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GOTHIC code simulation of thermal stratification in POOLEX facility

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Abstract

Pressure suppression pool is an important element of BWR containment. It serves as a heat sink and steam condenser to prevent containment pressure buildup during loss of coolant accident or safety relief valve opening during normal operations of a BWR. Insufficient mixing in the pool, in case of low mass flow rate of steam, can cause development of thermal stratification and reduction of pressure suppression pool capacity.

For reliable prediction of mixing and stratification phenomena validation of simulation tools has to be performed. Data produced in POOLEX/PPOOLEX facility at Lappeenranta University of Technology about development of thermal stratification in a large scale model of a pressure suppression pool is used for GOTHIC lumped and distributed parameter validation.

Sensitivity of GOTHIC solution to different boundary conditions and grid convergence study for 2D simulations of POOLEX STB-20 experiment are performed in the present study. CFD simulation was carried out with FLUENT code in order to get additional insights into physics of stratification phenomena.

In order to support development of experimental procedures for new tests in the PPOOLEX facility lumped parameter pre-test GOTHIC simulations were performed. Simulations show that drywell and wetwell pressures can be kept within safety margins during a long transient necessary for development of thermal stratification.

Key words

Thermal stratification, numerical simulation, pressure suppression pool

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Research Report

GOTHIC code simulation of thermal stratification in POOLEX facility

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Executive summary

Pressure suppression pool is an important element of BWR containment. It serves as a heat sink and steam condenser to prevent containment pressure buildup during loss of coolant accident or safety relief valve opening during normal operations of a BWR. Insufficient mixing in the pool, in case of low mass flow rate of steam, can cause development of thermal stratification and reduction of pressure suppression pool capacity.

For reliable prediction of mixing and stratification phenomena validation of simulation tools has to be performed. Data produced in POOLEX/PPOOLEX facility at Lappeenranta University of Technology about development of thermal stratification in a large scale model of a pressure suppression pool is used for GOTHIC lumped and distributed parameter validation.

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Acknowledgement

The support of the Nordic Nuclear Reactor Thermal-Hydraulics Network Road Map 3 (NORTHNET-RM3), and the Nordic Nuclear Safety Program (NKS) is gratefully acknowledged.

1. INTRODUCTION

Pressure suppression pool is an important element of passive safety system. It serves as a heat sink and steam condenser to prevent containment pressure buildup during loss of coolant accident or safety relief valve opening during normal operations of a BWR. Pool surface temperature defines saturation steam pressure in the containment. Weak mixing in the pool, in case of low mass flow rate of steam, may be insufficient for prevention of thermal stratification development. As a result, temperature of the pool top layer can be significantly increased, which will lead to reduction of pool's pressure suppression capacity, and to increasing of containment pressure. Therefore reliable prediction of mixing and stratification phenomena is a must for safety analysis of the pressure suppression pool operations.

Stratification and mixing phenomena in a large water pool with a heat source have been studied experimentally [1, 2, 3, 4, 5] and analytically [5, 6, 7, 8] in the past. Strong stratification above a heat source submerged in a water pool and heat transfer into the volume below the heat source only via conduction were observed in a number of experiments [1, 2, 3, 4, 5]. The results of tests in PUMA facility [3] show that the degree of thermal stratification in suppression pool can be affected by the vent opening submergence depth, the pool initial pressure, the steam injection rate, and volume fraction of non-condensable gases. Scaling approaches and 1D simulation methods for prediction of thermal stratification and mixing in a pool of simple geometry were developed in [6, 7, 8]. Condensation and mixing phenomena during loss of coolant accident in a scaled down pressure suppression pool of simplified boiling water reactor were studied in [5]. Results of experiments [5] were compared with the TRACE code predictions and showed the code deficiency for prediction of the pool thermal stratification.

Despite the quite representative experimental database, the success in methods developments for reliable prediction of thermal stratification and mixing phenomena in real conditions of plant pressure suppression pool operations is still weak.

Lumped-parameter models (used to successfully describe mixing processes in the suppression pool in other regimes) fail to provide consistent description of thermal stratification. One-dimensional models have problems with taking into account of real geometry of the nuclear power plant pool. On the other hand, high-order-accurate CFD (RANS, LES, DNS) methods are not practical due to excessive computing power needed to calculate 3D high-Rayleigh-number natural convection flows [9], especially in long transients.

In the present work our objective is to find a way for reasonably-accurate and yet computationally affordable simulations of thermal stratification transients in the prototypic suppression pools. Toward this objective, we test distributed-parameter, CFD-like option of a general-purpose thermal-hydraulic code GOTHIC (version 7.2a) [10, 11] as potential computational vehicle. In the present paper we apply a top-down approach, namely the GOTHIC CFD-like option is used to simulate POOLEX [4] experiments to validate GOTHIC's physical and numerical models, to identify need for improvement of the models.

Extensive validation of the GOTHIC was done in the past [10] including simulation of Marviken tests, which are unique full scale experiments on the venting through a pressure suppression pool in the wetwell [12]. GOTHIC was also validated against experiments performed in large scale PANDA facility on the mixing process in the drywells, initially filled with air, during the initial steam purging transient [13]. But we didn't find in open literature validation of GOTHIC against the problem of thermal stratification and mixing in a large water pool.

For GOTHIC validation we selected series of experiments on steam condensation, thermal stratification and mixing in a large water pool performed at Lappeenranta University of Technology (Finland) with POOLEX (POOL EXperiment) facility [4]. The main reason for this choice was quite detailed description of experimental conditions and results provided in the research report [4]. POOLEX facility is an open to the lab atmosphere, cylindrical stainless steel tank with outer diameter 2.4 m and water pool depth 2.95 m. Three vertical trains of thermocouples (with 16 thermocouples in each train) were installed in the tank to monitor water temperature during the test. Heating by steam injection through the blowdown pipe and cooling (after stop of steam injection) phases were studied in the POOLEX tests. During the experiment STB-20 [4] the steam mass flow rate was kept in range of 25-55 g/s to make sure that steam condenses inside the blowdown pipe. Strong stratification above outlet of the blowdown tube was observed in the test.

In the present work we focus on a validation of GOTHIC against separate effect problem of thermal stratification development at low steam mass flow rate, which was studied in the POOLEX test STB-20 [4]. After that, CFD simulation was performed in order to get additional information of thermal stratification. At last, pre-test calculation was done for PPOOLEX with GOTHIC code, to investigate the possible phenomenon during the PPOOLEX experiment.

2. LUMPED PARAMETER GOTHIC SIMULATION

Heat losses from the tank to ambient atmosphere were not directly measured in the POOLEX experiments. Therefore we have to use GOTHIC lumped parameter model for calculation of the lacking in the experiment data on heat fluxes through the vessel walls and on the pool free surface. Then we use data calculated in lumped parameter model as unsteady boundary conditions in GOTHIC distributed parameter model for simulations of thermal stratification.

Lumped parameter model developed for simulation of POOLEX experiment is shown on Fig. 1. The flow boundary condition (1F in Fig. 1) represents steam source. Experimental data [4] (steam temperature, pressure, and flow rate) were used as time dependent flow boundary condition for 1F. Atmosphere was modeled by a pressure boundary codition (2P on Fig. 1) with constant pressure (1 bar) and temperature (20°C). Volumes 1, 2s, and 3 (Fig. 1) are representing blowdown pipe, water pool, and lab correspondently. Thermal conductors 1 and 2 (Fig. 1) were used for simulation of heat transfer between the blowdown pipe and vapor and liquid phases in the pool correspondently. Thermal conductors 3, 4 and 5 (Fig. 1) were used to simulate heat transfer between the vessel walls and the lab atmosphere. Conductors 3 and 4 represent the parts of the vessel sidewall in vapor and liquid space correspondently. Conductor 5 represents bottom wall of the vessel. Heat transfer coefficients for all heat conductors were calculated by default GOTHIC models for natural convection on vertical (conductors 1, 2, 3, 4) and horizontal (conductor 5) surfaces [11].

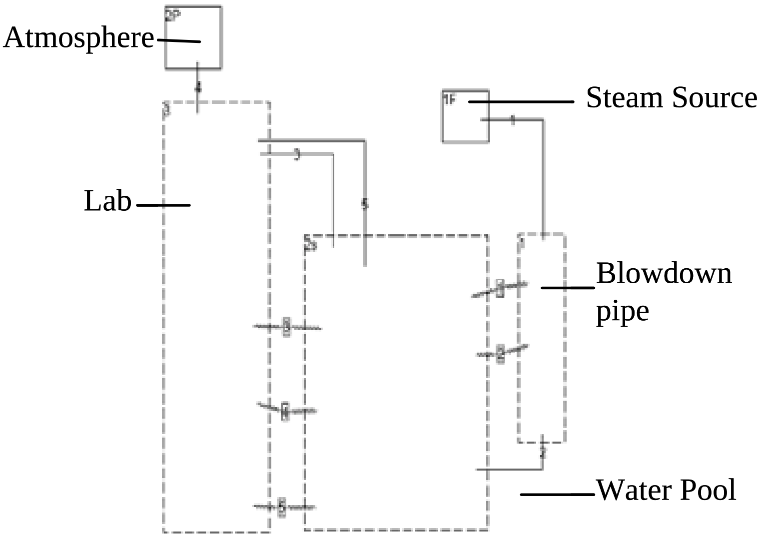


Fig. 1 GOTHIC lumped parameter input model

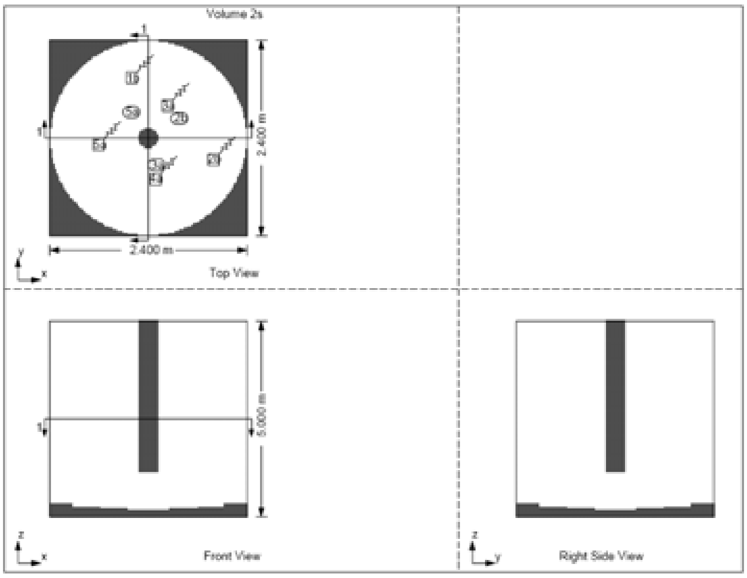


Fig. 2 POOLEX tank geometry representation in GOTHIC model.

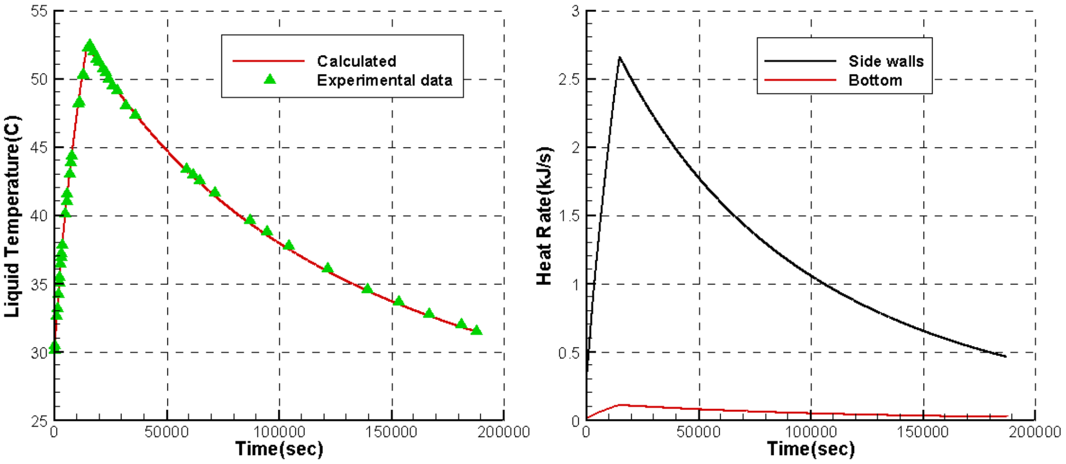
GOTHIC uses rectangular control volumes. In order to represent complex geometry one should use blockage [11]. Example of the tank geometry representation, obtained by partial blockage in GOTHIC rectangular cell is shown in the Fig. 2. Similar blockage was used to represent vessel geometry in distributed parameter model (see next section).

The POOLEX facility lab has a ventilation system. We didn't try to model lab ventilation system in the present work because parameters of this system are uncertain. Instead, an effect of ventilation system was introduced by a large (10^7 m3) volume of the lab. Temperature of the lab atmosphere in experiment and calculations was around 24°C. Natural circulation above the pool surface was taken into account (according to the recommendations of GOTHIC manual [11]) by two parallel flow paths (3 and 5, Fig. 1). Loss coefficients [11] in the flow paths were adjusted to match the experimental data.

In the STB-20 experiment, steam injection was started after 400 s of time start. Calculation were started directly from the moment of steam injection start, which means that heating phase (steam injection) was 14 600 s. The whole transient physical time is 187 600 s (~52 hours).

Comparison of experimental and simulation results for averaged pool water temperature are shown in the Fig. 3a. Good agreement between experimental and simulation data for both heating and cooling phases of the STB-20 test were obtained.

As we mentioned before, the main aim of lumped parameter model calculations was to obtain proper boundary conditions for the distributed parameter model simulation. In the Fig. 3b we show the heat losses from the tank to the lab through the side and bottom walls of the tank. One can see (Fig. 3b), that heat loss from the bottom of the tank is much smaller than from the side wall.



a) b)

Fig. 3 Lumped parameter model results:
a) averaged water temperature in the tank; b) heat fluxes to the vessel walls.

The CPU time for calculation of STB-20 whole transient, including heating and cooling phases (187 600 s of physical time), with lamped parameter model was around 250 seconds on the Pentium IV, 2.8 GHz.

3. DISTRIBUTED PARAMETER GOTHIC SIMULATOIN

The distributed parameter (CFD-like) model for POOLEX facility was developed to study thermal stratification in the pool. Water pool geometry was considered as axisymmetric.

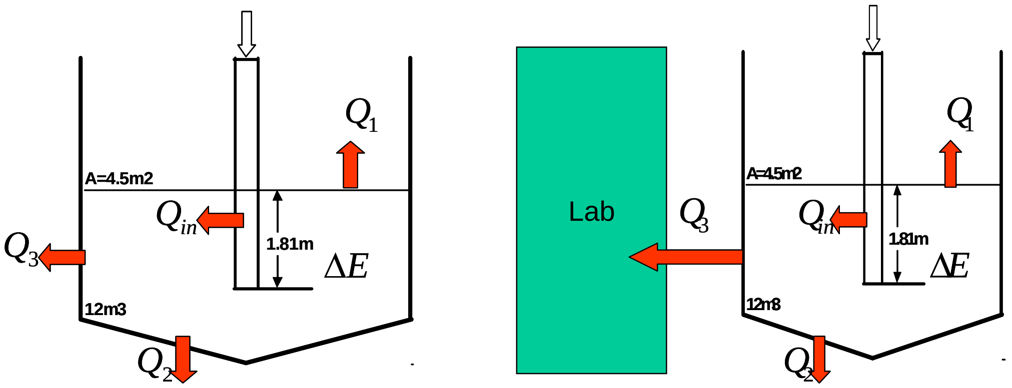
From preliminary steam injection simulation, it was shown that the computational time was affected significantly by condensation and evaporation process inside blowdown pipe and on the free surface of liquid tank in the GOTHIC simulation. Actually, during the experiment steam flow rate was controlled and position of water free surface was kept close the outlet and inside blowdown pipe. Only hot saturated condensate was coming out from the pipe. Such phenomenon can be assumed that all the heat will be transferred into the liquid through the wall of tube. Meanwhile, the mass inventory of liquid in the pool did not increase so much because of very slow steam flow rate.

According to the experimental procedure and phenomenon observed, it was assumed that there is no any fluid coming out from the pipe in our GOTHIC simulations, and heat source along the blowdown pipe wall was used instead of steam injection during simulation. Additionally, Water pool geometry was considered as axisymmetric in all of cases so that the numbers of mesh was reduced with 2D grid. Only liquid part of tank was considered in the simulation, in order to avoid computational expense due to evaporation in the top surface of liquid pool. Heat loss due to evaporation of free surface was simulated with one heat source imposed on the top of liquid.

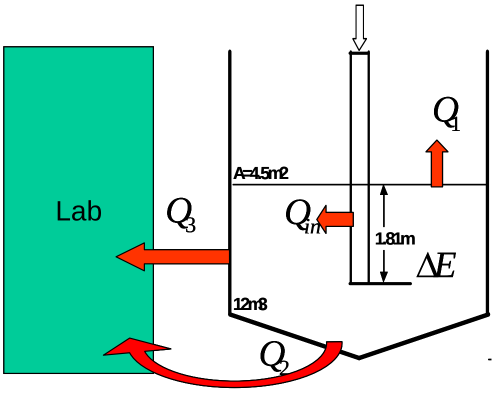
3.1. Investigation of boundary condition influence

The influence of boundary conditions of vessel wall on the thermal stratification was performed. In the simulations the liquid volume was divided into 12×30 meshes in X-direction and Z-direction, respectively. Three different kinds of thermal boundary conditions were used (Fig. 4):

- Boundary condition 1 (BC1): time dependent heat flux condition was used on all the surfaces. Heat flux distribution was uniform along each surface and the value of heat sources was obtained from the lumped parameter simulation with GOTHIC.
- Boundary condition 2 (BC2): Heat flux conditions were used on the top, bottom and pipe surfaces. For the side wall of the tank the build-in heat transfer model in GOTHIC was used to simulate heat transfer between the pool and lab through the wall as a heat conductor.
- Boundary condition 3 (BC3): Heat flux conditions were used on the top surface and on the pipe wall. For the side and bottom walls of the build-in heat transfer model in GOTHIC was used to simulate heat transfer between the pool and lab through the walls as heat conductors. In order to span the thermal conductor into the sub-volumes, the bottom shape was changed from cone into flat one.



a) Boundary Condition 1
b) Boundary Condition 2



c) Boundary Condition 3

Fig. 4: system scheme for BC1, BC2 and BC3.

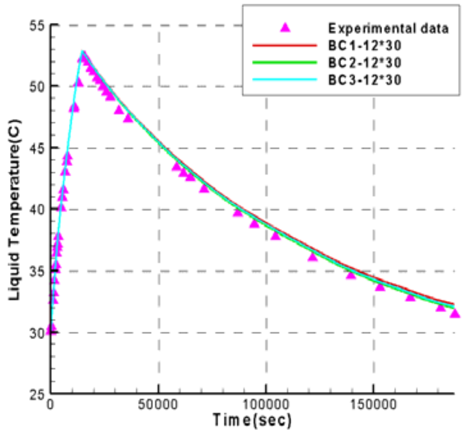
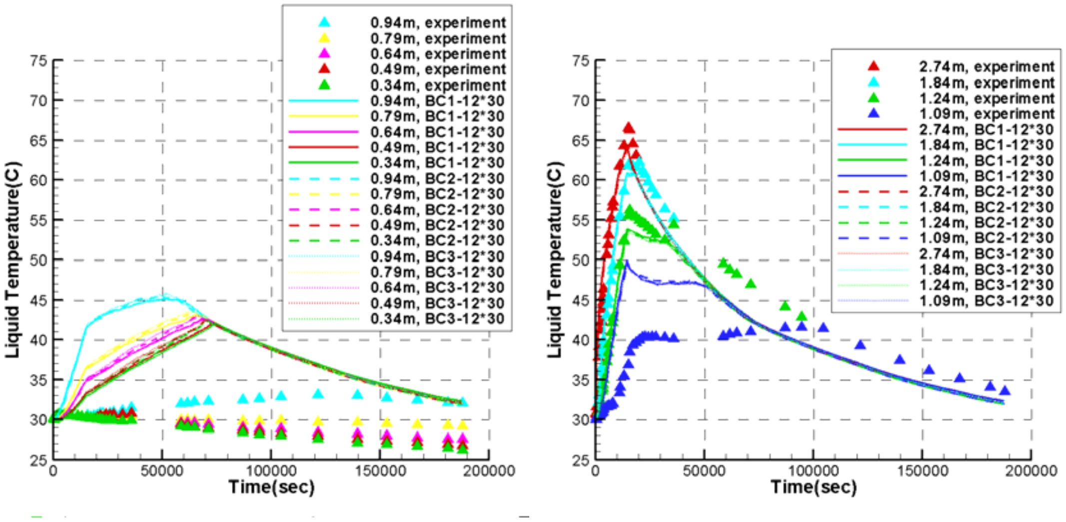


Fig. 5: Averaged liquid temperature with different boundary condition.

The total time of transient for simulation was 187600 seconds (~52 hours) and the computational time for simulations with different boundary conditions was nearly same and less than 5 hours. From Fig. 5, we can see the average liquid temperature was almost same with different boundary conditions. It confirms that the heat loss calculated with subdivided volume and with lumped parameter volume was almost identical in all the cases.

Fig. 6 shows the temperature distributions obtained with different boundary conditions. There was only slight difference in the results of three simulations. The reason for such difference is that when the fixed heat flux was used for side wall, heat flux was distributed uniformly along it. In fact, heat flux is variable along the surface because of different liquid temperatures and different heat transfer coefficients affected by liquid velocity. The heat loss from bottom part is smaller than from the side ant to surface of the pool because of lower liquid temperature and lower circulation velocity in bottom part. The prediction of temperature distribution obtained with build-in GOTHIC heat transfer model was in a good agreement with experimental data. However, the fraction of heat loss through side and bottom walls was much smaller compared to that from the top surface, so the total difference in temperature distribution was not significant. The figure also showed that using the flat bottom wall instead of cone in the boundary condition 3, did not affect simulation results, while it is much more convenient in GOTHIC to span thermal conductor on flat bottom.

The big deviation for simulation results compared to experimental data in the bottom part was probably due to relatively coarse grid resolution in the simulation.



a) b)

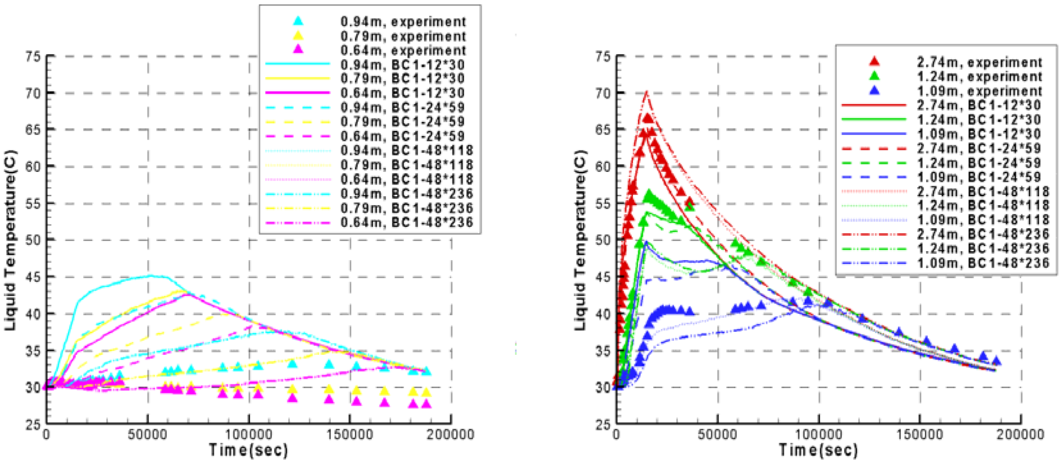
Fig. 6: Temperature distribution in the simulation with different boundary conditions: a) part below the pipe outlet; b) part above the pipe outlet.

3.2. Grid convergence study

In the previous chapter we presented 2D simulation in GOTHIC with grid 12×30 and different boundary condition. Although most of simulation results showed thermal stratification phenomenon and good agreement with experimental data, still some deviations from experimental data were observed in the bottom part of tank. One of the probable reasons for such discrepancy is numerical diffusion. In order to investigate influence of such numerical diffusion on thermal stratification simulation, four different grids with sequentially doubled space resolutions were used in GOTHIC for 2D simulation. The coarse grid solution was 12×30 with mesh size 0.1 m, medium gird resolution was 24×59 with mesh size 0.05 m and the fine grid solution was 48×118 with mesh size 0.025 m. The finest grid solution was 48×236. We tried to perform simulations with 96×236 cells but such calculations appears to be very computationally expensive for considered transient (52 hours of physical time). We also faced difficulties with development of GOTHIC input model for this case because graphic user interface was very much slowed down.

Since use of different boundary conditions has been proven to cause small influence for the simulations, for grid resolution analysis we used only boundary condition 1 (BC1) with heat flux boundary conditions imposed on all four surfaces.

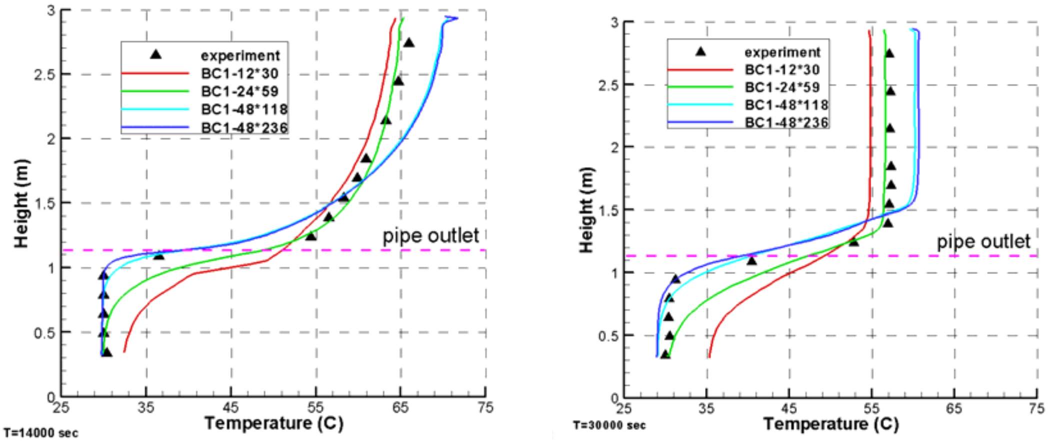
In Fig. 7 we can see an influence of grids resolution on the simulation results. Fig. 7a shows temperature distribution in the bottom part of the pool (i.e. below the pipe outlet) and in Fig. 7b temperature history above pipe outlet is presented.



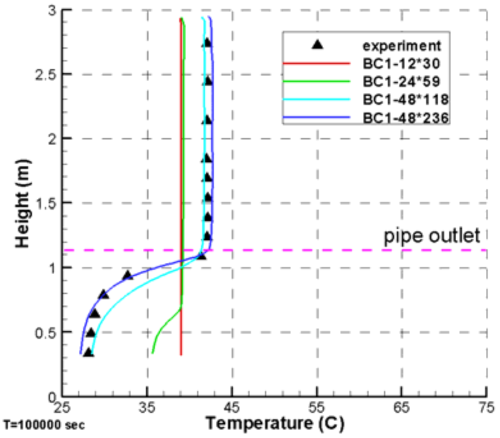
a) b)

Fig. 6: Temperature distribution in the simulation with different with different grids: a) part below the pipe outlet; b) part above the pipe outlet.

In Fig. 8 we show vertical distribution of liquid temperature in the pool obtained at three different moments of time with four different grid resolutions.



a) T=14000 second b) T=30000 second



c) T=100000 second

Fig. 8: liquid temperature along elevation at different transient time.

One can see that results obtained with grids 48×118 and 48×236 are practically overlapping with each other (Fig. 7, Fig. 8) even at the end of transient (Fig. 8c) which demonstrates grid convergence of the numerical solution. It is also clear from analysis of Fig. 7 and Fig. 8 that grids with lower resolution produces too high numerical diffusion which smears temperature gradients.

Temperature gradient in the top part of the pool during heating phase is slight over predicted (Fig. 8a). That can be explained if thermal turbulent diffusion in experiment was higher than that calculated with fine grid resolution. It worth to mention that solution obtained on low resolution grids is rather in a good agreement with experiment, which also confirms that thermal diffusion in reality turbulent diffusion was higher than predicted by GOTHIC on the fine grid.

Possible reason for such difference between simulation with fine grid and experiment was that momentum introduced by injected steam was ignored in the simulation. Although steam was mostly condensed within the pipe close to the pipe outlet, single bubbles still may come out of the tube and could introduce additional momentum which promoted additional mixing (thermal turbulent diffusion). From the analysis of experimental report [4], it can be concluded that there were some oscillations of the free surface inside the tube in the blowdown pipe especially at the beginning of experiment. Such oscillations also may introduce some additional momentum in the pool and enhance mixing in upper part.

At 30000 second (about 8 hours) (Fig. 8b) we can see that solution obtained with grid 24×59 still shows a reasonable agreement with experimental data. At 100000 second (about 28 hours), (Fig. 8c) the temperature distribution obtained on fine grids 48×118 and 48×236 agrees well with measured data in both upper part and bottom part of the pool.

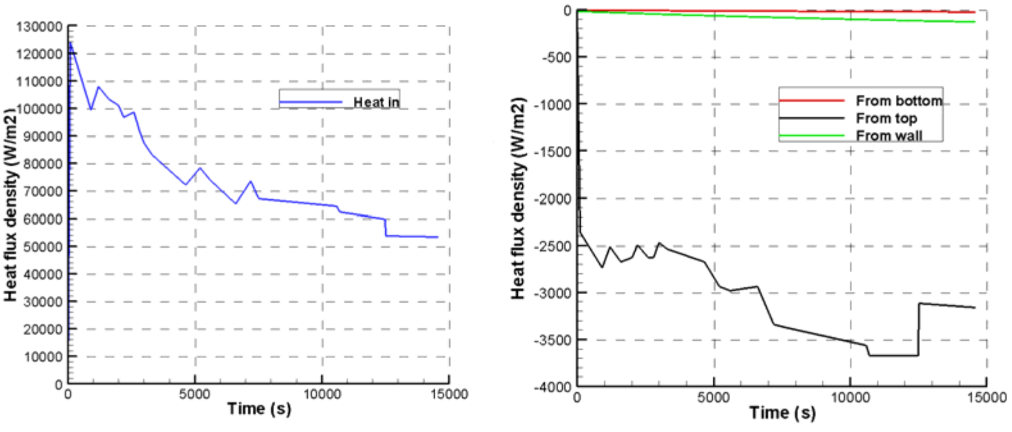
The computational time for grid 48×236 was about 17 days, while it was about 5 hours for simulation with the coarse grid 12×30.

4. CFD SIMULATION OF THERMAL STRATIFICATION

2D simulation with CFD code FLUENT, was carried out to get additional insight into physics of thermal stratification development in heating phase and isothermal layer development during the cooling phase.

4.1. Simulation of heating phase with time-dependent boundary condition

Input model was 2D axisymmetric similar to that used in GOTHIC. Only liquid part was simulated and there was no mass influx in the pool. Heat fluxes were imposed on all four surfaces (top, bottom, and side wall of the pool and the pipe wall) of simulated domain. Time dependent values of the heat fluxes obtained form lumped parameter simulation with GOTHIC were used as boundary conditions. The heat fluxes are shown in Fig. 9.



a) b)

Fig. 9: Thermal boundary conditions:
a) Heat flux through the tube wall b) Heat loss through bottom, top and side walls.

Heat transfer inside the solid walls was not modeled in the FLUENT, thus no heat was absorbed by the walls material was taken into account.

The transient time of simulation was 14600 seconds and it cost about 25 days computational time. The grid used in the simulation is shown in Fig. 10. Cell size was 0.1 m for general square cells above conic bottom. The grid was refined in the vicinity of side wall, top surface and the tube. Realizable k-e model, pressure based solver, 1st order implicit time scheme, and second order upwind scheme were used in the simulation.

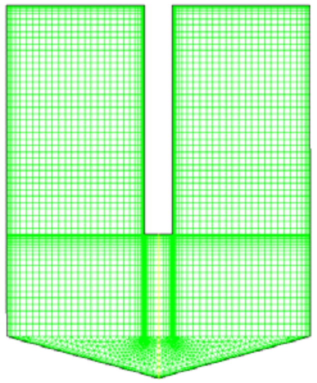


Fig. 10: Grid used in FLUENT simulations.

The average liquid temperature compared with experimental data is shown in Fig. 11. The difference was almost 3 degrees at the end of simulation, in comparison with experiment. The reason is that in FLUENT simulations geometry of the tank has a large volume for bottom than in reality, which was found after the finish of the simulations. Although such difference between experimental and simulation data for averaged temperature is undesirable, we still can analyze capabilities of FLUENT to predict thermal stratification phenomena.

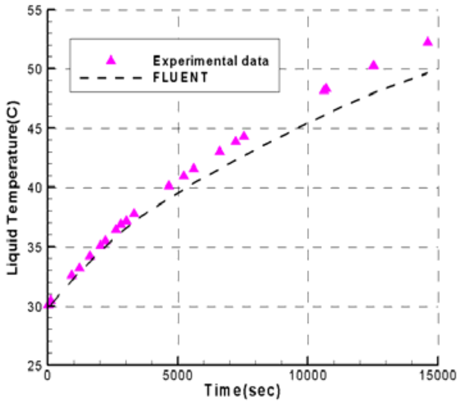
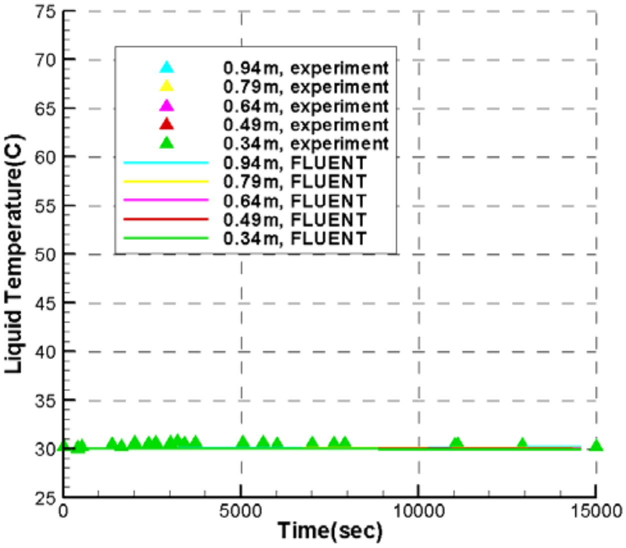
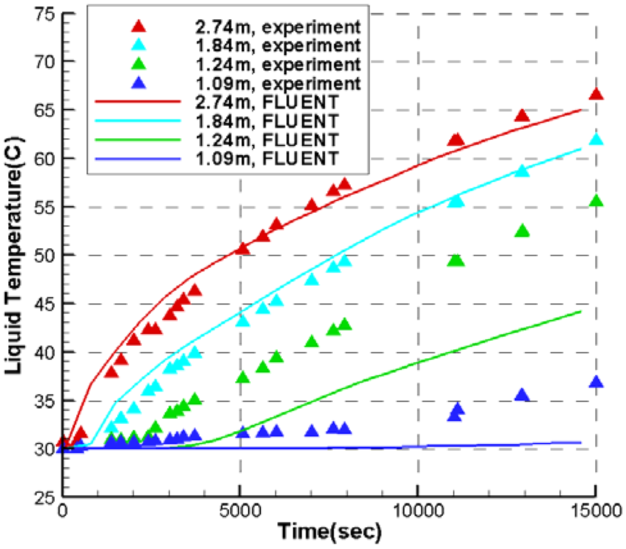


Fig. 11: Average liquid temperature compared with experiment.

We can see in the Fig. 12 with temperature history at different elevations that results of simulations agree well with experimental data. Thermal stratification was developing above the pipe outlet, while the part below the pipe outlet was at a constant temperature. Although some difference between prediction and experiment still exist in, for example, the layers close to the outlet of the pipe. The temperature in this part was increased in the experiment but not changed in simulation.



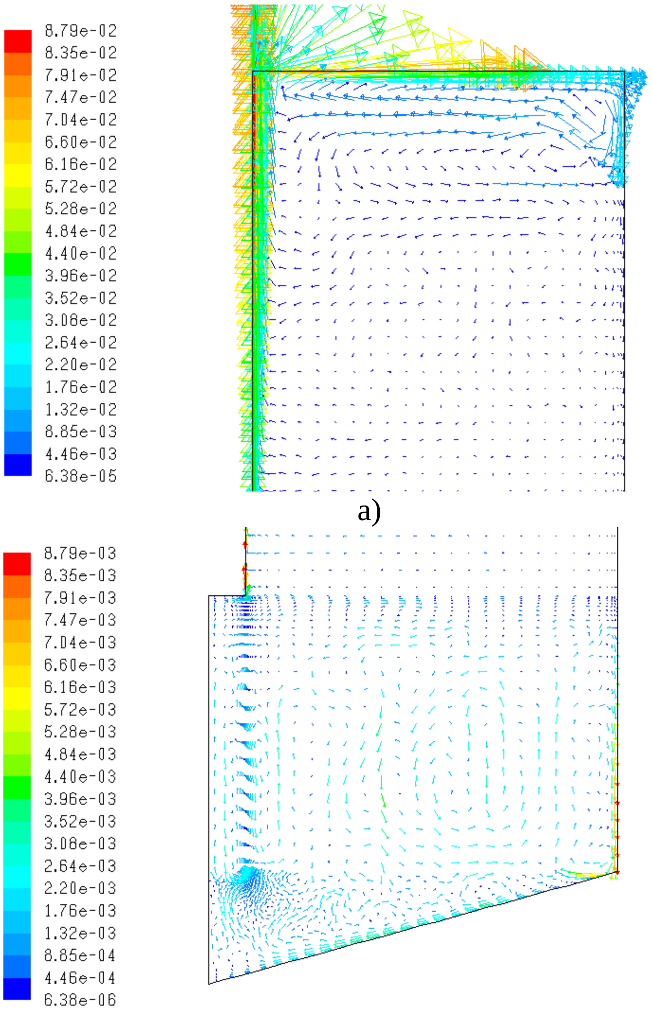
a)



b)

Fig. 12: Temperature distribution compared with experiment:
a) below the outlet of tube; b) above the outlet of tube

Fig. 13 shows the velocity vector field at 14000 seconds. In the part above outlet of pipe, liquid close to blowdown pipe wall flowing upward with speed around 9 cm/s driven by buoyancy force produced by the heat source (tube wall). Hot liquid reaching the top surfaces changes its direction and spreads horizontally in radial direction. Since heat loss on the side wall of tank was relatively small, and surface area was much larger then surface of the pipe, the downward flow velocity along the side wall is only around 1-2 cm/s. In the bottom part of the pool (Fig. 13b) there are week circulation patterns with characteristic velocity order of 3 mm/s.



a)

b)

Fig. 13: Velocity vector field at 14000 second:
a) above the outlet of tube; b) below the outlet of tube.

In Fig. 14 vertical temperature distribution is presented at 14000 seconds of transient time. The part below the outlet of blowdown pipe is predicted by CFD as almost isothermal up to the layer close to the outlet of the pipe. The temperature rapidly increases above pipe outlet and stratification starts to develop. The results of CFD simulations are consistent with experimental data. Compared to GOTHIC simulation, CFD simulation showed good agreement in the part both below and above the outlet of pipe.

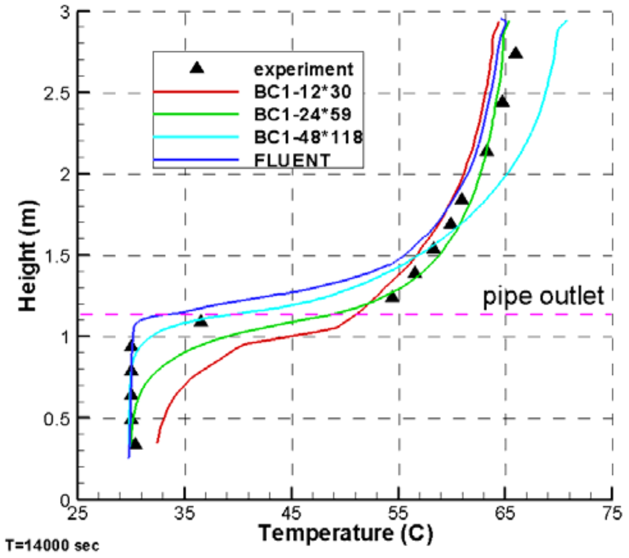


Fig. 14: Vertical temperature distribution.

4.2. Separate effect simulation of isothermal layer development during cooling phase

FLUENT was also used to simulate isothermal layer development with heat loss from top surface, side wall and bottom of wall. In the case, the small scale liquid domain with size 50cm×150cm was used. Heat flux conditions were imposed on three walls to simulate isothermal layer development during the cooling phase in POOLEX STB-20 experiment. The values of the heat fluxes were taken from the results of lumped parameter simulations in GOTHIC. After steam injection was stopped, the heat flux from the blowdown pipe wall was assumed to be zero during the cooling phase. Boussinesq model, laminar flow regime, 1^{st}-order implicit time solver and second order upwind scheme were used in the calculations. The grid resolution was 50×150 with square mesh.

CFD simulation started from a condition with thermal stratification. Temperature was linearly increasing from bottom to top of the computational domain. The temperature was 30 C at the bottom and 75 C at the top surface.

The transient time for CFD simulation was 1000 second. In the Fig. 15 temperature distribution at the end of simulation (1000 second) is presented. The isothermal top layer with temperature of about 57 C is clearly visible in the figure. The maximum water temperature decreased from 75 C, to about 57 C while temperature of the bottom part did not change during transient.

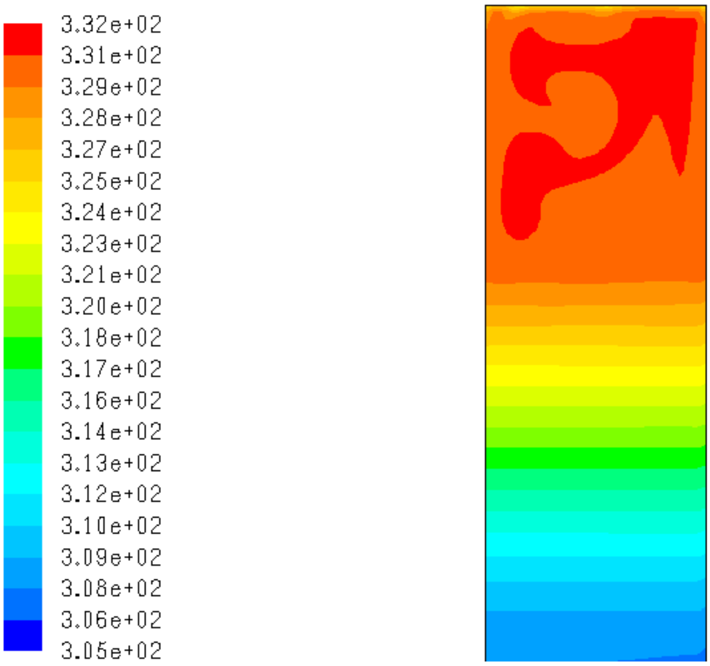


Fig. 15: Temperature distribution at 1000 second.

In Fig. 16 the velocity vector is shown at 1000 second. In the Fig.16b, we can see strong circulation in the part of isothermal layer. This circulation is caused by unstable thermal stratification (cooling on the top surface) and is the main reason for the isothermal layer formation during the cooling process.

In Fig. 17 vertical temperature distribution in the computational domain is presented at difference time moments. One can clearly see the downward propagation of isothermal layer with time. The speed of isothermal propagation can be estimated by analysis of the presented results:

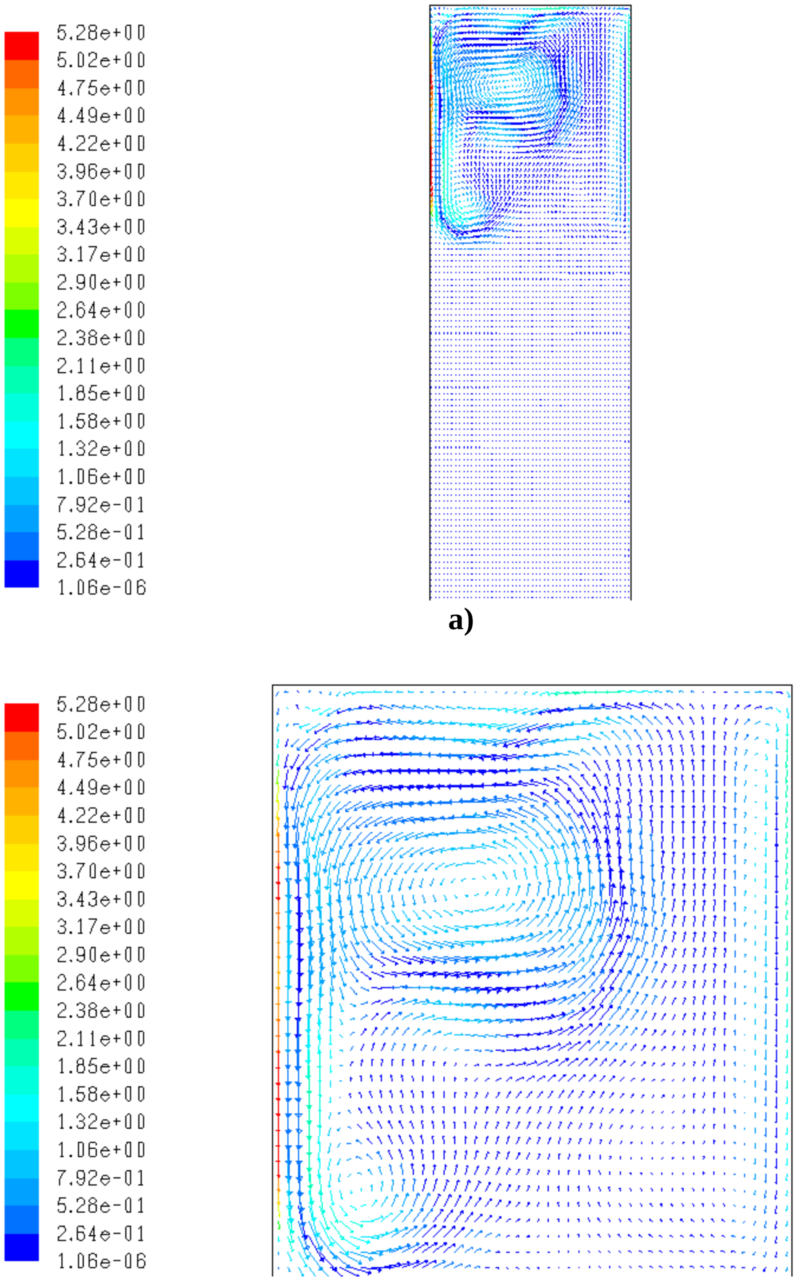
$$v = \frac{dh}{dt} = \frac{\Delta h}{\Delta t} \approx \frac{0.0425}{900} = 4.72 \times 10^{-5}\,\mathrm{m/s} = 0.17\,\mathrm{m/hr},$$

where *h* is height of the isothermal layer.

Data, presented in the report [4] about POOLEX STB-20 experiment, allows us to assess the temperature distribution in the cooling phase by the elevations of different thermocouples installed in the test facility. The downward propagation speed of isothermal layer in the experiment also could be estimated according to the change of thickness of isothermal layer and with time. From 20,000 second to 37,000 second, the isothermal layer went down from elevation of thermocouple T111 to T107. Thus speed of isothermal layer propagation can be estimated as follows:

$$v = \frac{dh}{dt} = \frac{\Delta h}{\Delta t} \approx \frac{600 \times 10^{-3}}{17000}$$
$$= 3.53 \times 10^{-5}\,\mathrm{m/s} = 0.127\,\mathrm{m/hr}$$

Predicted and experimental speeds of isothermal layer development are in a reasonable agreement.



a)

b)

Fig. 16: Vorticity Magnitude velocity distribution at 1000 second:
a) the whole domain**;** b) isothermal layer.

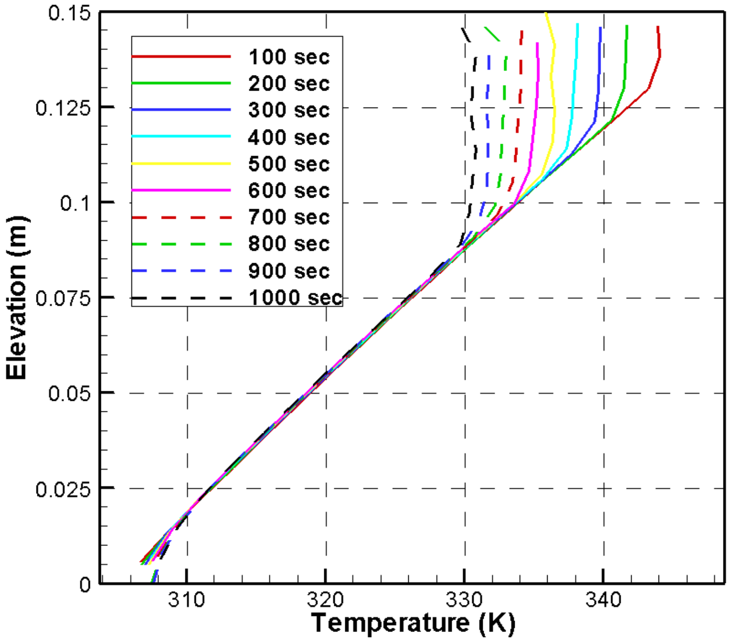


Fig. 17: Temperature distribution along with elevation at different transient time.

5. PRE-TEST GOTHIC SIMULATION OF PPOOLEX

The important task in the GOTHIC validation is pre-calculation of the PPOOLEX experiment with GOTHIC. Such simulations can be considered as a “blind” testing for GOTHIC against future PPOOLEX experiment data. PPOOLEX represents a model of BWR pressure suppression pool with drywell and wetwell isolated from ambient atmosphere by the vessel walls. Increasing pressure inside the vessel is a limiting factor for a long blowdown experiment. We use GOTHIC lumped parameter model to predict the pressure and temperature history during the experiment. It has to be noted that thermal stratification may affect actual pressure during the experiment.

5.1. Input model with pressure boundary condition

The GOTHIC input for PPOOLEX experiment is shown in Fig. 18. Drywell and wetwell are represented by volume 1s and volume 2s (Fig. 18). Volume 3 and volume 4 represents the blowdown pipe and the lab correspondently. The large volume of $10^7 m^3$ was used to simulate the lab. The blockage also was used to model the real geometry of the drywell and wetwell (Fig. 19 and Fig. 20). The table in Appendix 1 includes all parameters used in PPOOLEX calculations including detailed information for heat conductors.

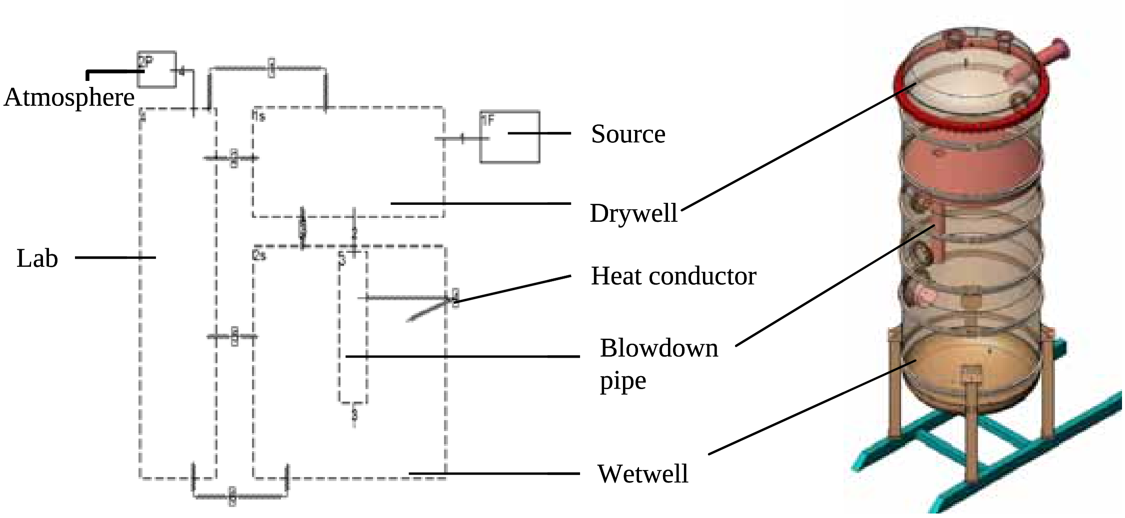


Fig. 18: Schematic of PPOOLEX input with lumped parameter model in GOTHIC.

Six heat conductors were used in the input model of PPOOLEX. Conductor 1 and 2 were used to simulate heat transfer between the drywell and the lab through the ceiling and side wall. Conductor 3 was to simulate the heat transfer between the drywell and wetwell and Conductor 4 was to model the heat transfer from the blowdown pipe to the wetwell. Conductor 5 and 6 were used for heat transfer between wetwell and the lab through the side and bottom walls.

Two boundary conditions were used in the simulation for PPOOLEX experiment. Boundary 1 was connected the drywell to supply the steam line and injection into the drywell. Pressure boundary 2 was connected to the lab to keep the lab with atmospheric pressure.

In reality the pressure will be increased in the drywell during steam injection and pressure in steam generator should be controlled to make injection rate constant. In this case the steam is always superheated before injection into the drywell. However, in the simulations it is difficult to control pressure boundary condition (unknown in advance) and change parameters according to the pressure in the drywell.

In order to supply the superheated steam into drywell the pressure boundary was used for boundary 1 and pressure at the steam line was increased from 110 kPa to 340 kPa linearly with time during the heating phase. The temperature of injected steam was changing from 114 C to 147 C also linearly. The initial temperature inside the drywell and wetwell was assumed to be 30 C. Initial temperature in the lab was assumed to be 20 C.

A valve was introduced in the model in the flow path which connects the pressure boundary and drywell. Steam injection lasts for 10000 seconds and then is terminated by closing of the isolate valve. The whole transient time was 160000 seconds.

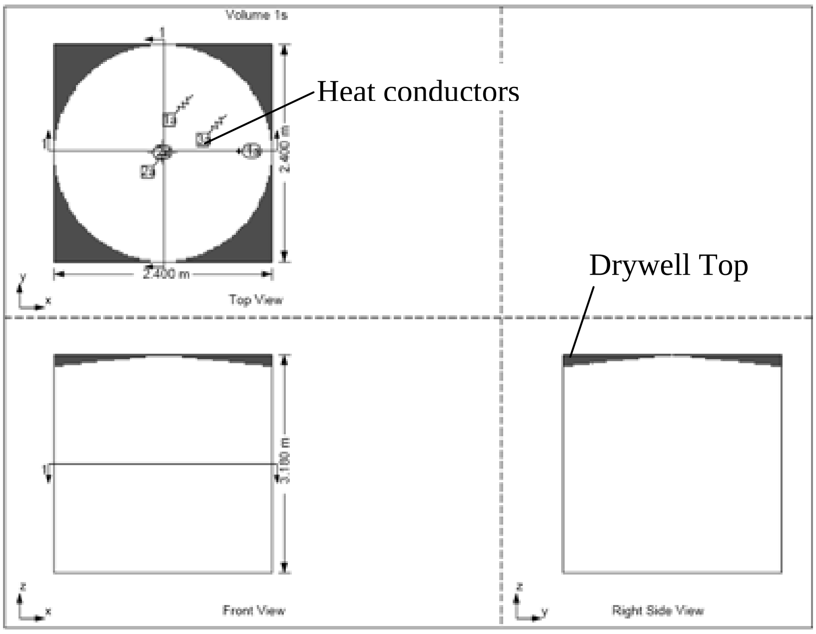


Fig. 19: Representation of PPOOLEX drywell geometry in lumped model of GOTHIC.

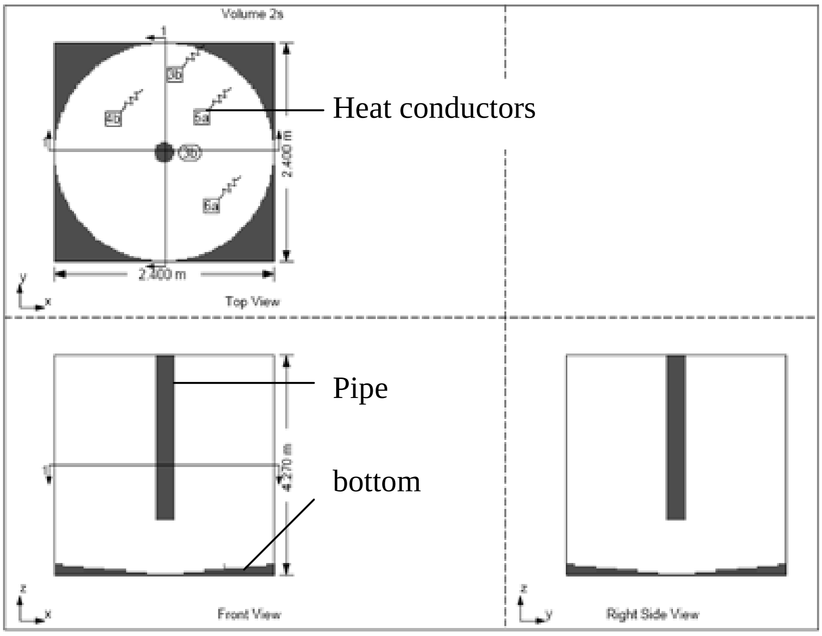


Fig. 20: Grid for wetwell of PPOOLEX.

Significant steam condensation in the drywell and blowdown pipe was observed in the preliminary calculation. Therefore two cases with different conditions were studied:

- Case I: With heat transfer between drywell and lab.
- Case II: With thermal insulation (zero heat flux at the outside wall of drywell) between the drywell wall and the lab.

Calculated pressure in the drywell was close to the pressure of the boundary condition during all heating phase (Fig. 21). Almost all the air was removed from the drywell into the wetwell through the blowdown pipe during hot steam injection. The air coming out from the tube moves up to the surface and accumulates at the upper space of the wetwell. During the cooling phase, no steam supply was provided to the drywell. As a result steam left in the drywell was cooled down and condensed quite quickly. Condensation in the drywell caused fast pressure dropped in the drywell. The water in the wetwell was then pushed into drywell once the pressure in the drywell became lower than in the wetwell, until balance of the pressures was established.

Fig. 21 shows pressure history during heating and cooling phase. The pressure changes accordingly to the physical picture described above. Pressure in the wetwell is smaller than pressure in the drywell because of the hydrostatic pressure difference in the blowdown tube which is submerged in the wetwell pool. The blowdown tube volume has same pressure as the drywell, because small friction and loss coefficients were used for flow path connecting the drywell and tube.

The condensation rate in the drywell is slower in the Case II than in the Case I because outside wall is insulated. Therefore after stop of steam injection the pressure in the vessel drops down later in the Case II than in the Case I (Fig. 21).

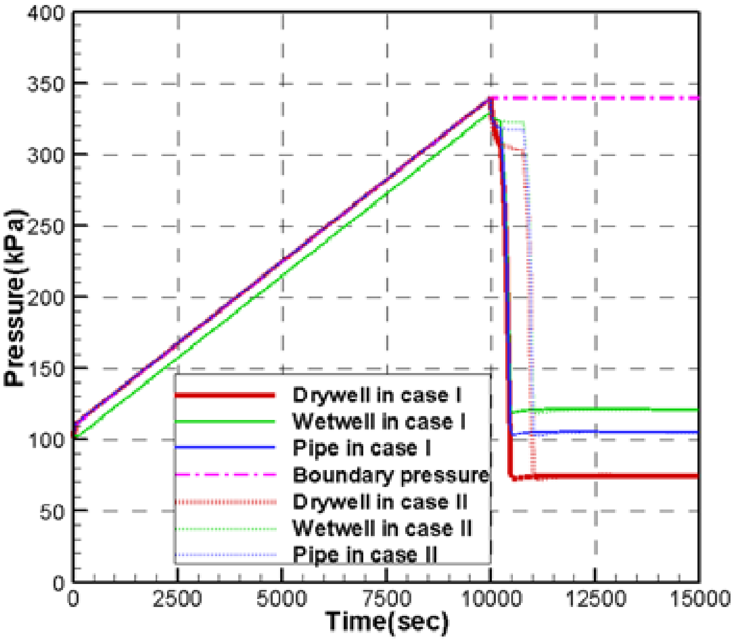


Fig. 21: Pressure history in Case I and Case II.

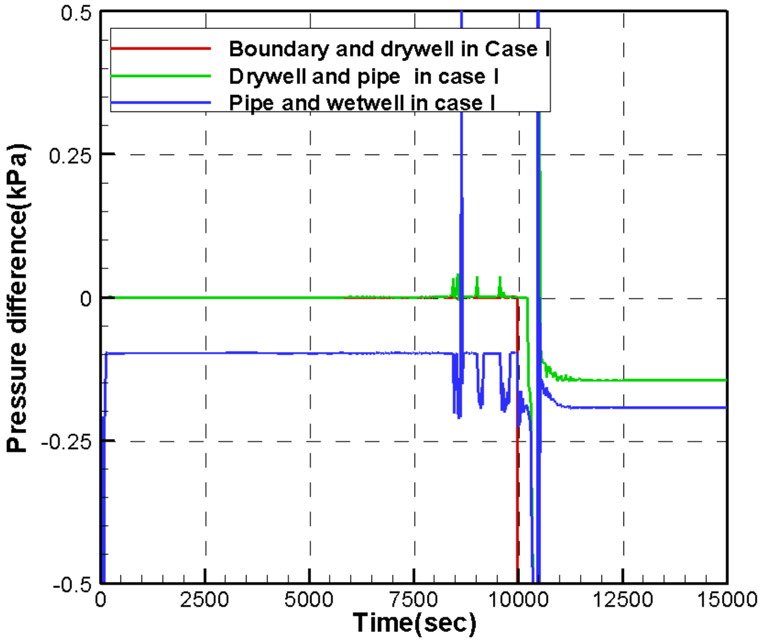


Fig. 22: Pressure difference in Case I.

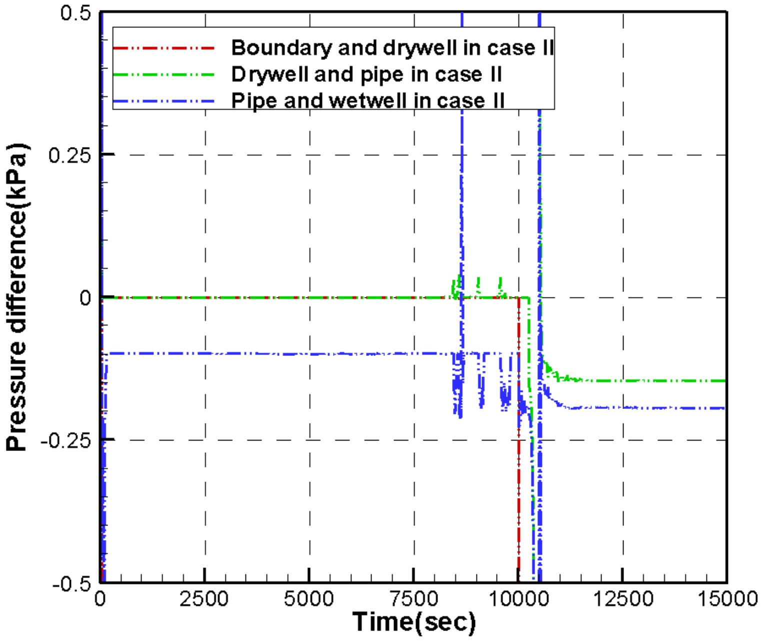


Fig. 23: Pressure difference in Case II.

Fig. 22 and Fig. 23 show the pressure difference between drywell and wetwell compartments. At the end of injection, there are several jumps of the pressure difference.

Big jump is observed for the pressure difference between the tube and the wetwell. For other pressure differences jumps are smaller. Nevertheless, small jumps still induced strong oscillation for vapor flow rate from the steam line to the drywell, which is shown in the Fig. 24. It is also visible in the Fig. 24 that oscillations of vapor flow rate exist during the whole heating phase. The vapor flow rate is very sensitive to small pressure differences.

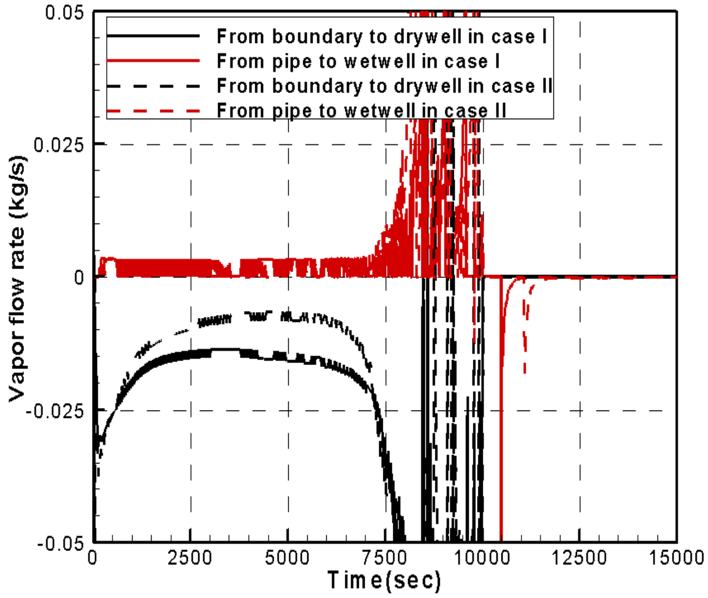


Fig. 24: Vapor flow rate.

In Fig. 25 liquid to vapor phase change rate during the transient in Case I and Case II is presented. One can see that the condensation rate in the drywell in Case II is lower than in Case I, but most of steam was still condensed inside the drywell in Case II, despite that the outside wall of drywell was insulated.

Strong oscillations of phase change rate are present at the end of steam injection phase especially in the pipe. Such oscillations are consistent with the oscillations of pressure and flow rate. It is difficult to distinguish which one is the cause as they all affected each other. The system is very sensitive to small disturbances. Each small deviation from equilibrium state causes heat-mass exchange between vapor and liquid at quite rates. Because of the system inertia such sources of mass and energy, although directed towards equilibrium, can be excessive and eventually can cause oscillations around an equilibrium state.

In Fig. 26 liquid flow rates from pipe to the wetwell are presented during heating and cooling phases. In Case II, less water was flowing into the wetwell than in Case I, because of both less steam injected from boundary and less steam condensed in the drywell and in the pipe. Large mount of water was flowing into the drywell from the wetwell during the cooling phase, because of pressure decrease in the drywell.

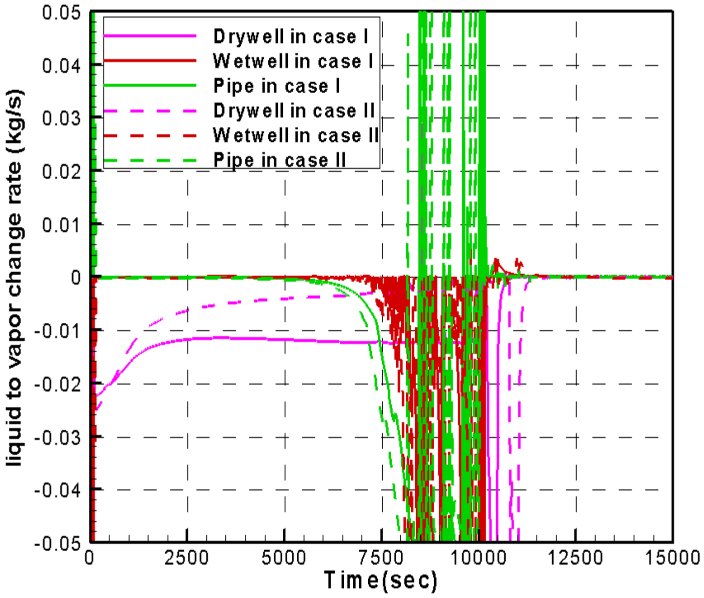


Fig. 25: Liquid to vapor phase change rate.

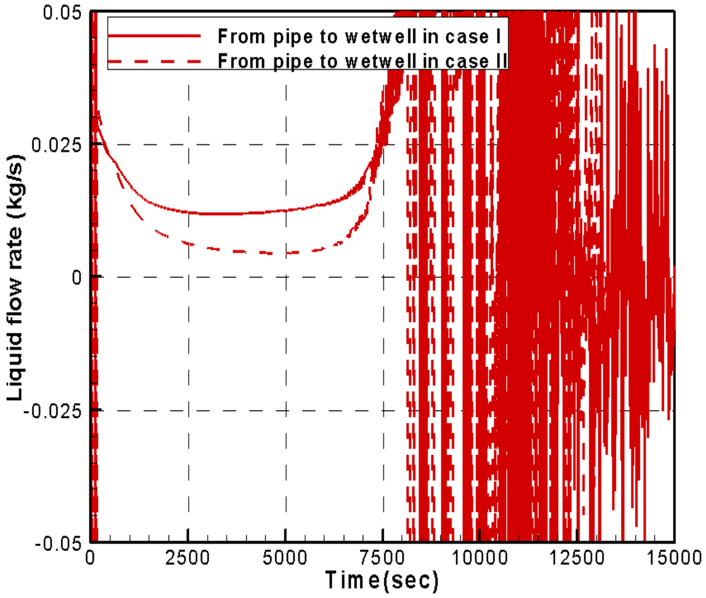


Fig. 26: Liquid flow rate from tube to wetwell.

Strong oscillations observed at the end of steam injection didn't cause significant changes in water level in the wetwell and in the pipe. It could be seen in Fig. 27. It shows that duration of each jump in pressure is relatively short and there is no significant water flow in the pipe. One can see that the liquid level in the tube is increased up to the top and then water level in the drywell is increased after stop of steam injection.

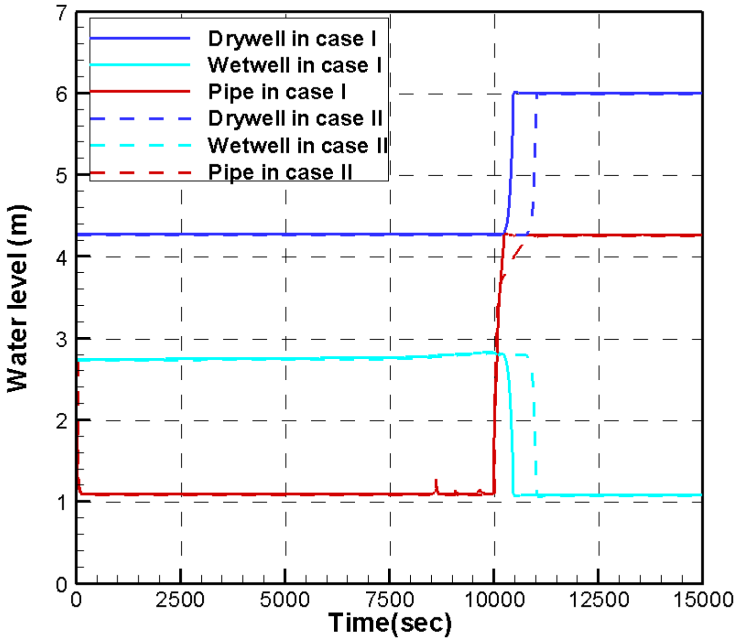


Fig. 27: Liquid level for Case I and II.

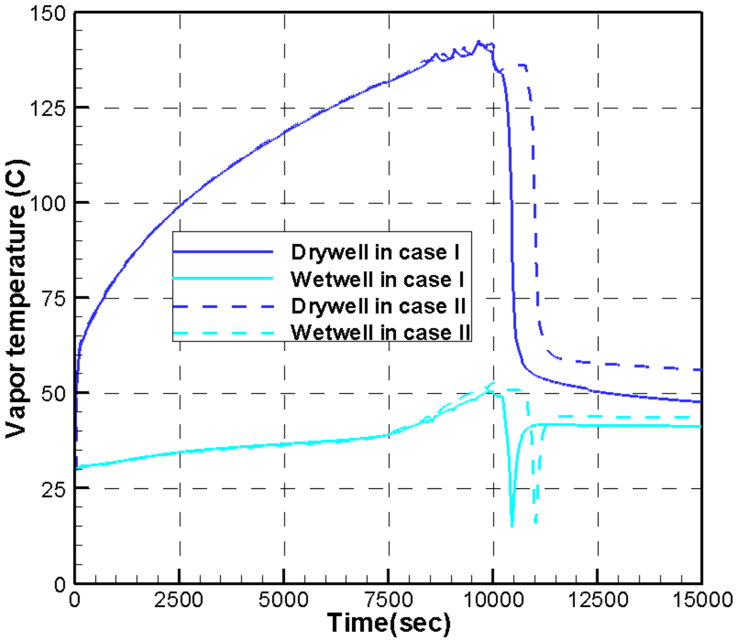


Fig. 28: Vapor temperature trend.

Fig. 28 shows the vapor temperature during the transient. There is no big difference for vapor temperature in the drywell and in the wetwell in Case I and Case II during steam injection. Vapor temperature is close to the saturation temperature in the drywell at drywell pressure, which is close to boundary pressure in both cases. In the wetwell, the vapor temperature is the same as the liquid temperature.

Fig. 29 shows the history of average liquid temperature. It is interesting to note that liquid temperature in the wetwell is almost the same in the Case I and in the Case II, despite that amount of steam injected in Case I was bigger than in Case II.

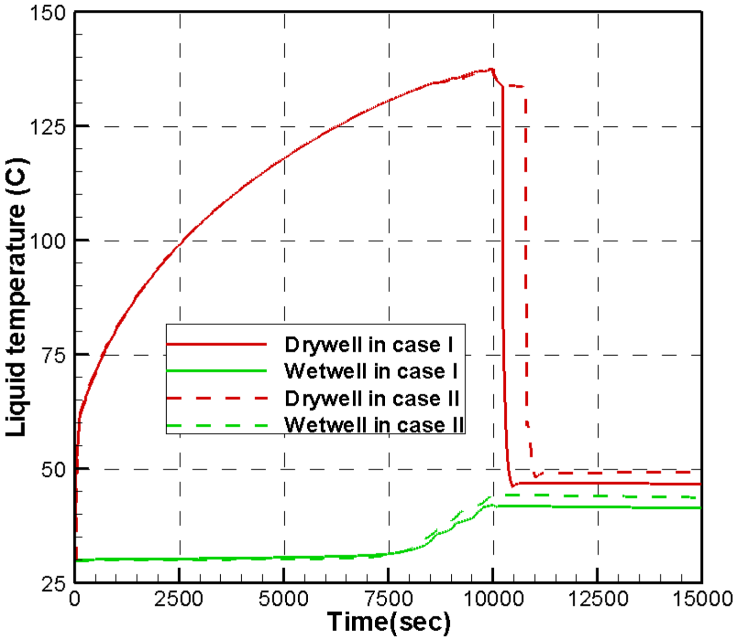


Fig. 29: Liquid temperature in the tank.

From the results of simulation with pressure boundary, we can see that the flow rate is difficult to control during the steam injection in the simulations. Results were not consistent with conditions of real experiment, in which steam flow rate could be controlled in principle as nearly constant value.

5.2. Simulations with flow boundary condition

It was decided to perform simulations with flow boundary condition to provide steam injection. Although the pressure of drywell will be increased during steam injection, the steam flow rate still could be kept as constant with flow boundary condition even if boundary pressure is lower than pressure in the drywell. The pressure defined in the flow boundary was only used to determine the steam state. However, the big pressure with 187kPa and high temperature with 117 C as shown in Appendix 1 were preferred to use for flow boundary to supply superheated steam at the beginning of the injection. The injection rate is 0.026kg/s, similar to the POOLEX STB-20 experiment and it lasts 10000 seconds. The check valve in the steam line was not used in the simulations. Other parameters were kept the same as in simulations with pressure boundary conditions (See Appendix 1 for details).

In Fig. 30 pressure in the vessel compartments during the transient are presented. Drywell pressure increases because of accumulation and compression of steam in it. In Fig. 31 pressure differences between drywell, pipe and wetwell are almost constant during injection.

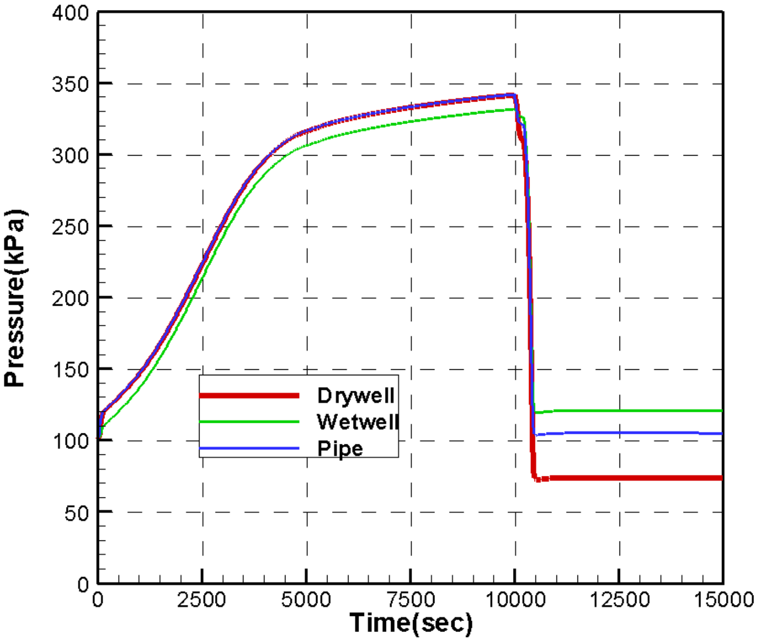


Fig. 30: Pressure history with flow boundary condition

Oscillations of vapor flow rate from the pipe to the wetwell are visible in Fig. 32. Almost all steam condenses in the drywell after about 5000 seconds as it can be seen in Fig 33. Also considerable amount of steam is condensed inside the pipe (Fig 33). In Fig. 34 liquid flow rate injected into wetwell is plotted. Fig 35 shows the same behavior of water levels as it was obtained in the simulations with the pressure boundary condition.

In the simulation, the liquid temperature rose up from 30 C to about 35 C. The temperature could be increased more if a larger flow rate can be provided through the flow boundary condition.

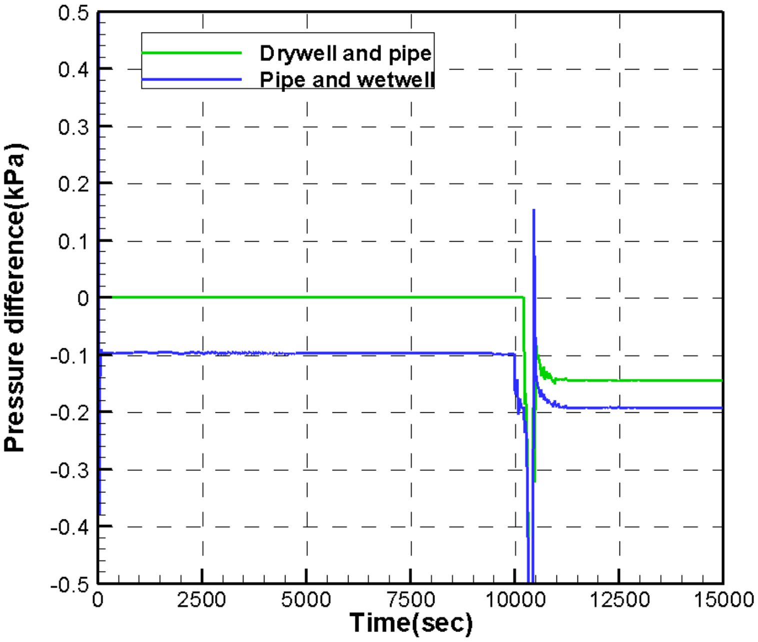


Fig. 31: Pressure difference history with flow boundary.

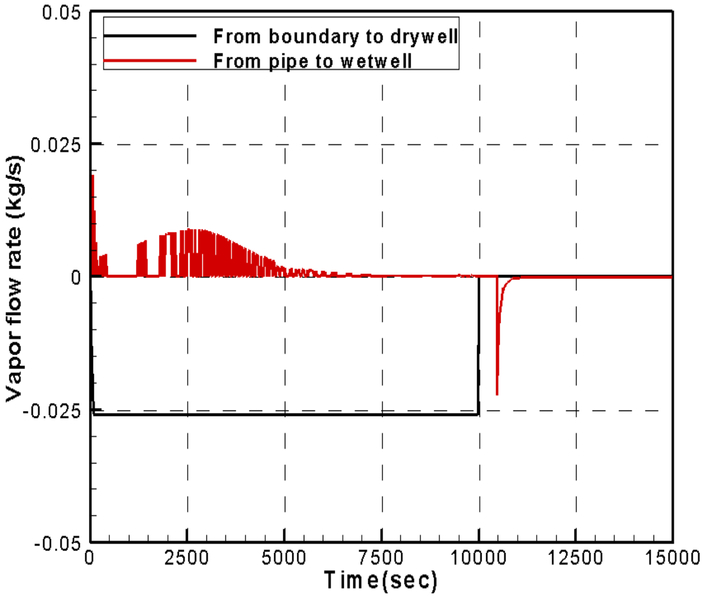


Fig. 32: Vapor flow rate.

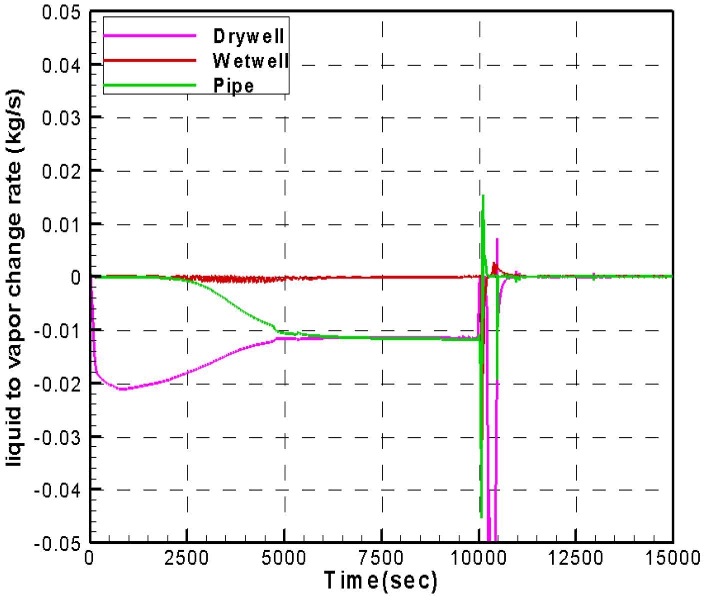


Fig. 33: Liquid to vapor phase change rate.

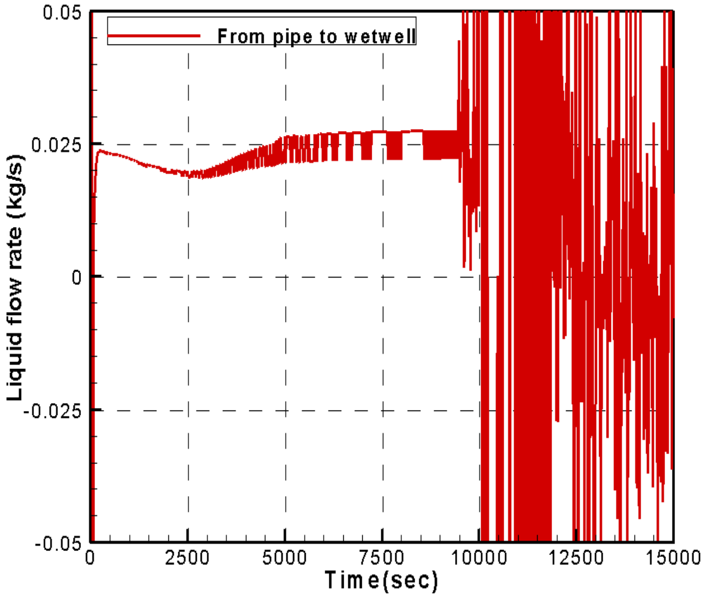


Fig. 34: Liquid flow rate from tube to wetwell.

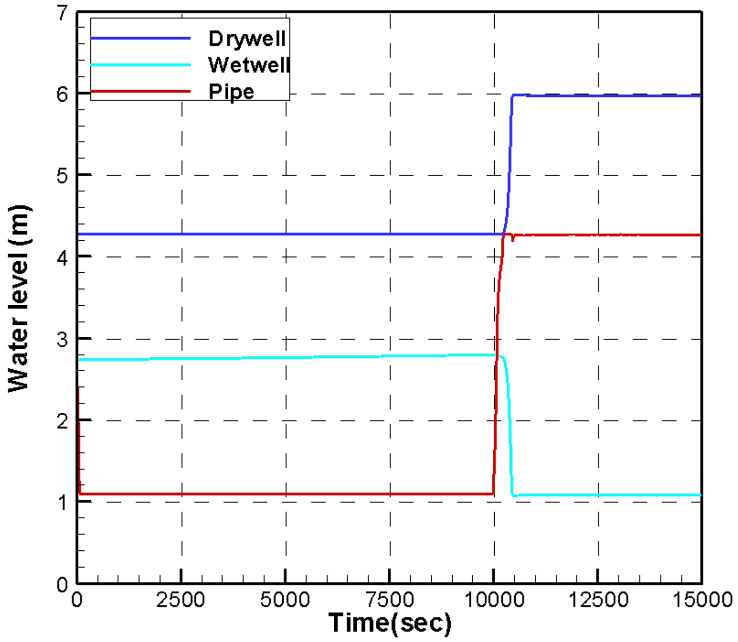


Fig. 35: Liquid level.

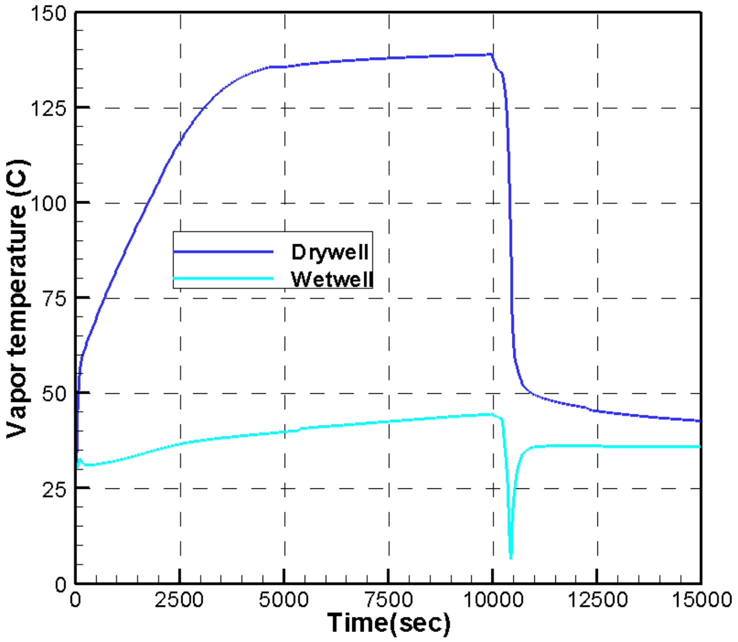


Fig. 36: Vapor temperature trend.

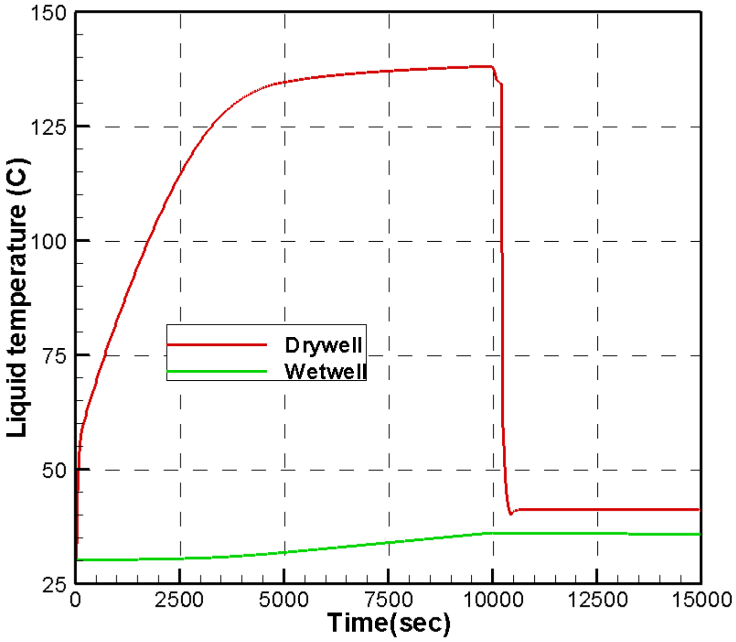


Fig. 37: Liquid temperature in the tank.

6. SUMMARY

Pressure suppression pool is important element of passive safety system of BWR containment. It serves as a heat sink and steam condenser to prevent containment pressure buildup during loss of coolant accident or safety relief valve opening during normal operations of a BWR. Insufficient mixing in the pool, in case of low mass flow rate of steam, can cause development of thermal stratification. As a result, capacity of pressure suppression pool to condense steam can be significantly reduced. Therefore reliable prediction of mixing and stratification phenomena is a must for safety analysis of the pressure suppression pool operations.

Analysis of past experiments with thermal stratification in POOLEX facility [4] and pre-test simulations of PPOOLEX tests with GOTHIC lumped and distributed parameter models are presented in the report.

Heat losses from the pool are not measured in the POOLEX/PPOOLEX experiments. GOTHIC lumped parameter simulations were performed in order to provide heat flux boundary conditions for distributed parameter simulations.

Distributed parameter model in GOTHIC is quite efficient tool for simulation of long transients with thermal stratification development. Results of distributed parameter simulations show fairly good qualitative and quantitative agreement between experimental and numerical data for the heating phase of the experiment and thermal stratification development.

Sensitivity of GOTHIC solution to different ways of boundary conditions simulation was investigated. Heat fluxes obtained from lumped parameter simulations as well as built-in GOTHIC models for heat transfer on a solid surface were used fro prediction of heat losses through the vessel walls. Both approaches give close results and good agreement with the experimental data. Built-in model of heat transfer through the wall can be used to model 2D or 3D problems related to POOLEX/PPOOLEX experiments. The results also shows that heat losses through the vessel walls have small influence on results of 2D simulation during both heating and cooling phase because dominant heat loss is from the free surface of the pool.

The grid convergence study for 2D simulations of POOLEX STB-20 experiment was performed with GOTHIC. Four different grids with sequentially doubled space grid resolutions were used. Grid convergence and reasonable accuracy of the simulation result was demonstrated.

The CFD simulation was carried out with FLUENT code in order to validate its capacity to predict POOLEX experiment with development of stratification. Heat flux boundary conditions obtained from the results of lumped parameter GOTHIC simulation were used. The simulations show details of thermal stratification phenomenon in the heating phase. A small scale separate effect simulation of cooling phase of the POOLEX STB-20 experiment was performed. Speed of isothermal layer propagation was compared with that from experimental data. The result showed that CFD simulation can reasonably reproduce development of isothermal layer during cooling phase.

Lumped parameter pre-test simulations for PPOOLEX experiment were performed. The simulation shows that drywell and wetwell pressures can be kept within safety margins during long steam injection transient which is necessary for development of thermal stratification.

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Appendix 1

The following table includes all of parameters used in PPOOLEX calculation with GOTHIC. The pure steam with flow rate of 0.026 kg/s was injected into drywell through a horizontal pipe. The pressure and temperature of steam were shown in table.
There are the air and steam mixture in the drywell and wetwell before injection. The initial pressure and temperature also were shown in the table.

INITIAL CONDITION	
Water level in the pool (m)	2.72
Submergence of pipe (m)	1.633
Water Temperature (C)	30
Pool Pressure (kpa)	101 kpa
Vapor Temperature (C)	30
Liquid Temperature (C)	30
Liquid fraction of pool	2.72/4.27= 0.637
Liquid fraction of pipe	1.633/3.183= 0.513
BOUNDARY 1 (Flow)	
Steam Source Pressure (kpa)	187
Steam Flow (kg/s)	0.026
Temperature (C)	117
Steam Fraction	1
Elevation (m)	6.342
BOUNDARY 2 (Pressure)	
Pressure (kpa)	101.1
Temperature (C)	20
Air Fraction	1
Elevation (m)	9
VOLUME 1	(Model **Dry well**)
Volume (m^3)	13.3
Cross-sectional area (m^2)	4.5
Hydraulics diameter (m)	2.4
Bottom Elevation (m)	4.27
Height (m)	3.18
VOLUME 2	(Model **Wetwell**)
Volume (m^3)	17.8
Pool cross-sectional area	4.5

(m^2)	
Hydraulic diameter (m)	2.4
Bottom Elevation (m)	0
Height (m)	4.27
VOLUME 3	(Model **Blowdown pipe**)
Volume (m^3)	0.1
Cross-sectional area (m^2)	0.0314
Hydraulics diameter (m)	0.2
Bottom Elevation (m)	1.087
Height (m)	3.183
VOLUME 4	(Model **lab**)
Volume (m^3)	1e7
Hydraulics diameter (m)	15
Bottom Elevation (m)	-1
Height (m)	10
JUNCTION 1	Connect flow boundary to drywell
Inner diameter of the blowdown pipe (mm)	214.1
Flow area (m^2)	0.036
Inertia length (m)	0.01
Friction length (m)	0.01
Elevation (m)	6.342
JUNCTION 2	Connect drywell to blowdown pipe
Inner diameter of the blowdown pipe (mm)	200
Outer diameter (mm)	205
Pipes submerged (m)	1.633
Flow area (m^2)	0.0314
Inertia length (m)	1.59
Friction length (m)	1.59
Elevation (m)	4.27
JUNCTION 3	Connect blowdown pipe to wetwell
Inner Diameter (m)	0.2
Thickness(mm)	0.025
Flow area (m^2)	0.0314
Inertia length (m)	1.59
Friction length (m)	1.59
Elevation (m)	1.087

CONDUCTOR 1	(Model ceiling in the drywell)
Thickness (mm)	10
Surface area (m^2)	4.5
CONDUCTOR 2	(Model side wall of drywell)
Thickness (mm)	10
Surface area (m^2)	23.98
CONDUCTOR 3	(Model floor between the drywell and wetwell)
Thickness (mm)	10
Surface area (m^2)	4.5
CONDUCTOR 4	(Model blowdown tube)
Thickness (mm)	2.5
Surface area (m^2)	2.0
CONDUCTOR 5	(Model wetwell side wall)
Thickness (mm)	10
Surface area (m^2)	32.2
CONDUCTOR 6	(Model bottom of wetwell)
Thickness (mm)	10
Surface area (m^2)	4.5

For pressure boundary	Time (sec)	Pressure (KPa)	Temperature (C)
	0	110	114
	10000	340	147
	160000	340	147

Bibliographic Data Sheet **NKS-196**

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Affiliation(s)	Royal Institute of Technology (KTH), Sweden
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Abstract

Pressure suppression pool is an important element of BWR containment. It serves as a heat sink and steam condenser to prevent containment pressure buildup during loss of coolant accident or safety relief valve opening during normal operations of a BWR. Insufficient mixing in the pool, in case of low mass flow rate of steam, can cause development of thermal stratification and reduction of pressure suppression pool capacity.

For reliable prediction of mixing and stratification phenomena validation of simulation tools has to be performed. Data produced in POOLEX/PPOOLEX facility at Lappeenranta University of Technology about development of thermal stratification in a large scale model of a pressure suppression pool is used for GOTHIC lumped and distributed parameter validation.

Sensitivity of GOTHIC solution to different boundary conditions and grid convergence study for 2D simulations of POOLEX STB-20 experiment are performed in the present study. CFD simulation was carried out with FLUENT code in order to get additional insights into physics of stratification phenomena.

In order to support development of experimental procedures for new tests in the PPOOLEX facility lumped parameter pre-test GOTHIC simulations were performed. Simulations show that drywell and wetwell pressures can be kept within safety margins during a long transient necessary for development of thermal stratification.

Key words Thermal stratification, numerical simulation, pressure suppression pool

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