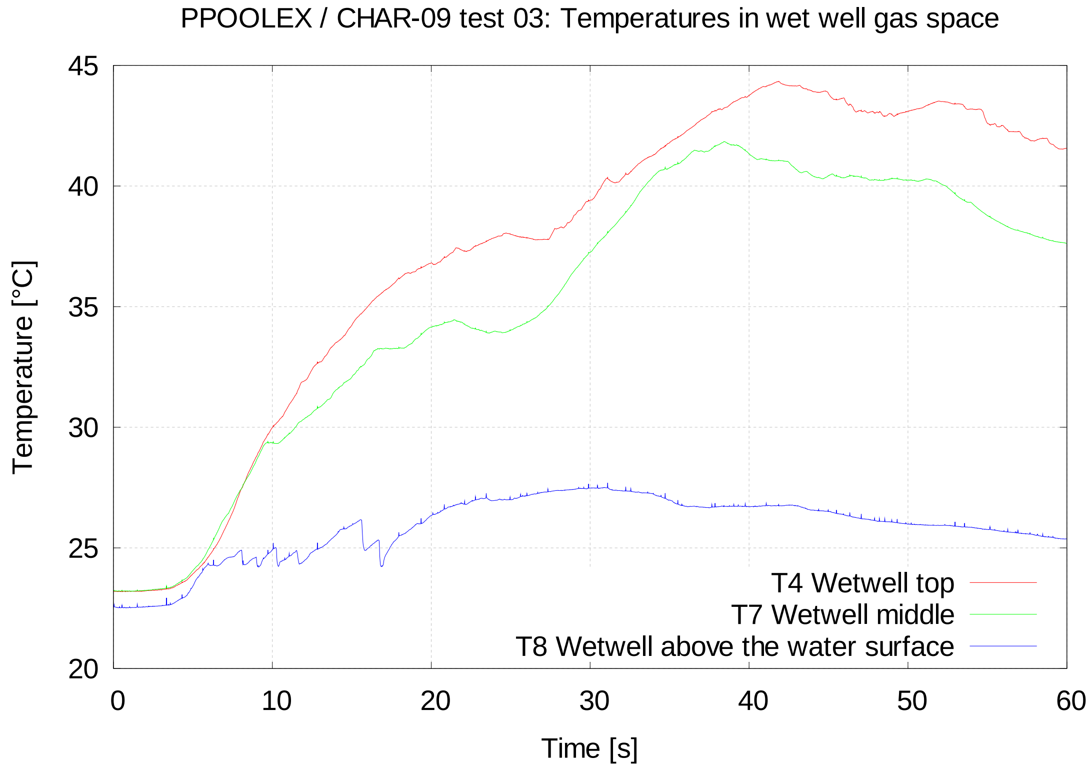


Figure 5. Stratification of temperatures in the wet well gas space during CHAR-09-3.

Two other tests (CHAR-09-2 and CHAR-09-4) from the same experiment but with somewhat different initial conditions and air flow rates have been simulated with CFD at VTT. The results of these calculations are presented in reference [6].

4 CFD SIMULATION MODEL

The PPOOLEX geometry is not symmetric enough for 2D or 2D-axisymmetric simulations. Thus a three dimensional grid is needed. The grid used in the simulations at LUT was obtained from VTT and is the same, or almost the same, as the grid VTT used in their simulations of CHAR-09-2 and CHAR-09-4. The grid contains 136501 hexahedral cells with 144242 nodes. Figure 6 shows the grid and its refined regions.

FLUENT code [7] [8] was used as a simulation tool of these cases at VTT and LUT. Some solver settings may differ between VTT and LUT, but the main guidelines should be similar. The solver settings related to material properties used in the simulations of CHAR-09-1 and CHAR-09-3 by LUT are presented in Table 4.

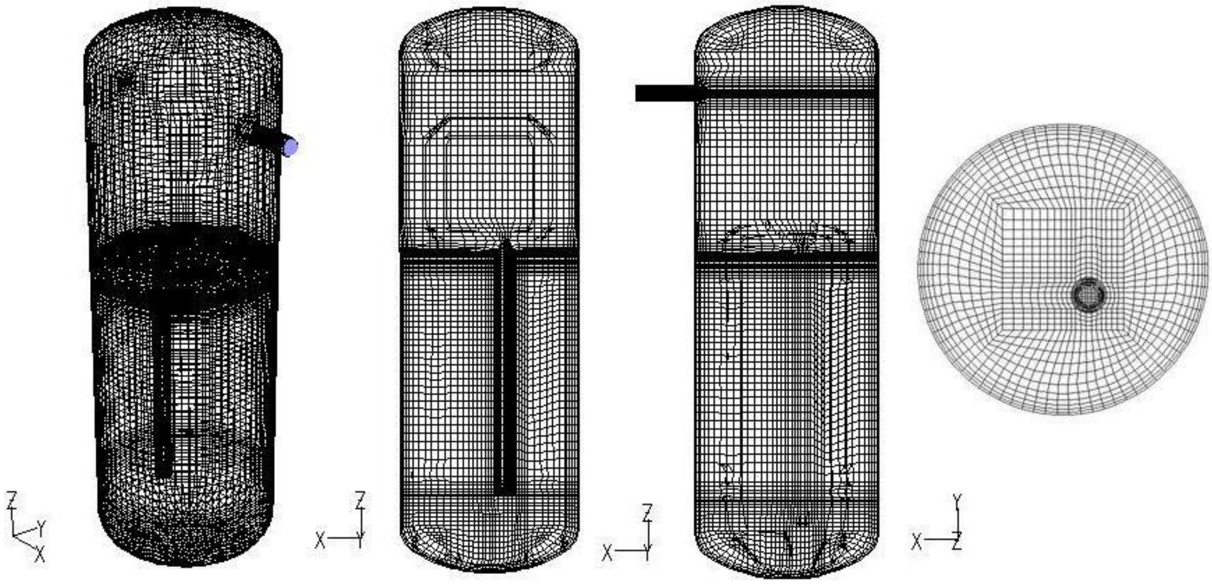


Figure 6. Calculation grid of the PPOOLEX facility for CFD simulations. Left: grid at boundaries. Right: 3 cross-cut planes of the grid (xz-planes in the middle of blowdown pipe and in the middle of vessel and a xy-plane in the blowdown pipe region).

Table 4. Air and water properties in simulations

CHAR-09-1	Air at (312 K, atm. pressure)	Water at (298 K, 1.10218 bar) (at point T1103)
ρ [kg/m^3]	ideal-gas law	997.22
c_p [J/kgK]	1005.521	4182.181
λ [W/mK]	0.027188	0.606095
μ [kg/ms]	1.9e-5	9.03e-4
CHAR-09-3	Air at (314 K, atm. pressure)	Water at (298 K, 1.1066 bar) (at point T1103)
ρ [kg/m^3]	ideal-gas law	997.214
c_p [J/kgK]	1005.598	4182.176
λ [W/mK]	0.027336	0.606106
μ [kg/ms]	1.9e-5	9.03e-4

As one can see from Table 3, the material properties are almost equal between these two cases. For the material properties of water, the initial temperatures and pressures at the measurement point of T1103 were applied. The coordinates of all measurement points (as used in the simulation) are presented in Appendix 3. Further solver settings are presented in Table 5 for these VOF simulations in FLUENT.

Variable time stepping was used in the simulations. The limiting criterions for the time step length needed to be modified many times during the calculation process. Global Courant number limitations between 1.25 and 2 were used depending on the state of convergence. The minimum time step was 1e-5 s in the worst case and the maximum 0.01 s in the best case. However, both of these conditions were rare. In CHAR-09-1, typical step limitations were 2.5e-4 – 5e-4 s for the minimum and 1e-3 – 7.5e-3 s for the maximum. In CHAR-09-3, these limits were 2.5e-4 s for the minimum and 5e-4 – 1e-3 s for the maximum step sizes.

Simulation of CHAR-09-1 was ended at 28.92 s of transient (test) time and CHAR-09-3 at 17.01 s. Simulations of 30-60 s of transient time would have been desirable, but long simulation times due to unstable convergence made this object too costly to be achieved in this subtask of the CONDEX project.

Table 5. Solver settings for Fluent [7] [8]

Settings			CHAR-09-1	CHAR-09-3
Models	Solver		3D, pressure based, implicit, unsteady	
	Multiphase		2 phase VOF, explicit scheme, implicit body force formulation	
	Energy equation		Enabled	
	Viscous		Standard k-ε, standard wall functions	
Phases	Primary phase		water, liquid	
	Secondary phase		air	
	Interactions		Constant surface tension: 73e-3 N/m	
Operating conditions	Operating pressure [Pa]		Floating operating pressure	
	Acceleration of gravity g [m/s^2]		[0,0,-9.81]	
	Operating density ρ [kg/m^3]		1.63	1.71
Boundary conditions	Inlet :			
	Type		Mass-flow-inlet	
	Initial P [Pa]		0	
	Turbulence intensity I [%]		5	
	Hydraulic diameter D_h [m]		0.211248	
	Total temperature T_{tot} [K]		UDF	
	Primary phase q_m [kg/s]		0	
	Secondary phase G [kg/m^2s]		UDF	
Solution controls	Pressure-velocity coupling		SIMPLEC	
	Pressure discretization		PRESTO!	
	ρ discretization		2nd order upwind	
	Momentum discretization		3rd order MUSCL	
	VOF discretization		Geo-Reconstruct	
	Turbulence k discretization		2nd order upwind	
	Turbulence ε discretization		2nd order upwind	
	Energy eq. discretization		2nd order upwind	
Initial conditions	Operating pressure [Pa]		103390	103890
	Gauge pressure [Pa]		0	
	Velocity [m/s]		[0,0,0]	
	Turbulence k [m^2/s^2]		1e-3	
	Turbulence ε [m^2/s^3]		1e-3	
	Temperature [K]		297.15	296.308
	Secondary phase α		1	
	Patched	Primary phase α	1 at z = [0, 2.14] m	
		T [K]	-	297.694 at z = [0, 2.14] m
Residuals and time stepping	Convergence criterion		1e-9 for all residuals	
	Time step		Variable time step	
Output	Case/data file save		every 50 time steps	
	Surface monitors		Pressures and temperatures at measurement points. Axial velocity in the blowdown pipe in later time steps.	

5 SIMULATION RESULTS

5.1 SIMULATION RESULTS OF CHAR-09-1 TEST

The simulation of case CHAR-09-1 was finished at 28.92 s of transient time. Figure 7 presents a sample of residuals during the last time steps. They are not very stable and occasionally poor convergence can become a nuisance. When poor convergence was met, the Courant number and time step size limitations were tightened. Due to computational time costs, these limitations were lightened during more stable periods.

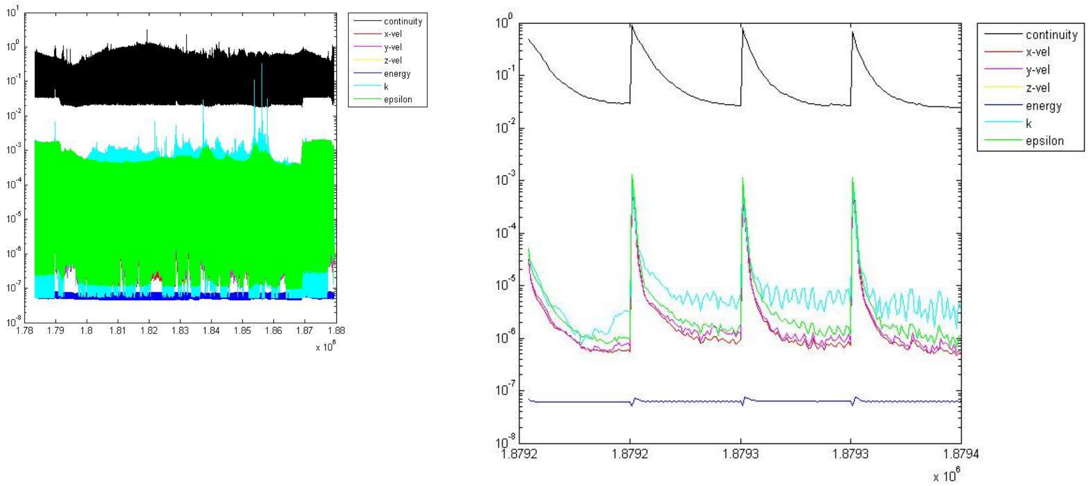


Figure 7 . Convergence in terms of residuals in the simulation of CHAR-09-1.

Figure 8 compares calculated and measured dry well (P1101) and air line (P1103) pressures. They are in a fairly good agreement. Figure 9 presents the pressures inside the test vessel.

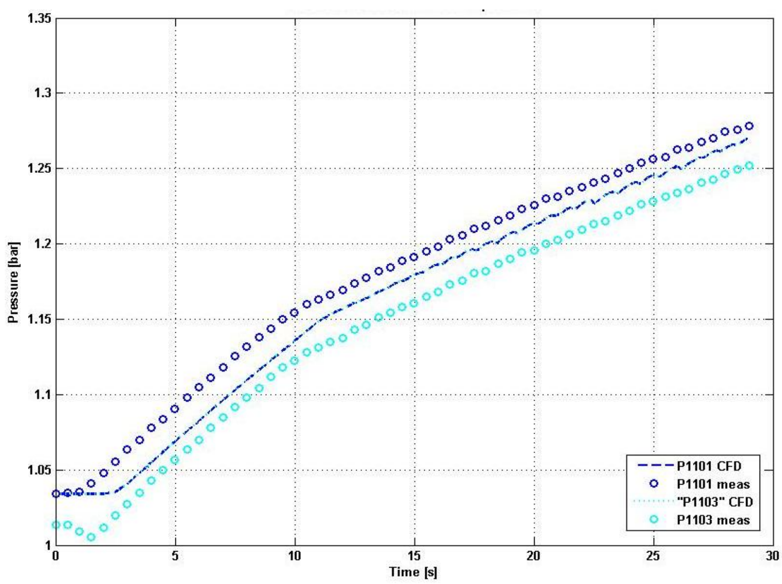


Figure 8. Simulated and measured drywell and air line pressures in CHAR-09-1.

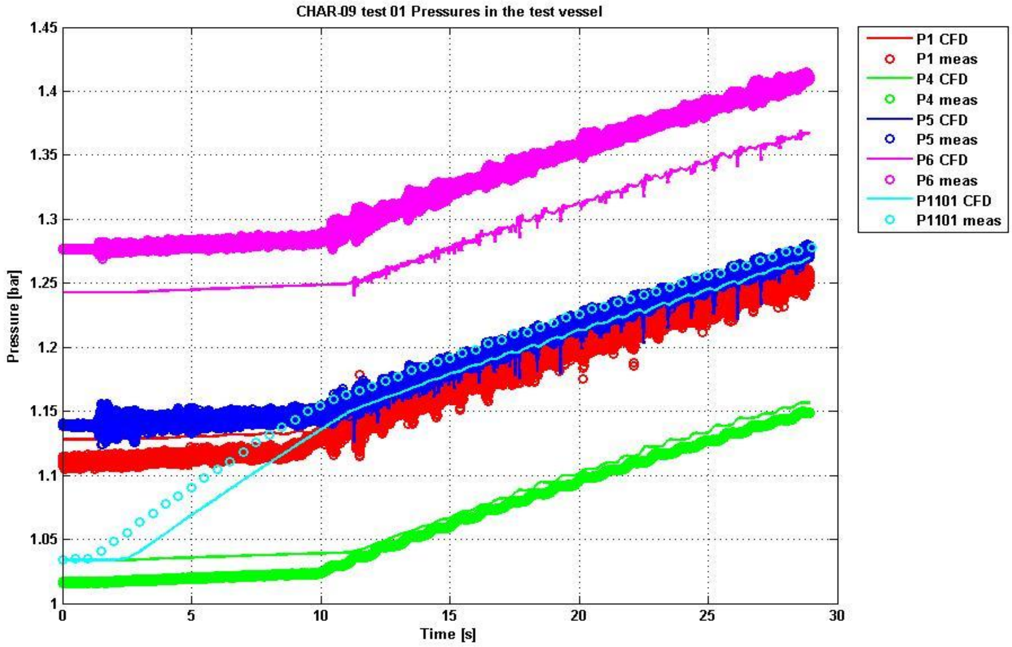


Figure 9. Simulated and measured pressures in the test vessel in CHAR-09-1.

Also the pressures inside the PPOOLEX test vessel have been captured well in the simulation, as Figure 9 shows. Pressure vibration due to bubble formation at the blowdown pipe outlet seems to be similar in the experiment and simulation. However, there seems to be a slight difference in the onset of pressure increase in both of the test vessel compartments.

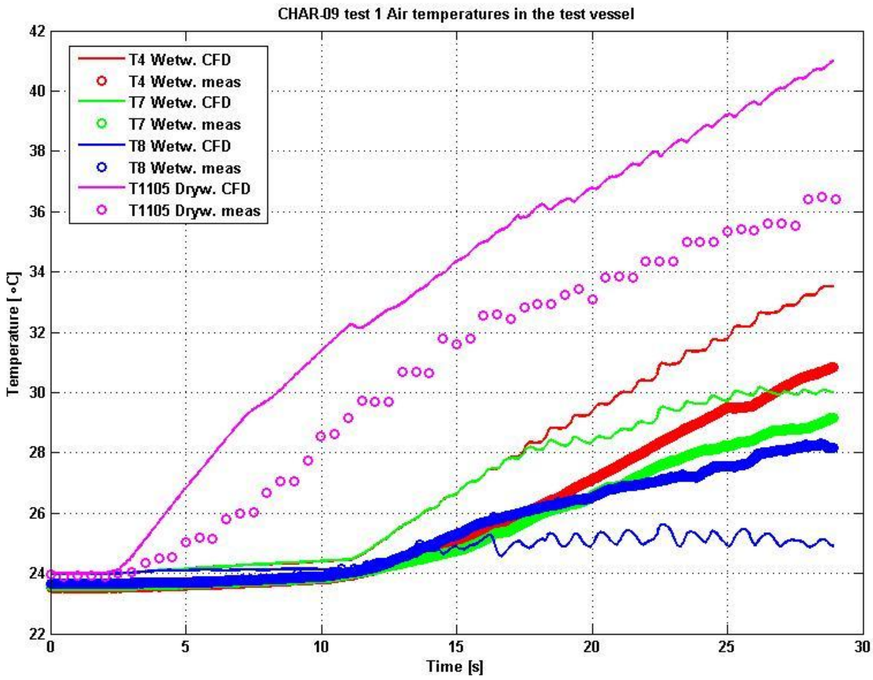
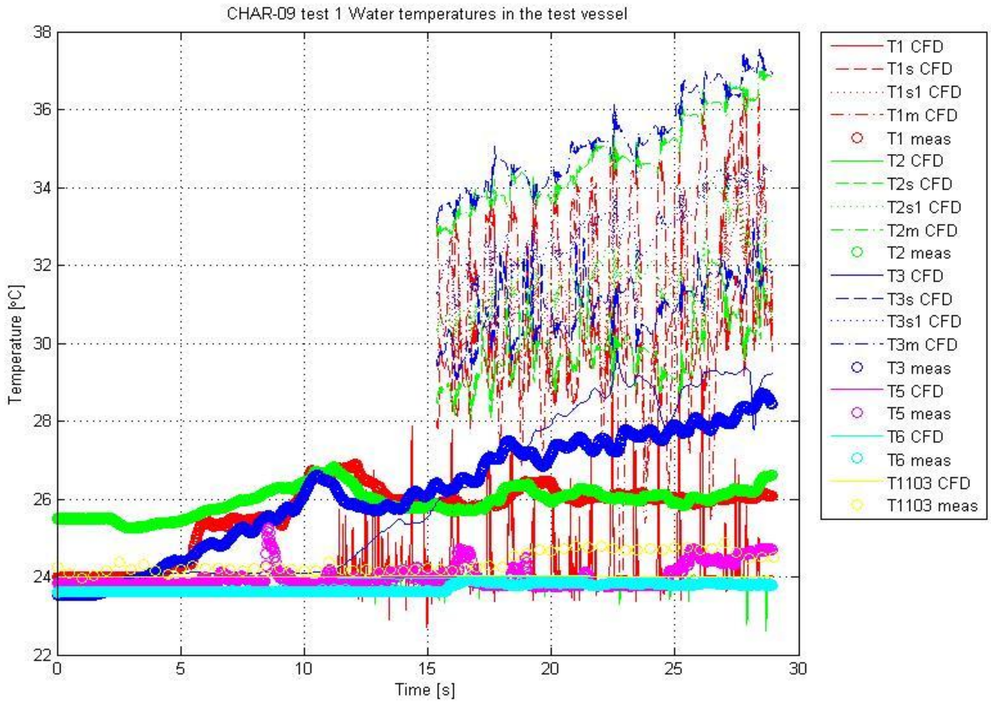


Figure 10. Simulated and measured air temperatures in the wet well and dry well.

Temperatures in the dry well and wet well compartments are shown in Figure 10. Temperatures are generally higher in the simulation than in the experiment. Only T8 is lower than in the experiment. The different behavior of T8 can be explained by its location in the vicinity of the water surface and splashes. Thermal stratification may be another reason for the behavior. More temperature results are shown in Figure 11.



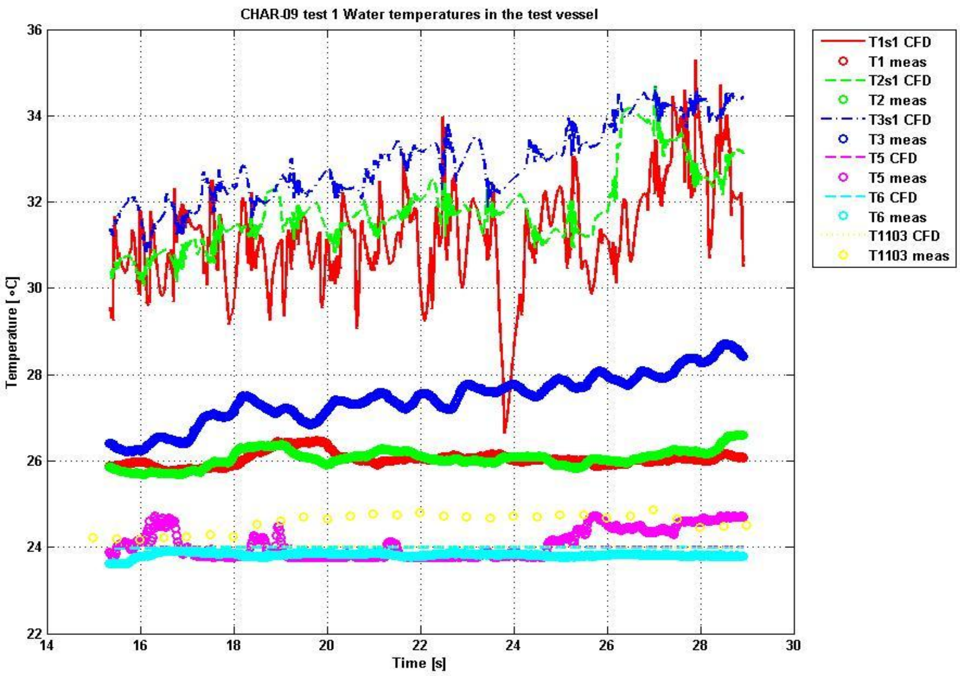


Figure 11. Simulated and measured temperatures in the test vessel in CHAR-09-1.

Simulated (air) temperatures inside the blowdown pipe (T1s1, T2s1 and T3s1) are approximately 5 °C higher than in the experiment (T1, T2 and T3), because the air entering the pipe heats up more in the dry well in the simulation. In the regions occupied by water, there are no significant differences between the simulation and the experiment.

Figure 12 shows the measured mass flow rate used as a boundary condition in the simulation and the measured and calculated pressure difference between the wet well and dry well compartments. The calculated pressure difference is in a good agreement with the measured one.

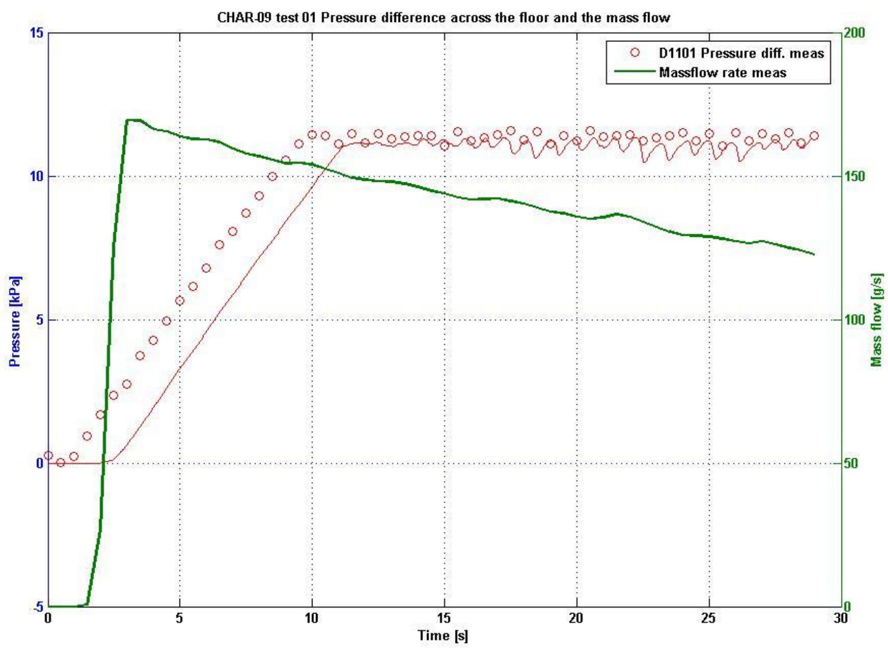


Figure 12. Simulated and measured pressure difference across the intermediate floor and measured mass flow rate (boundary condition in the simulation) of air in CHAR-09-1.

Later in the simulation, also recording of axial velocity in the blowdown pipe was incorporated. Figure 13 presents the results of this. Unfortunately, there was no blowdown pipe velocity measurement in the experiment and therefore no comparison to measured values can be done. Figure 14 shows the volume fractions in the test vessel at the moments of time marked in Figure 13.

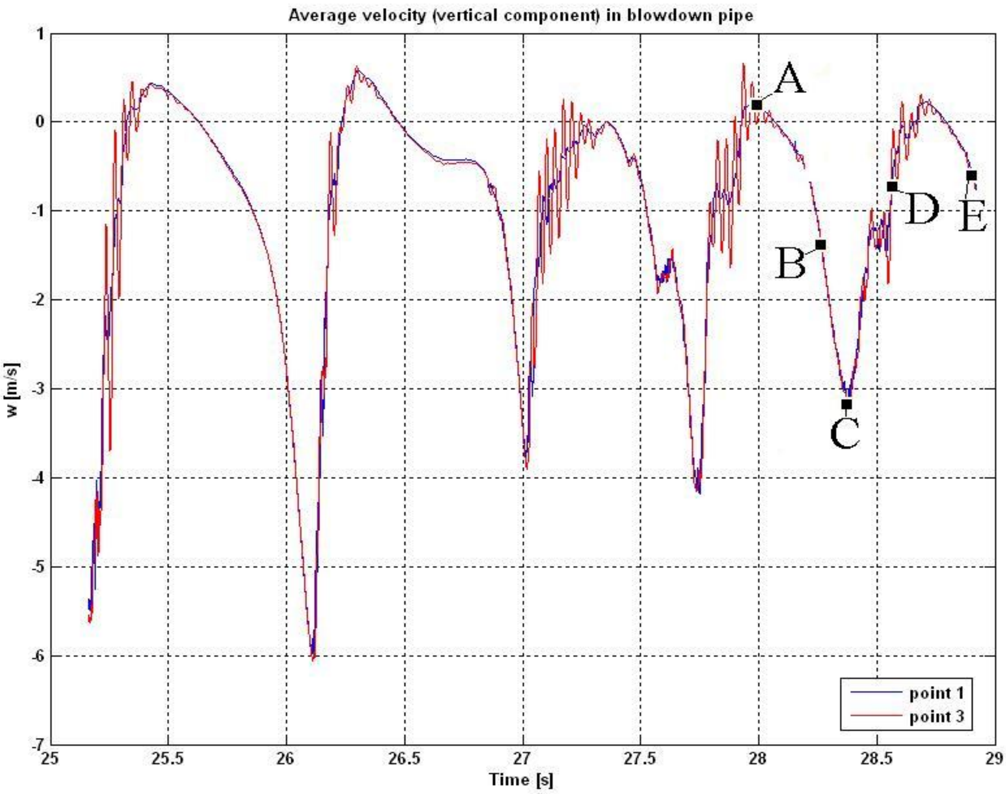


Figure 13. Average vertical velocity component in the blowdown pipe in CHAR-09-1.

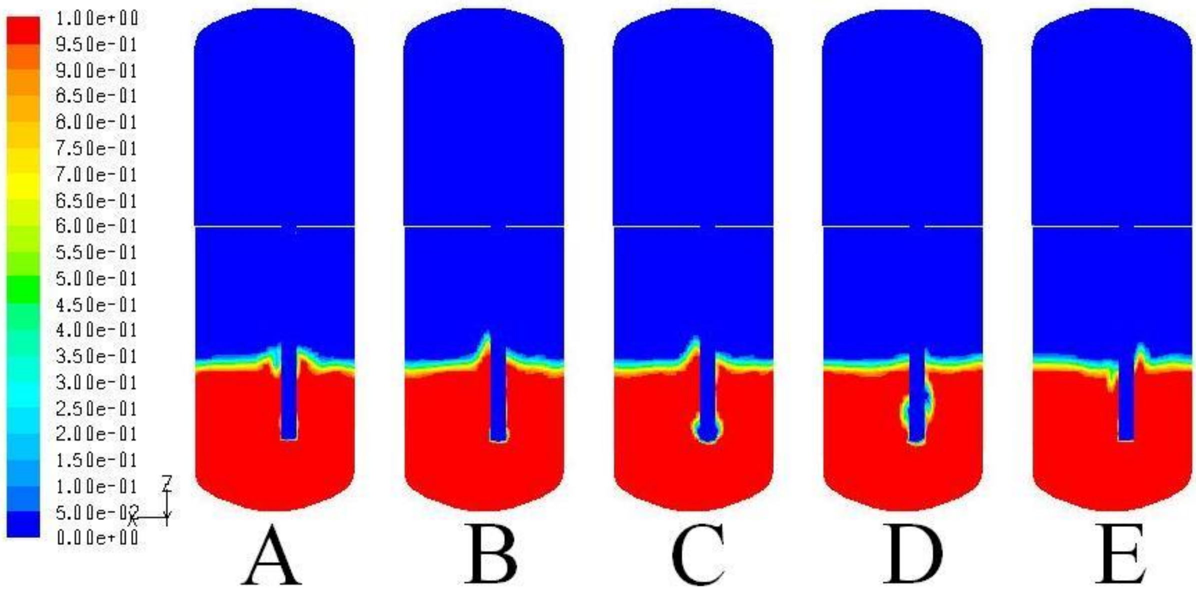


Figure 14. Volume fraction of water at the moments of time shown in Figure 12 .

From Figures 13 and 14 one can see the behavior of axial velocity in the blowdown pipe during the different states of bubble formation and break-up. When the bubble formation starts, the axial velocity accelerates and its direction is downwards. When the bubble reaches its maximum size, the velocity decreases eventually to zero or even turns slightly upwards. It seems that during these onset-to-formation phases, there are occasional difficulties to achieve convergence in the simulation.

Figure 15 presents the temperature stratification inside the test vessel. Air temperatures seem to stratify qualitatively in a realistic manner in the simulation. Exact comparison to the situation in the test is not possible since there were too few temperature measurements present. No heat conduction was modeled through the wet well / dry well wall in the simulation.

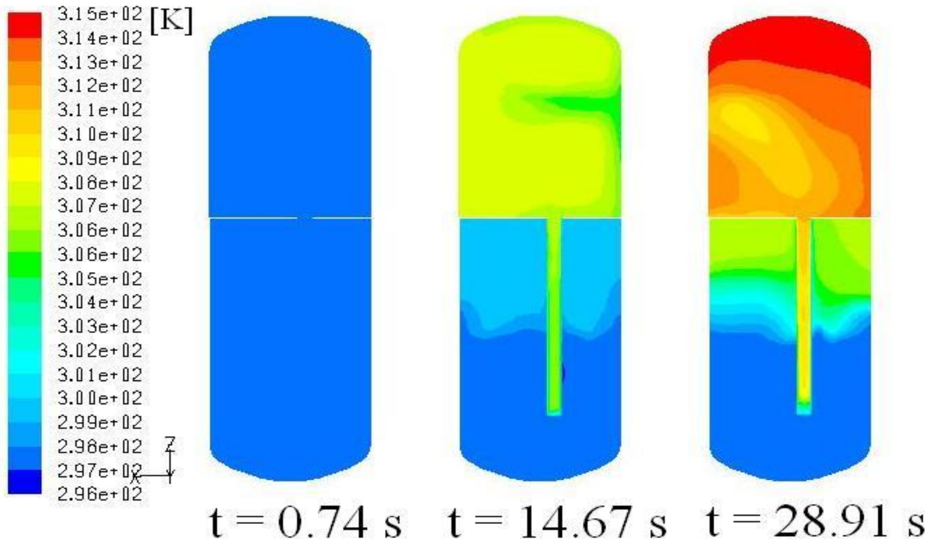


Figure 15. Static temperatures in the test vessel in CHAR-09-1.

5.2 SIMULATION RESULTS OF CHAR-09-3 TEST

The simulation of case CHAR-09-3 was finished at 17.01 s of transient time. Figure 16 presents a sample of residuals during the last time steps. The behavior of convergence varies strongly also in CHAR-09-3. When poor convergence was met, the Courant number and time step size limitations were again tightened. In CHAR-09-3, the air mass flow rate was clearly higher than in CHAR-09-1. Thus, further shortened time steps were required. Due to computational time costs, these limitations were lightened during more stable periods.

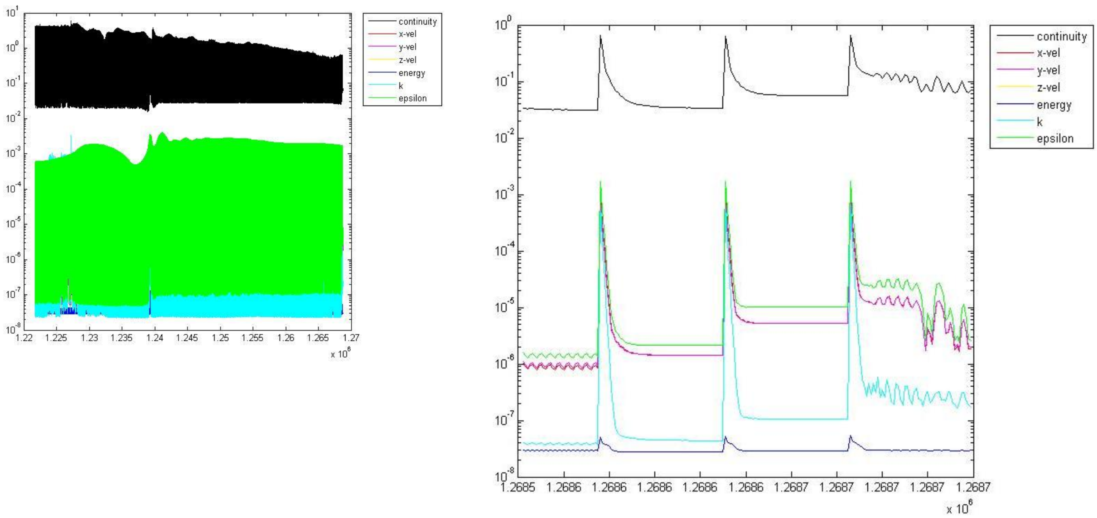


Figure 16. Convergence in terms of residuals in the simulation of CHAR-09-3.

Figure 17 shows the results of pressures in the dry well and air line. The trends of simulated pressures are close to the measured ones and the values fall between the measured pressures of P1101 and P1103, just like in the case of CHAR-09-1. In CHAR-09-3, pressure oscillations due to bubble formation and break-up are, however, more visible.

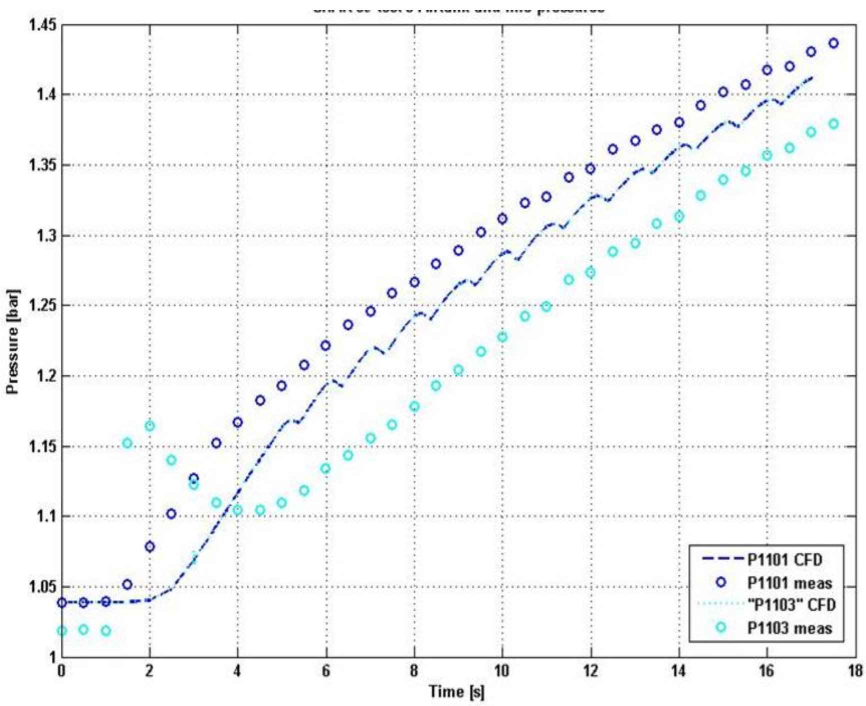


Figure 17. Simulated and measured dry well and air line pressures in CHAR-09-3.

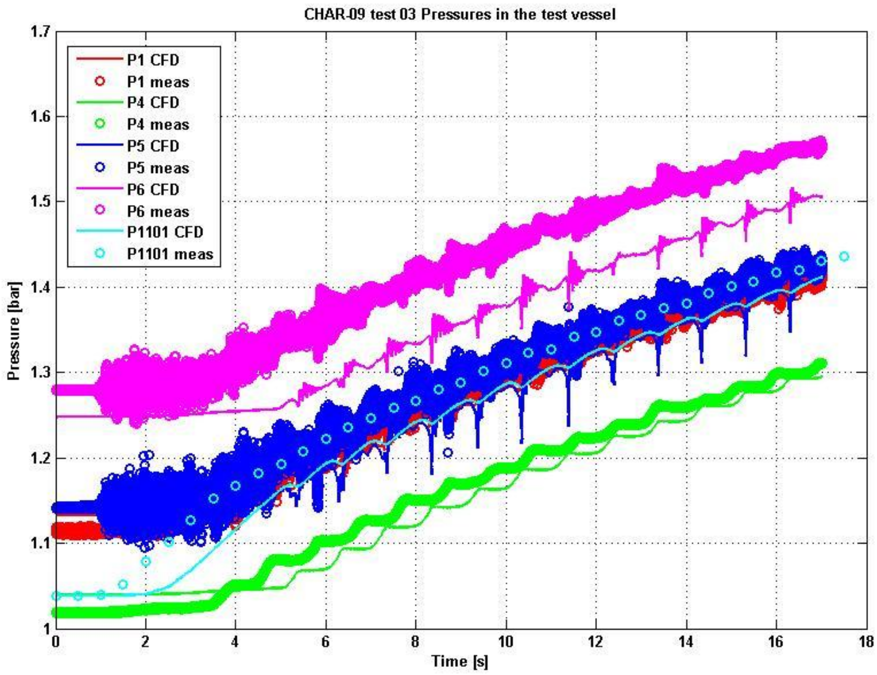


Figure 18. Simulated and measured pressures in the test vessel in CHAR-09-3.

Figure 18 presents the pressures inside the PPOOLEX test vessel. They have been captured well in the simulation. Particularly, pressure vibration due to bubble formation seems to be similar in the experiment and simulation. However, there again seems to be a slight difference in the onsets of pressure increase.

Figure 19 shows the results of temperature simulations in the dry well and wet well compartments. Temperatures are generally higher in the simulation than in the experiment. Also values measured by T8 are slightly over-estimated this time as opposed to the under-estimation in the case of CHAR-09-1. Temperature oscillations due to bubble formation can be seen in the simulation results.

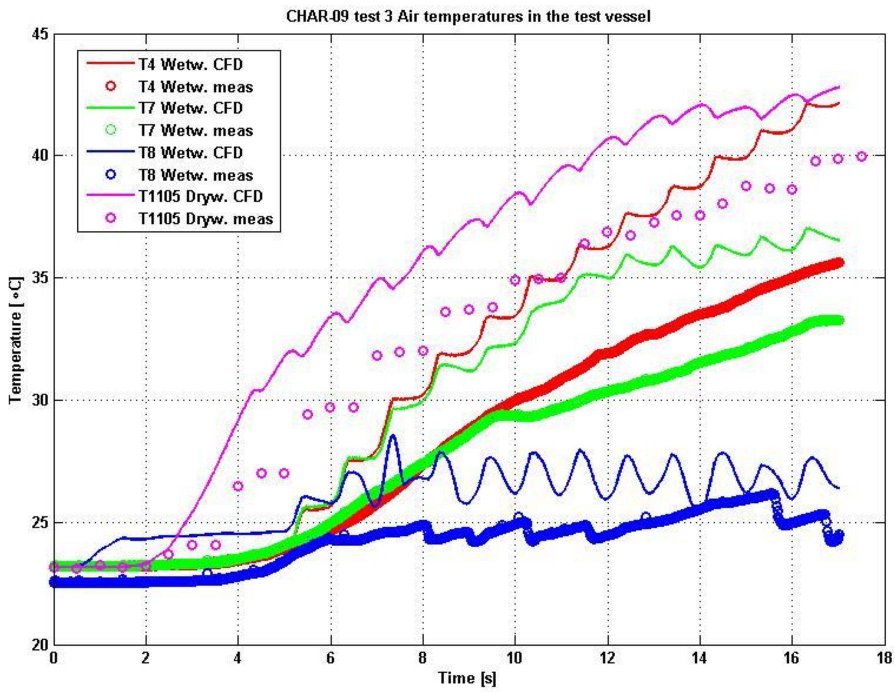


Figure 19. Simulated and measured air temperatures in the wet well and dry well.

More simulation results of temperatures are compared to measurements in Figure 20. Simulated (air) temperature inside the blowdown pipe (T1s1) and near the pipe outlet (T5) oscillate heavily (with a range of 0 - 14 °C). This kind of oscillation is not measured by T1 and T5 thermocouples in the experiment. However, this oscillation is probably real and a result of the periodical movement of air/water interface during bubble formations and break-ups. Due to the cooling/wetting effect of this water oscillation, the thermocouples close to the pipe outlet can not register the short heat-up periods by air flow in the experiment. It is believed that water droplets remain attached to the thermocouples for the whole air flow cycle. The simulated mid-pipe temperature (T2s1) increases by 10-14 °C while the measured value remains at the pool water temperature. The measurement T2 is also affected by the movement of the gas/water interface since its position is practically at the elevation of the initial water level. The temperature T3s1 in the upper part of the blowdown pipe seems to be in a good agreement with the experiment. In the pool regions occupied by water, no significant differences between the simulation and the experiment can be found.

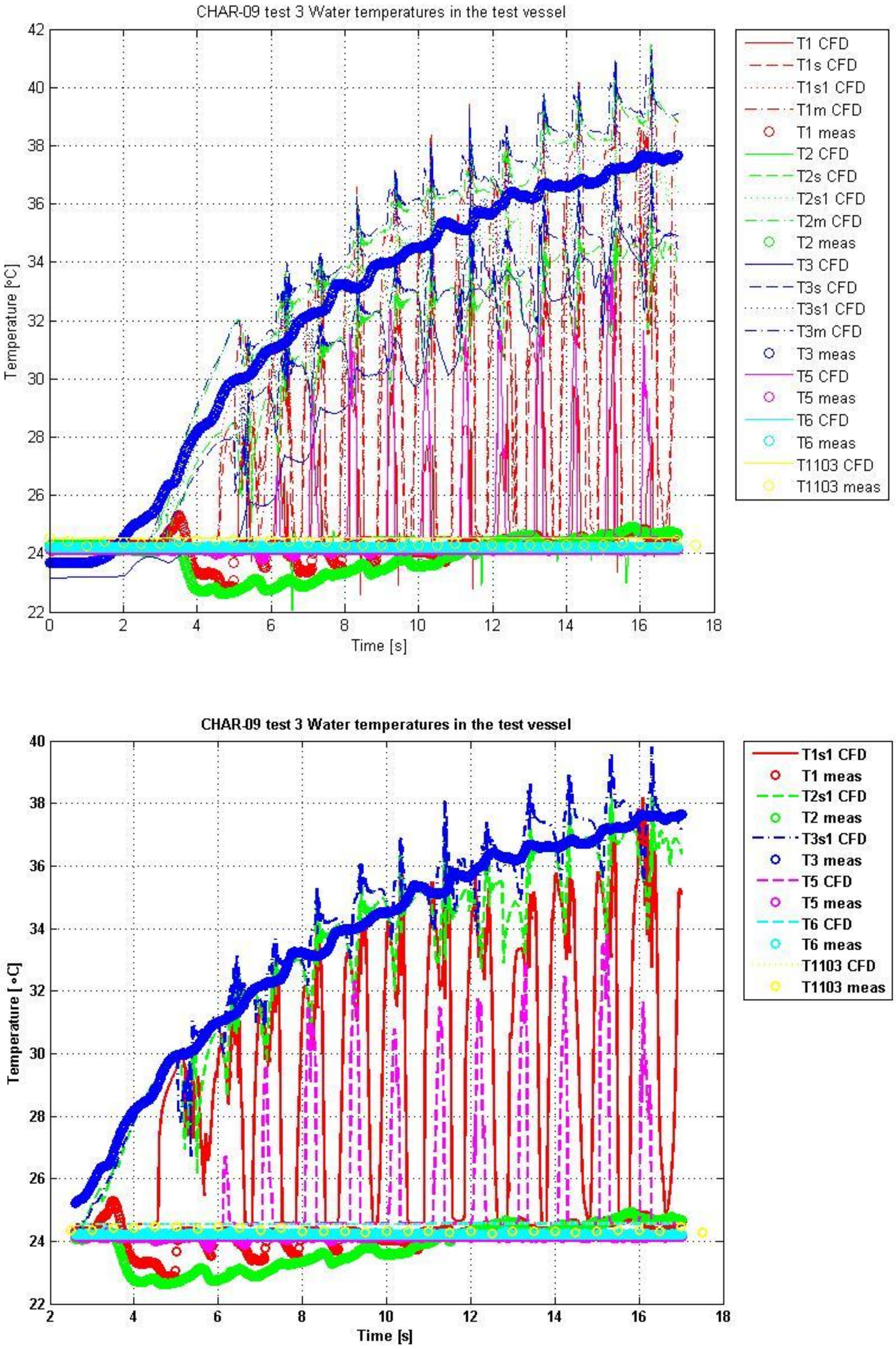


Figure 20. Simulated and measured water/air temperatures in the test vessel.

Figure 21 shows the measured mass flow rate in the air line used as a boundary condition in the simulation and the measured and calculated pressure difference across the intermediate floor. The calculated pressure difference is in a good agreement with the measured one. Only a small delay (about 1.5 s) in the onset of pressure difference build-up can be observed.

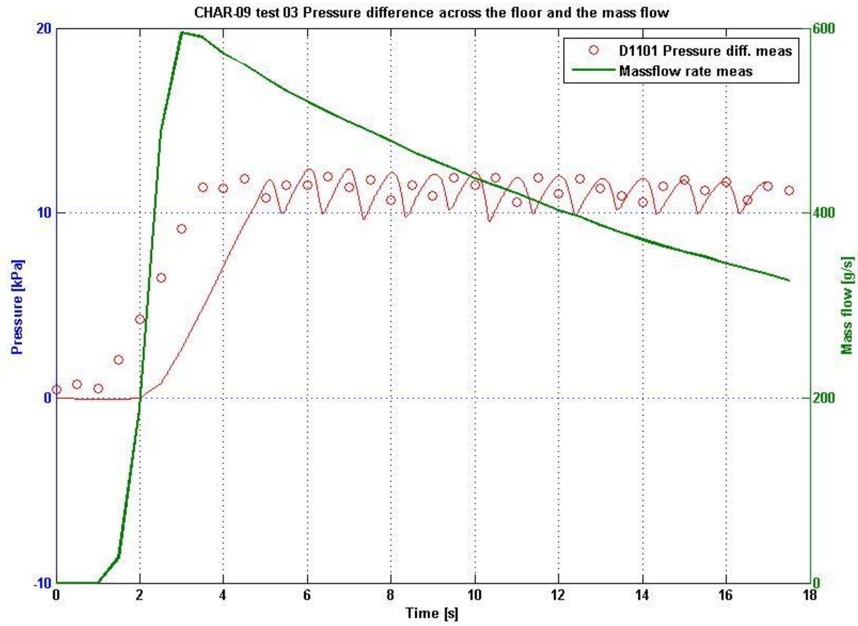


Figure 21. Simulated and measured pressure difference across the intermediate floor and measured mass flow rate (boundary condition in the simulation) of air in CHAR-09-3.

As the air flow enters the dry well compartment from the inlet plenum, it first hits to the opposite wall practically on the same elevation as the inlet plenum. The flow turns then mostly downwards and starts to circulate vigorously inside the dry well. Internal circulation in the gas space of the wet well compartment is quite small instead. Figure 22 presents the velocity vectors from the latter part of the CHAR-09-3 simulation in both compartments of the test vessel.

Later in the simulation, also recording of axial velocity in the blowdown pipe was incorporated. Figure 23 shows the behavior of this axial velocity due to different states of bubble formation and break-up. For further comments see Figures 13 and 14 and their explanation concerning test CHAR-09-1.

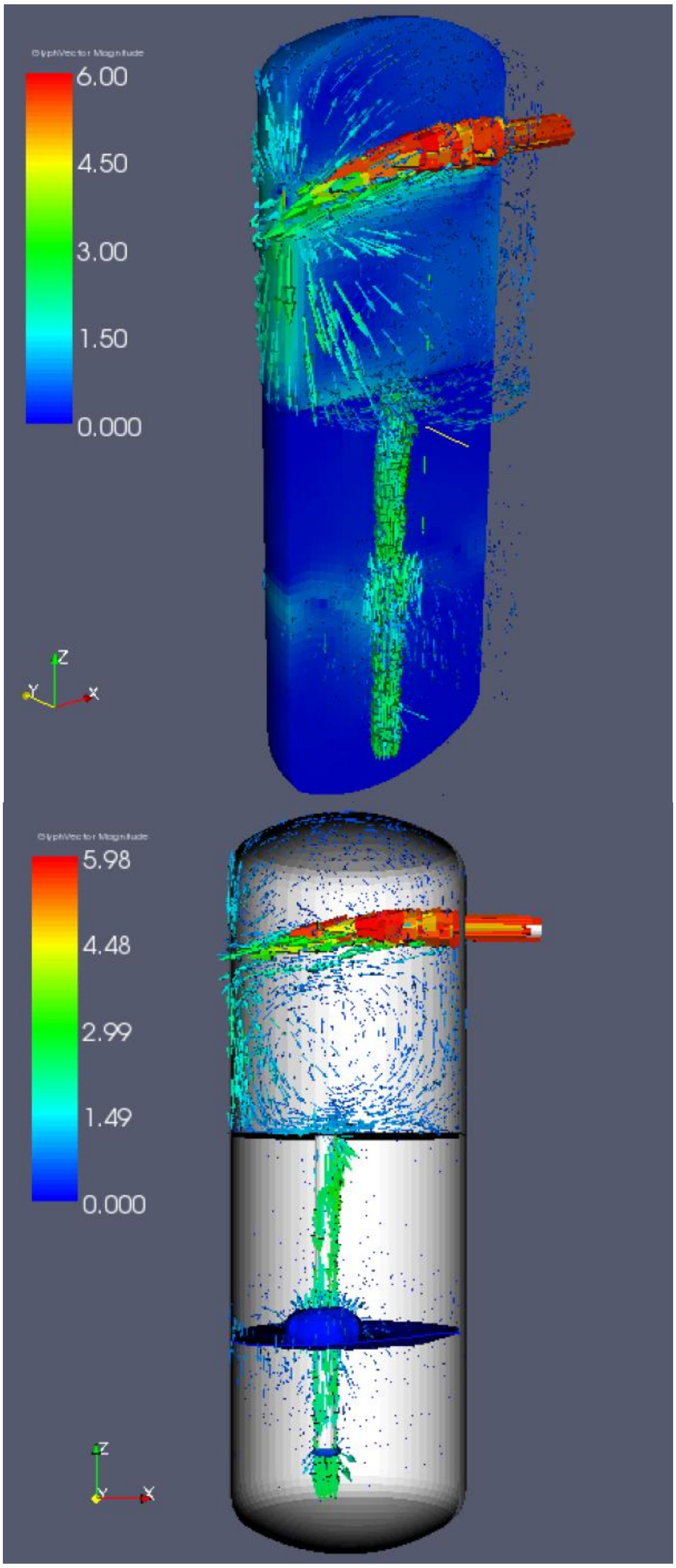


Figure 22. Velocity vectors inside the PPOOLEX test vessel in CHAR-09-3.

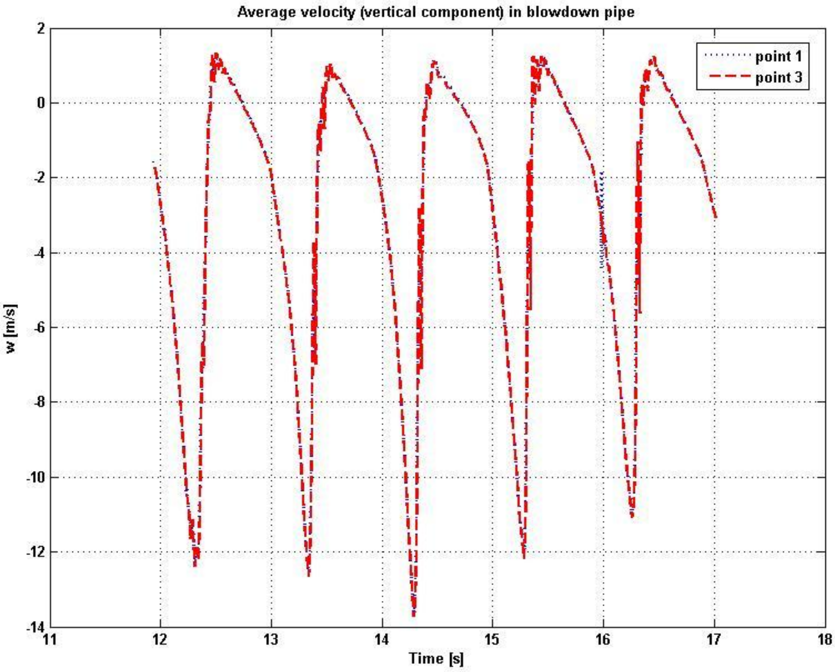


Figure 23. Average vertical velocity component in the blowdown pipe in CHAR-09-3.

Figure 24 presents the temperature stratification inside the pressure vessel. Air temperatures seem to stratify qualitatively in a realistic manner but yet in a slightly different way than in the simulation of CHAR-09-1. The higher flow rate of air in CHAR.09-3 surely effects on the stratification phenomenon especially in the dry well compartment. Exact comparison with the test is not possible since there were too few temperature measurements present. No heat conduction was modeled through the wet well / dry well wall in the simulation of CHAR-09-3.

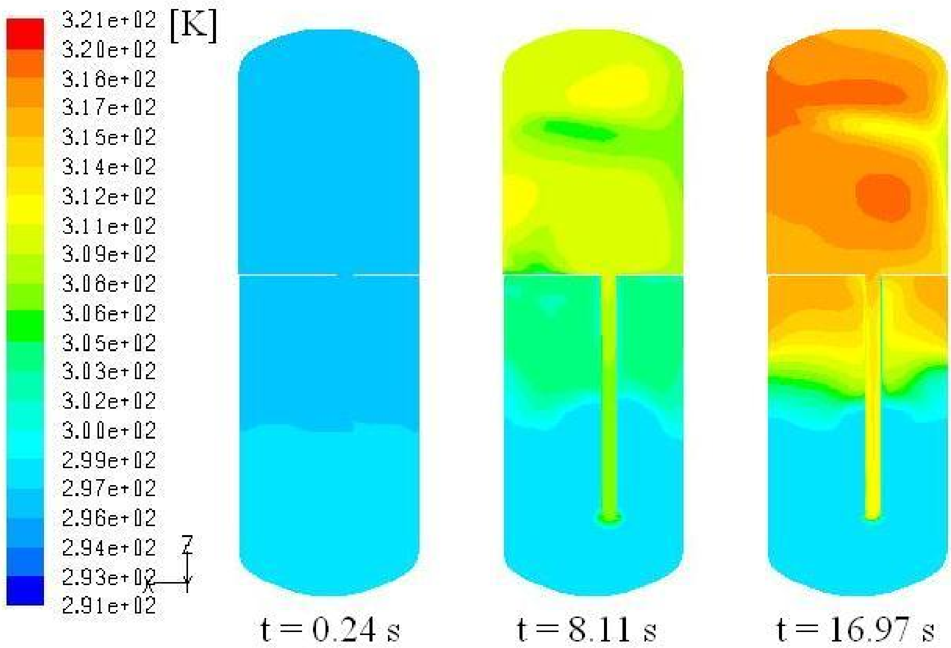


Figure 24. Static temperatures in the test vessel in CHAR-09-3.

6 SUMMARY AND CONCLUSIONS

Two tests from the characterizing test program in the PPOOLEX facility in 2007 were selected for a CFD simulation exercise. In both tests, only pure air was used. Before the tests the condensation pool (wet well) was filled with water to the level of 2.14 m i.e. the blowdown pipe outlet was submerged by 1.05 m. The initial pressure of the air accumulators before the blowdowns was 0.8 MPa. Pool water bulk temperature was about 24 °C. The air mass flow rate ranged from 10 to 170 g/s in CHAR-09-1 and from 10 to 600 g/s in CHAR-09-3. During the experiments the LabView data acquisition system recorded data with a frequency of 1 kHz.

Using FLUENT Inc. CFD-software, CHAR-09-1 was simulated to 28.92 seconds of real time and CHAR-09-3 to 17.01 seconds. The VOF model was used as a multiphase model and the standard k-ε-model as a turbulence model. Occasional convergence problems, usually at the beginning of bubble formation, required the use of relatively short time stepping. The simulation time costs threatened to become unbearable since weeks or months of wall-clock time with 1-2 processors were needed. Therefore, the simulated time periods were limited from the real duration of the experiments.

The results obtained from the CFD simulations are in a relatively good agreement with the experimental results. Simulated pressures correspond well to the measured ones and, in addition, fluctuations due to bubble formations and break-ups are also captured. Most of the differences in temperature values and in their behavior seem to depend on the locations of the measurements. In the vicinity of regions occupied by water in the experiments, thermocouples getting wet or drying slowly may have had an effect on the measured temperature values. Generally speaking, most temperatures were simulated satisfyingly and the largest discrepancies could be explained by wetted thermocouples. There are, however, still some measurements (dry well and blowdown pipe top), whose behavior cannot be explained directly by them getting wet. Heat losses and dry well / wet well heat transfer due to conduction have neither been estimated in the experiments nor modeled in the simulations. In short duration simulations, as is the case here, heat conduction to structures or heat losses to surroundings would probably have no effect on the calculation results. However, estimation of heat conduction and heat losses should be carried out in future experiments and in longer simulations they should be modeled, too.

7 REFERENCES

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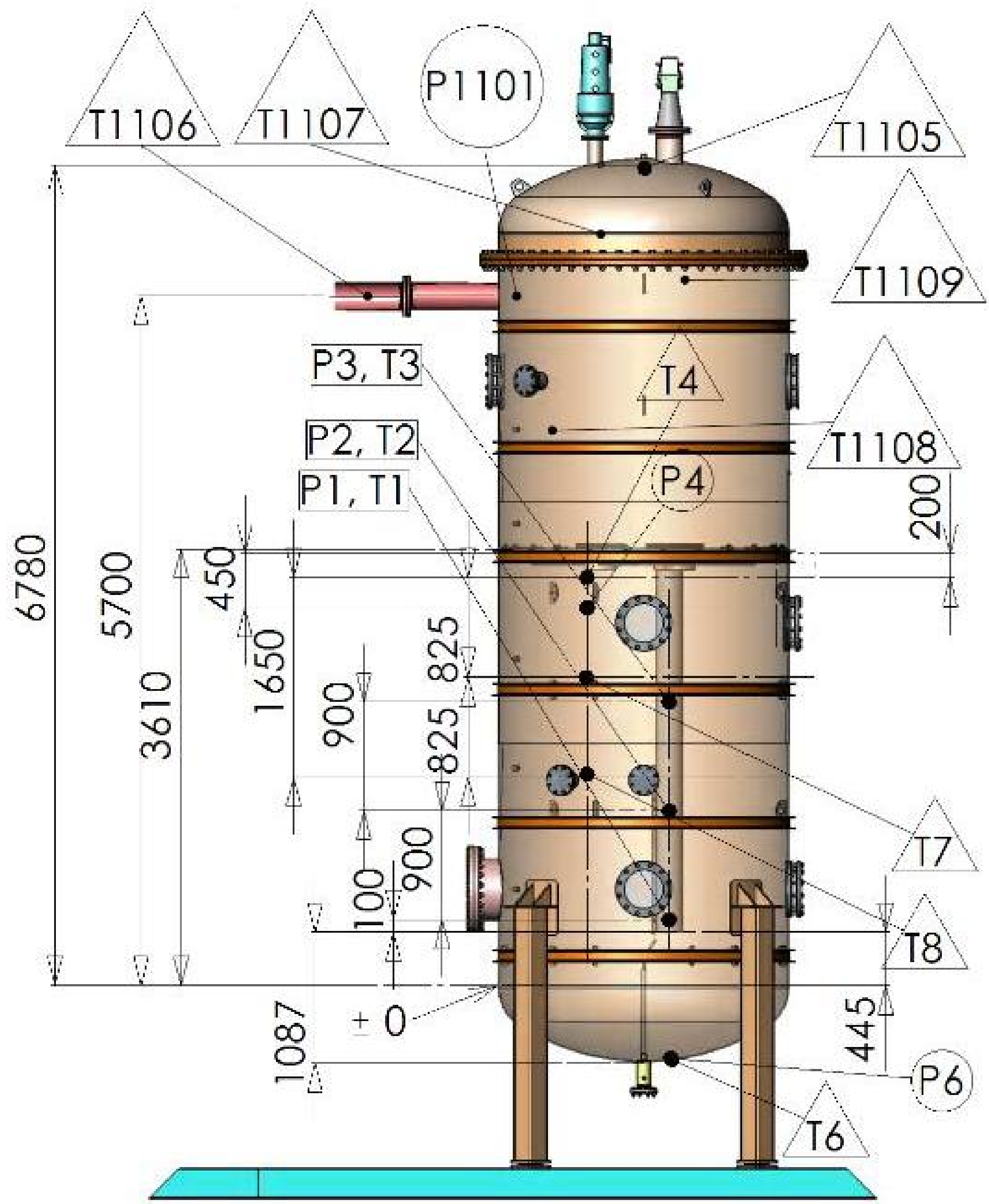
[6] Pättikangas, T., Timperi, A., Niemi, J. and Kuutti, J., Modelling of blowdown of air in the pressurized PPOOLEX facility, Research Report VTT-R-02233-08 (2008).

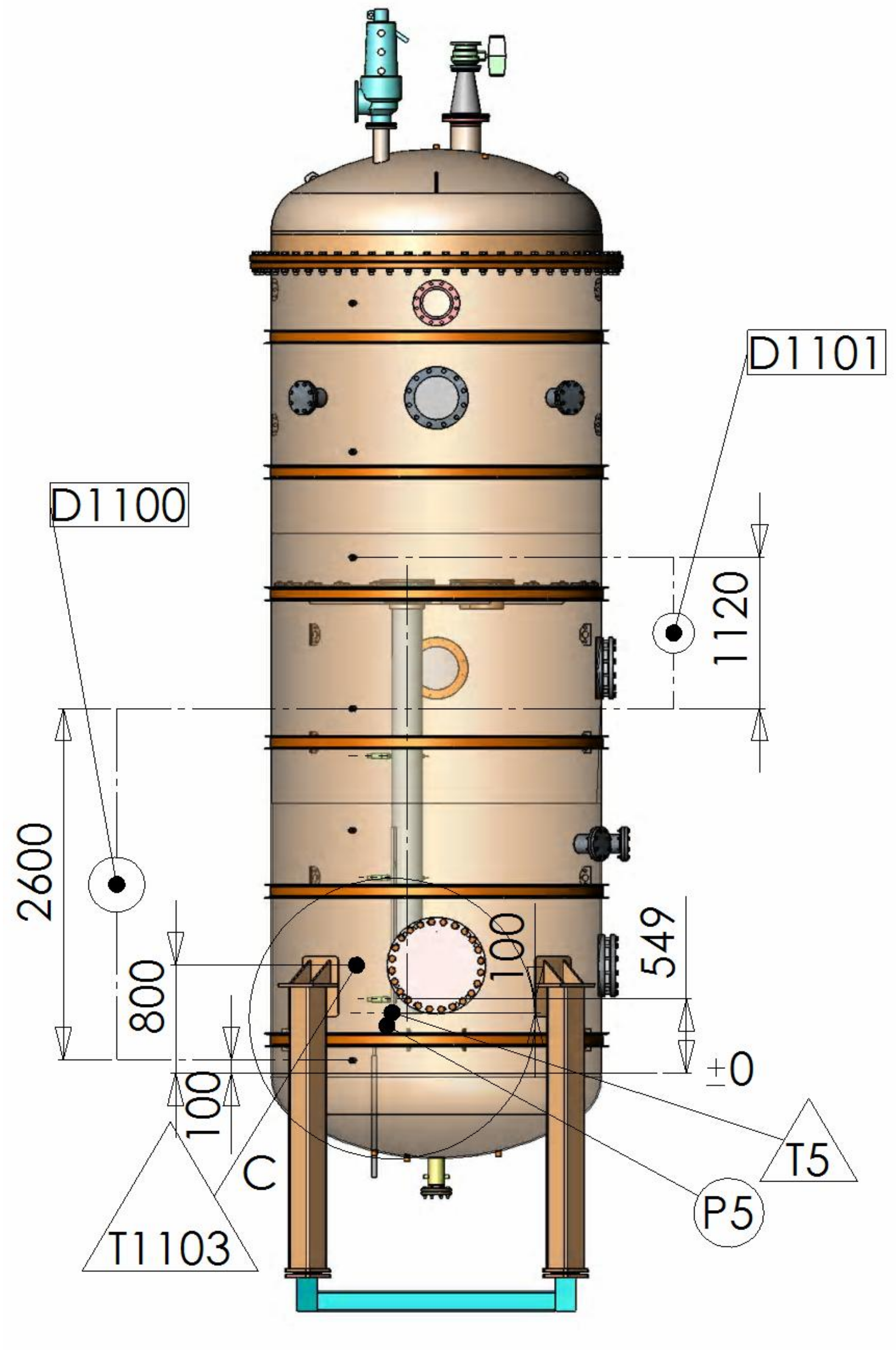
[7] Fluent 6.3 User's Guide, Copyright 2006 by Fluent Inc.

[8] Fluent 6.2 UDF Manual, Copyright 2005 by Fluent Inc.

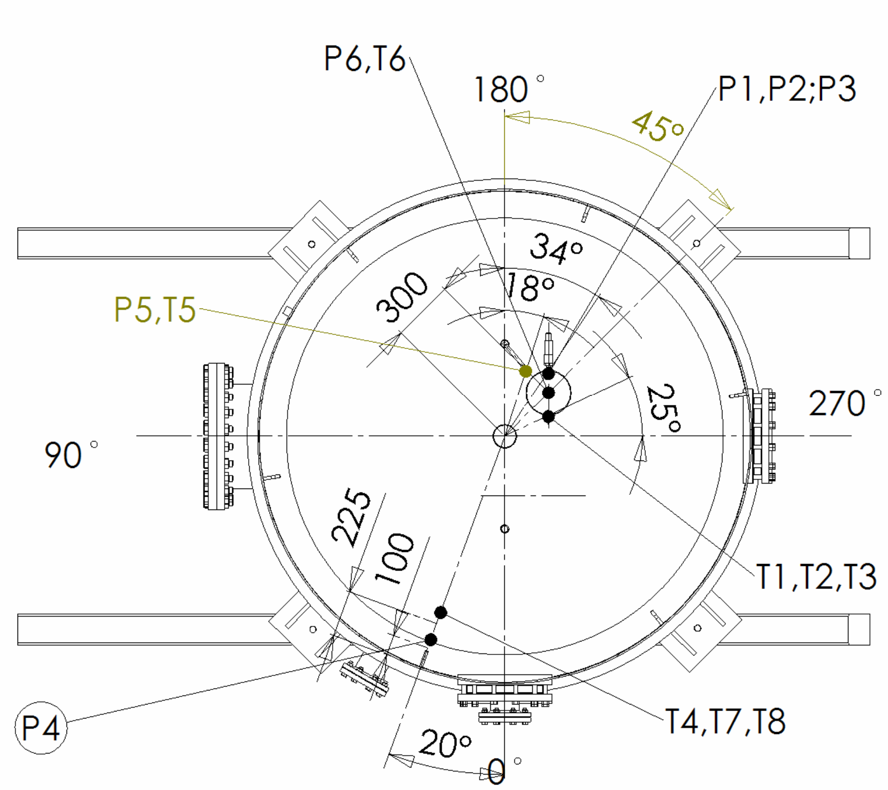
APPENDIX 1: INSTRUMENTATION OF THE PPOOLEX TEST FACILITY



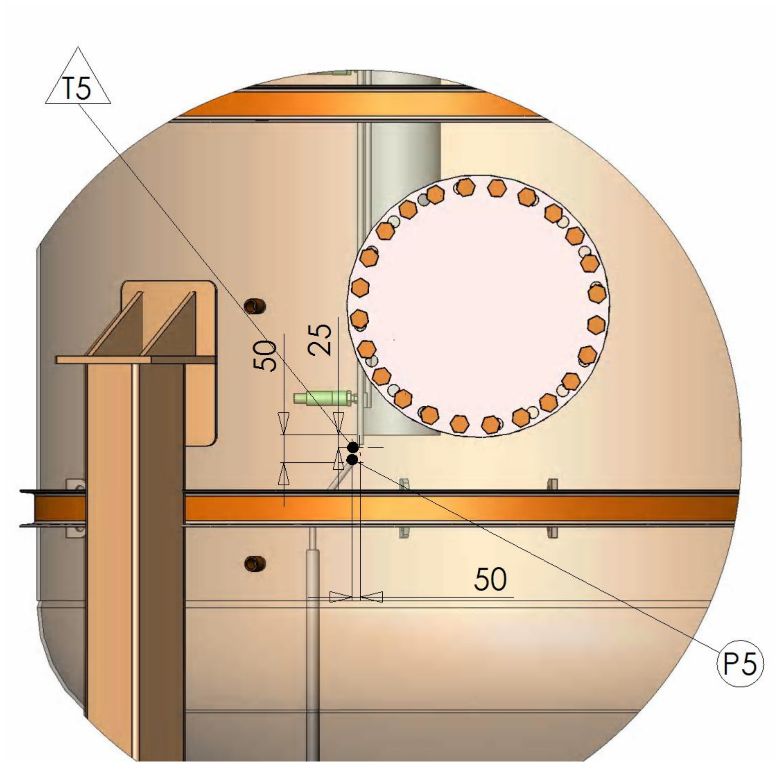
Test vessel measurements.



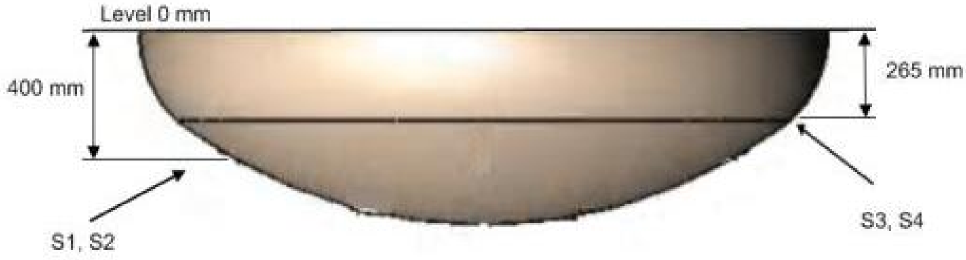
Test vessel measurements.

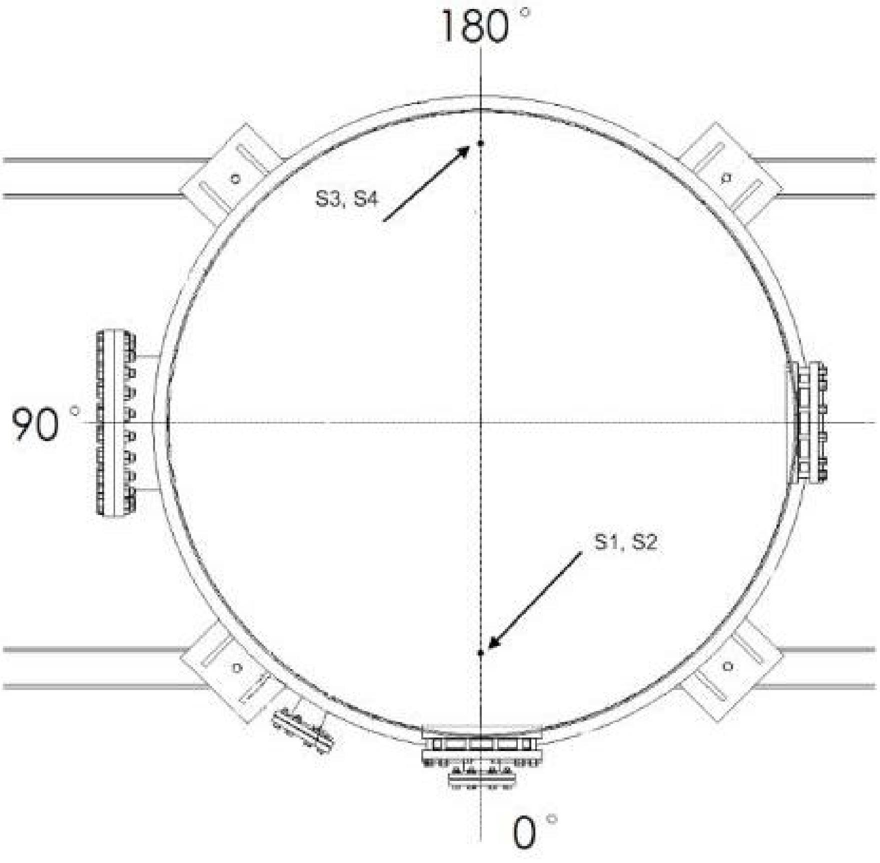


Measurement directions.



Pressure and temperature at the blowdown pipe outlet.



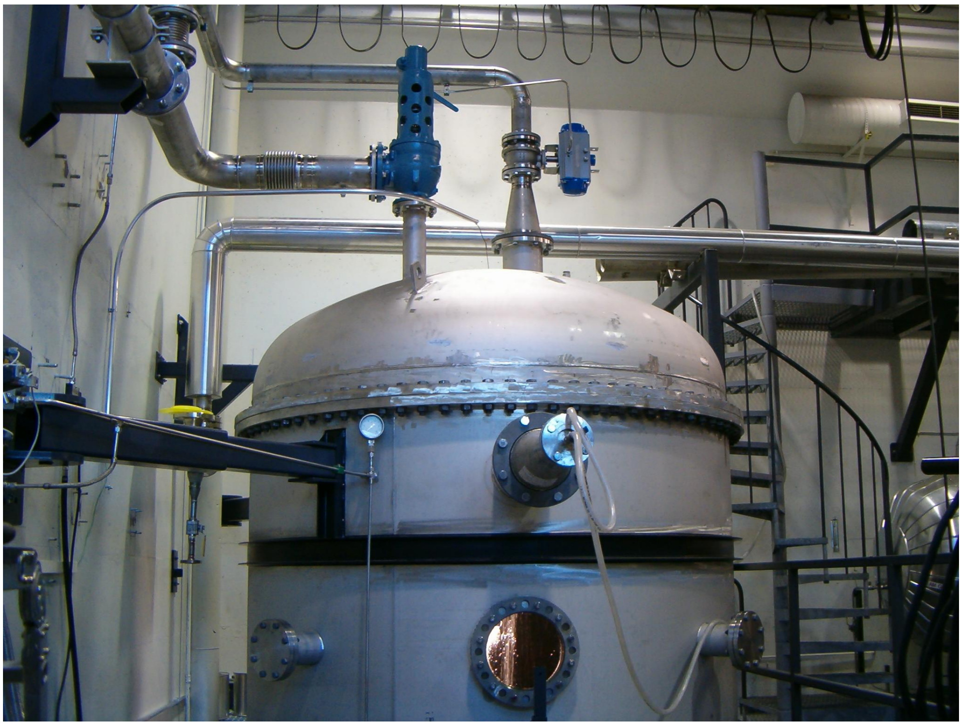


Strain gauges on the outer wall of the pool.

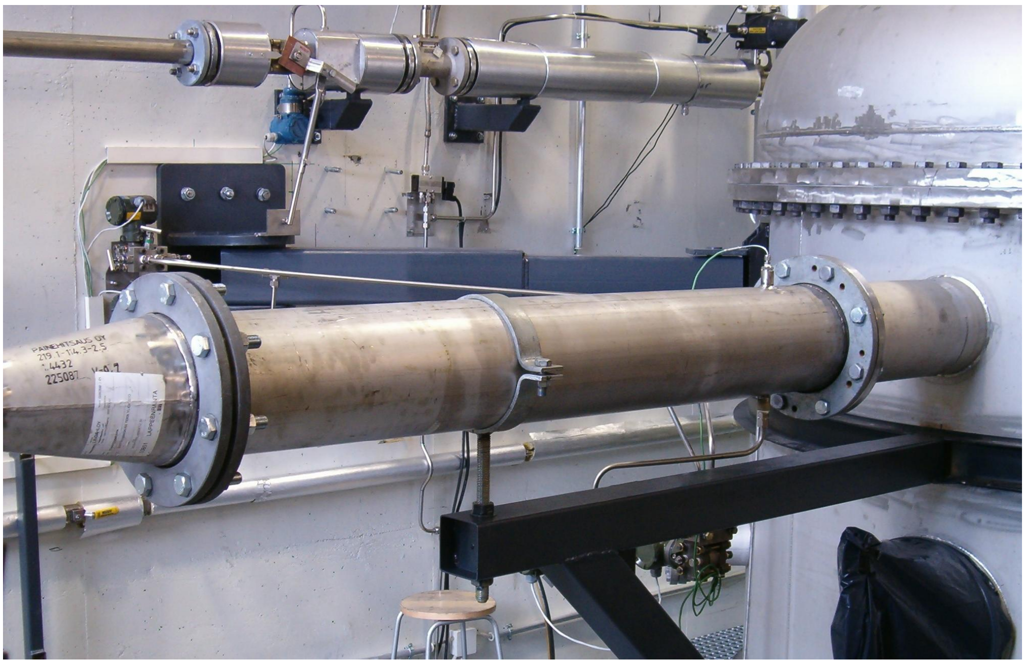
Measurement	Code	Elevation	Angle	Location	Comment
Pressure	P1	545	214	Blowdown pipe	
Temperature	T1	545	245	Blowdown pipe	
Temperature	T2	1445	245	Blowdown pipe	
Temperature	T3	2345	245	Blowdown pipe	
Pressure	P4	3160	20	Wet well gas space	
Temperature	T4	3410	20	Wet well gas space	
Pressure	P5	395	198	Blowdown pipe outlet	
Temperature	T5	420	198	Blowdown pipe outlet	
Pressure	P6	-1060	225	Wet well bottom	
Temperature	T6	-1060	225	Wet well bottom	
Temperature	T7	2585	20	Wet well	
Temperature	T8	1760	20	Wet well	
Pressure	P1101	5700	90	Dry well	
Temperature	T1104	-245	180	Outside wall	
Temperature	T1105	6780	-	Dry well top	
Temperature	T1107	6085	45	Dry well middle	Not installed in CHAR-09
Temperature	T1108	4600	120	Dry well bottom	Not installed in CHAR-09
Temperature	T1109	5790	225	Dry well lower middle	Not installed in CHAR-09
Temperature	T1103	800	120	Wet well	
Flow rate	F1101	5700	-	Inlet plenum	
Pressure	P1102	5700	-	Inlet plenum	
Temperature	T1106	5700	-	Inlet plenum	
Pressure	P1103	-	-	Air/steam line	
Pressure diff.	D1100	100-2700	120	Wet well	
Pressure diff.	D1101	2700-3820	120	Across the floor	
Flow rate	F1100	-	-	Steam line	
Temperature	T1102	-	-	At the steam line vortex	
Pressure	P1100	-	-	At the steam line vortex	
Flow rate	F9001	-	-	Air line	
Temperature	T9001	-	-	At the air line vortex	
Pressure	P9002	-	-	At the air line vortex	
Pressure	P9000	-	-	Air tank 1	
Temperature	T9000	-	-	Air tank 1	
Pressure	P9001	-	-	Air tank 2	
Temperature	T0460	-	-	Air tank 2	
Strain	S1	-400	0	Bottom segment	Not installed in CHAR-09
Strain	S2	-400	0	Bottom segment	Not installed in CHAR-09
Strain	S3	-265	180	Bottom segment	Not installed in CHAR-09
Strain	S4	-265	180	Bottom segment	Not installed in CHAR-09
Vertical pool movement	Z-axis	-	-	Below pool bottom	Not installed in CHAR-09

Measurements in the PPOOLEX facility.

APPENDIX 2: TEST FACILITY PHOTOGRAPHS



Dry well compartment and relief valves.



Inlet plenum.

Blowdown pipe and intermediate floor.

Pressure and temperature measurements at the blowdown pipe outlet.

APPENDIX 3: MEASUREMENT POINT COORDINATES

	X	Y	Z	Comments
Origin	0	0	0	At the centre of the pool bottom
P1	-0,21213200	-0,31449860	1,18700000	Inside the pipe
T1	-0,21213200	-0,09891880	1,18700000	Outside the pipe? For T1 inside see T1s1
P2	-0,21213200	-0,31449860	2,08700000	Inside the pipe
T2	-0,21213200	-0,09891880	2,08700000	Outside the pipe? For T2 inside see T2s1
P3	-0,21213200	-0,31449860	2,98700000	Inside the pipe
T3	-0,21213200	-0,09891880	2,98700000	Outside the pipe? For T3 inside see T3s1
P4	0,37451210	1,02900000	3,80200000	
T4	0,33175950	0,91150180	4,05200000	
P5	-0,10404540	-0,32021870	1,03700000	
T5	-0,10404540	-0,32021870	1,06200000	
P6	-0,21213200	-0,21213200	bottom	Bottom approximately at z = 0,025 m
T6	-0,21213200	-0,21213200	bottom	
T7	0,33175950	0,91150180	3,22700000	
T8	0,33175950	0,91150180	2,40200000	
T1105	0,00000000	0,00000000	7,42200000	
Pdrywell	1,10310000	-0,45692400	6,34200000	Corresponds to P1101 in means of elevation
D1100_lo	1,10310000	-0,45692400	0,74200000	Pressure difference between two points
D1100_hi	1,10310000	-0,45692400	3,34200000	
D1101_lo	1,10310000	-0,45692400	3,34200000	Pressure difference between two points
D1101_hi	1,10310000	-0,45692400	4,46200000	
T1103	1,10310000	-0,45692400	1,44200000	
P_alDN200	1,57350000	0,00000000	6,34200000	Middle of inlet pipe, corresponds to "P1103"
T1s	-0,21213200	-0,10800000	1,18700000	1-2mm inside the pipe
T2s	-0,21213200	-0,10800000	2,08700000	1-2mm inside the pipe
T3s	-0,21213200	-0,10800000	2,98700000	1-2mm inside the pipe
T1m	-0,21213200	-0,21213200	1,18700000	Inside, in the middle of pipe
T2m	-0,21213200	-0,21213200	2,08700000	Inside, in the middle of pipe
T3m	-0,21213200	-0,21213200	2,98700000	Inside, in the middle of pipe
T1s1	-0,21213200	-0,11600000	1,18700000	9-10mm inside the pipe
T2s1	-0,21213200	-0,11600000	2,08700000	9-10mm inside the pipe
T3s1	-0,21213200	-0,11600000	2,98700000	9-10mm inside the pipe

Coordinates of measurement points for Fluent simulations.

Bibliographic Data Sheet	**NKS-169**
Title	CFD Simulation of Air Discharge Tests in the PPOOLEX Facility
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Abstract	This report summarizes the CFD simulation results of two air discharge tests of the characterizing test program in 2007 with the scaled down PPOOLEX facility. Air was blown to the dry well compartment and from there through a DN200 blowdown pipe into the condensation pool (wet well). The selected tests were modeled with Fluent CFD code. Test CHAR-09-1 was simulated to 28.92 seconds of real time and test CHAR-09-3 to 17.01 seconds. The VOF model was used as a multiphase model and the standard k ε-model as a turbulence model. Occasional convergence problems, usually at the beginning of bubble formation, required the use of relatively short time stepping. The simulation time costs threatened to become unbearable since weeks or months of wall-clock time with 1-2 processors were needed. Therefore, the simulated time periods were limited from the real duration of the experiments. The results obtained from the CFD simulations are in a relatively good agreement with the experimental results. Simulated pressures correspond well to the measured ones and, in addition, fluctuations due to bubble formations and break-ups are also captured. Most of the differences in temperature values and in their behavior seem to depend on the locations of the measurements. In the vicinity of regions occupied by water in the experiments, thermocouples getting wet and drying slowly may have had an effect on the measured temperature values. Generally speaking, most temperatures were simulated satisfyingly and the largest discrepancies could be explained by wetted thermocouples. However, differences in the dry well and blowdown pipe top measurements could not be explained by thermocouples getting wet. Heat losses and dry well / wet well heat transfer due to conduction have neither been estimated in the experiments nor modeled in the simulations. Estimation of heat conduction and heat losses should be carried out in future experiments and they should be modeled in future simulations, too.
Key words	condensation pool, air discharge, non-condensable gas, CFD simulation

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