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Combined Effects Experiments with the Condensation Pool Test Facility

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Abstract

This report summarizes the results of the condensation pool experiments in spring 2006, where steam and steam/air mixture was blown into the pool through a DN200 blowdown pipe. Altogether three experiments, each consisting of several blows, were carried out with a scaled down test facility designed and constructed at Lappeenranta University of Technology. The main purpose of the experiments was to study the effects of non-condensable gas present in the discharge flow. Particularly pressure pulses inside the blowdown pipe and at the pool bottom caused by chugging were of interest.

The test pool was an open stainless steel tank with a wall thickness of 4 mm and a bottom thickness of 5 mm containing 15 m3 of water. The nearby PACTEL test facility was used as a steam source. During the experiments the initial pressure of the steam source was 0.5 MPa and the pool water bulk temperature ranged from 40 C to 70 C. The test facility was equipped with high frequency instrumentation for capturing different aspects of the investigated phenomena. The data acquisition program recorded data with the frequency of 10 kHz. A digital high-speed video camera was used for visual observation of the pool interior.

Air, in quantities even less than 1 %, reduced the condensation rate considerably. The high pressure pulses registered inside the blowdown pipe due to water hammer propagation during chugging almost disappeared when the combined discharge period of steam and air started. With non-condensable gas fractions above 3 % the damping of pressure oscillations inside the blowdown pipe was practically complete. Air quantities in the vicinity of 2 % started to have an effect also on the oscillations measured by the pressure sensor at the pool bottom. Both the amplitude and frequency of the pressure pulses decreased considerably.

The experiments demonstrated that even small quantities of non-condensable gas can have a strong diminishing effect on pressure oscillations and structural loads.

Key words

condensation pool, steam/air blowdown, non-condensable gas, pressure oscillations

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COMBINED EFFECTS EXPERIMENTS WITH THE CONDENSATION POOL TEST FACILITY

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Summary

This report summarizes the results of the condensation pool experiments in spring 2006, where steam and steam/air mixture was blown into the pool through a DN200 blowdown pipe. Altogether three successful experiments, each consisting of several blows (tests), were carried out with a scaled down test facility designed and constructed at Lappeenranta University of Technology. The main purpose of the experiment series was to study the effects of non-condensable gas present in the discharge flow. Particularly pressure pulses inside the blowdown pipe and at the pool bottom caused by chugging were of interest.

The test pool was an open stainless steel tank with a wall thickness of 4 mm and a bottom thickness of 5 mm containing 15 m^3 of water. The nearby PACTEL test facility was used as a steam source. During the experiments the initial pressure of the steam source was 0.5 MPa and the pool water bulk temperature ranged from 40 °C to 70 °C. The test facility was equipped with high frequency measurement instrumentation for capturing different aspects of the investigated phenomena. The data acquisition program recorded data with the frequency of 10 kHz. A digital high-speed video camera was used for visual observation of the pool interior.

Air, in quantities even less than 1 %, reduced the condensation rate considerably. The high pressure pulses registered inside the blowdown pipe due to water hammer propagation during chugging almost disappeared when the combined discharge period of steam and air started. With non-condensable gas fractions above 3 % the damping of pressure oscillations inside the blowdown pipe was practically complete. Air quantities in the vicinity of 2 % started to have an effect also on the oscillations measured by the pressure sensor at the pool bottom. Both the amplitude and frequency of the pressure pulses decreased considerably. However, no clear pattern in observed strains between pure steam and steam/air mixture discharge could be found.

The experiments demonstrated that even small quantities of non-condensable gas can have a strong diminishing effect on pressure oscillations and structural loads.

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PREFACE

The 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).

In these experiments, the formation, size and distribution of non-condensable gas bubbles in the condensation pool was studied with a 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 experiment conditions were modeled with the Fluent computational fluid dynamics (CFD) code at VTT. The Fluent simulations were utilized in the planning phase of the experiment to select the position, size and number of blowdown pipes. The post-test calculations were carried out for code validation purposes.

A new research project called Condensation POOL EXperiments (POOLEX) started in 2003 within the SAfety of Nuclear Power Plants - FInnish National Research Programme (SAFIR). The POOLEX project continues the work done within the FINNUS programme [1]. In the new experiments, steam is injected into the condensation pool test rig. The main objective of the POOLEX project is to increase the understanding of different phenomena in the condensation pool during steam discharge. The study is funded by the State Nuclear Waste Management Fund (VYR) and by the Nordic nuclear safety research (NKS).

CONTENTS

NOMENCLATURE

A	area
d	diameter
g	acceleration of gravity
G	mass flux
p	pressure
Q	volumetric flow rate
T	temperature

Greek symbols

Δ	change
ε	strain
ρ	density

Abbreviations

APROS	Advanced Process Simulation Software
BWR	boiling water reactor
CFD	computational fluid dynamics
ECCS	emergency core cooling system
fps	frames per second
LOCA	loss-of-coolant accident
LUT	Lappeenranta University of Technology
NKS	Nordic nuclear safety research
PACTEL	parallel channel test loop
POOLEX	condensation pool experiments project
PWR	pressurized water reactor
RAM	random access memory
SAFIR	Safety of Nuclear Power Plants – Finnish National Research Programme
SG	steam generator
SRV	safety/relief valve
TVO	Teollisuuden Voima Oy
VTT	Technical Research Centre of Finland
VYR	State Nuclear Waste Management Fund
VVER	Vodo Vodjanyi Energetitseskij Reaktor

1 INTRODUCTION

During a possible 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.

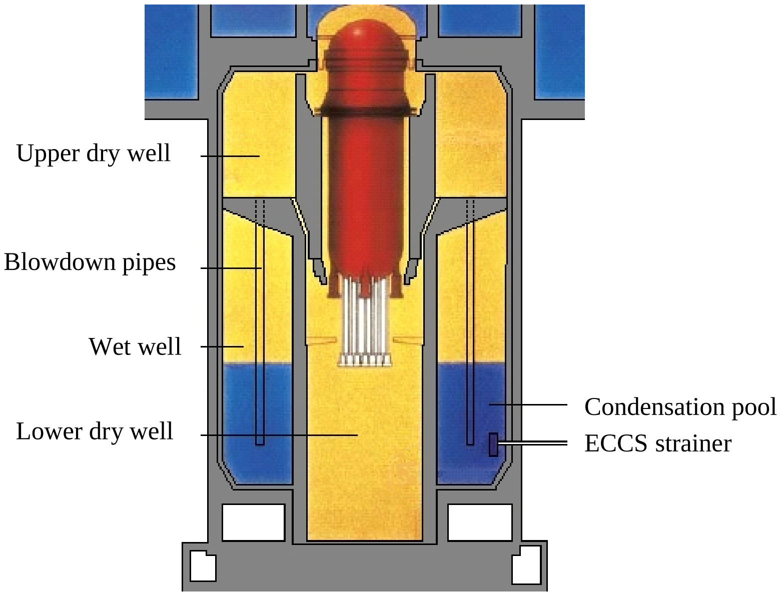


Figure 1. Schematic of the Olkiluoto type BWR containment.

The main objective of the POOLEX project is to increase the understanding of different phenomena in the condensation pool during steam injection. These phenomena could be connected to bubble dynamics issues such as bubble growth, upward acceleration, detachment and break-up. The bubbles interact with pool water by heat transfer and steam condensation and by momentum exchange via buoyancy and drag forces. Pressure oscillations due to rapid condensation are also among the issues of interest. The investigation of the 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. The needs for instrumentation, data acquisition and visualization were reviewed in the beginning of the project.

Experiment results of the POOLEX project, supposing that they are exact and of high-quality, can be used for the validation of different numerical methods for simulating steam injection through a blowdown pipe into liquid. Experimental studies on the process of formation, detachment and break-up and the simultaneous condensation of large steam bubbles are still sparse and thus the improvement of models for bubble dynamics is necessary for the reduction of uncertainties in predicting condensation pool behaviour during steam injection. Some of the 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.

With the aid of high-speed video observations used in the POOLEX experiments, the validity of correlations for steam bubble size and break-up heights as a function of total volumetric flow-rate and of pool sub-cooling can be investigated. In determining condensation rates during bubble formation direct measurement of heat and mass transfer is desirable, but virtually impossible. However, the process of direct-contact condensation of large steam bubbles in water is well suited for visual observation. Interfaces are macroscopic and well visible. To some extent, condensation rates can be determined indirectly from volume rates-of-change estimated from video images.

The development work of 3D two-phase flow models for CFD codes can be assisted by the POOLEX 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 2003, Lappeenranta University of Technology performed eight series of preliminary condensation pool experiments with steam using DN80 and DN100 blowdown pipes [2]. After that some improvements were made to the measurement instrumentation and also to the data acquisition system. In March 2004, three additional preliminary experiment series were carried out using a DN200 blowdown pipe [3].

Later in 2004, more high frequency instrumentation (particularly pressure transducers) was added to the test rig. A new faster data acquisition system was bought in order to be able to measure and record an adequate number of measurement channels with high sampling rates (10 kHz). For more accurate observation of steam bubbles, the test rig was furnished with a digital high-speed video camera. The results of the first detailed steam experiments are presented in reference [4].

In spring 2005, two thermal stratification experiments were carried out to study temperature stratification phenomenon in the condensation pool during steam discharge and to produce data for the validation of the stratification model of the APROS code [5]. Later in 2005, a series of steam blowdown experiments on chugging was executed [6]. A specific POOLEX experiment series with a thermally insulated blowdown pipe and a small steam mass flux was carried out for the purposes of the EU/NURESIM and SAFIR/ECE projects at the end of 2005 [7].

During the first seconds of a postulated steam line break inside the BWR containment the fraction of non-condensable gas among the steam discharging into the condensation pool is very high. Non-condensable gases have a strong effect on condensation heat transfer. The condensation heat transfer coefficient and heat transfer rate decrease with non-condensable gas. This has an effect on pressure oscillations related to rapid condensation and through that on loads experienced by the pool structures. Also bubble dynamics (formation at the blowdown pipe outlet, shape, detachment) could be affected by the presence of non-condensable gas.

In spring 2006, an experimental study was performed in the POOLEX test facility to investigate the effects of non-condensable gas on bubble dynamics and pressure loads during chugging. Experiment results can also be useful in the improvement of CFD models for condensation in the presence of non-condensable gases. In this report, the results of those combined effects experiments are presented. First, chapter two presents the different condensation modes in a BWR suppression pool during a loss-of-coolant accident (LOCA). Chapter three gives a short description of the test facility and its measurements as well as of the data acquisition system used. The test programme is introduced in chapter four. The test results are presented and shortly discussed in chapter five. A brief combined effects analysis is made in chapter six. Chapter seven summarizes the findings of the experiments.

2 CONDENSATION MODES DURING LOCA OR SAFETY/RELIEF VALVE BLOWDOWN

In the handbook of thermal hydraulics of BWRs, Lahey and Moody present a map of condensation modes that have been observed during either LOCA or safety/relief valve (SRV) steam discharge, see Figure 2.

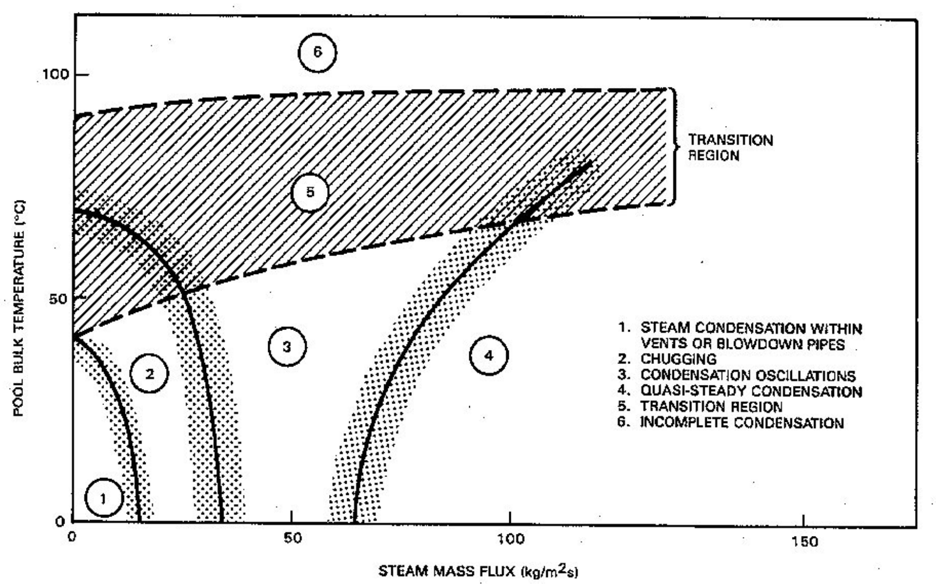


Figure 2. Condensation mode map for pure steam discharge [8].

With low steam mass flux and cold pool water temperature, condensation takes place within vents or blowdown pipes. A sharp drop in local steam pressure occurs as steam condenses rapidly when interacting with cold pool water. Because the condensation process is very rapid, an underpressure develops inside the blowdown pipe. Immediately after that, a condensation-induced water hammer is initiated as the pipe begins to fill with water. At the end of the collapse, a high pressure pulse occurs inside the pipe when it is filled with water. In this condensation mode, steam-water interface moves strongly up and down in the blowdown pipe.

As the steam mass flux increases, chugging or random condensation phenomena will commence. In chugging, the steam-water interface moves downwards inside the blowdown pipe and a steam bubble is formed at the pipe outlet (see steps 1-5 in Figure 3). The bubble condenses rapidly and an underpressure is generated (step 6). The steam-water interface begins to move upwards inside the pipe (steps 7-9) until the steam pressure is high enough to stop the interface and start to push it downwards again (steps 10). Chugging imposes dynamic loads on submerged pool structures [8].

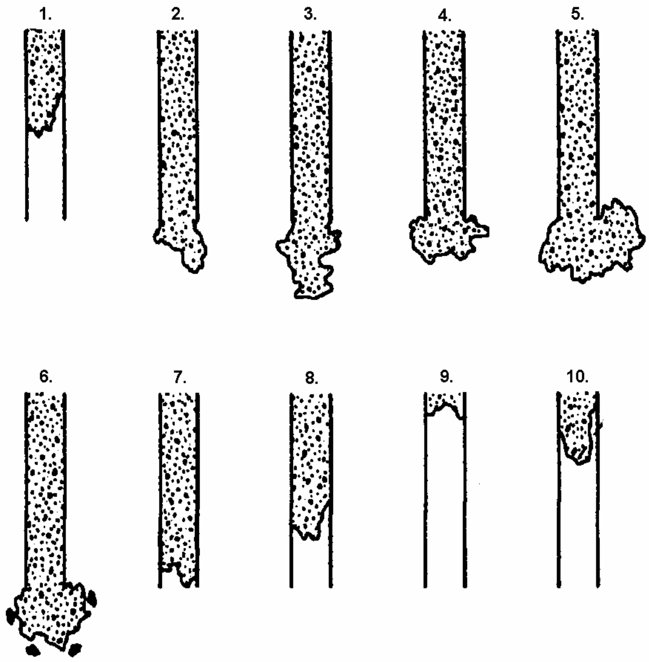


Figure 3. Sketch of the chugging phenomena [9].

Increasing the steam mass flux further leads to condensation oscillations. In this case, the steam-water interface undergoes a condensation event entirely in the pool. Steam bubble forms at the pipe outlet and begins to collapse. However, the high steam flow rate prevents water re-entry into the blowdown pipe. The next bubble is formed resulting to a condensation event and the cycle is repeated. Condensation oscillations cause unsteady loads on submerged pool structures [8].

With very high steam flows quasi-steady condensation is the dominating condensation mode. In this mode, high steam mass flux keeps the steam-water interface on the pipe outlet. Because the steam condenses steadily, no large loads are imposed on submerged pool structures.

3 TEST FACILITY

The condensation pool test facility was first used for the experiments where the effect of non-condensable gas on the performance of an ECCS pump was examined [1]. After some modifications, preliminary experiments with steam were executed by using DN80, DN100 and DN200 blowdown pipes [2, 3]. A new data acquisition system capable of measuring and recording a larger number of channels with adequate sampling rates was installed. For more accurate observation of the condensation phenomenon, the test rig was furnished with a digital high-speed video camera. After adding extra high-frequency instrumentation, particularly pressure transducers, the first experiment series on steam discharge and associated pressure oscillations was executed with the modified pool test facility by using one DN200 blowdown pipe [4]. A sketch of the test facility is presented in Figure 4. Table 1 shows the main dimensions of the test facility compared to Olkiluoto plant conditions.

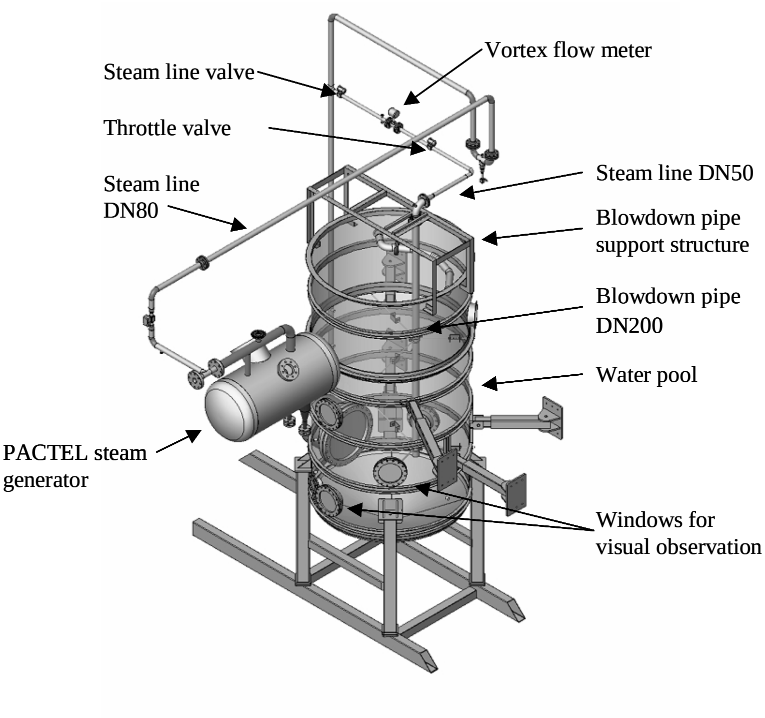


Figure 4. POOLEX test facility.

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

	POOLEX test facility	Olkiluoto 1 and 2
Number of blowdown pipes	1	16
Inner diameter of blowdown pipe [mm]	214.1	600
Pool cross-sectional area [m^2]	4.5	287.5
Water level in the pool [m]	3.5	9.5
Pipes submerged [m]	2.0	6.5
Pool water volume [m^3]	15	2700
A_{pipes}/A_{pool}x100%	0.8	1.6

3.1 MEASUREMENT INSRUMENTATION

The test facility is equipped with thermocouples for measuring steam, non-condensable gas and pool water temperatures (T), with pressure transducers (P) for observing pressure behavior in the blowdown pipe, in the steam line, in the non-condensable line and at the pool bottom and with one pressure transducer (DP) for detecting the pool water level. Steam flow is measured with a vortex flow meter in the DN50 steam line. Non-condensable gas flow is measured with a vortex flow meter in an adjacent line before the injection point. Additional instrumentation includes six strain gauges (ST) on the pool outer wall, valve position sensors and a high-speed video camera trigger. Appendix 1 shows the exact measurement locations. Table 2 lists the identification codes and error estimations of the measurements. The error estimations are calculated on the basis of variance analysis. The results agree with normal distributed data with 95% confidence interval.

Temperatures are measured by K-type thermocouples. ∅ 0.5 mm thermocouples have proved to be fast enough for capturing the investigated phenomena with sufficient accuracy.

Pressure oscillations in the blowdown pipe are measured by high-frequency pressure transducers (model: Kyowa PVL-100K). Also the pressure transducer on the pool bottom is a high-frequency transducer (Kyowa PVL-5K). Frequency responses of the transducers are 1 kHz.

Six uniaxial foil strain gauges (model: Kyowa KFG-5-120-C1-11 L1M2R) are attached with glue onto the pool outside wall, see Appendix 1. The gauge length and width are 5.0 mm and 1.4 mm, respectively. Frequency response of the amplifier is 5 kHz.

Table 2. Measurement instrumentation

Code	**Measurement**	**Error estimation**
T1	Temperature in the blowdown pipe (bottom)	±1.8°C
T2	Temperature in the blowdown pipe (middle)	±1.8°C
T3	Temperature in the blowdown pipe (top)	±1.8°C
T13	Temperature in the steam line	±3.5°C
T14	Temperature in the pool	±2.7°C
T15	Temperature at the pool bottom	±1.8°C
T16	Temperature on the pool outer wall	±2.6°C
T20	Temperature in the non-condensable gas line	±2.8°C
T401	Temperature on the blowdown pipe outer wall	±1.8°C
T402	Temperature 10 mm from the blowdown pipe outer wall	±1.8°C
T504	Temperature in the steam line	±1.8°C
P1	Pressure in the blowdown pipe (bottom)	±93 kPa
P2	Pressure in the blowdown pipe (middle)	±93 kPa
P3	Pressure in the blowdown pipe (top)	±93 kPa
DP6	Water level in the pool	±0.06 m
P7	Pressure in the steam line	±93 kPa
P8	Pressure in the steam generator	±60 kPa
P9	Pressure at the pool bottom	±5 kPa
P20	Pressure in the non-condensable gas line	±15 kPa
F1	Volumetric flow rate in the steam line	±4.9 l/s
F20	Mass flow rate in the non-condensable gas line	±0.9 g/s
ST1	Strain on the pool outer wall	±21 μS[1]
ST2	Strain on the pool outer wall	±21 μS[1]
ST3	Strain on the pool outer wall	±21 μS[1]
ST4	Strain on the pool outer wall	±21 μS[1]
ST5	Strain on the pool outer wall	±21 μS[1]
ST6	Strain on the pool outer wall	±21 μS[1]
Trig	High speed camera trigger	Not defined
Valve	Valve position	Not defined

[1] The error estimates do not contain the effect of the strain gauge and the amplifier.

3.2 DIGITAL HIGH-SPEED VIDEO CAMERA

A Citius Imaging digital high-speed video camera (model C10) is used for visual observation of the pool interior. The camera is controlled with a PC. The PC is also used for display and storage of video data. The camera is a single unit and it is connected to the PC through a USB bus. Several cameras can be networked e.g. for recording the same event from different angles simultaneously [10].

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 maximum available amount of memory; 2 GB. The camera can achieve over 10000 frames/second (fps) recording speed and up to 652x496 pixels resolution with 256 shades of gray [10].

However, speed and maximum recording time depend on the resolution used. During the experiments a recording speed of approximately 400 fps with maximum available resolution (264x264) was used. With these set-ups the maximum recording time is about 70-80 seconds (29 MB/s). Table 3 shows more examples of resolution/speed/recording time combinations that can be attained with the camera.

Table 3. Examples of resolution, speed and maximum recording time combinations of Citius Imaging high-speed digital video camera C10 [10]

Resolution [pixels]	Speed [fps]	Max. recording time [s]
640x480	99	70.9
340x256	330	74.7
172x128	1154	84.5
84x64	3551	112.5
40x20	10652	252

3.3 DATA ACQUISITION

National Instruments PCI-PXI-SCXI is a PC-driven multi-channel measurement system with a LabView user interface. The maximum number of measurement channels is 96 with additional eight channels for strain measurements. The maximum recording frequency depends on the number of measurements and is in the region of 300 kHz for all measured channels combined. The data acquisition system is discussed in more detail in reference [11].

Separate HPVee based software is used for monitoring and recording the essential measurements of the PACTEL facility producing the steam [12]. Both data acquisition systems measure signals as volts. After the experiments, the voltage readings are converted to engineering units by using special conversion software.

The used data recording frequency of LabView was 10 kHz for measurements P1-P3, P9 and ST1-ST6. For temperature measurements T1-T3, T15, T401, T402 and T504 the data recording frequency was 200 Hz (in the pre-tests the 122 Hz data recording frequency was found to be fast enough for capturing the investigated phenomena). The temperature measurements are therefore averages of 50 measured points. The rest of the measurements (for example in the non-condensable gas line) are recorded by HPVee software with the frequency of 1 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 either records the events from the triggering moment towards the future or from the past until the triggering moment. Boundary signal for the camera is approximately 3.5 V. Table 4 shows the structure of the engineering unit measurement database.

A high data recording frequency produces a large amount of measurement data. With the used data recording frequency and the number of measurement channels (10 kHz / 13 channels and 200 Hz / 7 channels for temperature readings); LabView produces approximately 12.5 MB of data per a 10 second time interval. As a comparison, HPVee produces no more than approximately 20 kB of data / 10 seconds. The large amount of measurement data causes problems when processing and archiving data.

Table 4. Structure of the measurement database

<experiment>_Temperatures.dat							
Data recording frequency: 200 Hz							
1	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Time	T1	T2	T3	T15	T401	T504	T402
[s]	[°C]	[°C]	[°C]	[°C]	[°C]	[°C]	[°C]

<experiment>_Pressures.dat												
Data recording frequency: 10 kHz												
1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**
Time	P1	P2	P3	P9	ST1	ST2	ST3	ST4	ST5	ST6	Trig	Valve
[s]	[bar]	[bar]	[bar]	[bar]	[μS]	[μS]	[μS]	[μS]	[μS]	[μS]	[V]	[V]

<experiment>_HPVee.dat									
Data recording frequency: 1 Hz									
1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Time	DP6	F1	F20	P20	P7	T13	T13sat	T14	T20
[s]	[m]	[l/s]	[g/s]	[bar]	[bar]	[°C]	[°C]	[°C]	[°C]

4 TEST PROGRAMME

In the earlier experiment series with the DN200 blowdown pipe in the POOLEX test facility pure[2] steam discharge has been used and the dominating condensation modes, as categorized by Lahey and Moody [8], have been "steam condensation within vents or blowdown pipes" and "chugging", see Figure 2. Pressure oscillations inside the blowdown pipe, loads on the pool structures and condensation rates (collapse times) of the steam bubbles at the blowdown pipe outlet have been the main interests of the experiments. Furthermore, aspects of thermal stratification have been studied in well defined conditions with the help of the experiment results. Some experiments have covered also parts of the "condensation oscillations" and "transition" regions of the condensation mode map.

The combined effects test program with steam/air mixture discharge in spring 2006 consisted of four experiments (labeled from STB-32 to STB-35). Experiment STB-32 was terminated soon after the beginning due to problems in the measurement of the gas flow rate. Experiments STB-33, STB-34 and STB-35 included twelve or thirteen separate steam/gas blowdown tests each. The experiments were performed by using the DN200 blowdown pipe. The three steam generators of the PACTEL test facility served as a steam source [12]. Before each experiment the pool was filled with water to the level of approximately 3.5 m i.e. the blowdown pipe outlet was submerged by 2 m. The position of the throttle valve (located just after the flow meter in the steam line) was adjusted before each experiment so that the desired steam flow rate would be achieved (150 l/s in STB-33, 230 l/s in STB-34 and 90 l/s in STB-35). During the pressure build-up of the PACTEL steam generators and between the individual tests the steam line was heated with a small bypass flow.

Each test consisted of two steps. After the correct initial pressure level in the steam generators had been achieved the remote-controlled shut-off valve in the steam line was opened. As a result, the blowdown pipe was filled with steam that immediately pushed its way to the pool. Then, the valve in the adjacent gas line was opened and air from the compressed air network was injected into the steam line, Air and steam mixed with each other before reaching the blowdown pipe.

In the first blow of STB-33 the thermocouple T3 was broken. It was not replaced during the experiment series. All other measurements worked properly during the test program. Table 5 shows the initial parameters of the experiments.

Table 5. Initial parameters for POOLEX experiments in spring 2006

Experiment	Steam generator initial pressure [MPa]	Initial pool water level [m]	Steam flow rate [l/s]	Comments
STB-32	0.5	~ 3.5	~160	Problems with gas flow measurement
STB-33	0.5	~ 3.5	~ 150	T3 broken
STB-34	0.5	~ 3.5	~ 230	T3 broken
STB-35	0.5	~ 3.5	~ 90	T3 broken

[2] The steam flow may have contained a small fraction of air since the amount of non-condensable gas dissolved in the coolant or present in the steam source is unknown.

5 ANALYSIS OF THE EXPERIMENTS

The following chapters give a more detailed description of the experiment program and also try to analyze the observed phenomena. Experiment STB-32 is omitted from the analysis since it was terminated soon after the beginning due to problems with the gas flow rate measurement.

5.1 STB-33

Twelve separate steam/air blowdown tests were executed (labeled from STB-33-1 to STB-33-12). LabView recorded data during the blowdowns. First, there was a period when discharge of pure steam was recorded. Then air injection was started without changing the steam flow rate. Figure 5 illustrates how steam and gas discharge was executed in each single test of the experiment. The main purpose of the experiment was to assess the effect of non-condensable gas present in the discharge flow on the measured pressure pulses inside the blowdown pipe and at the pool bottom caused by chugging. In each separate test, LabView data recording was started 15-25 seconds after initiating the steam blowdown so that the flow had enough time to level off. Furthermore, visual material from steam bubble formation at the blowdown pipe outlet both with and without non-condensable gas was produced with the digital high-speed video camera through the pool windows.

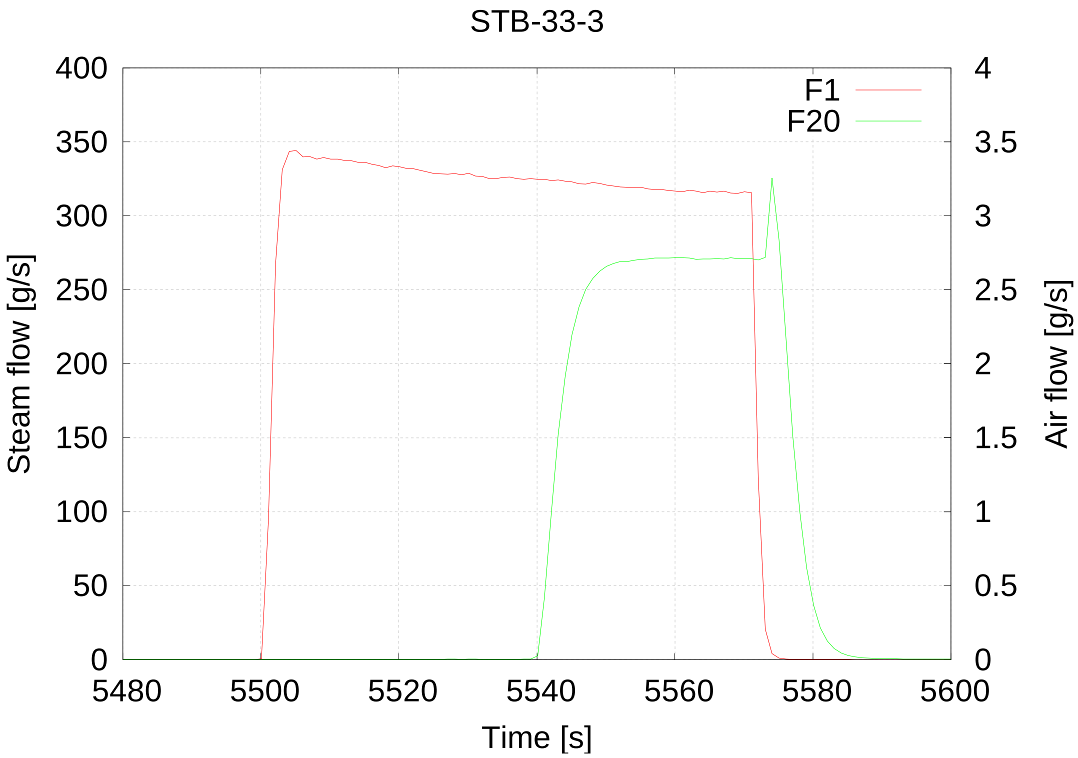


Figure 5. An example of the used procedure for steam (F1) and gas (F20) discharge in the combined effects experiments.

During the experiment the initial pressure of the PACTEL steam generator varied from 0.39 to 0.5 MPa (all three SGs in use). Before the first blowdown was initiated the temperature of the pool water was 40 °C. After the last blowdown the temperature had increased to 63 °C.

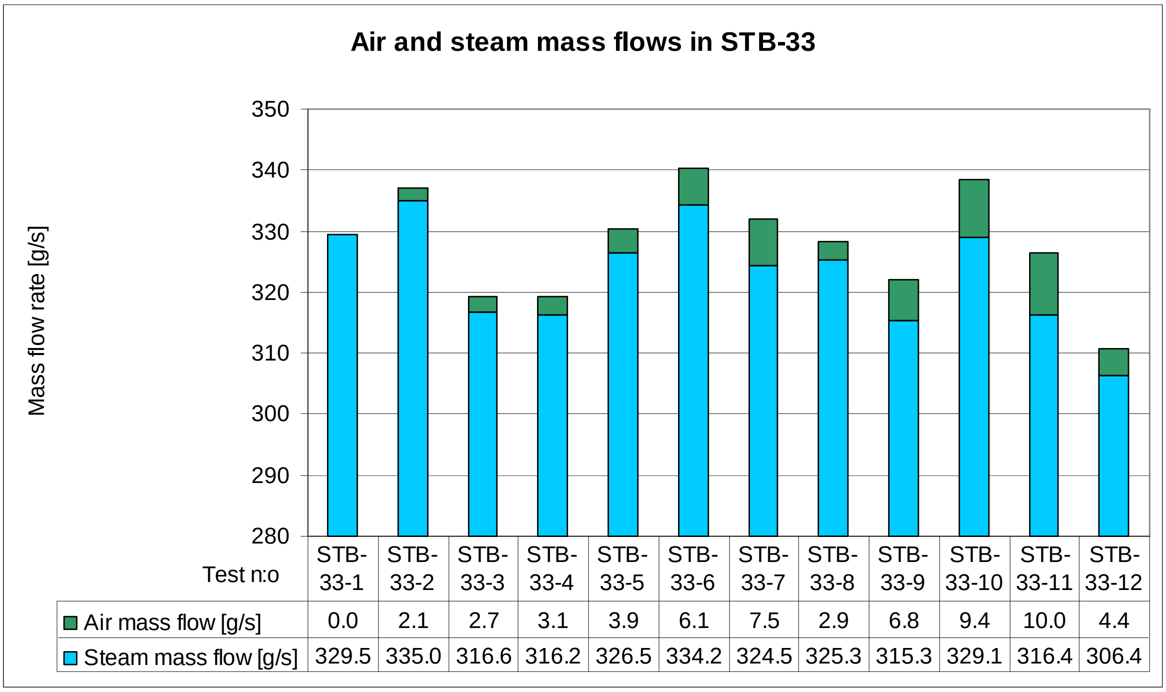


Figure 6. The ratio of air and steam mass flow in separate blowdowns of STB-33.

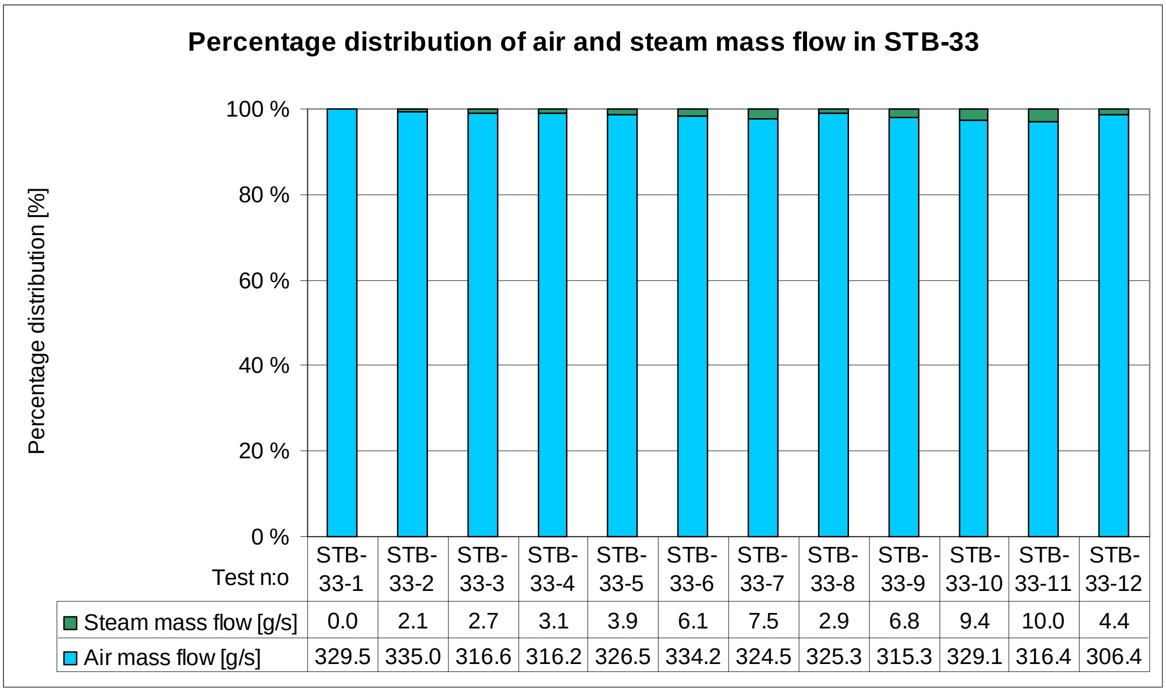


Figure 7. Percentage distribution of air and steam in separate blowdowns of STB-33.

Between 8000 and 9000 seconds into the experiment there was an intentional continuous steam blowdown period to increase the pool temperature by about 10 °C (from 49 to 59 °C). The steam flow rate was kept as constant as possible throughout the experiment i.e. the position of the throttle valve in the steam line was not changed at any time. However, small fluctuations in the steam mass flow rate could be observed. During the recorded blowdowns the steam mass flow ranged therefore from 306 to 335 g/s. These correspond to mass flux values of 8.6 and 9.4 kg/m^{2}s, respectively. The mass flow rate of non-condensable gas (air) ranged from 2.1 to 10.0 g/s. In the first blowdown (STB-33-1), the gas flow was below the flow meter range. Air mass fraction of the total flow ranged from 0.6 to 3.1 %. Figure 6 presents the ratio of air and steam mass flows in separate blowdowns of STB-33 as stacked columns. In Figure 7, the percentage distribution of air and steam mass flow is shown. Figure 8 shows steam, air and pool water temperature from the whole duration of STB-33.

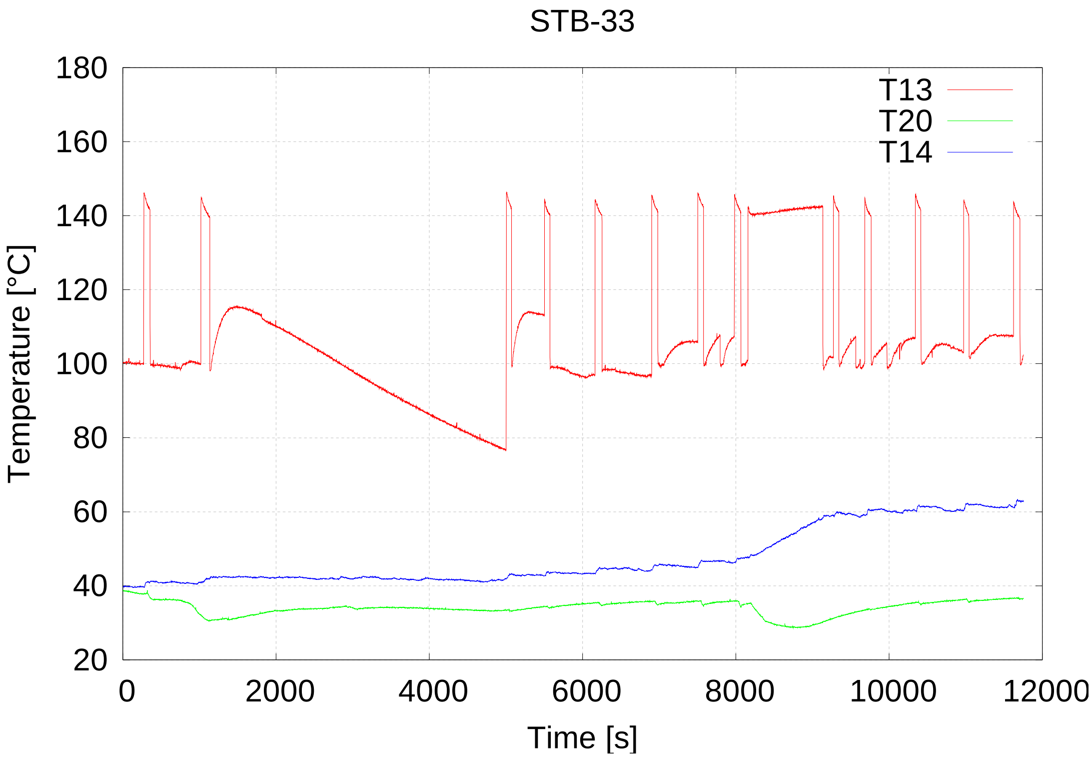


Figure 8. Steam (T13), non-condensable gas (T20) and pool (T14) temperature in STB-33.

The effect of non-condensable gas among the steam flow can be clearly seen from Figures 9 and 10. The nature of the condensation phenomenon changes drastically, when steam is mixed with air (at about 21 seconds in the above mentioned Figures). Air, in quantities even less than 1 %, reduces the condensation rate considerably. Those phenomena, which are typical for the chugging region of the condensation mode map, look different after the combined discharge of steam and air starts. Pool water is no longer sucked back into the blowdown pipe as often and the upward movement of the steam/water interface inside the pipe is smaller i.e. temperature in the middle of the pipe drops only a few times after the introduction of air (see Figure 9).

The high pressure pulses registered inside the blowdown pipe due to water hammer propagation during chugging almost disappear at 21 seconds when the combined discharge period of steam and air starts (see Figure 10). The same kind of change in the condensation phenomenon and related temperature and pressure behavior can be observed practically in every single test of the STB-33 experiment. Only in STB-33-2, where the air mass fraction is just 0.6 %, the change is not as radical and one can also see some pressure pulses after the combined discharge has started.

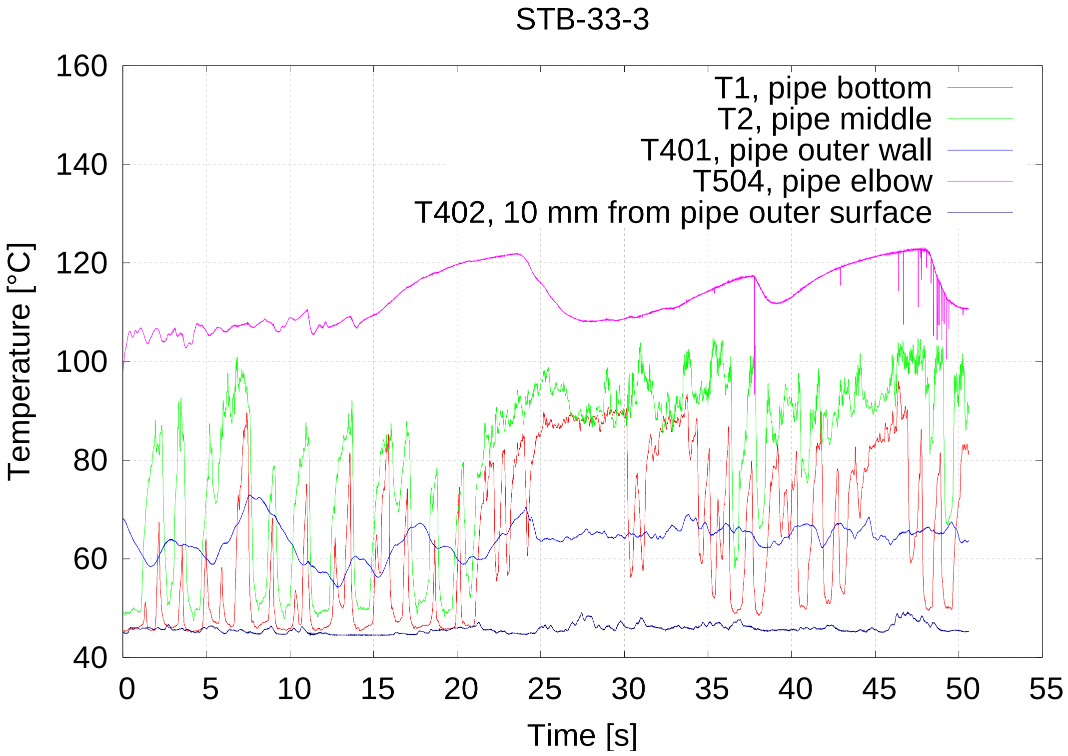


Figure 9. Temperatures during the third test of STB-33 (Air is introduced at 21 s).

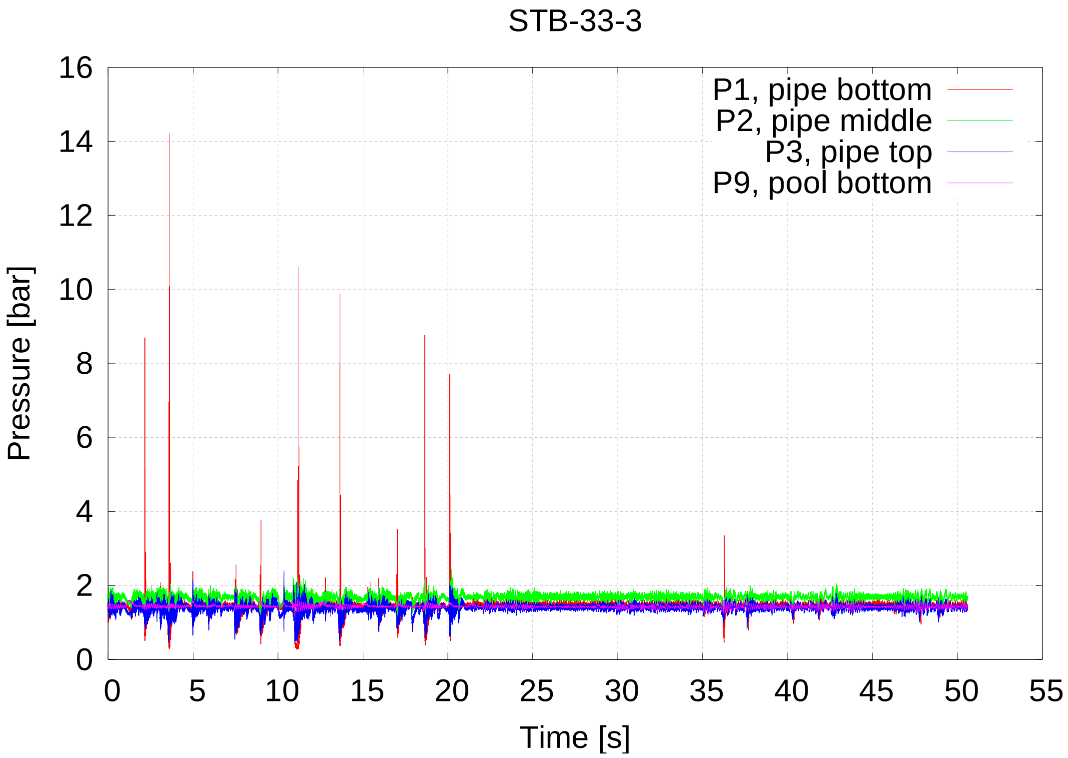


Figure 10. Pressures during the third test of STB-33 (Air is introduced at 21 s).

Contrary to the large changes in the behavior inside the blowdown pipe the effect of air injection on the pressure behavior at the pool bottom is minimal (see Figure 11). That is at least the case with air fractions near 1%. One can observe no change in the amplitude of the measured pressure signal when the combined discharge starts (at 21 seconds). The maximum pressure pulses are about 15 kPa both before and after the beginning of air injection. By looking very carefully one can probably see a small decrease in the frequency of the oscillations.

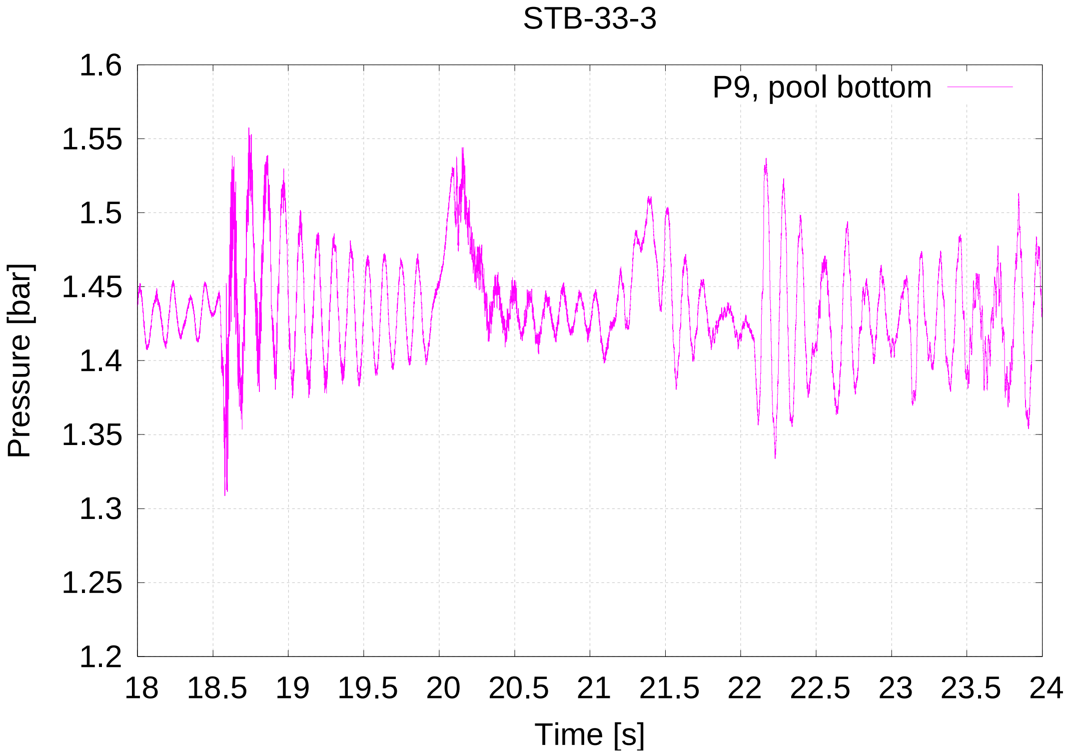


Figure 11. Pressure behavior at the pool bottom during STB-33-3 (Air is introduced at 21 s).

Strain gauges attached on the pool structures close to the bottom rounding indicate no radical change in the measured maximum load amplitude due to the introduction of non-condensable gas. Furthermore, it seems that there is no clear relation between the air mass fraction and strain amplitude but the changes are almost random. However, decaying of the oscillations is somewhat different after the air injection has started. With pure steam discharge there is a clear decaying period after every collapse of a large steam bubble. This is due to the fact that after such a collapse it takes some time before the steam/water interface reaches the pipe outlet again and a new bubble forms. When there is air among steam, the condensation process is more continuous and oscillations have no chance to die away.

Table 6 summarizes the values of the main parameters during experiment STB-33. In the table, the steam blowdown column lists the time periods when steam/air was blown into the pool. The LabView data recording column lists the time periods when data was recorded using LabView software. T_{pool} shows the temperature of pool water during LabView data recording. Steam mass flux (G_{steam}) is calculated on the basis of volumetric flow rate measurement F1 (Q_{steam}), steam density (ρ) and the cross-sectional area of the blowdown pipe (A), see

Equation 1. Steam density is determined on the basis of temperature measurement T13 and pressure measurement P7.

$$G_{steam} = \frac{Q\,\rho}{A} \qquad (1)$$

Maximum pressure (p_{max}) inside the blowdown pipe and maximum strain ($\Delta\varepsilon_{max}$) on the pool bottom rounding are listed in the table both from the period of pure steam discharge and from the period of combined steam/gas discharge.

Table 6. Main parameters during STB-33

Test n:o	Steam generator initial pressure [MPa]	Steam blowdown [s]	Air injection [s]	LabView data recording [s]
STB-33-1	0.48	271…354	320…354	298…352
STB-33-2	0.49	5001…5071	5043…5071	5020…5066
STB-33-3	0.48	5500…5572	5540…5572	5518…5569
STB-33-4	0.47	6161…6252	6217…6252	6196…6249
STB-33-5	0.49	6900…6981	6949…6981	6927…6977
STB-33-6	0.49	7501…7577	7547…7577	7528…7573
STB-33-7	0.48	7980…8064	8040…8064	7997…8060
STB-33-8	0.48	9271…9342	9310…9342	9295…9339
STB-33-9	0.48	9680…9762	9725…9762	9706…9758
STB-33-10	0.49	10340…10414	10382…10414	10366…10412
STB-33-11	0.47	10971…11040	11012…11040	10996…11037
STB-33-12	0.46	11621…11707	11666…11707	11646…11704

Test n:o	Values during LabView data recording						
	T_{pool} [°C]	G_{steam} [kg/m^{2}s]	Air mass flow [g/s]	Air mass fraction [%]	p_{max} in the DN200 pipe [MPa] *	Δp_{max} at the pool bottom [kPa]	$\Delta\varepsilon_{max}$ [µS] *
STB-33-1	41	~9.2	NA	NA	1.60/0.05	23	190/100
STB-33-2	42	~9.4	2.1	0.6	1.25/0.47	25	170/180
STB-33-3	43	~8.9	2.7	0.9	1.27/0.18	20	200/140
STB-33-4	44	~8.8	3.1	1.0	0.73/0.07	20	160/130
STB-33-5	45	~9.1	3.9	1.2	1.28/0.07	22	150/130
STB-33-6	46	~9.4	6.1	1.8	1.47/0.12	22	180/150
STB-33-7	47	~9.2	7.5	2.3	1.14/0.04	25	170/130
STB-33-8	59	~9.0	2.9	0.9	1.29/0.07	21	170/150
STB-33-9	59	~8.8	6.8	2.1	0.43/0.03	25	210/140
STB-33-10	61	~9.1	9.4	2.8	0.83/0.10	38	210/150
STB-33-11	62	~8.9	10.0	3.1	0.36/0.03	29	220/120
STB-33-12	62	~8.6	4.4	1.4	0.44/0.05	35	220/150

* Without/with gas among steam

5.2 STB-34

Thirteen steam/air blowdown tests were executed (labeled from STB-34-1 to STB-34-13). LabView recorded data during the blowdowns. The test procedure was the same as in STB-33. First, a period of pure steam discharge was recorded. Then air injection was started without changing the steam flow rate. In each separate test, the data recording was started 20-30 seconds after initiating the steam blowdown so that the flow had enough time to level off. Visual material from steam bubble formation at the blowdown pipe outlet both with and without non-condensable gas was again produced with the digital high-speed video camera.

During the experiment the initial pressure of the PACTEL steam generator varied from 0.32 to 0.5 MPa (all three SGs in use). Before the first blowdown was initiated the temperature of the pool water was 41 °C. After the last blowdown the temperature had increased to 70 °C. Between 4500 and 7000 seconds in the experiment there was a heating period, where the pool temperature increased by about 15 °C (from 49 to 64 °C) as a result of continuous steam blowdown. The steam flow rate was kept as constant as possible throughout the experiment i.e. the position of the throttle valve in the steam line was not changed at any time. However, small fluctuations in the steam mass flow rate could be observed. During the recorded blowdowns the steam mass flow ranged therefore from 400 to 471 g/s. These correspond to mass flux values of 11.1 and 13.1 kg/m^{2}s, respectively. Non-condensable gas (air) mass flow rate ranged from 3.7 to 13.1 g/s. In the seventh blowdown (STB-34-7), the gas flow was below the flow meter range. Air mass fraction of the total flow ranged from 0.8 to 2.8 %. Figure 12 presents the ratio of air and steam mass flows in separate blowdowns of STB-34 as stacked columns. In Figure 13, the percentage distribution of air and steam mass flow is shown.

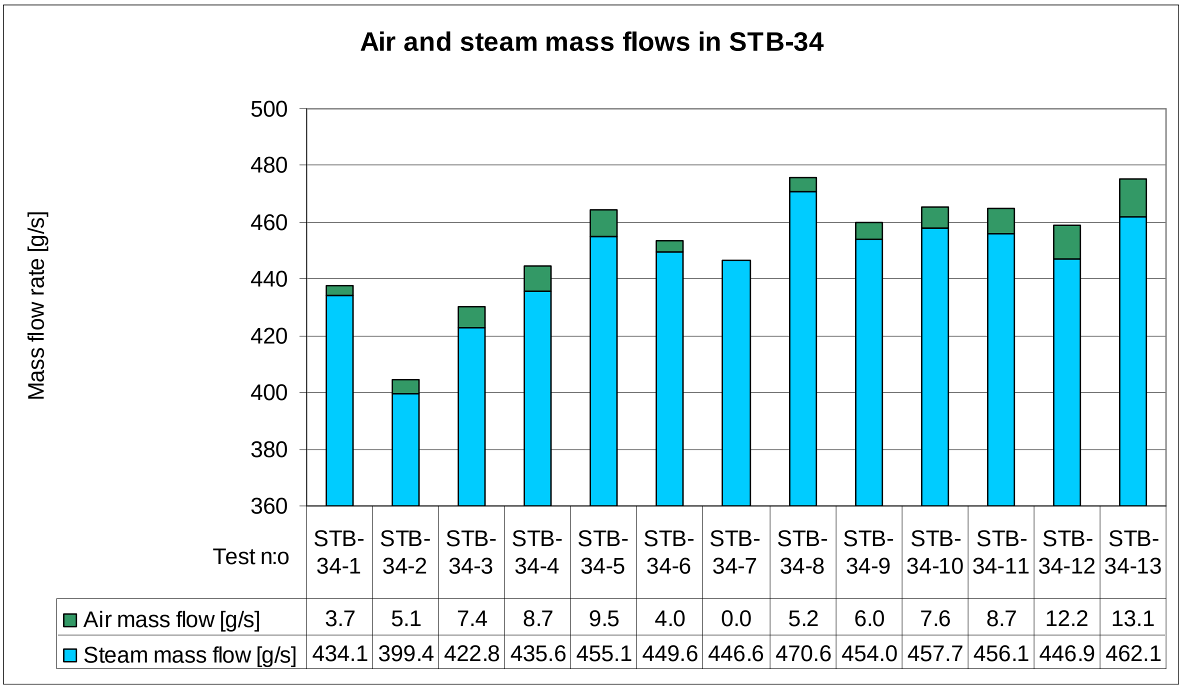
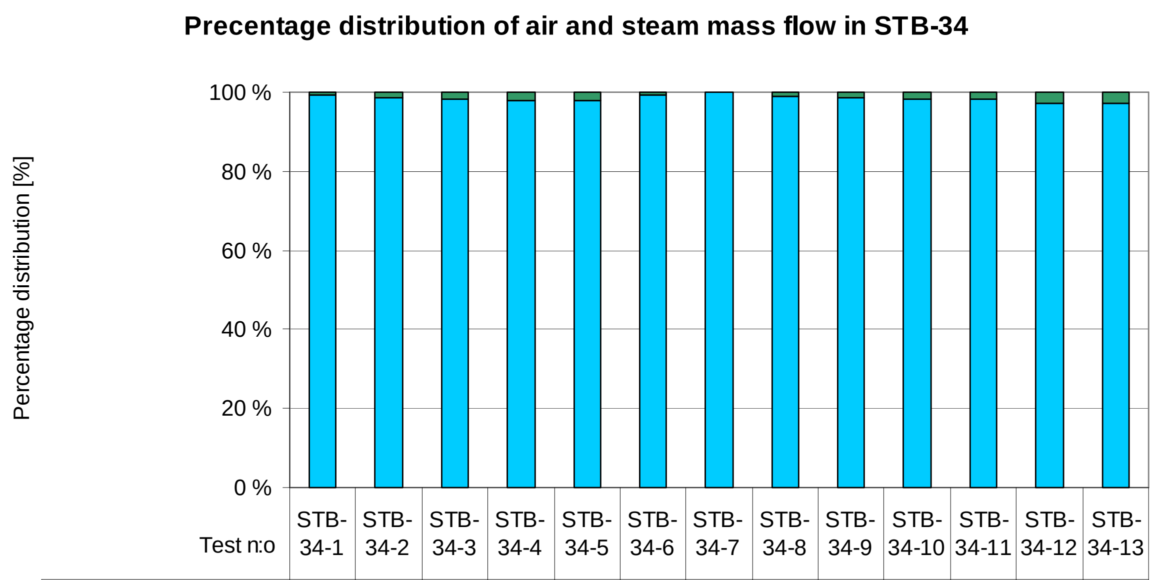


Figure 12. The ratio of air and steam mass flow in separate blowdowns of STB-34.



Test n:o	STB-34-1	STB-34-2	STB-34-3	STB-34-4	STB-34-5	STB-34-6	STB-34-7	STB-34-8	STB-34-9	STB-34-10	STB-34-11	STB-34-12	STB-34-13
Air mass flow [g/s]	3.7	5.1	7.4	8.7	9.5	4.0	0.0	5.2	6.0	7.6	8.7	12.2	13.1
Steam mass flow [g/s]	434.1	399.4	422.8	435.6	455.1	449.6	446.6	470.6	454.0	457.7	456.1	446.9	462.1

Figure 13. Percentage distribution of air and steam in separate blowdowns of STB-34.

The effect of non-condensable gas among steam in STB-34 is practically similar as in the previous experiment. Now the steam flow rate is somewhat higher but the air mass fraction of the total flow is about the same (0.8-2.8 %) as in STB-33. Therefore the condensation process follows the same trend, i.e. soon after the gas injection is initiated water is sucked back into the blowdown pipe only occasionally. Maximum pressure pulses registered inside the blowdown pipe during pure steam discharge are very close to those observed in STB-33 and disappear almost entirely after the combined discharge period of steam and air has started.

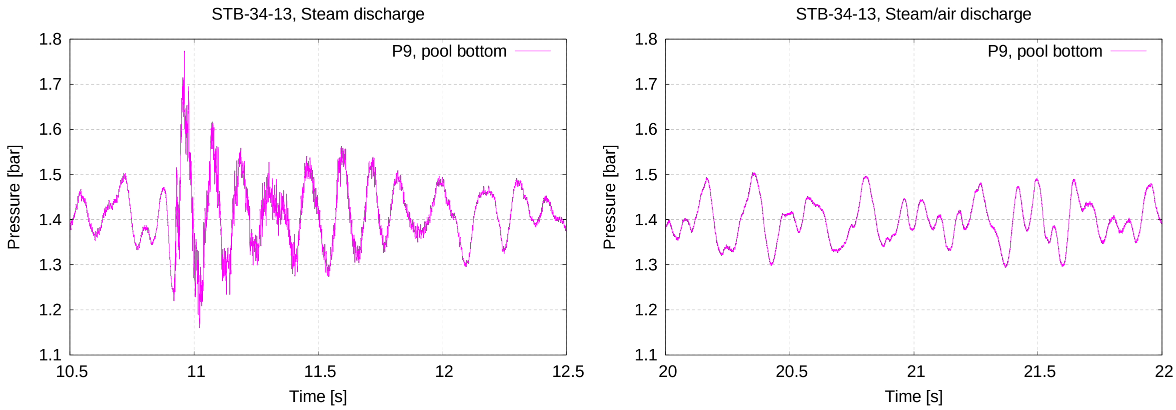


Figure 14. Pressure at the pool bottom during STB-34-13 (left with pure steam, right with steam and air).

During the experiment the highest measured pressure load at the pool bottom caused by a condensation-induced water hammer was 48 kPa. It was measured with a pure steam discharge of 12.4 kg/m^{2}s and with a pool water temperature of 66 °C. Air quantities in the vicinity of 2 %

start to have a clear effect also on the oscillations measured by the pressure sensor at the pool bottom. Both the amplitude and frequency of the pressure pulses decrease considerably. After the combined discharge of steam and air started the maximum amplitude of the pressure signal at the pool bottom was, for example in STB-34-13, only a third of that with the pure steam discharge. In Figure 14 the two cases are compared with the same time and pressure scales.

The change in the measured strain amplitude due to the initiation of gas injection is ambiguous. No clear pattern or relation between the air mass fraction and the observed strains can be found. In some tests, the strains can halve as a result of gas among steam but in other tests, there is no change at all. Table 7 summarizes the values of main parameters during STB-34.

Table 7. Main parameters during STB-34

Test n:o	Steam generator initial pressure [MPa]	Steam blowdown [s]	Air injection [s]	LabView data recording [s]
STB-34-1	0.48	182…273	244…273	221…269
STB-34-2	0.46	990…1073	1048…1073	1021…1068
STB-34-3	0.47	1791…1860	1833…1860	1816…1856
STB-34-4	0.48	2312…2389	2361…2389	2337…2385
STB-34-5	0.48	3422…3494	3461…3494	3443…3492
STB-34-6	0.48	8996…9076	9052…9076	9026…9073
STB-34-7	0.46	9642…9714	9676…9714	9667…9712
STB-34-8	0.49	10230…10282	10265…10282	10251…10278
STB-34-9	0.47	10731…10790	10765…10790	10751…10787
STB-34-10	0.47	11291…11347	11325…11347	11310…11344
STB-34-11	0.47	11781…11838	11813…11838	11801…11835
STB-34-12	0.47	12251…12307	12283…12307	12271…12305
STB-24-13	0.48	12677…12736	12707…12736	12695…12732

Test n:o	Values during LabView data recording						
	T_{pool} [°C]	G_{steam} [kg/m^{2}s]	Air mass flow [g/s]	Air mass fraction [%]	p_{max} in the DN200 pipe [MPa] *	Δp_{max} at the pool bottom [kPa]	$\Delta\varepsilon_{max}$ [µS] *
STB-34-1	42	~12.2	3.7	0.8	1.13/0.07	28	190/170
STB-34-2	44	~11.1	5.1	1.3	1.36/0.03	23	160/170
STB-34-3	45	~11.7	7.4	1.7	0.81/0.03	21	210/140
STB-34-4	46	~12.2	8.7	2.0	1.61/0.06	25	180/160
STB-34-5	47	~12.6	9.5	2.0	1.23/0.05	26	180/180
STB-34-6	65	~12.6	4.0	0.9	0.82/0.04	35	240/220
STB-34-7	66	~12.4	NA	NA	0.46/0.07	48	150/120
STB-34-8	67	~13.1	5.2	1.1	0.37/0.04	35	220/150
STB-34-9	66	~12.6	6.0	1.3	0.48/0.04	34	250/190
STB-34-10	67	~12.8	7.6	1.6	0.39/0.04	40	300/130
STB-34-11	67	~12.6	8.7	1.9	0.39/0.03	37	240/140
STB-34-12	68	~12.4	12.2	2.6	0.26/0.02	25	190/140
STB-34-13	68	~12.8	13.1	2.8	0.44/0.03	35	230/140

* Without/with gas among steam

5.3 STB-35

Twelve steam/air blowdown tests were executed (labeled from STB-35-1 to STB-35-12). LabView recorded data during the blowdowns. First, a period of pure steam discharge was recorded. Then air injection was started without changing the steam flow rate. In each separate test, the data recording was started 20-30 seconds after initiating the steam blowdown so that the flow had enough time to level off. Visual material from steam bubble formation at the blowdown pipe outlet both with and without non-condensable gas was also produced with the digital high-speed video camera.

During the experiment the initial pressure of the PACTEL steam generator varied from 0.42 to 0.5 MPa (all three SGs in use). Before the first blowdown was initiated the temperature of the pool water was 42 °C. After the last blowdown the temperature had increased to 66 °C. Between 2800 and 5100 seconds in the experiment there was a heating period to increase the pool temperature (by about 18 degrees from 46 to 64 °C). The steam flow rate was kept as constant as possible throughout the experiment i.e. the position of the throttle valve in the steam line was not changed at any time. However, small fluctuations in the steam mass flow rate could be observed. During the recorded blowdowns the steam mass flow ranged therefore from 201 to 223 g/s. These correspond to mass flux values of 5.5 and 6.2 kg/m^2s, respectively. Non-condensable gas (air) mass flow rate ranged from 5.4 to 20.9 g/s. Air mass fraction of the total flow ranged from 2.4 to 8.9 %. Figure 15 presents the ratio of air and steam mass flows in separate blowdowns of STB-35 as stacked columns. In Figure 16, the percentage distribution of air and steam mass flow is shown.

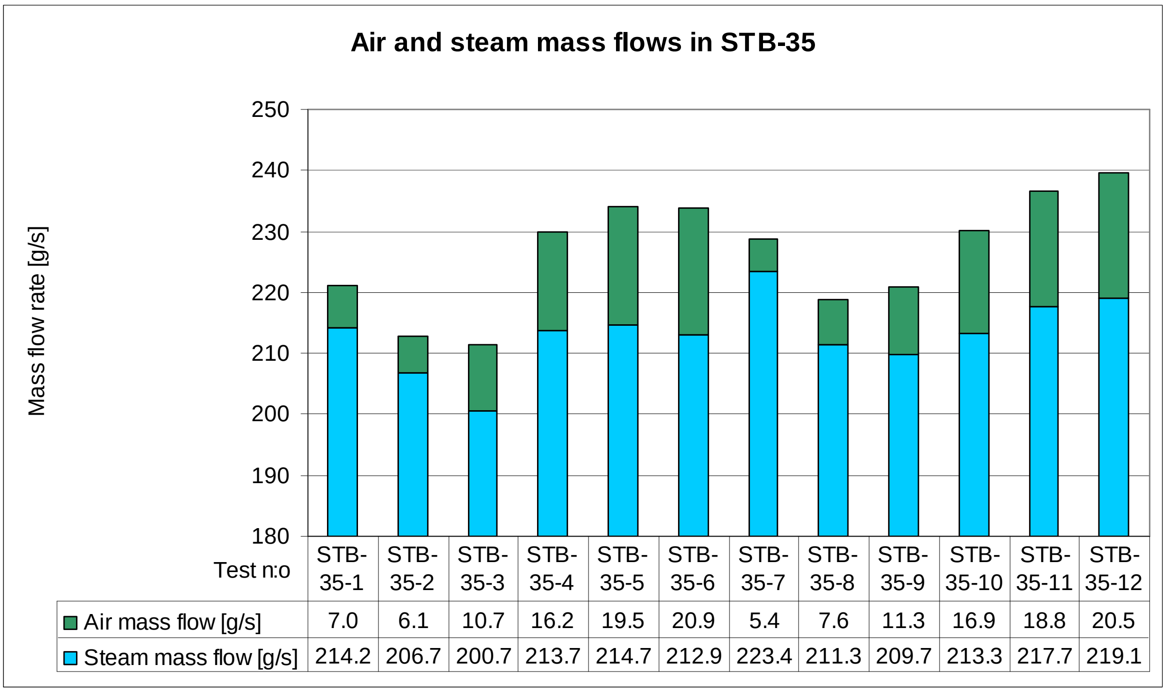
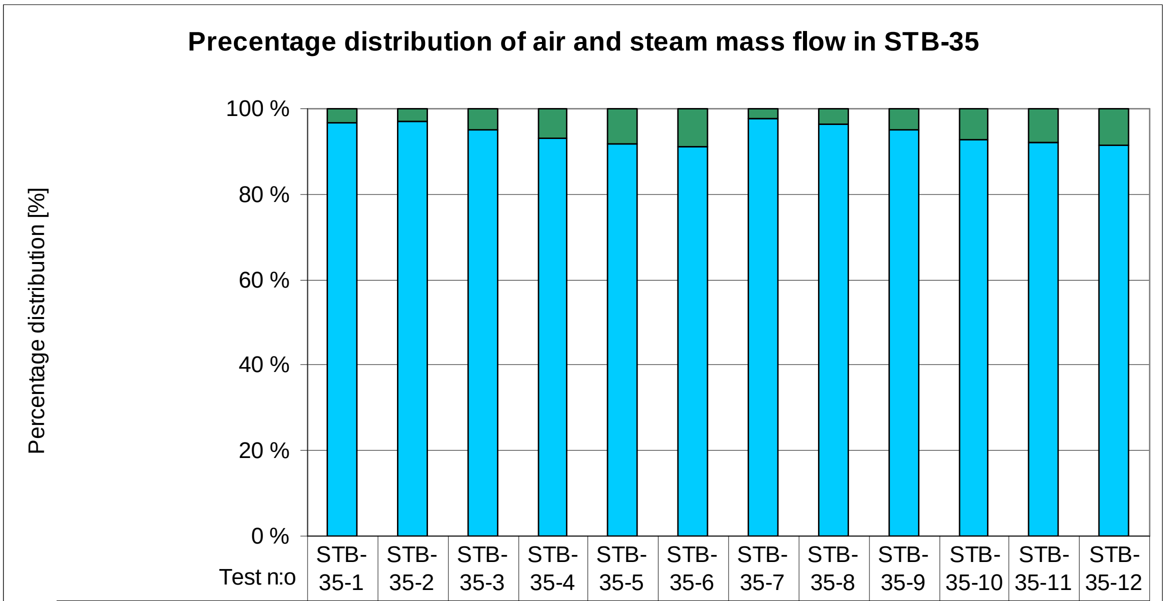


Figure 15. The ratio of air and steam mass flow in separate blowdowns of STB-35.



Test n:o	STB-35-1	STB-35-2	STB-35-3	STB-35-4	STB-35-5	STB-35-6	STB-35-7	STB-35-8	STB-35-9	STB-35-10	STB-35-11	STB-35-12
Air mass flow [g/s]	7.0	6.1	10.7	16.2	19.5	20.9	5.4	7.6	11.3	16.9	18.8	20.5
Steam mass flow [g/s]	214.2	206.7	200.7	213.7	214.7	212.9	223.4	211.3	209.7	213.3	217.7	219.1

Figure 16. Percentage distribution of air and steam in separate blowdowns of STB-35.

In STB-35, the mass fraction of air (2.4-8.9 %) of the total flow was clearly higher than in the two preceding experiments. This was achieved by increasing the mass flow rate of non-condensable gas with an extra air compressor connected between the compressed air network and the test facility and by reducing the steam mass flux to 5.5-6.2 kg/sm^2. The effect of these high air quantities among steam can be seen from Figure 17, where measured temperatures inside the blowdown pipe from test STB-35-5 (air fraction 8.3 %) are presented. As soon as the air injection is started (at about 16 seconds in Figure 17) the 40-50 °C amplitude oscillation of the pipe outlet and pipe middle temperatures almost disappears. This happens although the pool water is quite cold (45 °C). Low pool temperature and quite small steam mass flux usually mean that it is not possible to avoid heavy temperature oscillations in case of pure steam discharge, not near the pipe outlet anyway.

The measured pressure pulses inside the blowdown pipe during pure steam discharge are between 0.20-0.63 MPa i.e. they are somewhat smaller than in the two preceding experiments. This is due to the fact that the steam mass flux is smaller and the flow mode is therefore at the very low end of the chugging region. Nevertheless, the effect of air among steam on the pressure behavior can be clearly seen also in this experiment. Practically no pressure pulses (maximum 0.05 MPa) are registered inside the blowdown pipe after the combined discharge of steam and air has started.

During the experiment the highest measured pressure load at the pool bottom caused by a condensation-induced water hammer is only 29 kPa. It was measured with a pure steam discharge of 5.9 kg/m^{2}s and with a pool water temperature of 64 °C in test STB-35-8. The reason for the very moderate measured loads at the pool bottom during STB-35 is the use of small steam flow rates compared to the earlier experiments.

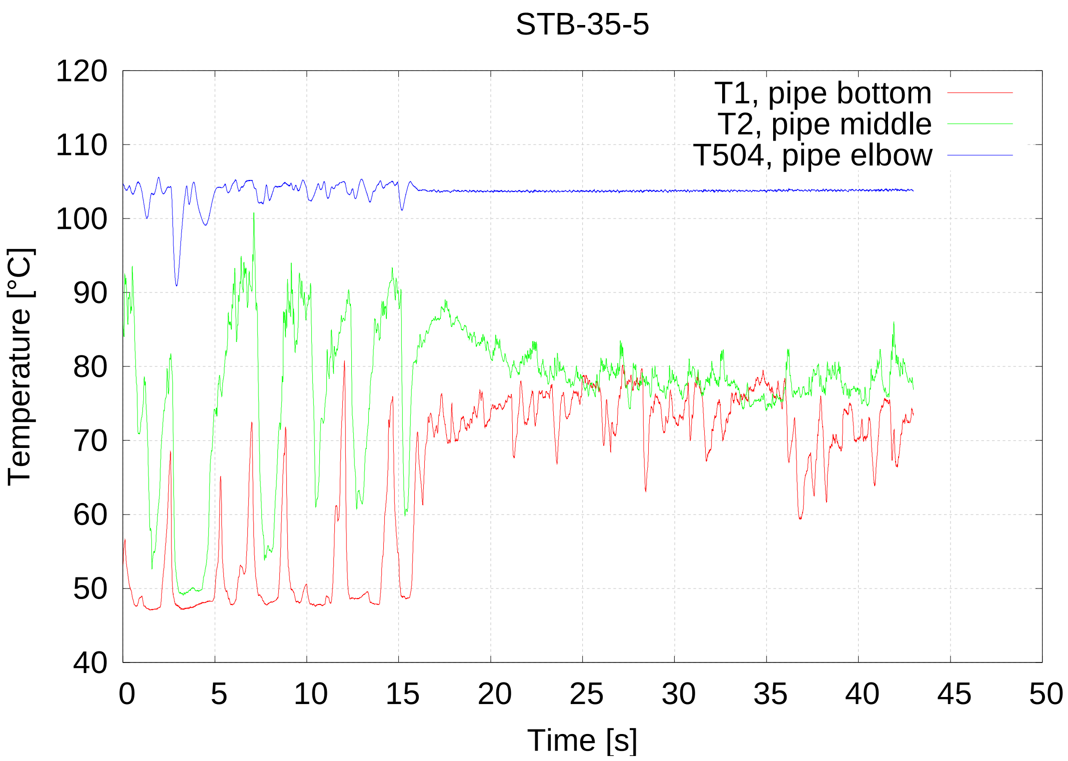


Figure 17. Temperatures in the blowdown pipe during STB-35-5 (Air is introduced at 16 s).

Figure 18 shows the measured pressure behavior at the pool bottom during STB-35-10. One can easily see the diminishing effect that high quantities of non-condensable gas have on structural loads. At 15 seconds, when the combined discharge of steam and non-condensable gas (air mass fraction 7.3 %) starts, the nature of the curve changes drastically. The damped oscillations associated with collapses of pure steam bubbles disappear and from there on the curve indicates only uniform oscillations caused by smooth condensation of steam/air mixture.

In STB-35, the behavior of strains is even more random than in the two previous experiments. In some tests, strains during combined discharge of steam and air are only one third of the value during pure steam discharge while in some tests they are higher with steam/air mixture than with pure steam. The highest strain value (160 µS, measured by ST5) of the whole experiment was though registered during pure steam discharge.

Figure 19 shows two frame captures from STB-35-10. On the right side the 7.3 % air mass fraction among the flow has distorted the quite symmetrical shape of bubbles typically found with pure steam discharge; like in the frame on the left side. Table 8 summarizes the values of main parameters during the experiment STB-35.

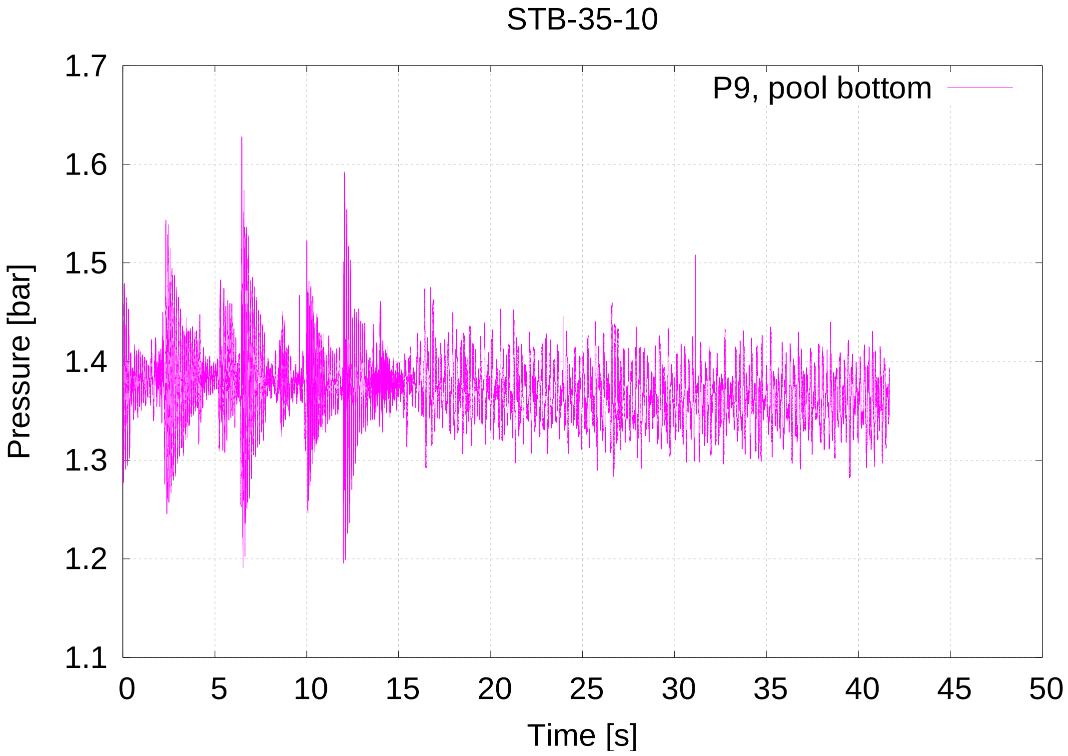


Figure 18. Pressure behavior at the pool bottom in test STB-35-10 (Air is introduced at 15 s).

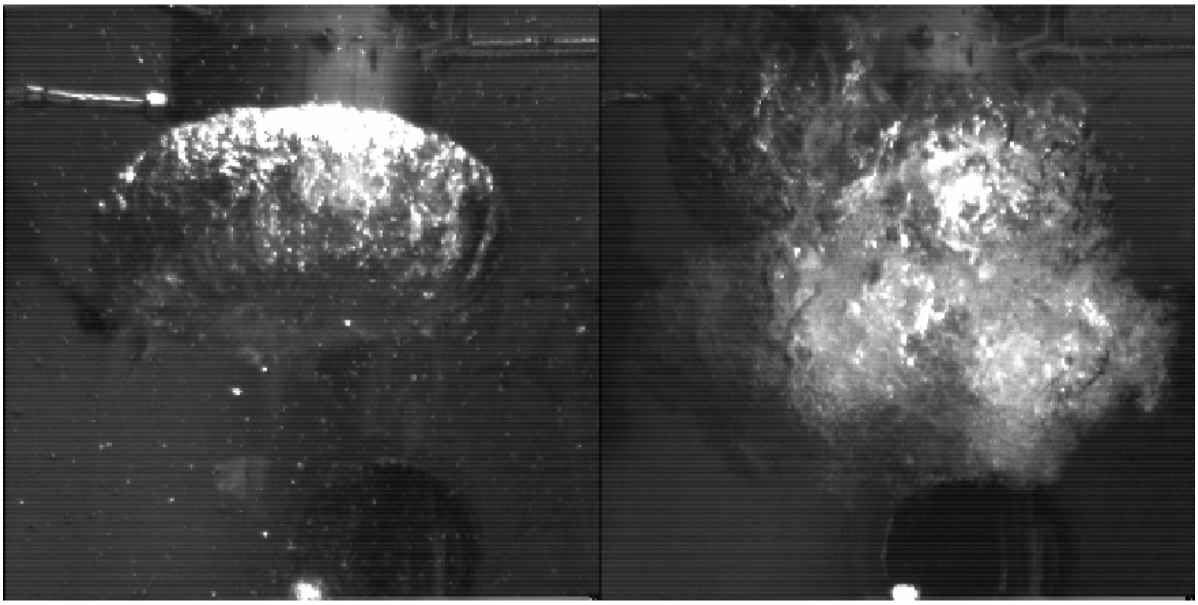


Figure 19. Frame captures from STB-35-10 (left pure steam, right steam/air mixture).

Table 8. Main parameters during STB-35

Test n:o	Steam generator initial pressure [MPa]	Steam blowdown [s]	Air injection [s]	LabView data recording [s]
STB-35-1	0.49	110…191	158…191	141…187
STB-35-2	0.47	813…884	850…884	832…879
STB-35-3	0.44	1227…1286	1258…1286	1245…1283
STB-35-4	0.47	1667…1731	1701…1731	1683…1729
STB-35-5	0.47	2171…2236	2207…2236	2191…2234
STB-35-6	0.47	2577…2645	2615…2645	2598…2643
STB-35-7	0.49	9162…9231	9200…9231	9186…9229
STB-35-8	0.47	9608…9671	9639…9671	9627…9667
STB-35-9	0.46	10102…10169	10136…10169	10123…10167
STB-35-10	0.47	10542…10606	10576…10606	10561…10603
STB-35-11	0.46	10982…11041	11014…11041	10998…11038
STB-35-12	0.48	11327…11382	11353…11382	11342…11378

Test n:o	Values during LabView data recording						
	T_{pool} [°C]	G_{steam} [kg/m^{2}s]	Air mass flow [g/s]	Air mass fraction [%]	p_{max} in the DN200 pipe [MPa] *	Δp_{max} at the pool bottom [kPa]	$\Delta\varepsilon_{max}$ [µS] *
STB-35-1	43	~5.9	7.0	3.2	0.20/0.05	18	110/150
STB-35-2	43	~5.7	6.1	2.9	0.26/0.03	20	60/80
STB-35-3	44	~5.5	10.7	5.1	0.24/0.03	14	50/110
STB-35-4	44	~5.9	16.2	7.1	0.36/0.02	21	90/80
STB-35-5	45	~6.0	19.5	8.3	0.26/0.02	19	90/90
STB-35-6	45	~5.9	20.9	8.9	0.42/0.02	15	70/90
STB-35-7	63	~6.2	5.4	2.4	0.17/0.04	22	120/110
STB-35-8	64	~5.9	7.6	3.5	0.62/0.02	29	160/100
STB-35-9	64	~5.8	11.3	5.1	0.28/0.02	20	140/60
STB-35-10	65	~5.9	16.9	7.3	0.40/0.02	25	160/50
STB-35-11	65	~6.0	18.8	8.0	0.63/0.02	22	120/60
STB-35-12	65	~6.1	20.5	8.5	0.30/0.02	20	110/50

* Without/with gas among steam

6 COMBINED EFFECTS

To evaluate the effect of non-condensable gas among steam on pressure pulses inside the blowdown pipe the maximum observed pressure values from different tests were plotted on the same graph as a function of air mass fraction. Figure 20 shows these maximum registered pressures with two different pool temperature ranges (41-47 and 59-68 ºC) that were used in the experiments. One can see that with air mass fractions below 1 % a few considerable pressure oscillations take place. Between 1 and 3 % the damping of pressure oscillations due to non-condensable gas among steam is quite strong and above 3 % it is practically complete. In the 41-47 ºC temperature range the pressure pulses are somewhat larger than in the 59-68 ºC range as can be expected on the basis of the results of earlier experiments in the chugging region with pure steam. Because gas mass flow rates that would result in air mass fractions below 0.5 % were outside the measurement range of the flow meter no assessment of the effect of very low gas fractions can be given here.

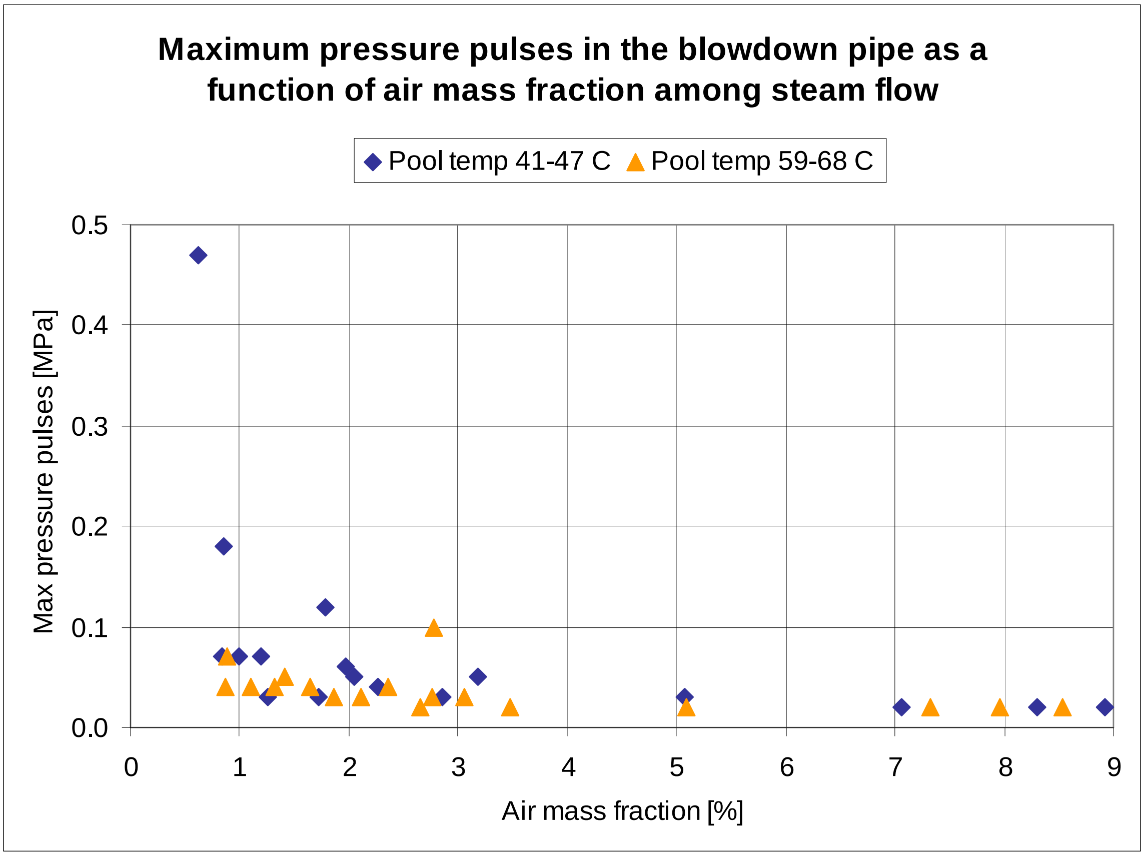


Figure 20. Maximum pressure pulses in the blowdown pipe as a function of air mass fraction.

As mentioned earlier in the chapter dealing with individual experiments the behavior of strains on the pool bottom rounding was somewhat random. This is true especially when the maximum strain values of pure steam and steam/air mixture discharge are compared to each other. If only the strain values during steam/air discharge are taken into account and plotted as a function of air mass fraction (Figure 21), the same kind of logic in behavior as with pressure pulses inside the blowdown pipe can be found. The maximum measured strains decrease with increasing air mass fraction and the effect of pool temperature can be clearly detected. However, the effect in the 1-3 % region is not as strong as with pressures and some randomness can still be found there. Therefore it is not possible to determine an exact air mass fraction above which the maximum strains become negligible.

During the experiments dynamic unsteady loadings were caused to submerged pool structures due to chugging phenomenon. In addition, static loads were caused by the hydrostatic pressure of water. Maximum strain amplitudes in the experiments reported here are, however, clearly smaller than in the previous POOLEX experiments dealing with chugging. This is due to the fact that in the earlier experiments the initial parameters and test conditions (colder pool water, large steam mass flux range) were more suitable for notable stresses to be generated. Stresses experienced by the pool structures in this experiment series are therefore smaller than in the earlier experiments and hence actual stress values are not calculated now. Typical stress values in the earlier POOLEX experiments associated with chugging can be found for example in reference [6].

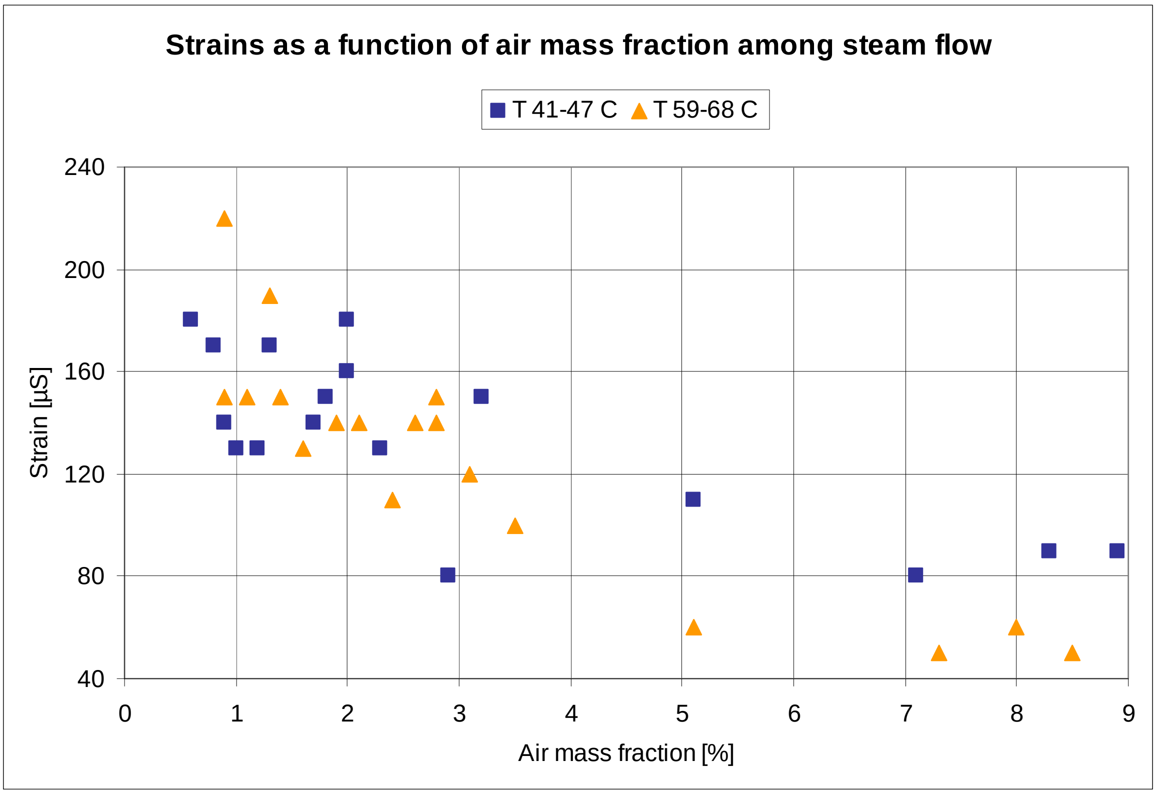


Figure 21. Maximum strains on the pool bottom rounding as a function of air mass fraction.

7 SUMMARY AND CONCLUSIONS

Three successful (plus one unsuccessful and terminated) combined effects experiments were carried out in spring 2006 to investigate the effect of non-condensable gas among steam discharged into a large water pool with a scaled down test facility designed and constructed at Lappeenranta University of Technology. Each experiment had several individual blows of steam and steam/air mixture. The initial system pressure of the steam source (the nearby PACTEL facility) before the blowdowns was 0.5 MPa. The steam mass flux ranged from 5.5 to 13.1 kg/m^{2}s and the air mass fraction of the total flow from 0.6 to 8.9 %. Pool water bulk temperature varied from 40 °C to 70 °C. The experiments were performed using the DN200 (∅219.1x2.5) blowdown pipe. Before each experiment the pool was filled with water to the level of approximately 3.5 m i.e. the blowdown pipe outlet was submerged by 2 m. During the experiments the data acquisition system recorded data with a frequency of 10 kHz. A digital high-speed video camera was used for accurate observation of steam bubbles at the blowdown pipe outlet. The main purpose of the experiment series was to assess the effect of non-condensable gas present in the discharge flow on the measured pressure pulses inside the blowdown pipe and at the pool bottom caused by chugging.

Each test (blow) consisted of two steps. First, a period of pure steam discharge was recoded. Then non-condensable gas (air) was added to the flow in the steam line without changing the steam flow rate. Measurements were on also during the introduction of non-condensable gas. Depending on the test in question 15 to 30 seconds of data were recorded both from the pure steam and mixture periods. Furthermore, visual material from steam bubble formation at the blowdown pipe outlet both with and without non-condensable gas was produced with the digital high-speed video camera through the pool windows.

The nature of the condensation phenomenon changes drastically, when steam is mixed with air. Air, even in quantities less than 1 %, reduces the condensation rate considerably. Those phenomena, which are typical for the chugging region of the condensation mode map, look different after the combined discharge of steam and air starts. Pool water is no longer sucked back into the blowdown pipe as often and the upward movement of the steam/water interface inside the pipe is smaller i.e. temperature in the middle of the pipe drops only a few times after the introduction of air. Furthermore, the high pressure pulses registered inside the blowdown pipe due to water hammer propagation during chugging almost disappear when the combined discharge period of steam and air starts. With non-condensable gas fractions above 3 % the damping of pressure oscillations inside the blowdown pipe is practically complete.

Air quantities in the vicinity of 2 % start to have an effect also on the oscillations measured by the pressure sensor at the pool bottom. Both the amplitude and frequency of the pressure pulses decrease considerably. The change in the measured strain amplitude on the pool bottom rounding due to the initiation of gas injection is, however, ambiguous. No clear pattern in the observed strains between pure steam and steam/air mixture discharge can be found. In some tests, the strain value can almost halve as a result of gas among steam but in other tests, there is no change at all. If only the strain values during steam/air discharge are taken into account, the same kind of logic in behavior as with pressure pulses inside the blowdown pipe can be found. The maximum measured strains decrease with increasing air mass fraction.

During the experiments dynamic unsteady loadings were caused to submerged pool structures due to chugging phenomenon and rapid condensation of steam bubbles at the blowdown pipe outlet. The stress values experienced during the experiments did not risk the integrity of the test pool. However, the experiments demonstrated the strong diminishing effect that even small quantities of non-condensable gas can have on pressure oscillations and structural loads.

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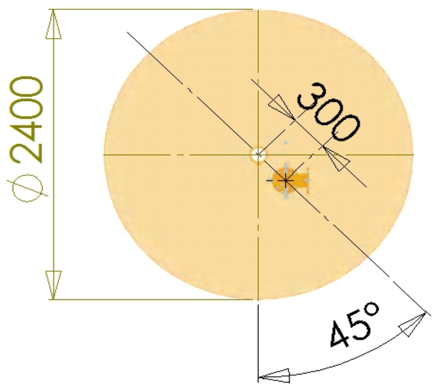
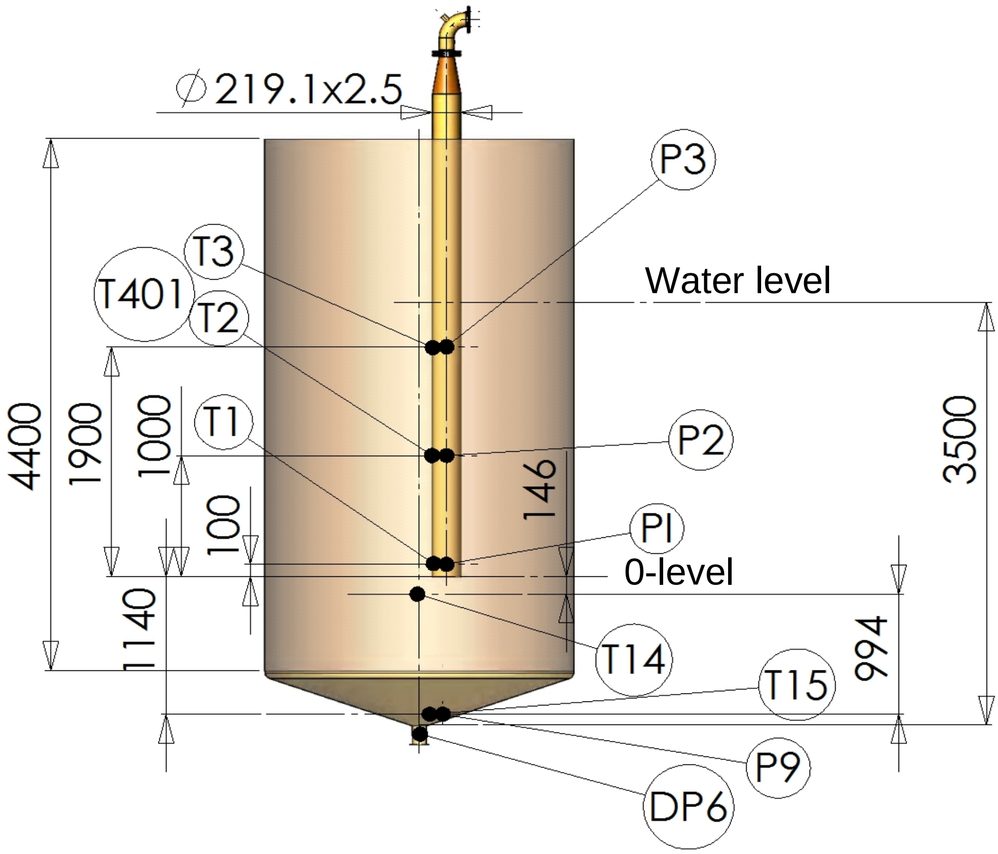
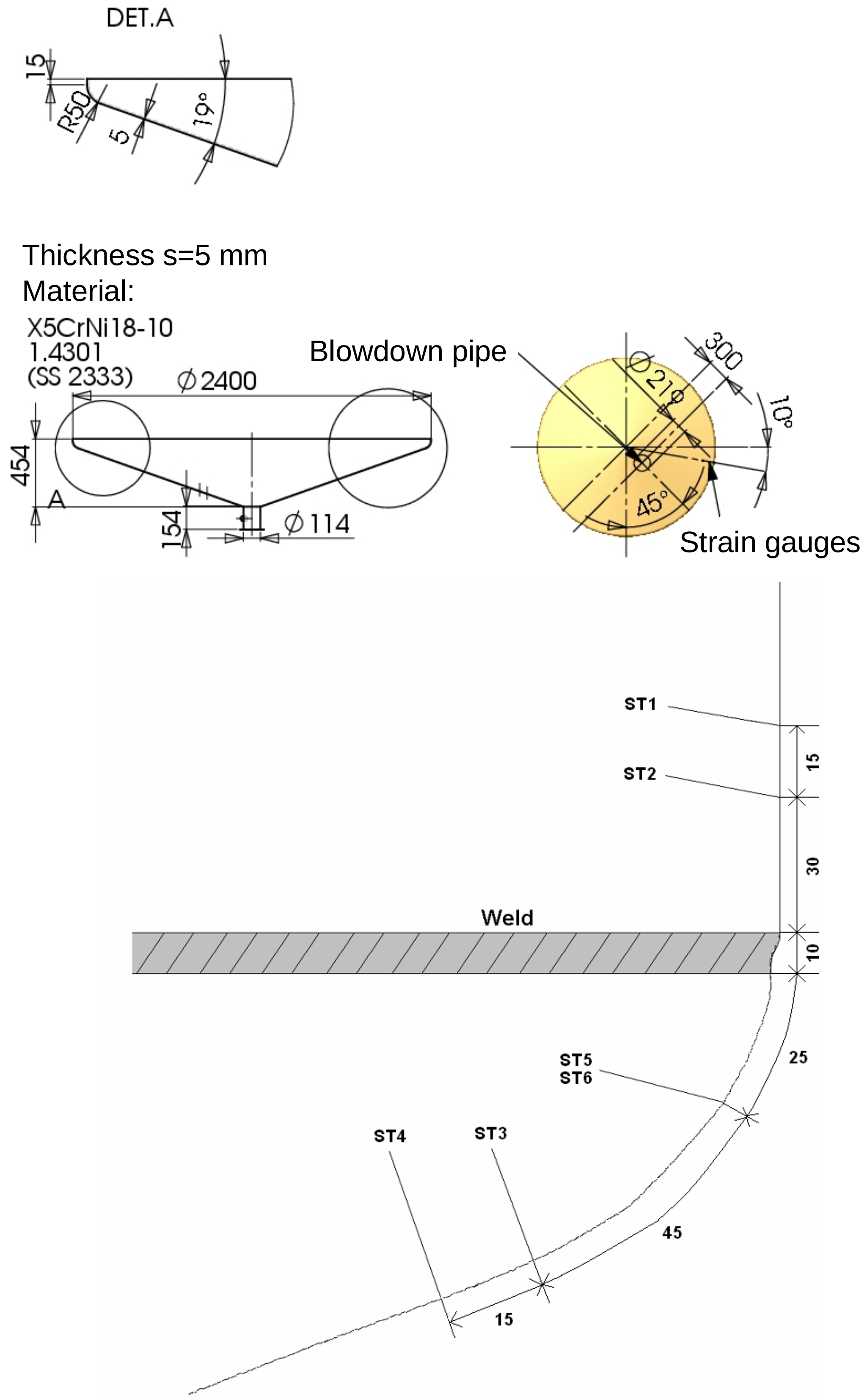
APPENDIX 1: INSTRUMENTATION OF THE POOLEX TEST FACILITY



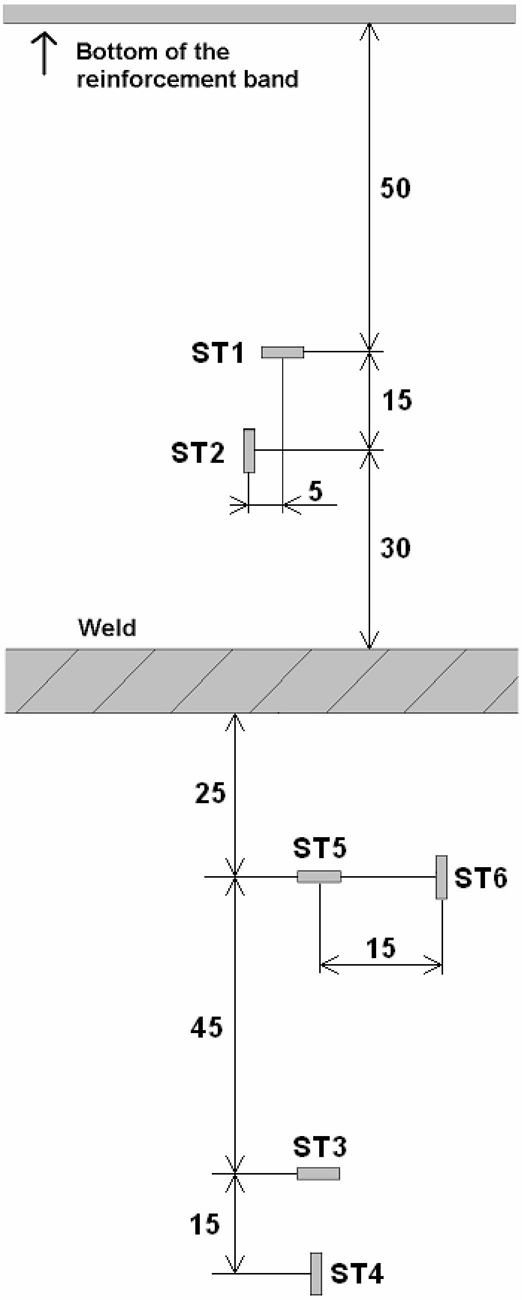
Code	Level
T1	100
T2	1000
T3	1900
T14	-146
T15	-1140
T401	1000
P1	100
P2	1000
P3	1900
P9	-1140



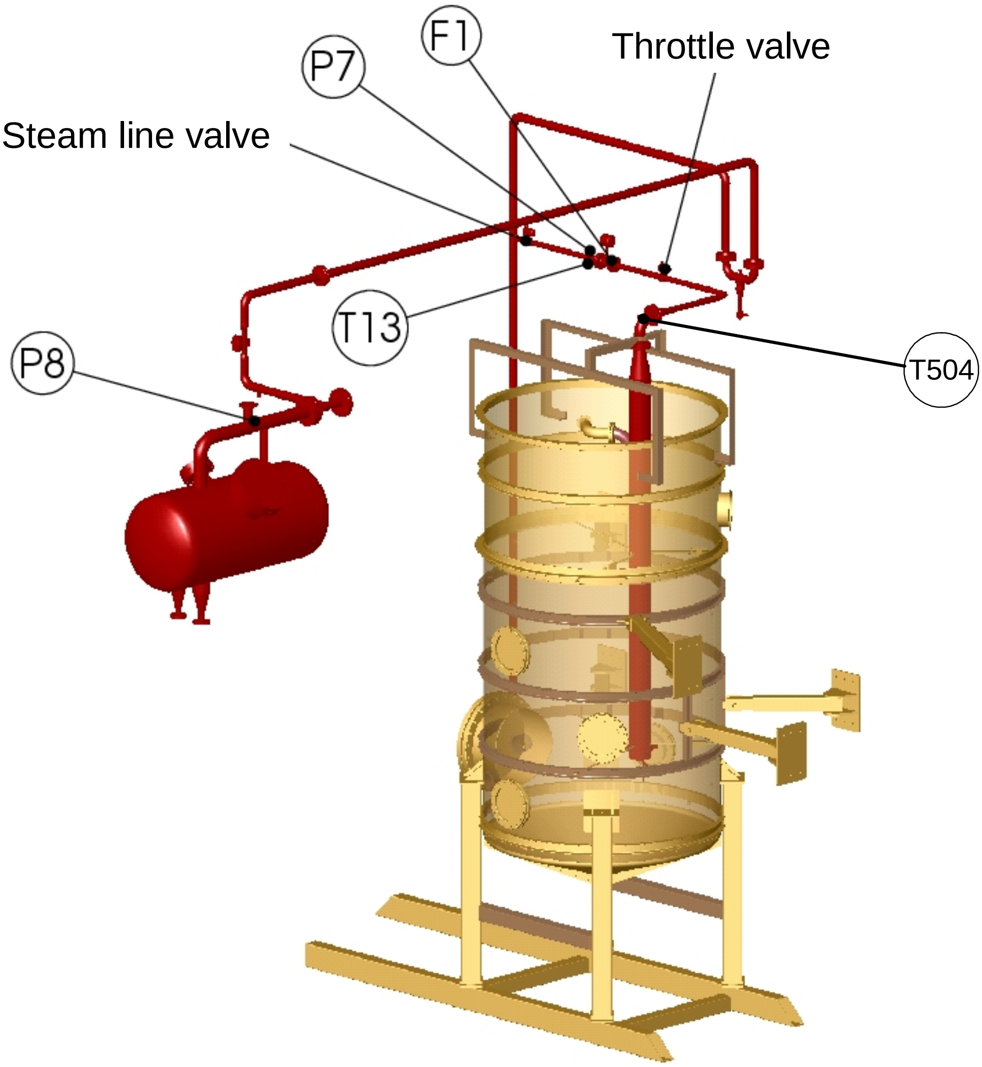
Instrumentation inside the blowdown pipe and at the pool bottom.



Strain gauges on the outer wall of the pool.

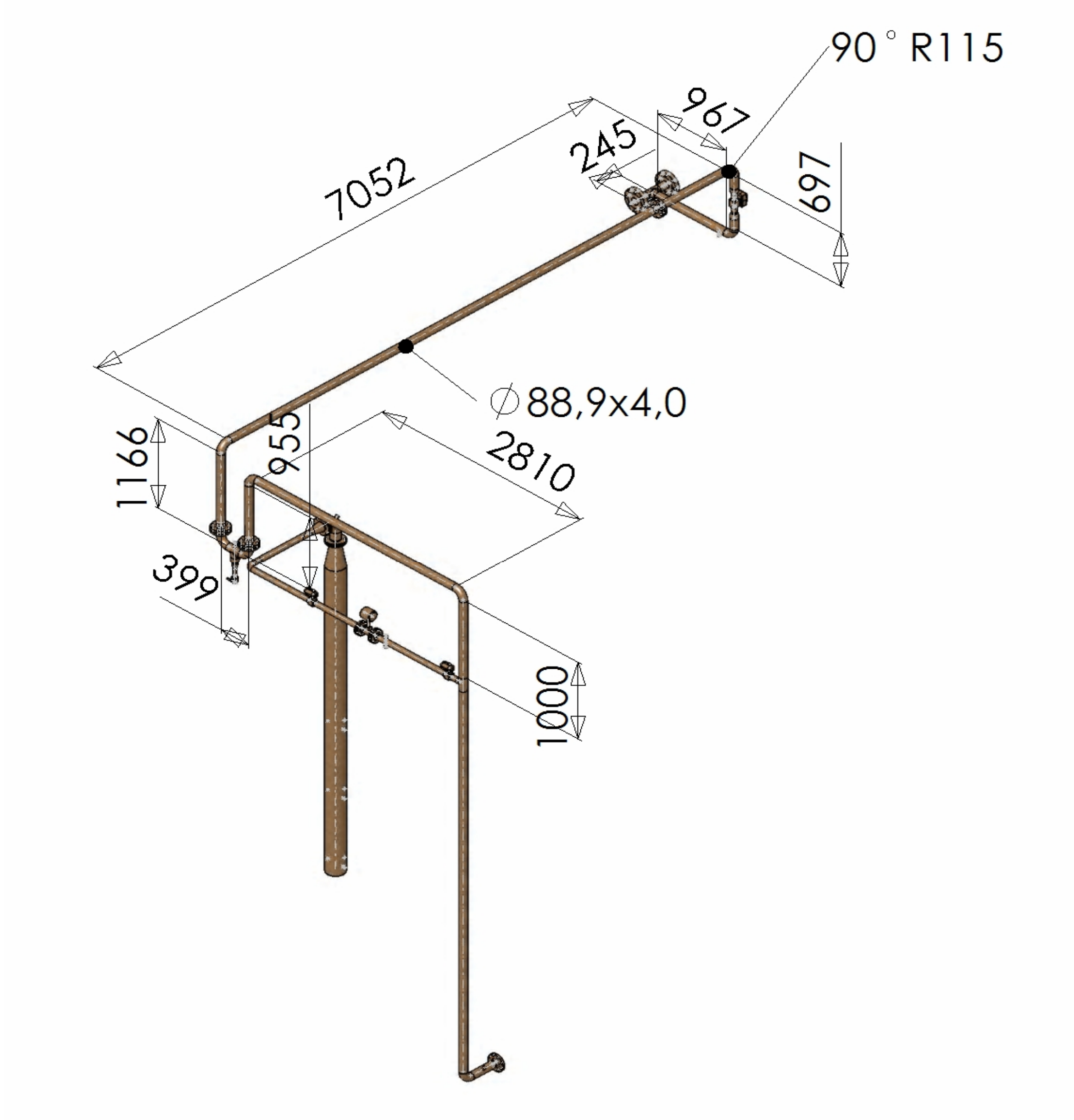


Strain gauges on the outer wall of the pool.

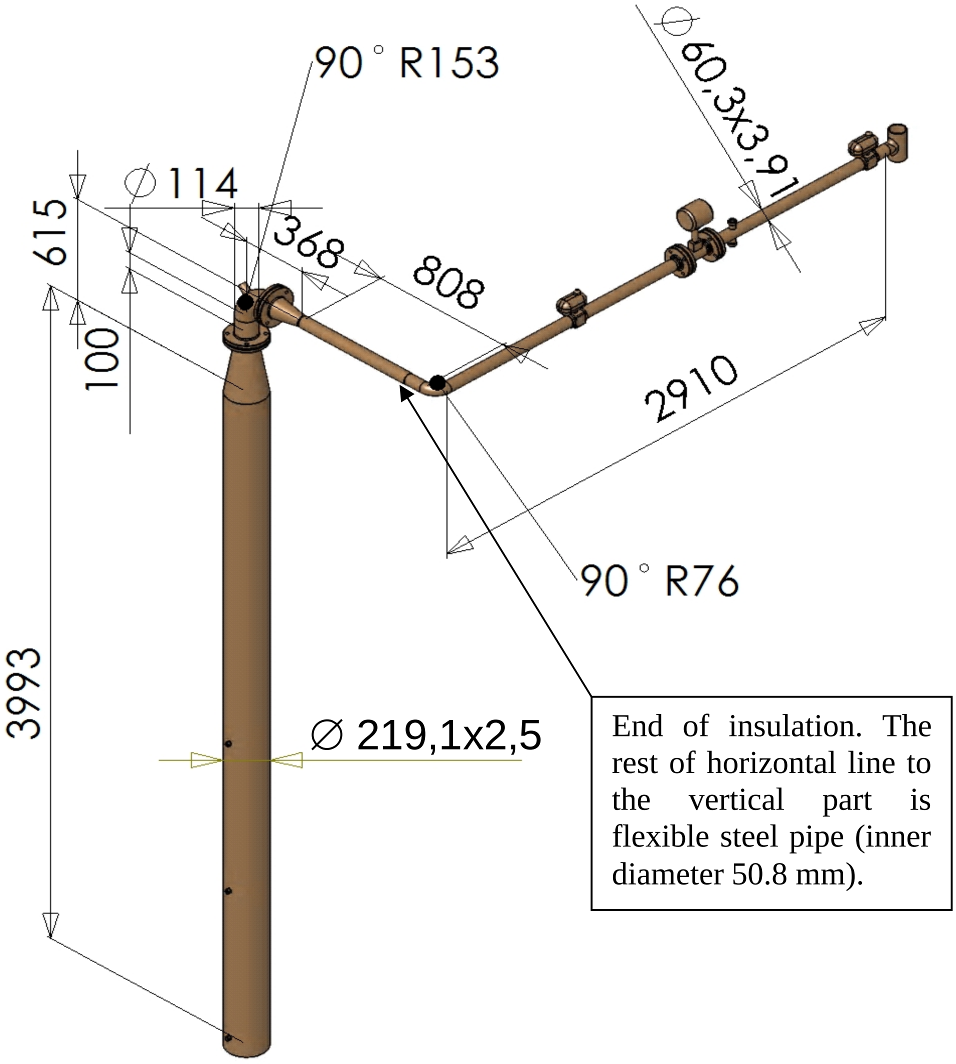


Flow rate (F1), temperature (T13, T504) and pressure (P7, P8) of steam.

APPENDIX 2: DIMENSIONS OF THE STEAM LINE



Steam line from the PACTEL steam generators to the beginning of the blowdown line (branch). The line (AISI 304L) is insulated with mineral wool (thickness 50 mm) and covered with 0.7 mm aluminum plate.



Blowdown line. The line (AISI 304L) is insulated with mineral wool (thickness 50 mm) and covered with 0.7 mm aluminum plate.

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Affiliation(s)	Lappeenranta University of Technology, Nuclear Safety Research Unit, Finland
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Abstract

This report summarizes the results of the condensation pool experiments in spring 2006, where steam and steam/air mixture was blown into the pool through a DN200 blowdown pipe. Altogether three experiments, each consisting of several blows, were carried out with a scaled down test facility designed and constructed at Lappeenranta University of Technology. The main purpose of the experiments was to study the effects of non-condensable gas present in the discharge flow. Particularly pressure pulses inside the blowdown pipe and at the pool bottom caused by chugging were of interest.

The test pool was an open stainless steel tank with a wall thickness of 4 mm and a bottom thickness of 5 mm containing 15 m3 of water. The nearby PACTEL test facility was used as a steam source. During the experiments the initial pressure of the steam source was 0.5 MPa and the pool water bulk temperature ranged from 40 C to 70 C. The test facility was equipped with high frequency instrumentation for capturing different aspects of the investigated phenomena. The data acquisition program recorded data with the frequency of 10 kHz. A digital high-speed video camera was used for visual observation of the pool interior.

Air, in quantities even less than 1 %, reduced the condensation rate considerably. The high pressure pulses registered inside the blowdown pipe due to water hammer propagation during chugging almost disappeared when the combined discharge period of steam and air started. With non-condensable gas fractions above 3 % the damping of pressure oscillations inside the blowdown pipe was practically complete. Air quantities in the vicinity of 2 % started to have an effect also on the oscillations measured by the pressure sensor at the pool bottom. Both the amplitude and frequency of the pressure pulses decreased considerably.

The experiments demonstrated that even small quantities of non-condensable gas can have a strong diminishing effect on pressure oscillations and structural loads.

Key words	condensation pool, steam/air blowdown, non-condensable gas, pressure oscillations

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