

Nordisk kernesikkerhedsforskning Norrænar kjarnöryggisrannsóknir Pohjoismainen ydinturvallisuustutkimus Nordisk kjernesikkerhetsforskning Nordisk kärnsäkerhetsforskning Nordic nuclear safety research

> NKS-117 ISBN 87-7893-178-9

Thermal stratification experiments with the condensation pool test rig

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Abstract

This report summarizes the results of the thermal stratification experiments with the condensation pool test rig. One experiment was carried out in March and another one in May 2005 with a scaled down test facility designed and constructed at Lappeenranta University of Technology. The main purpose of the experiments was to study thermal stratification phenomenon in the condensation pool during steam discharge and to produce data for the validation of the stratification model of the APROS code.

Key words

Experiments, condensation, blowdown, steam

NKS-117 ISBN 87-7893-178-9

Electronic report, January 2006

The report can be obtained from NKS Secretariat NKS-775 P.O. Box 49 DK - 4000 Roskilde, Denmark

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Research Report Lappeenranta University of Technology Nuclear Safety Research Unit

POOLEX 1/2005

THERMAL STRATIFICATION EXPERIMENTS WITH THE CONDENSATION POOL TEST RIG

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Lappeenranta, 23.11.2005



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Diary code	Order reference	
Project title and reference code	Report identification & Pages Date	
SAFIR / POOLEX	POOLEX 1/2005 23.11.2	005
NKS / Delipool	23 p. + app. 8 p.	

Report title and author(s)

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Summary

This report summarizes the results of the thermal stratification experiments with the condensation pool test rig. One experiment was carried out in March and another one in May 2005 with a scaled down test facility designed and constructed at Lappeenranta University of Technology. The main purpose of the experiments was to study thermal stratification phenomenon in the condensation pool during steam discharge and to produce data for the validation of the stratification model of the APROS code.

The test pool was a stainless steel tank with a wall thickness of 4 mm and a bottom thickness of 5 mm at atmospheric pressure containing 12 m^3 of water. The PACTEL test facility was used as a steam source. During the experiments the steam mass flow rate ranged from 25 g/s to 210 g/s and the temperature of pool water from 27 °C to 67 °C. The test rig was equipped with dozens of thermocouples for measuring both vertical and horizontal temperature distribution in the pool.

The total duration of both experiments, including the heating and cooling phase, was approximately 52 hours. Before initiating steam blowdowns the test pool was filled with isothermal water (temperature 27 °C and 30 °C). During the first four hours pool water was heated with steam flow. When the steam flow rate was low enough, steam condensed totally inside the blowdown pipe and the steam-water interface stayed close to the blowdown pipe outlet. Because steam condensed inside the pipe, the water inventory in the pool did not mix but stratified strongly. When the steam flow rate was higher the steam-water interface moved up and down inside the blowdown pipe and steam flow pushed water as plugs from the blowdown pipe to the pool bottom. In this case, a uniform temperature distribution was preserved in the pool. After the heating phase, the pool water was let to cool down freely for the next 48 hours. The heating phase of both experiments was measured with a frequency of 1 Hz and the cooling phase with a frequency of 0.1 Hz.

Distribution

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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 <u>FIN</u>nish research programme on <u>NU</u>clear power plant <u>Safety (FINNUS)</u>. The tests were designed to correspond to the conditions in the Finnish BWRs and the test programme was partially funded by Teollisuuden Voima Oy (TVO).

In these tests, the formation, size and distribution of non-condensable gas bubbles in the condensation pool was studied experimentally with a scaled down pool test facility. Also the effect of non-condensable gas on the performance of an ECCS pump was examined [1]. The test conditions were modelled with the Fluent CFD-code at VTT. The Fluent simulations were utilized in the planning phase of the tests to select the position, size and number of blowdown pipes [2]. The post-test calculations were carried out for code validation purposes [3, 4].

A new research project called Condensation <u>POOL</u> <u>EX</u>periments (POOLEX) started in 2003 within the <u>SA</u>fety of Nuclear Power Plants - <u>FI</u>nnish National <u>Research</u> Programme (<u>SAFIR</u>). The POOLEX project continues the work done within the FINNUS programme. In the new tests, steam instead of non-condensable gas 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 injection. The study is funded by the State Nuclear Waste Management Fund (VYR) and by the Nordic nuclear safety research (NKS).



CONTENTS

1	INTRODUCTION	4
2	STUDIED LOCA TRANSIENT	5
3	TEST FACILITY	5
	3.1 SCALING PRINCIPLES OF THE TEST RIG	5
	3.2 MEASUREMENT INSRUMENTATION	6
	3.3 DATA ACQUISITION	7
4	TEST PROGRAMME	8
5	ANALYSIS OF THE EXPERIMENTS	9
	5.1 STB-20	9
	5.1.1 Heating phase	9
	5.1.2 Cooling down phase	14
	5.2 STB-21	16
	5.2.1 Heating phase	
	5.2.2 Cooling down phase	
6	SUMMARY AND CONCLUSIONS	
7	REFERENCES	23

APPENDIXES:

Appendix 1: Instrumentation of the POOLEX test rig Appendix 2: Photographs of the POOLEX test rig



NOMENCLATURE

Abbreviations

BWR	boiling water reactor
ECCS	emergency core cooling system
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
SAFIR	Safety of Nuclear Power Plants – Finnish National Research Programme
TVO	Teollisuuden Voima Oy
VTT	Technical Research Centre of Finland
VYR	State Nuclear Waste Management Fund



1 INTRODUCTION

During a possible steam line break accident inside the containment a large amount of noncondensable (nitrogen) and condensable (steam) gas is blown from the upper drywell to the condensation pool through the blowdown pipes in the Olkiluoto type boiling water reactors (BWRs). The wetwell 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 results of the experiments focusing on some of the phenomena mentioned above are presented in reports [5, 6, and 7].

In the latter phase of a possible steam line break accident when the steam flow rate has decreased and the mixing effect is not so strong anymore, thermal stratification of water in the condensation pool could take place. This issue has been studied at LUT in spring 2005 with two experiments, where a small steam discharge through the DN200 blowdown pipe into the pool was used. Results of these experiments have also been used in the validation process of the stratification model of the APROS code in the SAFIR/TIFANY project.

In this report, the results of the thermal stratification experiments are presented. First, chapter two presents the studied LOCA transient. Chapter three gives a short description of the test facility and its measurements. Then, the test programme is introduced in chapter four. The test results are presented and discussed in chapter five. Chapter six summarizes the findings of the test series.



2 STUDIED LOCA TRANSIENT

The main purpose of the experiments is to study thermal stratification of the pool water during steam discharge. During a possible steam line break inside the containment a large amount of non-condensable (nitrogen) and condensable (steam) gas will be blown from the upper drywell of the containment to the condensation pool through the blowdown pipes in the Olkiluoto type BWRs. After a couple dozens of seconds, most of the nitrogen has escaped to the wetwell pool and mainly steam flows through the blowdown pipes.

The studied LOCA transient is the following [8]:

- Main steam line double-ended break at 1 s
- Feed water flow to reactor (25 kg/s) starts at 1.5 s (I-isolation)
 - \circ stops, when reactor water level is too high (5 m)
 - \circ starts again, when water level is too low (2 m)
- No containment spray, no cooling of the condensation pool
- Time interval from 40 to 13200 seconds is studied

During the transient steam flow into the condensation pool varies as a function of time. To simplify the experiments, an average steam mass flow rate value scaled with the ratio of the water volumes in the test rig and in the plant is used.

3 TEST FACILITY

The pool test facility was originally scaled and constructed for the experiments with noncondensable gas [1]. After some modifications, preliminary experiments with steam were executed by using the same pool test facility and DN80, DN100 and DN200 blowdown pipes [5, 6]. After installing extra high-speed instrumentation, the first detailed steam test series were executed with the modified pool test facility by using one DN200 blowdown pipe [7].

More instrumentation (particularly thermocouples) was added to the test rig before executing the thermal stratification experiments. A sketch of the test rig is presented in Figure 2. Table 1 shows the main dimensions of the test rig compared to Olkiluoto plant conditions.

3.1 SCALING PRINCIPLES OF THE TEST RIG

In the Olkiluoto plant conditions water level in the condensation pool is 9.5 m and the blowdown pipes are submerged by 6.5 m, see Table 1. This means that 68.4% of the pool water is located above the blowdown pipe outlets (6.5 / 9.5). In order to keep this ratio the same in the test rig, the water level should be 2.95 m and the blowdown pipe submergence depth 1.81 m. Water level of 2.95 m correspond approximately to water volume of 12 m³ in the test pool.

In the Olkiluoto plant conditions the total average steam mass flow into the condensation pool during the studied transient (40...13200 s) is 11.4 kg/s. Steam mass flow rate for the experiments is scaled with the ratio of water volumes in the pools:

$$\frac{12 m^3}{2 700 m^3} \cdot 11.4 kg/s = 51g/s.$$





Figure 2. POOLEX test rig.

	Test rig	Olkiluoto 1 and 2
Number of blowdown pipes	1	16
Inner diameter of blowdown pipes [mm]	214.1	600
Pool cross-sectional area [m ²]	4.5	287.5
Water level in the pool [m]	2.95	9.5
Pipes submerged [m]	1.81	6.5
Pool water volume [m ³]	12	2700
Apipes/Apoolx100%	0.8	1.6

3.2 MEASUREMENT INSRUMENTATION

The test facility is equipped with thermocouples for measuring steam and pool water temperatures (T), with pressure transducers (P) for observing pressure behaviour in the blowdown pipe, in the steam line and at the pool bottom and with one pressure transducer (DP) for detecting the pool water level. Additional instrumentation includes valve position sensors. Before the second experiment (STB-21) was run, three new thermocouples (T410, T413 and T503) were installed into the test rig. 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 61 thermocouples. Two different types of thermocouples are used; NiCrNi, type K, \emptyset 3.0 mm (thermocouples T13, T14 and T503) and NiCrNi, type K, \emptyset 0.5 mm.



Temperature distribution in vertical and horizontal direction in the pool is measured by 48 \emptyset 0.5 mm thermocouples installed in three vertical supporting rods, see Appendix 1.

Pressures are measured with pressure transducers (P1 and P2; model Kyowa PVL-100K, P9; model Kyowa PVL-5K, P7; model Rosemount 3051) and with differential pressure transmitters (P103 and DP6; model Yokogawa EAJ 110).

Steam flow rate (F) is measured with a vortex flow meter (Foxboro E83FA). The flow meter is installed in the DN50 steam line few meters upstream of the beginning of the blowdown pipe.

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	±3.6 °C
T14	Temperature in the pool	±2.7 °C
T15	Temperature on the pool bottom	±1.8 °C
T101T116	Temperature in the pool (rod 1)	±1.8 °C
T201T216	Temperature in the pool (rod 2)	±1.8 °C
T301T316	Temperature in the pool (rod 3)	±1.8 °C
T401	Temperature on the blowdown pipe outer wall	±1.8 °C
T402	Temperature in the pool	±1.8 °C
T403	Temperature on the pool outer wall	±1.8 °C
T404	Temperature in the laboratory	±1.8 °C
T410	Temperature on the pool outer wall	±1.8 °C
T413	Temperature on the pool outer wall	±1.8 °C
T503	Temperature in the blowdown pipe (top, centre of pipe)	±1.8 °C
P1	Pressure in the blowdown pipe (bottom)	±93 kPa
P2	Pressure in the blowdown pipe (middle)	±93 kPa
P103	Pressure in the blowdown pipe (top)	±4 kPa
DP6	Water level in the pool	±0.06 m
P7	Pressure in the steam line	±97 kPa
P8	Pressure in the steam generator	±62 kPa
P9	Pressure on the pool bottom	±5 kPa
F1	Volumetric flow rate in the steam line	±4.9 l/s
Valve	Valve position	Not defined

 Table 2. Measurement instrumentation

3.3 DATA ACQUISITION

National Instruments PCI-PXI-SCXI is a PC-driven 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 [9].



Separate HPVee based software is used for monitoring and recording the essential measurements of the PACTEL facility [10] producing the steam. Both data acquisition systems measure signals as volts. After the experiments, the voltage readings expect valve position signals are converted to engineering units by using special conversion software.

In the thermal stratification experiments, measurement data was recorded with a frequency of 1Hz. With LabView an average value of 500 time steps was recorded to reduce the amount of noise in the measurement signal. During the cooling down period the data recording frequency was reduced to the value of 0.1 Hz. Residual measurements were recorded by HPVee software (1 Hz) only during the heating period.

A separate measurement channel is used for 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. Table 3 shows the structure of the engineering unit measurement database.

<pre>experiment> LabView.dat</pre>								
Data recording frequency: 0.1 or 1 Hz								
Time	Time T1 T2 T3 T15 T101 T116 T201 T216							
[s] [°C] [°C] [°C] [°C] [°C] [°C] [°C]								

Table 3 Structure of the measurement database

<experiment>_LabView.dat (continued)</experiment>							
Data recording frequency: 0.1 or 1 Hz							
T301 T316 T401 T402 T403 T404 T410 T413 T503							T503
$\begin{bmatrix} \circ C \end{bmatrix} \begin{bmatrix} \circ C \end{bmatrix}$							

<experiment>_LabView.dat (continued)</experiment>							
Data recording frequency: 0.1 or 1 Hz							
P1	P1 P2 P103 P9 Valve						
[bar] [bar] [bar] [V]							

<experiment>_HPVee.dat</experiment>							
Data recording frequency: 1 Hz							
Time P8 P7 T14 T13 DP6 F1 Valve							
$\begin{bmatrix} s \end{bmatrix} \begin{bmatrix} bar \end{bmatrix} \begin{bmatrix} bar \end{bmatrix} \begin{bmatrix} \circ C \end{bmatrix} \begin{bmatrix} \circ C \end{bmatrix} \begin{bmatrix} m \end{bmatrix} \begin{bmatrix} l/s \end{bmatrix} \begin{bmatrix} V \end{bmatrix}$							[V]

4 TEST PROGRAMME

The thermal stratification test programme in March and May 2005 consisted of two separate experiments (labelled as STB-20 and STB-21). Both experiments were performed by using the DN200 blowdown pipe. All three steam generators of the PACTEL test facility were used as a steam source during the experiments. Before the experiments the pool was filled with isothermal water to a level of 2.95 m i.e. total water volume was approximately 12 m³ and the blowdown pipe was submerged by 1.81 m.



The total duration of the first experiment (STB-20) was approximately 52 hours. The initial pool water temperature was 30 °C. During the first four hours, the pool water was heated with steam flow. The initial steam mass flow rate of 55 g/s was slowly reduced to 25 g/s as the experiment progressed to make sure that steam condenses inside the blowdown pipe and that the steam-water interface remains close to the blowdown pipe outlet. Steam blowdown was terminated when the water maximum temperature in the upper part of the pool was 67 °C. After the heating phase, the pool water was let to cool down for the next 48 hours so that the LabView measurement system was still recording data with a frequency of 0.1 Hz.

Before the second experiment (STB-21) was run, three new thermocouples (T410, T413 and T503, see exact locations in Appendix 1) were installed into the test rig. The total duration of STB-21 was also approximately 52 hours. The initial pool water temperature was 27 °C. During the first four hours, the pool water was heated with steam flow. Between 4200 and 5200 seconds into the experiment, mixing of the pool water was executed by radically increasing the steam flow up to 210 g/s Otherwise, the steam flow rate ranged during the heating phase from the initial value of 75 g/s to about 25 g/s. The steam mass flow rate was slowly reduced to make sure that steam condenses inside the blowdown pipe and that the steam-water interface remains close to the blowdown pipe outlet. Steam blowdown was terminated when the temperature of water in the upper part of the pool reached the value of 65 °C. After the heating phase, a cooling period of about 48 hours was measured. Table 4 shows the test parameters of the POOLEX thermal stratification experiments.

1				
Experiment	Pool water	Initial pool	Steam flow	Duration
	temperature	water level	rate	(heating phase [h] +
	[°C]	[m]	[g/s]	cooling phase [h])
STB-20	3065	2.95	2555	4+48
STB-21	2767	2.95	25210	4+48

Table 4. Test parameters of the POOLEX thermal stratification experiments

5 ANALYSIS OF THE EXPERIMENTS

The following chapters give a more detailed description of the experiments and also shortly try to analyze the observed phenomena.

5.1 STB-20

The first thermal stratification experiment began on March 30th 2005 at 10:24 and did not end until on April 1st 2005 at 14:40. Thus, the total duration of the experiment was more than 52 hours. During the first four hours, the pool water was heated with steam flow. After the heating phase, the pool water cooled down freely for the next 48 hours.

5.1.1 Heating phase

The measured temperatures between 0...400 seconds give the temperature distribution in the pool before the experiment; see Figure 3 (vertical temperature distribution) and Figure 4 (horizontal temperature distribution). All the thermocouples located below the water level (2.95 m) show temperature of approximately 30 °C indicating isothermal pool water.





Figure 3. Vertical temperature distribution in the pool (T101...T114) in STB-20 during the heating phase.



Figure 4. Horizontal temperature distribution in the pool on the level of -800 mm (T101...T301), 250 mm (T108...T308) and 1600 mm (T114...T314) and temperature of the laboratory (T404) in STB-20 during the heating phase.



The steam blowdown was initiated at 400 s. At first, the steam mass flow rate was set to a value of approximately 55 g/s, see Figure 5. With this flow rate, steam condensed inside the blowdown pipe and the steam-water interface stayed close to the pipe outlet. As the experiment progressed, the temperature of pool water got higher and the steam-water interface tended to undergo a condensation event in the pool. To make sure that steam condenses inside the pipe steam flow was reduced every now and then by adjusting the pressure of the steam generators. When steam discharge was terminated (at 15100 s), the steam mass flow rate was no more than 25 g/s.



Figure 5. Mass flow rate (F1), temperature (T13) and pressure (P7) of steam in STB-20 during the heating phase. T13sat is saturated steam temperature and P8 is steam generator pressure.

After initiating the steam blowdown, the readings of the uppermost thermocouples below the water level (T114, T214 and T314) started to rise, because heat released in the condensation process inside the blowdown pipe was transferred through the pipe wall to the pool side. Between 550...2100 s, the temperature readings of T113...T107, T213...T207 and T313...T307 also started to raise one after another as more and more steam was discharged into the pool.

After 2800 s, also the readings of thermocouples T106, T206 and T306 (located 50 mm below the blowdown pipe outlet level, see Appendix 1) started to rise slowly. It means that heat was transported downwards to the region just below the blowdown pipe outlet by convection. The boundary layer of warm water flowing upwards on the outer surface of the blowdown pipe draws also colder water from the layers below whereupon the boundary between cold and warm water moves downwards. Meanwhile, the readings of the thermocouples in the lower part of the pool (T101...T105, T201...T205 and T301...T305) still showed constant temperatures of approximately 30 °C.

At 15100 s, the steam discharge was terminated. Just above the blowdown pipe outlet the temperature of pool water was then 56 °C (registered by T107, T207 and T307). When we move



upwards, the water temperature rises smoothly. The maximum water temperature (67 °C) was measured just below the water surface (registered by T114, T214 and T314). Meanwhile, at the lower part of the pool a uniform temperature distribution (30 °C) prevailed. Pool water was also strongly stratified as was expected. The temperature difference between the bottom and top was 37 °C. In the horizontal direction, no temperature differences were observed during the heating phase, see Figure 4.

Temperature measurements T115, T215 and T315 (not shown in Figure 3) were initially above the pool water level. At the end of the steam discharge they were, however, almost submerged. This was due to the facts that the long steam discharge increased water inventory in the pool and the density decrease associated with water heat up caused level swelling.

During the heating phase the room temperature of the laboratory increased slightly due to heat losses from the pool (the pool is not insulated and there is an open top) and from the PACTEL facility. Before the steam blowdown was initiated, the room temperature of the laboratory was approximately 24 °C (registered by T404). When the blowdown was terminated the temperature of the laboratory had increased to the 26 °C, see Figure 4

Figure 6 shows the temperatures inside the blowdown pipe during the heating phase. Figure 7 shows some frame captures from the pool during the experiment. From these two figures it can be seen that practically all steam condenses inside the blowdown pipe and steam-water interface stays close to the pipe outlet. However, from temperature readings of T1 and T2, which differ from saturation temperatures, it can be concluded that there was a falling liquid film on the inside surface of the bottom half of the blowdown pipe.



Figure 6. Temperatures inside the blowdown pipe (T1: pipe bottom, T2: pipe middle and T3: pipe top) in STB-20 during the heating phase.





Figure 7. Frame captures from STB-20 during the heating phase.

Figure 8 shows temperatures on the level of 1000 mm above the blowdown pipe outlet. One reading is from inside of the blowdown pipe and the others are from the pool side at different distances from the pipe. The small oscillation visible in the reading of T402 at 10 mm distance from the outer surface of the pipe reveals that the boundary layer, where a small upwards flow of warm water is present, almost stretches this far.





Figure 8. Temperatures on the level of 1000 mm in STB-20 during the heating phase (T2: inside the blowdown pipe, T401: on the pipe outer wall, T402: 10 mm distance from the pipe outer wall, T112: 900 mm distance from the pipe, T212: 410 mm distance from the pipe, T312: 600 mm distance from the pipe).

5.1.2 Cooling phase

After the heating phase, the pool water was let to cool down freely for the next 173000 seconds (48 hours). To reduce the amount of measurement data the recording frequency of the LabView data acquisition system was set to 0.1 Hz.

When the heating process was terminated at 15100 s, the pool water was clearly stratified above the blowdown pipe outlet elevation (56 °C...67 °C). Meanwhile, at the lower part of the pool a uniform temperature distribution (30 °C) prevailed. Thus, the maximum temperature difference between the upper and lower part of the pool was 37 °C.

As the cooling phase proceeded, the temperature stratification located above the blowdown pipe outlet balanced out. After 40000 s, thermocouple readings of T107...T114, T207...T214 and T307...T314 showed uniform temperature values indicating isothermal pool water. After 110000 s, also thermocouples T106, T206 and T306 measured same values as the thermocouples located above them.

At the same time, however, the isothermal water located below the blowdown pipe outlet began to stratify. The readings of thermocouples T105, T205 and T305 started to rise and reached the maximum value of 33 °C somewhere at 125000 s. They then began to cool down. The rise was a result of heat convention from the layers above. The readings of thermocouples T101...T104, T201...T204 and T301...T304 decreased smoothly from the beginning of the cooling phase.





Figure 9. Vertical temperature distribution in the pool (T101...T114) in STB-20 during the cooling phase.



Figure 10. Horizontal temperature distribution in the pool on the level of -800 mm (T101...T301), 250 mm (T108...T308) and 1600 mm (T114...T314) and temperature of the laboratory (T404) in STB-20 during the cooling phase.



When the data recording was terminated (at 188000 s), the thermocouples located above the blowdown pipe outlet (T107...T114, T207...T214 and T307...T314) and also thermocouples T106, T206 and T306 showed uniform water temperature of approximately 33 °C. The readings of the thermocouples below the blowdown pipe outlet (T101...T105, T201...T205 and T301...T305) ranged from 26 °C to 32 °C. Thus, the temperature difference between the bottom and top of the pool had decreased to 7 °C. Figure 9 shows the vertical temperature distribution in the pool during the cooling phase.

A minor distraction effecting on the cooling process was discovered when the temperature curve of the laboratory was plotted. Forced ventilation of the laboratory was automatically switched off at 19:00 in the evenings and on again at 7:00 in the next morning. This raised the room temperature of the laboratory in the periods of 30000...74000 s and 117000...161000 s. The thermocouple measuring the laboratory temperature, located at 1 m distance from the pool wall (T404), indicated a 2-3 °C rise as ventilation was switched off, see Figure 10. However, no effect on the other temperature measurements due to ventilation was observed.

5.2 STB-21

The second thermal stratification experiment was executed in May 2005. The experiment began on May 18th at 9:43 and ended on May 20th at 13:28. The total duration of the experiment was approximately 52 hours. During the first four hours, the pool water was heated with steam flow. After the heating phase, the pool water cooled down freely for the next 48 hours. During the experiment some problems were met. The LabView data acquisition system crashed on May 20th at 3:05. The program was rebooted at 7:40 on the same morning. Thus, a 4 hours 35 minutes period of measurement data from the cooling phase is missing.

5.2.1 Heating phase

The pool was initially filled with isothermal (27 °C) water to the level of 2.95 m, see Figures 11 and 12. Steam blowdown was initiated at 170 s. At first, the steam mass flow rate was set to the value of approximately 75 g/s, see Figure 13. With this flow rate the steam-water interface moved downwards inside the blowdown pipe and some steam was pushed into the pool. After rapid condensation of steam, the steam-water interface began to move upwards inside the pipe until the steam pressure was high enough to stop the interface and began to push it downwards again. Thus, the steam-water interface moved up and down inside the blowdown pipe (see Figure 14) and the steam flow pushed water as plugs from the blowdown pipe to the bottom of the pool. For this reason a uniform pool water temperature distribution remained and no sings of temperature stratification was observed.

In order to find the conditions when the steam-water interface stays inside the blowdown pipe close to the pipe outlet and thermal stratification begins, the steam flow rate was decreased step by step. The flow was adjusted by controlling the pressure of PACTEL's steam generators, see Figure 13. At 3250 s, the steam flow was down at 45 g/s and all the thermocouples below the blowdown pipe outlet began to show uniform water temperature of 35 °C, see Figure 11. Thus plugs of water were not pushed to the bottom of the pool anymore and a threshold value for steam flow rate had been found. With this flow rate the condensation event took place totally inside the blowdown pipe and the steam-water interface stayed close to the blowdown pipe outlet. As the pool water got warmer steam tended to escape from the blowdown pipe into the pool. To prevent this, the steam flow rate was decreased to 40 g/s at 3750 s.





Figure 11. Vertical temperature distribution in the pool (T101...T115) in STB-21 during the heating phase.



Figure 12. Horizontal temperature distribution in the pool on the level of -800 mm (T101...T301), 250 mm (T108...T308) and 1600 mm (T114...T314) and temperature of the laboratory (T404) in STB-21 during the heating phase.





Figure 13. Mass flow rate (F1), temperature (T13) and pressure (P7) of steam in STB-21 during the heating phase. T13sat is saturated steam temperature and P8 is steam generator pressure.

To proceed according to the test plan, the pool water was mixed when temperature at the surface layer had gone up about 15 °C from the initial value. The mixing process started at 4200 s by increasing the set value for the steam generator pressure from 0.2 MPa to 0.45 MPa. The pressure was increased in order to get a high steam flow that would produce the mixing effect. At 4900 s, the steam flow rate was 210 g/s and an isothermal temperature distribution (40 °C) was again attained in the pool. At 5200 s, the pool water temperature had increased to 42 °C and the flow was then set to the value of 75 g/s.

As the test continued the steam flow rate was again decreased step by step to find a new threshold value, now with a higher pool bulk water temperature than before, where steam condenses totally inside the blowdown pipe. At 7700 s, the steam flow was 35 g/s and the thermocouples located below the blowdown pipe outlet began to show uniform water temperature of 46 °C. The new threshold value for steam flow is smaller than the one found at 3250 s (45 g/s), just as expected. During the rest of the heating phase, the steam flow rate was reduced occasionally to make sure that steam condensed inside the blowdown pipe.

At 14700 s, the temperature of water in the upper part of the pool reached the value of 65 $^{\circ}$ C (registered by T115, T215 and T315). The steam discharge was then terminated. The thermocouples that are closest above the blowdown pipe outlet level (T107, T207 and T307) shoved values of 54 $^{\circ}$ C. Meanwhile, below the blowdown pipe outlet a uniform temperature distribution (46 $^{\circ}$ C) prevailed. The pool water above the blowdown pipe outlet level was strongly stratified.





Figure 14. Temperatures inside the blowdown pipe (T1: pipe bottom, T2: pipe middle, T3: pipe top and T503: pipe top, centre of pipe) in STB-21 during the heating phase.



STB-21

Figure 15. Temperatures on the level of 1000 mm in STB-21 during the heating phase (T2: inside the blowdown pipe, T401: the pipe outer wall, T402: 10 mm distance from the pipe outer wall, T112: 900 mm distance from the pipe, T212: 410 mm distance from the pipe, T312: 600 mm distance from the pipe).



During the experiment approximately 6001 of water (in the form of steam) flowed into the pool from the steam generators. This amount of water increased the pool water level by 0.13 m. Also the pool water swelling due to the decrease of water density through warming increased the pool water level by some centimetres. As a result of the level increase, thermocouples T115, T215 and T315 were submerged during the experiment although they were initially 0.20 m above the water level, see Figure 11.

Figure 14 shows the temperatures inside the blowdown pipe during the heating phase. The curves verify those visual observations during the experiment that concern finding such threshold values for the steam flow rate, where practically all steam condenses inside the blowdown pipe and the steam-water interface stays close to the pipe outlet. From temperature reading of T3 one can conclude that the falling liquid film on the inside surface of the blowdown pipe was present in STB-21 also at the top part of the pipe from about 9000 s on.

Figure 15 shows temperatures on the level of 1000 mm above the blowdown pipe outlet. Again, one reading is from inside of the blowdown pipe and the others are from the pool side at different distances from the pipe. The boundary layer of small upwards flow of warm water on the outer surface of the blowdown pipe is present also in this experiment as can be seen from the small oscillation in the reading of T402.

5.2.2 Cooling phase

After the heating phase, the pool water was let to cool down freely for the next 171500 seconds (approximately 48 hours). During the cooling phase the recording frequency of the LabView data acquisition system was 0.1 Hz.

When the heating process was over, the pool water was clearly stratified. The temperature of water above the blowdown pipe outlet level ranged from 54 °C to 65 °C. Meanwhile, below the blowdown pipe outlet level a uniform temperature (46°C) distribution prevailed. Thus, the maximum temperature difference between the pool bottom and top was 19°C.

The upper part of the pool cooled down similarly as in STB-20. After about seven hours, a uniform temperature distribution was attained above the blowdown pipe outlet. Because of the higher initial temperature below the blowdown pipe outlet in the beginning of the cooling phase in STB-21 than in STB-20, the temperature difference between the upper and lower part of the pool balanced out faster in STB-21. Data acquisition was terminated after approximately 48 hours (at 186000 s). All the thermocouples below the water level showed temperatures of about 35 °C and thus indicated isothermal pool water. Figure 16 gives the vertical temperature distribution in the pool during the cooling phase. Note that water level dropped below the elevation of thermocouple T115 as cooling proceeded. The time interval of 149000...165000 s is missing from the measurement data due to crashing of the LabView data acquisition system.

Like during STB-20, forced ventilation of the laboratory was automatically switched off for the nights. This raised the laboratory temperature approximately by 2-3°C, see Figure 17.





Figure 16. Vertical temperature distribution in the pool (T101...T115) in STB-21 during the cooling phase.



Figure 17. Horizontal temperature distribution in the pool on the level of -800 mm (T101...T301), 250 mm (T108...T308) and 1600 mm (T114...T314) and temperature of the laboratory (T404) in STB-21 during the cooling phase.



6 SUMMARY AND CONCLUSIONS

Two experiments were carried out to study thermal stratification in a large water pool (height 5.0 m, diameter 2.4 m) during steam injection with a scaled down test facility designed and constructed at Lappeenranta University of Technology. The experiments were performed using a DN200 (\emptyset 219.1x2.5) blowdown pipe. All three steam generators of the PACTEL test facility were used as a steam source. The data acquisition system recorded measurement data with a frequency of 1 Hz during the heating phase and with a frequency of 0.1 Hz during the cooling phase. Initially, the test pool was filled with isothermal water to a level of 2.95 m i.e. the total volume of water was approximately 12 m³ and the blowdown pipe was submerged by 1.81 m.

The total duration of the first experiment was approximately 52 hours. Before the steam blowdown was initiated, the pool water temperature was 30 °C. During the first four hours, pool water was heated with steam flow. The steam flow rate (25...55 g/s) was slowly reduced during the experiment to make sure that steam condenses inside the blowdown pipe and the steam-water interface remains close to the blowdown pipe outlet. Because steam condensed steadily inside the blowdown pipe, the water inventory in the pool did not mix. Therefore, pool water stratified strongly during the heating phase. After four hours, the temperature of water in the upper part of the pool reached the value of 67 °C. The temperature below the blowdown pipe outlet level stayed at the initial value of 30 °C. After the heating phase, the pool water was let to cool down freely for the next 48 hours. Uniform pool water temperature above the blowdown pipe outlet was attained again after about seven hours. After a cooling period of 48 hours, the temperature difference between the pool bottom and top had decreased to 7 °C.

The total duration of the second experiment was also approximately 52 hours. Initially, the pool water temperature was 27 °C. During the first four hours, pool water was heated with steam flow. At first, the steam mass flow rate was set to the value of 75 g/s. With this flow, the steam-water interface moved up and down inside the blowdown pipe and steam flow pushed water as plugs from the blowdown pipe to the pool bottom. The water inventory in the pool mixed and there were no sings of temperature stratification. To find the conditions when the steam-water interface stays inside the blowdown pipe close to the pipe outlet and thermal stratification begins, the steam flow rate was decreased step by step. When the flow rate was 45 g/s, practically all steam condensed inside the blowdown pipe. When temperature at the surface layer was about 15 °C higher than in the beginning of the experiment, the water inventory in the pool was mixed by increasing the steam flow rate radically. After an isothermal temperature distribution was attained again (40°C), the second part of the heating phase was initiated and a new threshold value for the steam flow rate (where all steam condenses inside the blowdown pipe) was searched by decreasing the flow step by step. The new threshold value (35 g/s) was smaller than the one found with colder pool water. The experiment was terminated when the maximum temperature of water in the upper part of the pool was 65 °C. The temperature of water below the blowdown pipe outlet level was then 46 °C. After the heating phase, the pool was let to cool down for about 48 hours. Uniform pool water temperature above the blowdown pipe outlet was attained after about seven hours. After 48 hours, all the thermocouples below the pool water level showed temperatures of 35 °C and indicated isothermal pool water.



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APPENDIX 1. INSTRUMENTATION OF THE POOLEX TEST RIG



Instrumentation inside the blowdown pipe and on the pool bottom





Horizontal cross-section of the pool





Thermocouples T401...T404, T410 and T413 (cross-section A-A)





Thermocouples T101...T116 (cross-section A-A)





Thermocouples T201...216 (cross-section A-A)





Thermocouples T301...T316 (cross-section D-D)





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



APPENDIX 2. PHOTOGRAPHS OF THE POOLEX TEST RIG



Inside view of the pool

Bibliographic Data Sheet

Title	Thermal stratification experiments with the condensation pool test rig
Author(s)	Jani Laine & Markku Puustinen
Affiliation(s)	Lappeenranta University of Technology, Finland
ISBN	87-7893-178-9 (Electronic report)
Date	January 2006
Project	NKS_R_2002_01
No. of pages	23 + app. 8
No. of tables	4
No. of illustrations	17 + app. 8
No. of references	10
Abstract	This report summarizes the results of the thermal stratification experiments with the condensation pool test rig. One experiment was carried out in March and another one in May 2005 with a scaled down test facility designed and constructed at Lappeenranta University of Technology. The main purpose of the experiments was to study thermal stratification phenomenon in the condensation pool during steam discharge and to produce data for the validation of the stratification model of the APROS code.

Key words

Experiments, condensation, blowdown, steam