Lappeenranta University of Technology
School of Energy Systems
Degree Program in Nuclear Engineering

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STEAM SPARGER MODELLING FOR BOILING WATER REACTOR SUPPRESSION POOL

Examiners: Prof. Juhani Hyvärinen
Mr. Markku Puustinen

Supervisors: Mr. Markku Puustinen
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ABSTRACT

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Steam sparger modelling for boiling water reactor suppression pool

Master's Thesis

74 pages, 36 figures and 6 tables

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Suppression pool, boiling water reactor, containment, TRACE, modelling, experiment SPA T3, PPOOLEX facility, nuclear power plant safety

During the Fukushima accident a pressure inside the containment was twice higher than it was supposed to be under fully mixed pool conditions. It became clear, that there's a need for a more detailed study of the pressure decreasing phenomenon in pressure suppression pools. This kind of pools are an essential part of the nuclear plant containment in BWRs.

Several tests have been done in PPOOLEX facility with the aim to get more data for the development of the EHS and EMS model and further implementing these models in GOTHIC

code. In the current master’s thesis an experiment under the PPOOLEX facility, namely the SPA-T3 test, has been modelled using TRACE code for nuclear power plants.

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Espoo, July 2017

Vladislav Vasilyev

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LIST OF SYMBOLS AND ABBREVIATIONS

Roman and Greek letters

$H_{eff_{total}}$	total effective heat source
$\dot{\bar{M}}_{steam}$	steam mass flow rate
$\dot{\bar{h}}_{steam}$	steam enthalpy
t	time
Q_{eff}	spatial flux distribution;
Δt	aveaged time
Q	heat flux
T	temperature
H	thickness of stratified layer
R	tank radius
k_n	the n^{th} root of the derivative of the first order Bessel function
g'	reduced gravity
f_n	the frequency of natural oscillations

Subscripts

Exp	Experiment
Lab	Laboratory
Stratif	Stratification
Mix	Mixing
Tem	Temperature

Acronyms

NPPs	Nuclear Power Plants
BWR	Boiling Water Reactor
POOLEX	Experiment with Pool
EHS	Effective Heat Source
EMS	Effective Momentum Source
PWR	Pressurized Water Reactor
LOCA	Lost of Coolant Accident
EPR	European Pressurized Water Reactor
MSLB	Main Steam Line Break
PSP	Pressure Suppression Pool
RPV	Reactor Pressure Vessel
SRV	Safety Relief Valve
SBO	Station Black-Out
LRR	Load Reduction Ring
NRC	Nuclear Regulatory Commission
KHNP	Korea Hydro & Nuclear Power Company
KOPEC	Korea Power Engineering Company
KTH	Kungliga Tekniska Högskolan, (Royal Institute of Technology)
TRACE	TRAC/RELAP Advanced Computational Engine

1 INTRODUCTION

1.1 Background of the Thesis

The widespread operation of nuclear power plants (NPPs) for the production of electric power put the safety issue at the forefront. The peculiarity of this problem in relation to nuclear power plants is that in case of an accident there could happen an appalling destruction of the environment and society as well. The history experience shows that even more harmful damage can be inflicted on the nuclear industry as a whole, which leads to a lower rate of its development.

Conducting the experimental studies of processes and phenomena related to safety of nuclear power plants in case of severe accident is limited by the high cost of experiments - the actual scale of the linear dimensions of the facilities does not exceed 1:10 relative to the size of the containment. Therefore, scaled-down modeling is the main way of researching accident processes. So the development of adequate calculation models of processes and phenomena is essential for solving the current problem. The problem of safety analysis from the point of view of physics is a complex task. We have wide ranges in the characteristic scales of the time and length of the processes. At the same time, the numerical model should reproduce the entire complex physics of the essential phenomena in sufficient detail and be effective so that the numerical calculation can be done in an acceptable time. (Bolshov et al., 2016)

One of the most important components of Boiling Water Reactor containment is pressure suppression pool, which is located in the wet-well. Nuclear reactor containment with a pressure suppression system is divided into two main parts, one is called wet-well and the other is dry-well. These two compartments are connected by blow-down pipes that allow gas and steam discharge from the dry-well to wet-well. When the pressure in the dry-well is significantly higher than the pressure in wet-well the steam and noncondensable gases flow from the dry-well to the wet-well. The steam is condensing in the pressure suppression pool, full of cold water. There are several processes happening during condensation under different steam mass flow rates, but for the water mass in the pool, the most significant are thermal stratification and mixing. (Union of Concerned Scientists, 2014)

During steam discharge into the suppression pool, the temperature of water gradually increases. Stratification takes place and as a result the pressure suppression capacity decreases, because the water mass acting as a heat sink is smaller than the whole pool. Water absorbs the latent heat of evaporation as the steam condenses. It can lead to the pressure increasing in reactor containment. And the condensation mode may change nevertheless, because the steam flow changes during accidents. So the mixing of water happens and decreases water stratification. There is also another way to introduce mixing – use of special equipment at NPP, designed exactly for that purpose. (M. Puustinen et al., 2017)

1.2 Goals and delimitations

The reason to choose actual topic is observation and studying of processes taking place in the pressure suppression pool located at Nuclear Engineering Laboratory of Lappeenranta University of Technology. The experts performed several sparger and blowdown pipe tests under different steam flow conditions with the POOLEX and PPOOLEX facilities, which are scaled down models of a pressure suppression pool of BWR. The main course of the tests was to get more data for the development work of the Effective Heat Source (EHS) and Effective Momentum Source (EMS) models being done at Kungliga Tekniska Högskolan (KTH) in Stockholm. The models are planned to be used in GOTHIC code in order to reduce uncertainties and increase accuracy in predicting stratification and mixing processes. KTH also aims to extend the models for some other elements of the suppression pool. Such activities are crucial, because proper safety analysis capability of BWR containment should be provided.

The reason for paying so much attention to the suppression pool is the fact that there could be some conditions in which the capability of pressure reduction has decreased. It was assumed to be the reason of unsuspected pressure increase during the Fukushima accident (Mizokami et al., 2013), when a pressure inside the containment was twice higher than it was supposed to be under fully mixed pool conditions.

The purposes of the current thesis are:

- Prepare an overview of the condensation data

- Identify conditions in which condensation oscillations take place in the sparger
- Present the current status of “Enhanced” models
- Model the sparger experiments using TRACE, focusing on exploring if the observed phenomena, like stratification and mixing, can be reproduced

1.3 Structure of the Thesis

The Thesis is divided into two parts: Theory and Literature study and Sparger experiment. In the first part there is an observation of the nuclear reactor containment types, steam injection devices and processes in pressure suppression pool. In chapter 2 there is a description of an experiment in the PPOOLEX facility, modeling of the tests by TRACE code and comparison of the results. In the last part there is a conclusion of the whole master thesis’ discussion and observation.

2 PASSIVE SAFETY SYSTEM OF BWR

2.1 Introduction

Boiling water reactors are widely introduced at the world of nuclear power engineering. During the 60-years history of BWR technology development, more than 120 BWR reactors have been put into operation, more than half of them are still in operation. Single-loop reactor facilities keep great potential for simplifying the process of steam generating, that contributes to improve cost-effectiveness as well as safety and compete with other types of nuclear reactors (PWR, VVER).

The steam-water mixture of BWR is produced in the reactor core. Boiling reactors have a number of advantages, compare to non-boiling. In boiling reactors, the vessel operates at a lower pressure and there is no steam generator in the nuclear power plant scheme. The peculiarity of boiling reactors is that they do not have boron control, because the compensation for slow changes in reactivity (for example, fuel burn-up) is done only by cross-cassette absorbers made in the form of a cross (Bolshov et al., 2016).

The principle of BWR passive safety systems operation is a very important object of studying. This system ensures the reliable cooling of nuclear reactor, its radiation safety and prevention of possible heat spreading.

The use of passive systems is one of the main directions in the development of containment design for the future generations of nuclear power plants. To ensure complete removal of heat from the containment, passive systems must be able to perform their functions regardless of external sources of electricity, so they must use natural physical laws, for example, gravity.

The potential advantage of passive systems is obviously their reliability, simplicity and independence from other systems, moreover, they do not require operators' action, which excludes errors related to the human factor (General Electric, 2011).

2.2 Containment in general

Containment is a passive safety system for nuclear power reactors. The main function of such systems is to prevent a release of radiation into the environment in case of severe accidents. The containment is a massive structure of special design, where the main equipment of the reactor installation is located. It is the most important element of nuclear power plants from the safety point of view, as the last physical barrier to the spread of radiation. Almost all nuclear power units that were built over the past few decades are equipped with containment. It's application is necessary for protection in the event of an internal accident with the rupture of large pipelines and loss of coolant (LOCA, Loss-of-coolant accident), as well as in case of external events: earthquakes, hurricanes, tornadoes, airplane crashes, explosions, etc. The containment is designed to perform its functions taking into account all possible mechanical, thermal and chemical influences, that could provoke the loss of coolant and the core melting. Most of containments have ancillary equipment: localizing safety systems for condensing steam and thus reducing pressure, special ventilation systems equipped with filters for purification from radioactive isotopes of iodine, cesium and other fission products. (Saito et al., 2011)

Nowadays the construction of containments is directed mainly towards increasing number of passive safety systems, not requiring sources of energy and signal for the inclusion of systems. All the reactor emergency systems being actively developed in this direction. Currently, four VVER-1200 (Novovoronezh NPP-2 and Leningrad NPP-2) are under construction in Russia, four AP1000 (Westinghouse) in China and four EPR (Areva together with Siemens) in Finland, France and China. Russia has already used new solutions for the construction of the Tianwan NPP in China and the Kudankulam nuclear power plant in India. The implementation of several projects from other different companies has not begun yet.

In all new projects, the containments are double containments. The purpose of external containment is protection against outside and inside influences in order to localize the accidents with primary cycle depressurization. In VVER-1200 and EPR, the outer shell is made of reinforced concrete, and the inner shell is of pre-stressed reinforced concrete. In AP1000 the inner shell is steel. In AP1000 and the VVER-1200 (Moscow version) between the inner and outer shells in the event of an accident, natural circulation of air is organized to cool the inner shell.

Another direction of safety improving process is the protection of containment in case of nuclear fuel melting and the failure of the reactor vessel. For the first time a special device was built in the Tianwan NPP containment of VVER-1000 (commissioning in 2007) and adopted for projects with VVER-1200. In the Russian containments, the core catcher is built under the reactor. In its body a filler, mainly of iron and aluminum oxides, is used. The filler dissolves in the melt of the fuel in order to reduce its volumetric energy release and increase the heat exchange surface. Water cools the core catcher from outside through special pipelines. In EPR, the core catcher is organized differently - the melt falls on inclined surface, guiding its flow into a pool with water and a cooled metal bottom of a special design. In AP1000 the core catcher is absent, but reactor vessel failure is prevented by In-Vessel Retention – external cooling of the reactor vessel itself. In the event of such accident, the reactor shaft is filled with water, which cools the outside of the vessel. (Fédération internationale du béton, 2001)

The Pressure suppression pool (PSP) is one of the important parts of Boiling Water Reactor containments. The suppression pool is designed to receive steam in the event of an accidents, like main steam line break (MSLB) or loss of coolant accident (LOCA), avoiding or reducing pressure buildup. It has to provide reception of the total amount of steam generated by the reactor. Suppression pool is a horizontal vessel with a submerged pipe filled with water to a nominal level. Large amount of noncondensable (nitrogen) and condensable (steam) gas enters the bubbler through the discharge devices. (J. Laine et al., 2015)

As it was said before, the PSP is a part of reactor containment. All BWRs are designed with a pressure suppression system. There are two main components of which the containment consists: dry-well and wet-well. If the LOCA or MSLB happens, the steam together with air go down into the suppression pool into wet-well through special devices, then the steam condenses in water. (Fédération internationale du béton, 2001)

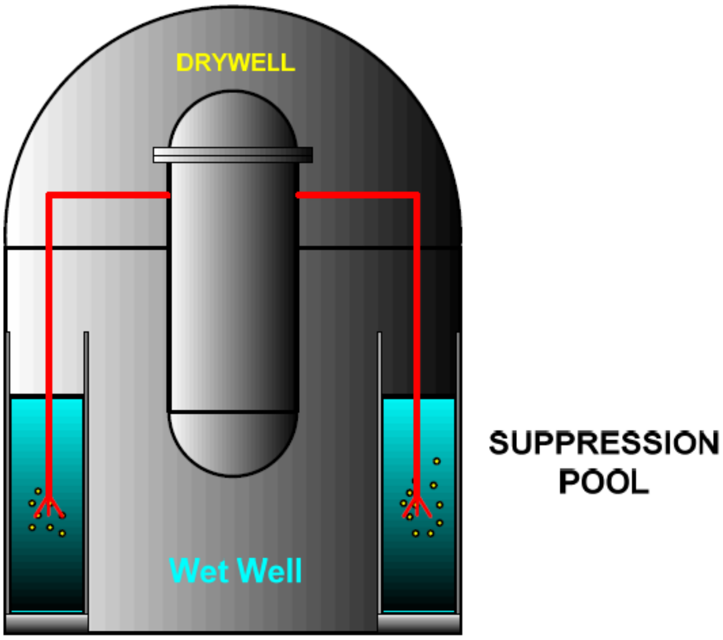


Figure 2.1 Containment pressure reduction following a LOCA using steam condensation in suppression pools. (IAEA, 2009)

2.3 Containment types

Depending on the type of reactor and specific external threats (for example, seismicity), the design of containment can vary significantly. Most of modern containments (about 95%) are shell structures of various sizes from reinforced or pre-stressed concrete, most often cylindrical shape.

In Sweden and Finland there are several boiling water reactors, designed by Asea-Atom. Olkiluoto and Oskarshamn nuclear reactors have same pressure suppression containment system. (Fédération internationale du béton, 2001)

The containment of these reactors has a cylindrical form and it is separated into lower and upper dry-well and wet-well. The condensation pool is located between the containment wall and inner cylindrical wall, that has a biological shield. The vent pipes are directed from the upper dry-well to the pressure suppression pool. The steam from reactor relief valve goes through the blowdown pipes from each valve into water of pressure suppression pool where condensation is happening. (TVO, 2008)

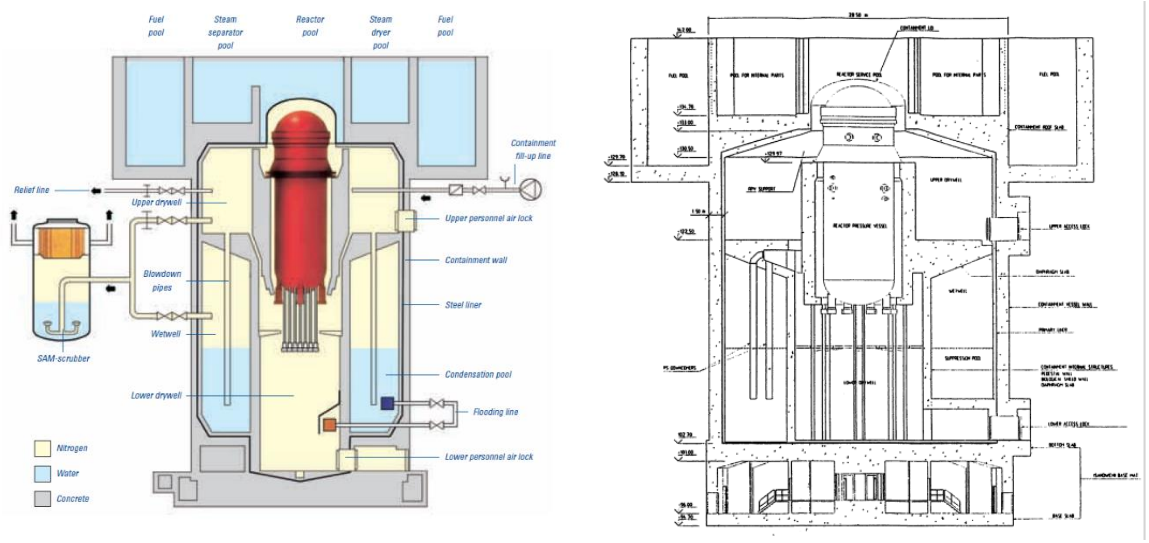


Figure 2.2 Olkiluoto and Oskarshamn containment (TVO, 2008)

USA had designed three different types of BWR pressure suppression containment systems: Mark I, Mark II and Mark III. In each of these designs, the reactor pressure vessel is placed inside a primary containment structure, that includes three main parts: the dry-well, the wet-well, and the system of vents. The wet-well includes suppression pool, filled with water.

The major components of the Mark I containment system are described further. The dry-well has a shape of light-bulb, fortified with reinforced concrete, located around the reactor pressure vessel (RPV) and recirculation loops. The wet-well has a shape of toroid, made of either steel or concrete and it is located beneath the dry-well. These two wells are connected to each other by a system of vent pipes. Half of wet-well's height is filled with water. Due to its function the wet-well is referred to as a suppression pool. So this pool resides in a large metal torus. The dry-well and wet-well have interrelation. The vents are open to the dry-well and to the header of the wet-well, which has downcomer vents lower than the water level inside the pressure suppression pool (General Electric, 2011).

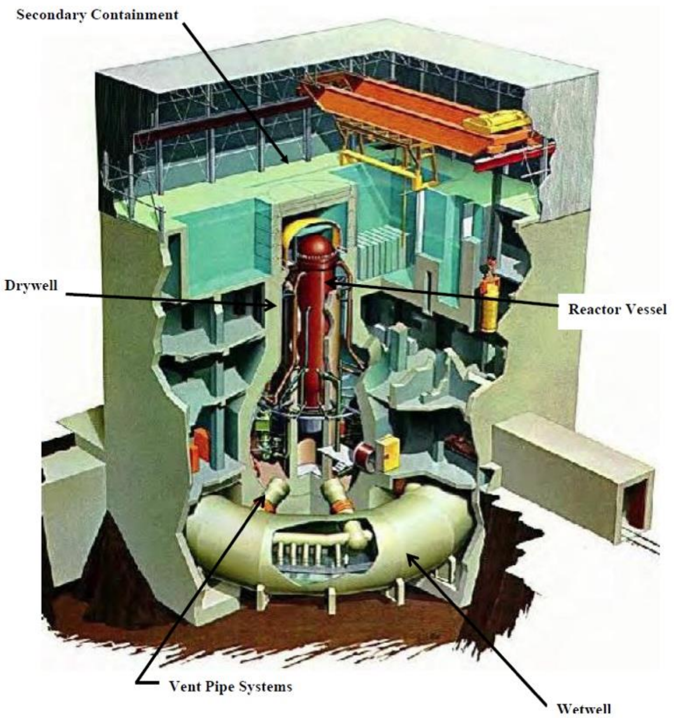


Figure 2.3 Mark I containment (General Electric, 2011)

The containment of the second US designed type (Mark II) represents a steel dome head and a wall made of reinforced concrete is installed on a base mat. The inner part of containment has a steel plate on the surface, which is used as a leak-tight membrane. The containment wall has additional function as a support for the floor slabs of the building, where reactor and refueling pools are located. The dry-well has the form of a frustum of a cone. It is located right over the suppression pool. The suppression chamber has a shape of a cylinder. Between the suppression chamber and the dry-well there is a reinforced concrete slab. So the pressure suppression pool is located in a concrete pit. Above the dry-well there is a dry-well head, that is a steel dome with elliptical shape. Downcomer pipes connect the dry-well with the suppression chamber. These pipes are penetrating and supported with a floor of the dry-well (General Electric, 2011).

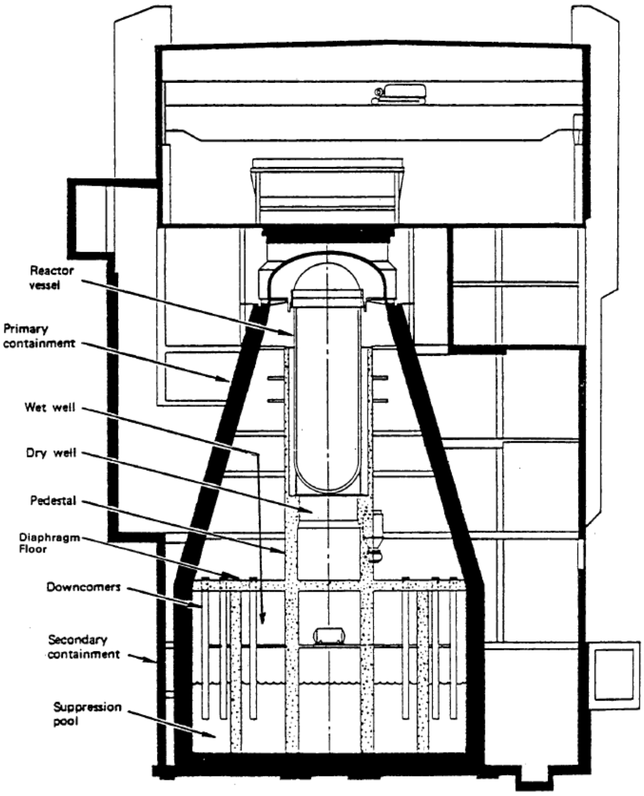


Figure 2.4 Mark II containment (General Electric, 2011)

The Mark III containment includes several important components, many of them can be seen in Figure 2.5. The dry-well has a cylindrical shape, made of reinforced concrete and it has a removable head. The design of the dry-well is supposed to withstand and constrain steam, which is generated in case of a pipe break inside the containment and to direct the steam right to the pressure suppression pool through the weir wall. There is a large volume of water inside the pressure suppression pool for fast condensing of steam vent to it. The containment vessel has a cylindrical shape, made of steel. It surrounds the dry-well and pressure suppression pool with the aim to prevent an escape of some fission products to the environment due to a pipe rupture inside the containment (General Electric, 2011).

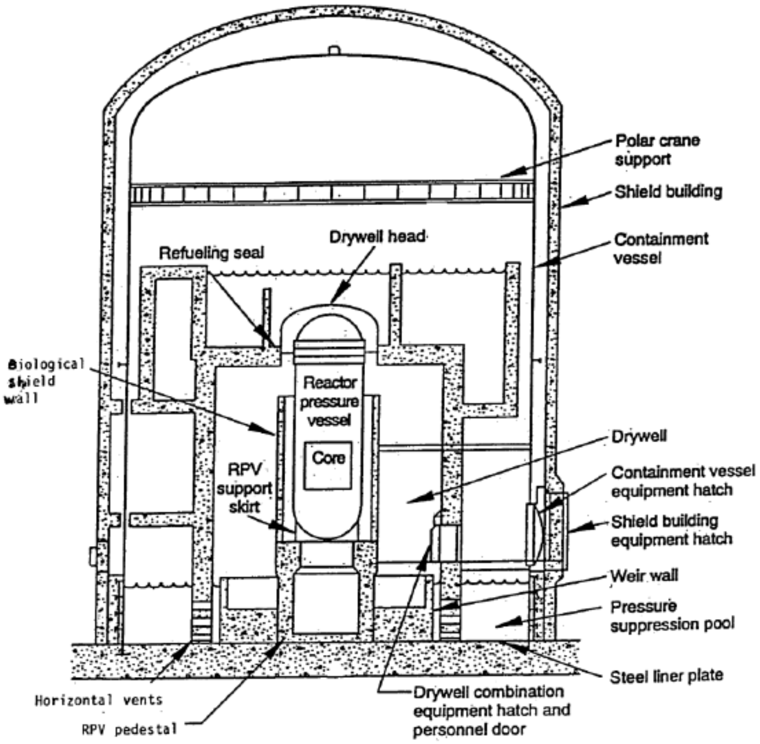


Figure 2.5 Mark III containment (General Electric, 2011)

2.4 Types of steam discharging devices

There are several different discharging devices, that are used to direct steam into suppression pool.

The X-quencher system is used in the Lungmen NPS design as well as in Mark III and Mark II containments. The X-quencher, which is shown in Figure 2.6, is a diffuser device of a short conical extension of the SRV discharge line and a plenum with four perforated arms. Each arm has many small holes; steam and air are injected through these holes. (B.J. Patterson, 1979)

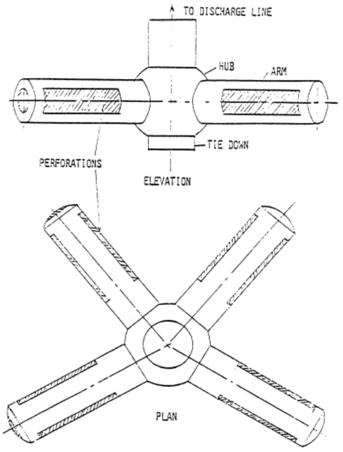


Figure 2.6 X-quencher head (B.J. Patterson, 1979)

Nuclear reactor containment at the Hatch Nuclear Power Plant in Georgia has 11 T-Quenchers, that are are fixed at the end of relief valve discharge piping under the torus water level. This system represents piping with a "T" shape steam spargers. This device is used to reduce unbalanced forces on the piping and to solve the problem with hydrodynamic loads on the torus when the relief valve is active. (B.J. Patterson, 1979)

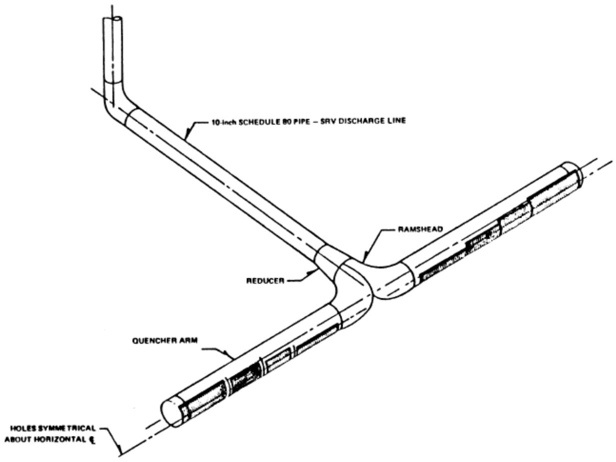


Figure 2.7 Mark I T-Quencher Shell Discharge Device (B.J. Patterson, 1979)

In the Olkiluoto and Oskarshamn containments either blowdown pipes or sparger pipes are applied depending on the situation . If there is a Loss of Coolant Accident, then steam goes from the dry-well to the wet-well through the blowdown pipes. (Ignacio Gallego-Marcos et al., 2015)

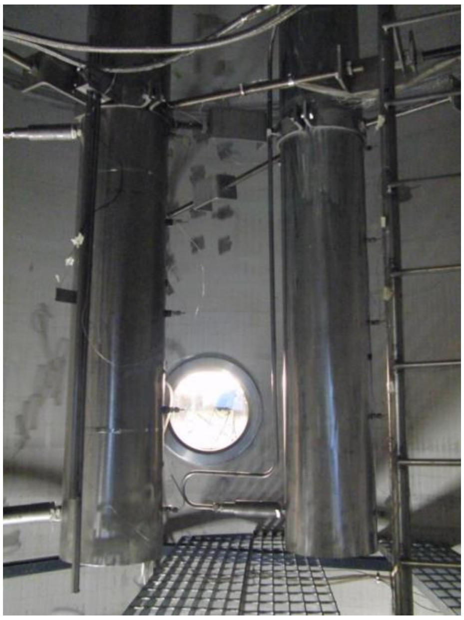


Figure 2.8 Two parallel steel blowdown pipes in the PPOOLEX test facility (M. Puustinen et al., 2011)

The Olkiluoto containment has 16 blowdown pipes, whose inner diameter is 600 mm and submergence is 6.5 m. (M. Puustinen et al., 2011)

In case of Station Black-Out (SBO) the Safety Relief Valves open with the aim to avoid overpressure in the primary circuit and steam goes into the pressure-suppression pool through the spargers. In the Olkiluoto containment spargers are pipes, whose diameter is about 150 mm and there are many holes of 10 mm in diameter. The submergence depth is 6.4 m (Ignacio Gallego-Marcos et al., 2015).

The same kind of sparger pipe was used in the PPOOLEX experiments at Lappeenranta University of Technology, but in another scale; a more detailed description of the sparger is below.

The sparger is a submerged DN65 pipe, whose length is approximately 5 m and diameter is 76.1 mm. There are 32 injection holes in the sparger head, the diameter of each hole is 8 mm. These holes are located in 4 rows with 8 holes in each. There is a LRR (load reduction ring) at the distance of 700 mm is set above the pipe outlet and it also has holes (8 axially located with a diameter of 8 mm). Steam goes into this pipe and then injects through the holes of the sparger head in form of jets with further condensing in the pool. (M. Puustinen et al., 2016)

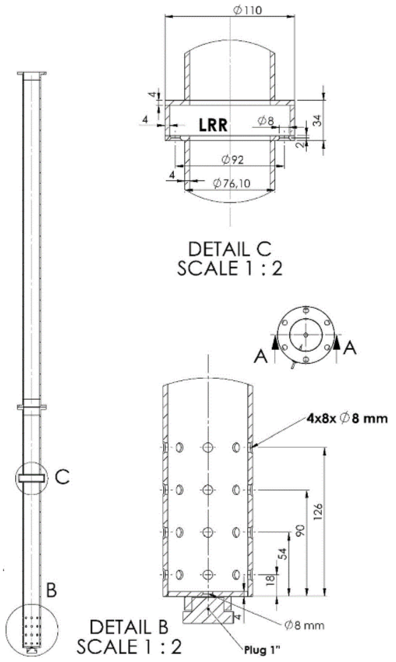


Figure 2.9 Sparger scheme and dimensions in PPOOLEX (M. Puustinen et al., 2011)

There are many different cases or scenarios that involve use of the spargers at some conditions such as

- steam mass flows,
- pressure of steam,
- suppression pool temperature
- number of spargers that are active or not active. It can be changeable depending on the transient in question.

The nuclear reactor containment of APR1400 could be overviewed as an example of sparger application. The total thermal power capacity of this reactor is 4000 MW and its type is pressurized water reactor, made by Korea. The safety system of APR1400 is actively designed and improved by KHNP and KOPEC. This reactor includes several modern design solutions that help to increase safety level. The APR1400 design has one special feature, related to sparger pipes, that shows a great advance in the safety of the reactor. Some experiments were were conducted with steam sparger were conducted by KAERI. The aim was to evaluate the performance of the sparger, which is assumed to be in use in this reactor. The results of the experiments were used for further code development.

The points of interests in the experiments were temperature change and distribution in the area of sparger head holes while steam condensation was happening (PARK et al., 2007).

The structure of APR1400 will have about 12 spargers. These devices will be used for depressurization of pressurizer in an emergency situation. The length of such unit cell sparger is about 6 inches. The pipe has a LRR, which is located close to the top of the sparger and supposed to decrease the air clearing load. Close to the outlet of the sparger there are 144 holes of 10 mm in a diameter (Fig. 2.10).

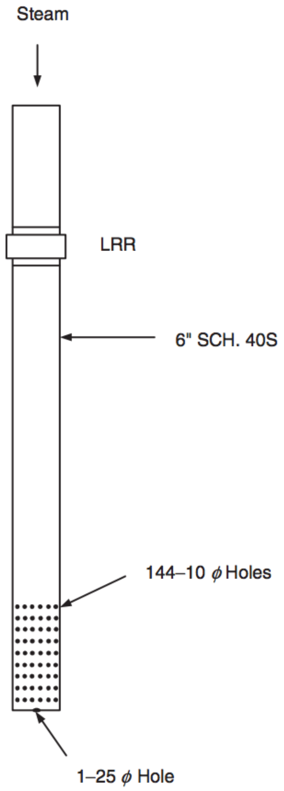


Figure 2.10 Sparger pipe for APR 1400 containment (PARK et al., 2007)

3 THERMAL STRATIFICATION AND MIXING

3.1 Introduction

The EHS (Effective heat source) and EMS (Effective momentum source) models , designed by Li et al. (2014 a), describe pool behavior in detail and can be used for the simulation of thermal stratification and thermal mixing after steam jets injection. These models do not describe the small scale phenomena occurring at the level of direct contact condensation of steam jets, instead the time averaged heat and momentum transferred from the steam to the large scale pool circulation is provided to forecast forecast the global processes in the pool. The effective heat and momentum source models have been validated for the chugging condensation regime for blowdown pipes. (Gallego-Marcos et al., 2016)

The reason for developing the EMS and EHS models is the computational efficiency they provide in predicting the pool behavior. This is also important from the safety point of view as there could be some conditions in the pool, which decrease pool's capability of pressure reduction. Reduces pressure reduction capability is assumed to be the reason for the unsuspected pressure increase during the Fukushima accident (Mizokami et al., 2013), when the pressure level was twofold compared to the predicted level under fully mixed pool conditions.

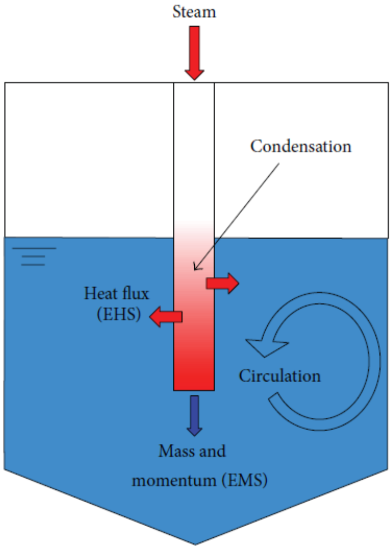


Figure 3.1 EMS and EHS models explanation (Gallego-Marcos et al., 2016)

It should be mentioned that the pool behavior is dependent upon the way of steam discharge into the pressure suppression pool: discharge through blowdown pipes leads to a different kind of pool behavior than discharge through spargers. To estimate the effective momentum and effective heat transferred to water from the steam jets the steam condensation region approach was used. This approach assumes solution of three conservation equations: energy, momentum and mass in some volume, where steam jets finally condense. Next these two models are introduced separately. (Gallego-Marcos et al., 2016)

3.2 Effective heat source model

This model describes the heat source of steam, which is injected into the pool. Its goal is to preserve steam's mass and thermal energy. It is assumed that only hot saturated water goes out of the submerged pipe. In fact, there could be a case, when not all steam is condensed in the submerged pipe. The used assumption properly conserves the mass balance in the system, also in a case where some fraction of steam was not condensed inside the pipe, but outside.

The total effective heat source is determined by mass flow and enthalpy; both are time averaged:

$$H_{eff_{total}}(t) = \bar{\dot{M}}_{steam}(t) \cdot \bar{\dot{h}}_{steam}(t) = \frac{1}{t}\int_{t-\Delta t}^{t} \dot{M}_{steam}(\tau) \cdot h_{steam}(\tau) d\tau \quad (3.1)$$

Spatial distribution of EHS is:

$$Q_{eff_{total}}(t) = \int_S \; Q_{eff}(x,t) dS \quad (3.2)$$

$$Q_{eff}(x,t) = \frac{1}{\Delta t}\int_{t-\Delta t}^{t} Q(x,\tau) d\tau \quad (3.3)$$

Where $Q_{eff}(x,t)$ – spatial flux distribution of time averaged EHS at time t; Δt – aveaged time, which is much larger time scale of DCC oscillations; $Q(x,\tau)$ – heat flux at some moment through S which defines wall area of the pipe and it's outlet.

The Figure 3.2 shows the process of steam condensation inside of submerged pipe. Steam flows through the submerged pipe, it condenses on the surface of the walls and it also condenses on so-called free surface of water. Steam flow rate and regime of condensation define the spatial distribution of the EHS. For instance, in case of pool water low temperature and low steam mass flow rate the distribution of EHS along the submerged surface of the pipe will be uniform. In case of high steam mass flow rate there will be limited condensation of steam in the pipe; the condensation will happen mostly close to the submerged pipe outlet. (Hua Li et al., 2016)

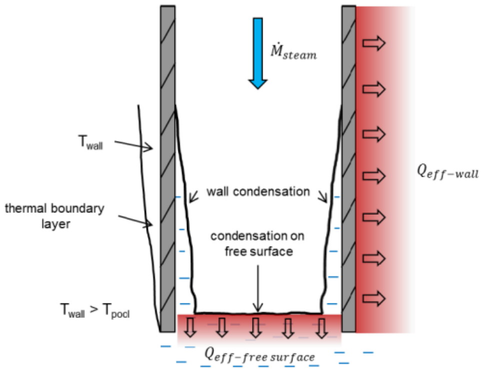


Figure 3.2 Spatial flux distribution (Hua Li et al., 2016)

3.3 Effective momentum source model.

This model describes the time averaged momentum source which is a result of steam injection into the pool. This momentum can create circulation of the pool water and such a large scale circulation can lead to pool mixing and erosion of the thermally stratified layers. Next formula is used to define EMS:

$$M_{eff}(t) = \frac{1}{\Delta t}\int_{t-\Delta t}^{t} M(\tau)d\tau \qquad (3.4)$$

It should be mentioned, that condensation of steam may cause different effective momentum rates, while steam mass flow rate stays unchanged. Thereby the effective momentum source model is used to create a connection between the conditions of the pool, the resulting momentum and different parameters of the steam.

As it is known, steam flux and temperature of pool bulk define the regime of condensation. By considering the POOLEX/PPOOLEX experiments, the initial condensation regime is condensation within the pipe when the steam mass flow rate is small enough. Region 2, which is the chugging regime, is reached with increasing of the steam mass flow rate. In some experiments there is a transition regime as the temperature of pool bulk increases (Hua Li et al., 2016).

3.4 Thermal stratification in details

The harmful effect of thermal stratification in water of the suppression pool is evident if we think the Fukushima Daiichi accident at Unit 3. In this case during the steam injection into the pressure suppression pool through the SRVs the RCIC systems had been exhausted resulting to significant thermal stratification in the pool, which then lead to pressure increase.

Stratification is a natural physical process of a hot liquid rises above the cold one. Thermal stratification was studied in detail by several tests under PUMA facility (Cheng et al., 2006). The results of these experiments explained the main causes of strong stratification: the submergence depth of vent opening, initial pressure value of the pool, flow rate of non-condensable gas, flow rate of steam.

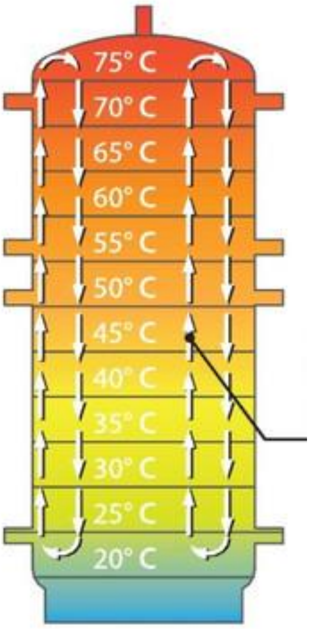


Figure 3.3 Thermal stratification in a vessel (Cheng et al., 2006)

While the process of steam injection is happening sharp temperature and density gradients take place in the vertical direction, in other words a sharp interface, thermocline, between the cold and hot layers develops. Heat and momentum are reduced by buoyancy effect. (Gallego-Marcos et al., 2016)

There is a competition between momentum and heat, and as a result the pool could be either thermally mixed or stratified . Thermal stratification is developed by heat source and there are two types of transient stratification configurations can be identified. The first one is a stratified layer with prolonged rise in temperature of water above the bottom elevation of the sparger or blowdown pipe and a constant temperature of cold water beneath the heat source. The second is an isothermal upper layer detached by a small thermocline layer from the lower volume of cold water. In the region of the thermocline temperature changes rapidly (Hua Li et al., 2016).

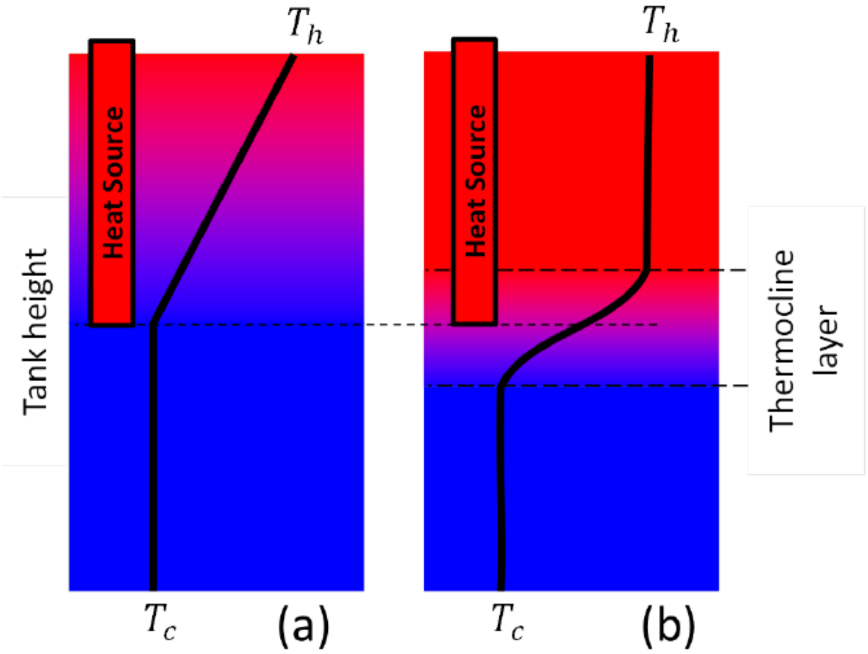


Figure 3.4 Thermal stratification in a water of suppression pool (Hua Li et al., 2016)

Another point of interests is the momentum as a result of steam condensation. The circulation in the pool, mixing the water, appears due to momentum. The momentum rate defines how fast this mixing will proceed. The time scale is a very important parameter, because restoration of suppression pool’s capacity depends on time, which is needed to achieve mixing. (Hua Li et al., 2016)

Steam condensation leads to pool temperature increase and as it goes up, pressure suppression capacity of the pool is reduced. The success of pressure suppression depends on the pool surface temperature. This temperature defines the partial pressure of steam, which is contained in the wet-well gas space. As a result of thermal stratification, temperature of pool’s surface goes up and this could lead to a large rise of pressure in a containment. (Gamble et al., 2000) This threat of thermal stratification is a point of interests and it has been explored in several experiments, but still needs to be investigated further.

4 EXPERIMENTS WITH MODELS OF PRESSURE SUPPRESSION POOL

4.1 Introduction

The goal of experiments was to simulate condensation regimes inside the pool, reproduce thermal stratification and mixing.

The aim of experiments in the PANDA facility was to retain parameters and condensation regimes, which define important physical processes in plant scale. Then the measured data would processed through validated codes to predict plant behavior.

The aim of experiments in the POOLEX and PPOOLEX facilities was to receive data for making further progress in the development of the EMS and EHS models, used in GOTHIC code at KTH Royal Institute of Technology. Then these two models will be extended to be able for using them with steam injection through the sparger into the pool. Quite precise agreement was achieved in temperature and water level between the simulation with the EMS and EHS models and the experiment results. Also the development of mixing and thermal stratification was observed. One of the points of interests during these experiments was the behavior of the thermocline.

4.2 Experiments in POOLEX and PPOOLEX facility

Some experiments were carried out at Lappeenranta University of Technology with the POOLEX and PPOOLEX facilities. During these tests steam discharging processes were studied in detail and simulated with computer codes.

Conditions of the experiments were the following:
PPOOLEX represents a boiling water reactor containment and consists of wet-well, dry-well, inlet plenum and air or steam piping. During the experiments with the sparger steam was flowing directly into the wet-well (condensation pool) through the sparger, i.e. the dry-well was bypassed. The volume of the test vessel was approximately 31 m^3. It had a cylindrical shape, 7.45 m in height and 2.4 m in diameter. Comparative dimensions with the

Olkiluoto containment are about 1:320. The sparger is a submerged DN65 pipe, which length is approximately 5 m, diameter 76.1 mm and which was located at the distance of 420 mm away from the pool's center. There are 32 injection holes in the sparger, the diameter of each hole is 8 mm. These holes are located in 4 rows with 8 holes in each. There is a LRR (load reduction ring) at the distance of 700 mm above the pipe outlet and it also has holes (8 axially located with diameter 8 mm).

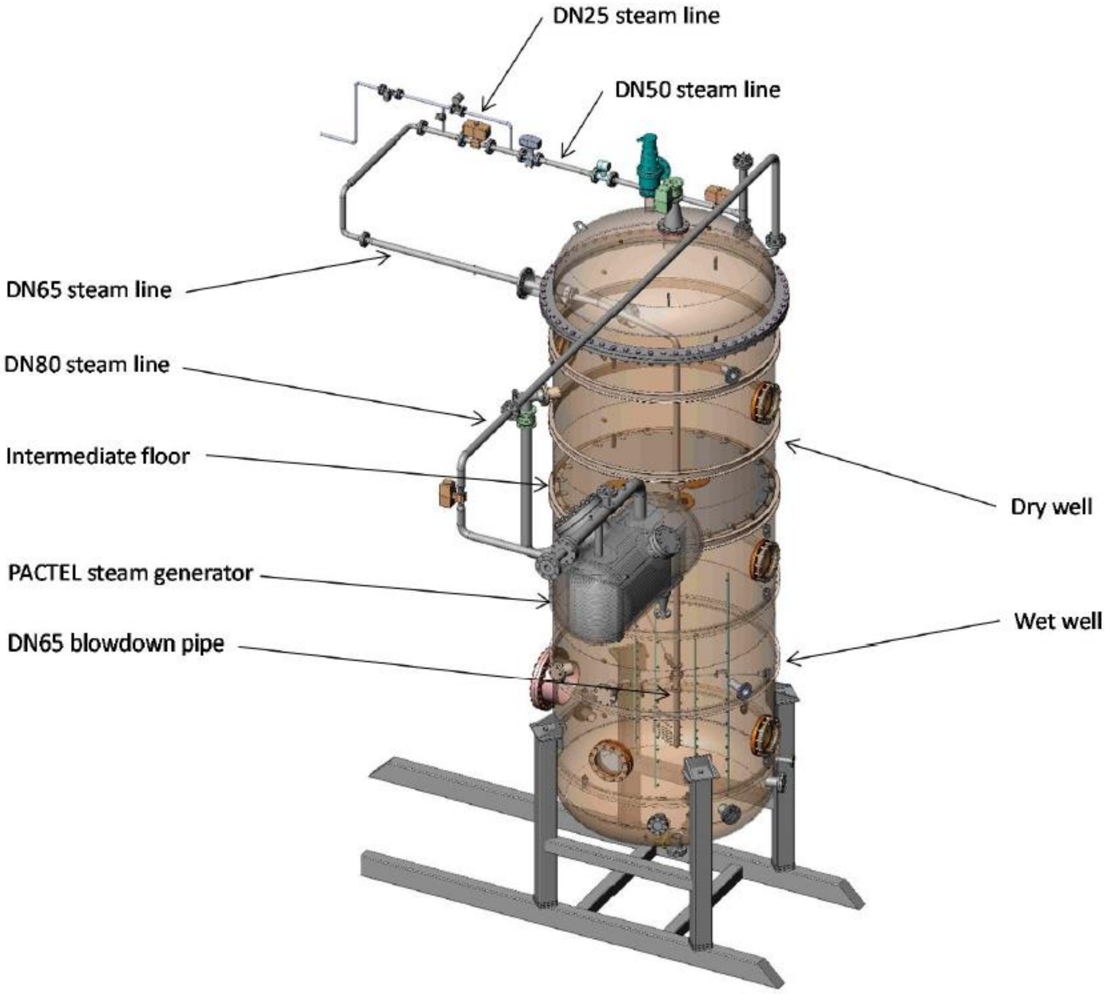


Figure 4.1 PPOOLEX vessel scheme (M.Puustinen et al., 2016)

There were several tests, when all the holes of the LRR were closed and steam was discharged into the pool only through the holes of the head of the sparger in horizontal direction. During the other tests all holes, including the LRR holes, were blocked, except the lowest row of 8 holes at the sparger head. In one experiment the sparger head holes were closed, but the eight holes of load reduction ring were functioning.

Experiments included stratification periods and mixing periods. During these periods there were different steam flow rates. With the flow rate used during the stratification period the steam flowed through the holes of the sparger as jets and condensed later in pool water, not inside the sparger. Due to the lack of chugging and due to small weak jets there was almost no turbulence inside the pool. So, the conditions were suitable for thermal stratification.

The location of the transition region depended on the direction of steam injection. When steam was injected through the sparger head, the transition region was below the sparger head. When steam discharge was vertically downwards from the load reduction ring, the transition region was located deeper, than in the case of horizontal position of the jets.

In some experiments complete mixing was not achieved. In case where all 32 holes of the sparger were functional large flow rate was not sufficient to achieve full mixing. There was mixing only above and a little below the head of the sparger outlet. (M.Puustinen et al., 2016)

4.3 Experiments in PANDA facility

Conditions of experiment in the PANDA facility were the following: water pool depth was chosen such that the ratio of depth to square root of the area of one sparger in a BWR could be preserved; the sparger was put in the middle and immersion depth was about 0.7 of the whole pool depth. Total injection hole area was 2800 mm^2, steam flow rates: 2.2 and 0.65 kg/s were used; pressure was 230 kPa.

Three values (inverse time constants) were calculated: mass, momentum and energy. The next formulas were used in order to define them:

$$\omega_M = \frac{\dot{m}_s}{m_L} \tag{4.1}$$

$$\omega_E = \frac{\dot{m_s} h_s}{m_L h_L} \tag{4.2}$$

$$\omega_P = \frac{\dot{m}_s v_s}{m_L\sqrt{gH}} \tag{4.3}$$

The sparger pipe was used to control heat and momentum sources' distribution inside the pool. The inner diameter of sparger pipe was 80 mm and wall thickness 4 mm; the load reduction ring's diameter was 126 mm, height – 100 mm. These dimensions allow to simulate required condensation regime into pipe. Location of the LRR was about half of the sparger depth, which allowed to simulate almost similar spatial distribution of the steam as in real BWR.

The injection holes in the sparger were used in order to reproduce similar to real BWR's steam jets, which total injection area of the holes was 2800 mm^2 and the diameter of the injection holes 9.5 mm. The range of steam mass fluxes was up to 230 kg/(m^{2}s). The LRR had 8 holes in a single ring, while the sparger head had 32 holes in 4 rings with 8 holes per each. Other dimensions of the sparger system used in the PANDA facility can be observed from Figure 4.2 (Ignacio Gallego-Marcos et al.)

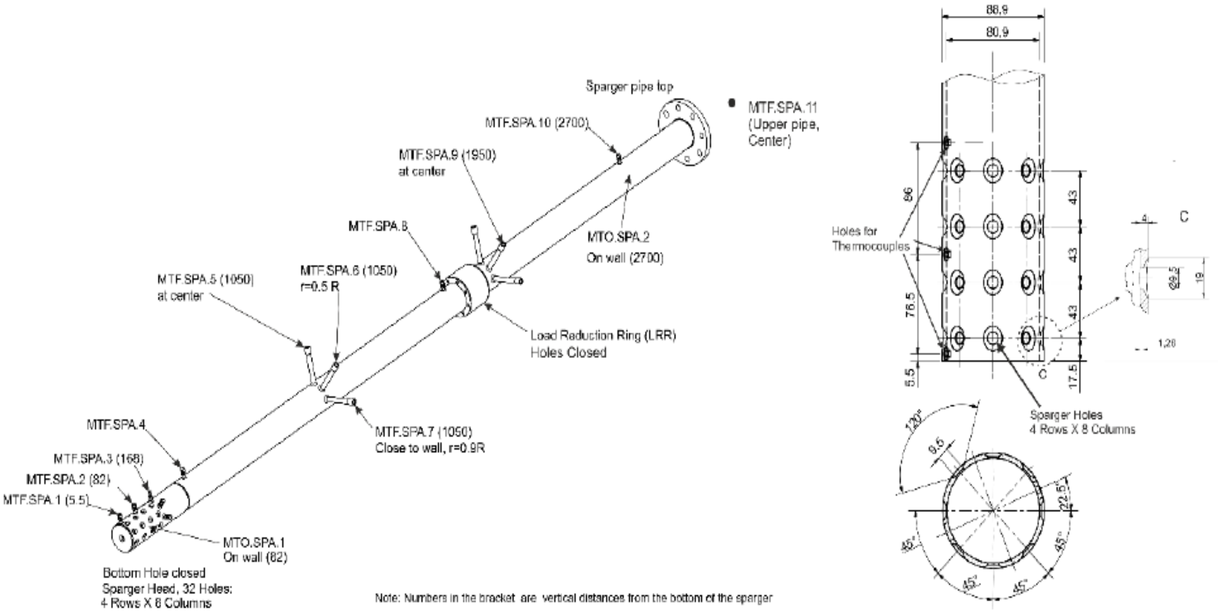
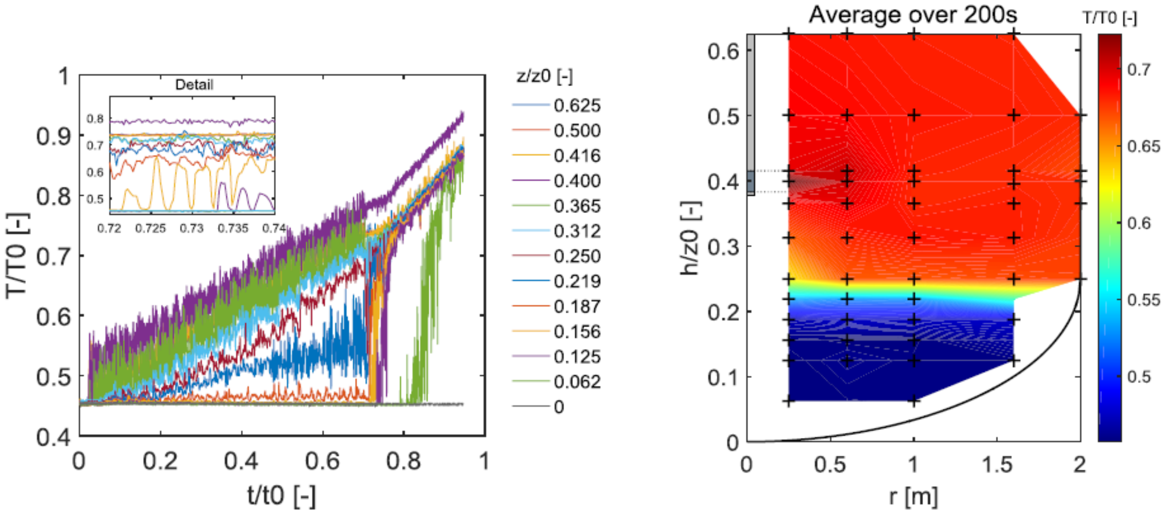


Figure 4.2 Sparger in the PANDA facility (Ignacio Gallego-Marcos et al.)

Next three PANDA tests, which were done by injecting steam through the sparger, will be described. During each of the experiments the holes of the LRR were first closed and then open with the aim to first observe the performance of the sparger head alone and then the performance of the whole sparger.

At the beginning the steam mass flow rate was as low as possible to avoid the chugging regime. As a result the momentum of injected steam was low and the pool stratified. Then the mass flow rate was increased to create mixing. Next an analysis of the HP5_1 test will be performed (Paranjape et al., 2016). Temperature measurements during this test are shown below.



(a) (b)

Figure 4.3 Temperature distribution in experiment under PANDA facility (Ignacio Gallego-Marcos et al.)

The inaccuracy of the measured temperature values is about 0.7 °C. During the stratification phase the flow could not reach the bottom of the container because of buoyancy effect. At t/t0 = 0.7, the flow rate of steam was increased and steam jets were set in horizontal position, interacting with the walls of the container. This process induced fast mixing under z/z0 = 0.125.

Stratification and mixing create two attributes which need to be in focus. One of those: the thermocouple located at midst of the sparger holes indicated higher values of temperature than other thermocouples. This difference was more significant during a mixing process.

Thereby this parameter could be used to define the boundary conditions. The other feature is that located at the thermocline thermocouple showed low frequency and significant oscillations of temperature (Figure 4.3 (a)). According to Fourier analyses the frequency f/f0 between 0.14-0.2 is considered to be close to the natural oscillation frequencies. It is assumed that turbulence induced by steam injection sets the pool to natural oscillation frequency. It was discovered that the slow erosion of the thermocline at z/z0 = 0.062 happens due to discontinuous breaking of these oscillations. The natural oscillations at the thermocline had been defined by two equations (Madarame et al., 2009)

$$f_n = \frac{1}{2\pi} \cdot \sqrt{g' \cdot \frac{k_n}{R} \cdot \tanh(H \cdot \frac{k_n}{R})} \tag{4.4}$$

$$g' = g \cdot \frac{\rho(T_c) - \rho(T_h)}{\rho(T_c)}, \tag{4.5}$$

Where H – thickness of stratified layer, R – tank radius, k_n – the nth root of the derivative of the first order Bessel function, g' - reduced gravity

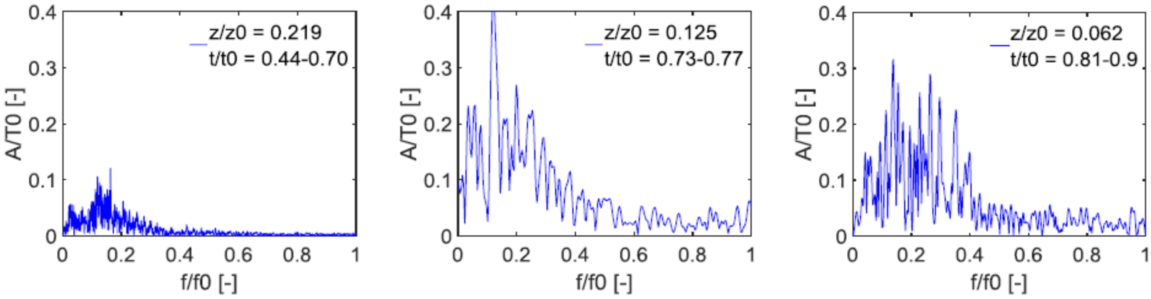


Figure 4.4 Natural oscillations (Ignacio Gallego-Marcos et al.)

4.4 Experiments in PUMA-E facility

Experiments in steady state and transients were conducted in the PUMA-E facility with the aim to study processes in suppression pool. There were several simulations in both states. In steady state various flow rates of air were introduced into the downcomer of the facility. The actual purge period in the dry-well was performed in the transients. The subsequent injection of successive air streams, a vapor-air mixture and pure steam with different flow regimes were modeled using a reactor pressure vessel, dry-well and suppression pool of current facility.

The PUMA-E facility is a model of ESBWR. Every element of this facility has been modelled by scaling down this reactor. The reactor pressure vessel, dry-well, and wet-well geometries are not different to the PUMA facility, which is a previous version of the PUMA-E facility. The scheme is shown in figure 4.5.

During the steady state experiment, a downcomer pipe has been used to direct air right into the suppression pool. The sixteen tests were conducted under different air flow rates, different void fraction conditions, and various air velocities. The air injection phase and the quasi-steady phase were overviewed. During the initial air injection phase the largest depth of void penetration was observed. The quasi-steady period had much more less void penetration, although there was oscillation. Tit turned out that the flow rate of air provides insignificant effect on the distribution of void fraction and penetration in the initial air injection stage under high values of flow rate of air while it significantly influences the distribution of void fraction and penetration in the quasi-steady stage during the whole range of air flow rates. It was observed that initial downcomer void conditions significantly affect the distribution of void fraction and penetration in the initial period (L. Cheng et al., 2006)

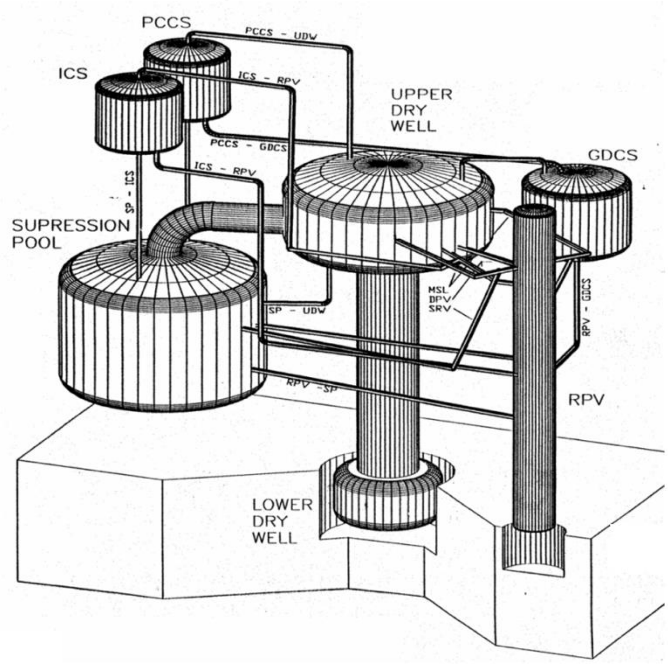


Figure 4.5 PUMA experimental facility (L. Cheng et al., 2006)

For the transient experiments, consecutive air streams, air-steam mixtures, vapour-air mixtures and pure steam with different flow rates were injected from the dry-well through the downcomer pipe in the SP. The eight tests were conducted under various gas volumetric fluxes at the downcomer, two different downcomer sizes, and two different initial air concentration conditions in the dry-well. Three periods, namely, initial period, quasi-steady period, and chugging period are observed in the experiments. The void penetration depth had its maximum in the initial period and reduced in the quasi-steady period. The penetration of non-condensable gases during the chugging period, which occurs at the end of the transient, reached depths similar to those observed during the initial period. It was determined that the void distribution and area of void penetration in the SP is governed by the gas volumetric flux at the downcomer and by air concentration in the downcomer. It is noted that the transient conditions were well scaled for the initial period but not necessarily well scaled to simulate the chugging phenomena. Chugging is a complex phenomenon that depends primarily on periodic sudden condensation of steam into colder water, but also depends on gas volumetric flux, non-condensable gas concentration, frequency of the phenomenon, heat transfer, and pool water sub-cooling, as well as the downcomer and suppression pool geometry. The rudimentary scaling methods used here are not suitable for use with such a complex phenomenon. Instead, more specific and advanced scaling techniques would be needed (L. Cheng et al., 2006).

4.5 Oscillations

When steam is blown into a suppression pool the chugging regime could be observed. Typical for this regime are steam-water interface oscillations inside the blowdown pipe. It is obvious that the oscillations introduce momentum that is directly proportional to the frequency and amplitude of these oscillations. The momentum can generate water mixing and decrease thermal stratification, in other words allow to increase capability of the pool to suppress high pressure (M.Puustinen et al., 2016).

The figure below shows a brief description of the occurrence of momentum due to oscillations. The time scale of oscillations happening during condensation is about 1 second.

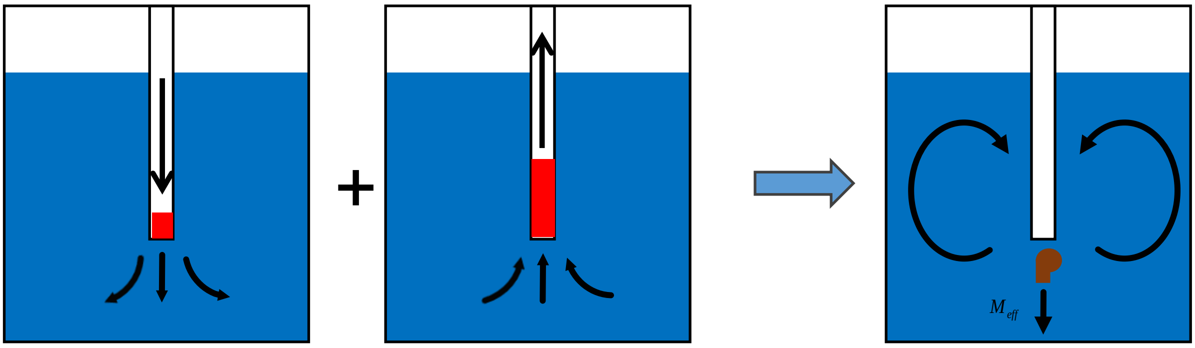


Figure 4.6 The Occurrence of momentum due to oscillations in the blowdown pipe (Hua Li et al, 2012)

Steam condensation process in a subcooled pool can proceed under several possible regimes. During the chugging regime oscillations of steam-water interface inside a submerged pipe are happening. Some small-scale experiments were conducted to study the chugging regime with an amplitude of 0.3 m and frequency of 75 Hz (Aya and Nariai, 1985;Aya et al., 1980; Nariai and Aya, 1986). The same kind of experiments, but in different scale, were made in 2014 and 40 - 200 Hz oscillations were detected. In the PPOOLEX facility, with bigger scale experiments than previous, 0.5 m amplitudes under 3.5 Hz frequency oscillations were discovered. It is important to note that mixing and thermal stratification had been induced by oscillations in all condensation regimes during the experiments. According to measured data a smaller pipe diameter corresponds to larger a oscillation frequency and vice-versa.

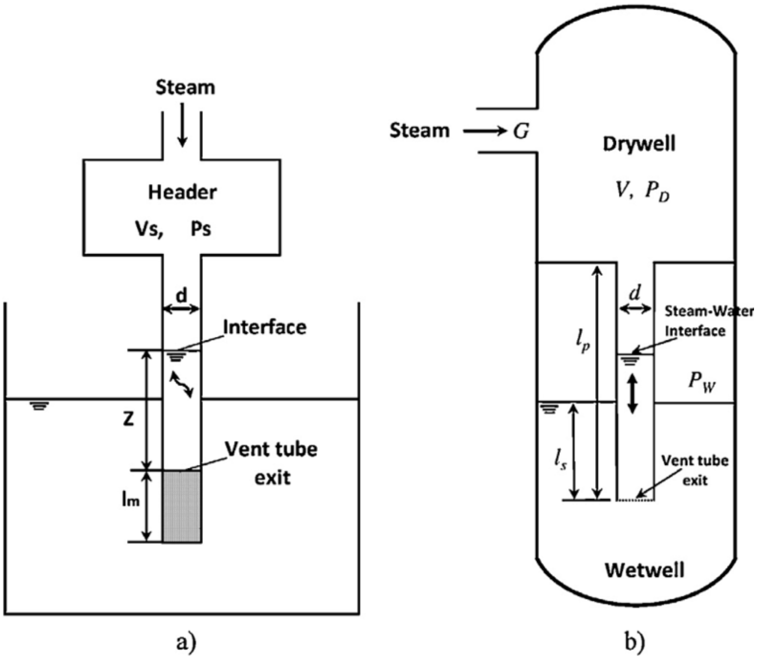


Figure 4.7 Drawings for experiments: (a) Aya and Nariai; (b) PPOOLEX MIX tests

Momentum could be defined by oscillation’s amplitude and frequency (Li et al. 2014a, b), and it is possible to use effective momentum in order to determine Richardson number, which allows to calculate occurrence of thermal stratification (Song et al., 2014).

Aya and Nariai made an analytical model with the aim to calculate frequency and amplitudes of oscillations that they had during experiments, but some issues about scalability contradicted other data of experiments (Li et al., 2014 b). Information gained in the new and old experiments allows to make further progress in defining oscillation characteristics in the chugging regime in different scales.

5 DESCRIPTION OF THE SPARGER EXPERIMENT

5.1 Test facility

The experiment was carried out at Nuclear Engineering laboratory of Lappeenranta University of Technology. The aim of the experiments in the PPOOLEX facility and its structure was described earlier in chapter 4.1. This facility has been used since 2006 and it represents containment of boiling water reactor, but in smaller scale. Air removal system was used In order to get rid of air from the pool. This system contains the device for air removing and filter.

The thermocouples were used with the aim to measure temperatures of water, steam and temperature of structures. The grid of thermocouples in front of the injection holes was 6x7. Nine of thermocouples were used for measuring vertical distribution of temperature in the sparger pipe and four trains for measurements in the pool. The pressure transducers were used to measure pressure in the system. Vortex flow meter was used for steam flow observation.

Video cameras were used for filming the processes during the experiment. The frame frequency was 25 fps.

There were several tests: SPA-T2 – SPA-T6 that differed by several parameters. Each experiment had two stages: stratification and mixing. At the beginning of the experiments, the pool of the PPOOLEX facility was filled with water, which temperature was in range from 15 to 20 degrees Celsius and the surface of water was at a point of 3 meters above the bottom of the pool. The submergence depth of the sparger head was 1.8 meters. The steam flow was initiated by the PACTEL, that is a steam generator, and controlled by valve. (M.Puustinen et al., 2014)

5.2 Initial test conditions

The initial pressure in test facility was atmospheric. Then the valve was opened with the aim to start inject steam injection into the pool, so pressure in the steam source system was at a constant level of 0.6 MPa during the whole experiment. During the first 200 seconds after valve opening the value of steam flow rate was high. The reason of this action is need in facility heating up and air removing.

To start the first stratification period, the steam flow rate was set to a certain level, that is lower than during the first 200 seconds. To start mixing in the pool, steam flow was decreased or increased very fast after reached desired temperature difference between layers of water at the bottom and at the surface of water. To initiate the second stratification process, the uniform temperature distribution after mixing of water of pressure suppression pool had to be reached. To start the second period of mixing, again the desired difference between temperatures of water layers had to be reached (M. Puustinen et al., 2014)

The initial and some other parameters of tests SPA-T2 – SPA-T6 are shown below

Table 5.1 Initial parameters and other data of tests SPA-T2 – SPA-T6

Exp.	Initial water level [m]	Initial water tem. [°C]	Steam source pressure [MPa]	Steam flow rate [g/s]			
				Stratif. I	Mix. I	Stratif. II	Mix. II
SPA-T2	3.0	14	0.6	130	70	70	200
SPA-T3	3.0	19	0.6	120	260	95	250
SPA-T4	3.0	16	0.6	130	175	93	130
SPA-T5	3.0	15	0.6	123	208	97	150
SPA-T6	3.0	15	0.6	130	150	90	40

Steam mass flux and pool bulk temperature defined the path of these experiments and they are marked on the map of condensation regimes for a sparger of Chan and Lee in figures below.

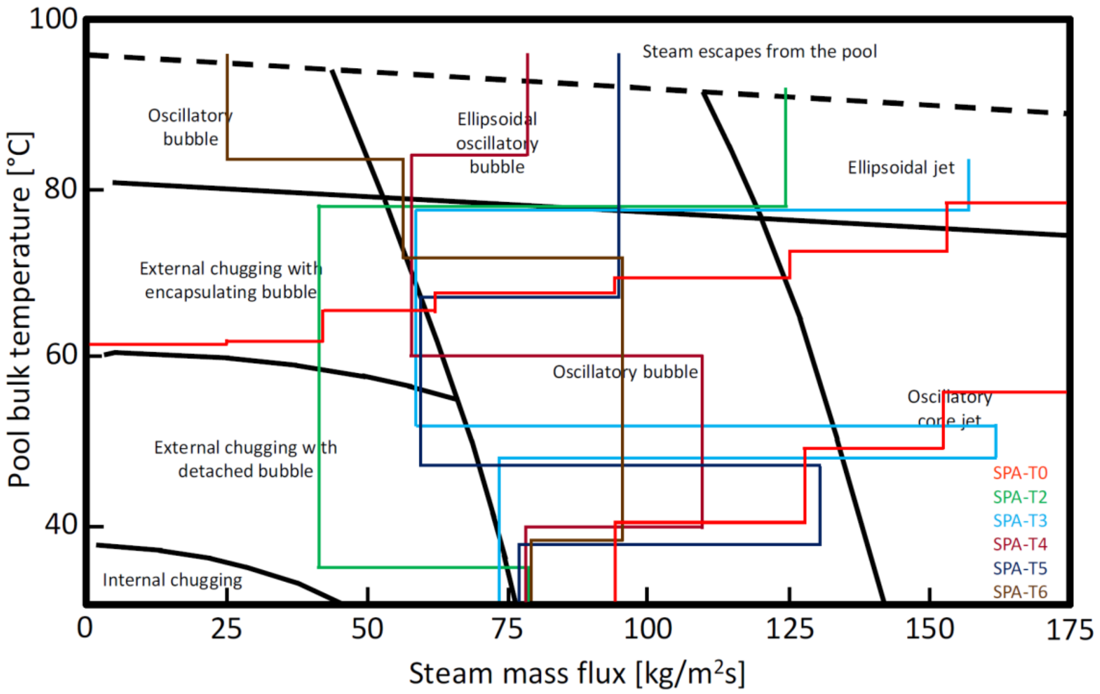


Figure 5.1 Tracks of experiments with sparger on the condensation mode map of Chan and Lee (M.Puustinen et al., 2014)

5.3 Results of experiment

As it was mentioned before each experiment had several stages. The first period was a heat up period that was initiated with the aim to remove air and heat up the structures. Steam flow rate values were in range: 220 – 240 g/s. The pool water temperature increased by 2 °C and the duration of this period was 200 seconds. Main parameters of the heat up period are shown in table below.

As all the experiments had the same periods, only one experiment, SPA-T3, will be overviewed further.

Table 5.2 The main parameters of heat up period during sparger experiments.

Exp.	Time period [s]	Steam flow rate [g/s]	Pool water temperature increase [°C]
SPA-T3	35 – 235	~220	19 – 21

The first stratification period came right after the heat up period ended, accompanied with decrease of steam flow rate down to 120 g/s. The steam flow was performed in the form of small jets that were going through the holes of the sparger head. Condensation of steam occured outside of the sparger pipe. Due to the size of jets and lack of chugging there was almost no turbulence, in other words – good conditions for stratification. Temperatures at the bottom of the pool were approximately constant, but in the direction to surface of the suppression pool the temperatures increased. The distinct thermal stratification had place in this case. This period continued until a temperature difference of 26 °C between the surface and bottom had been reached. Temperature change as a function of time is shown in Figure 5.2. The values related to this period are shown in table 5.3 (M. Puustinen et al., 2014)

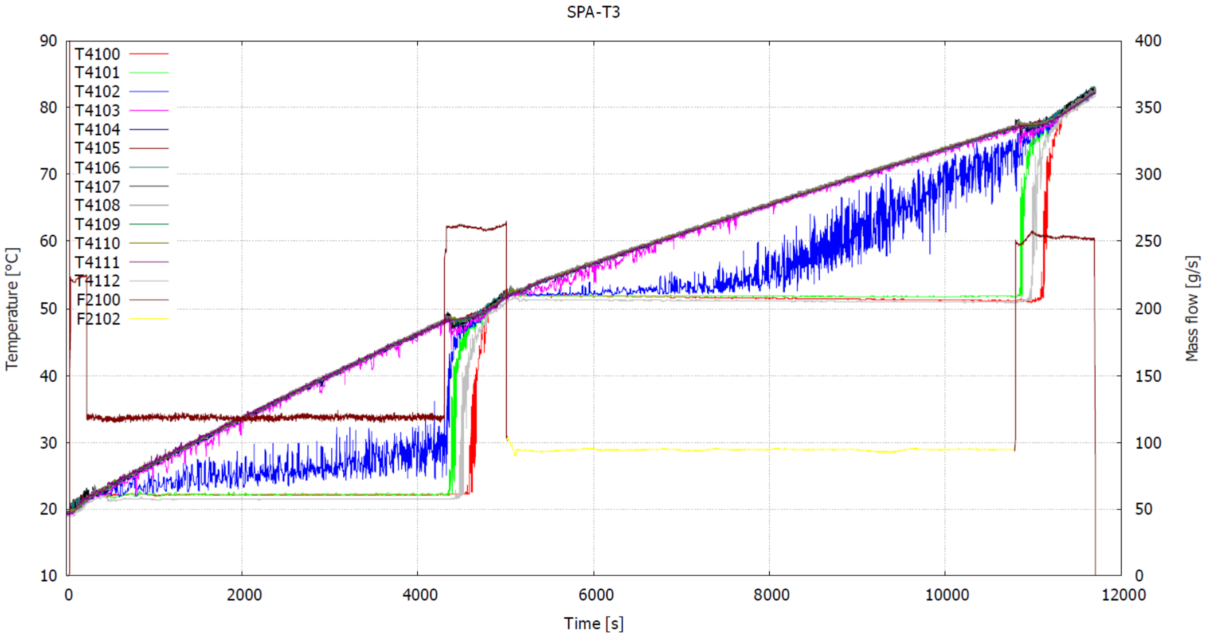


Figure 5.2 Distribution of pool water temperature in vertical direction (M. Puustinen et al., 2014)

Table 5.3 The main values of Stratification I period during sparger experiment.

Exp.	Time period [s]	Steam flow rate [g/s]	Initial water temperature [°C]	Stratification time [s]	Final water temperature bottom/ surface [°C]	Final temperature difference between bottom and surface [°C]
SPA-T3	35 – 235	~220	19 – 21	4068	22/48	26

After Stratification I period the steam mass flow rate was changed from 220 g/s to 260 g/s with the aim to induce turbulence in pool water and as a result to create mixing. It took about 702 seconds to achieve a full mixing in the pool volume. The values related to this period are shown in table 5.4.

Table 5.4 The main values of Mixing I period during sparger experiment.

Exp.	Time period [s]	Steam flow rate [g/s]	Mixing time	Final temperature [°C]
SPA-T3	4303 – 5005	260	~500	52

To start the next period the steam flow rate was decreased to 95 g/s, so the mixing was eliminated. Steam condensation was happening outside the sparger pipe, as a result the pool water had thermal stratification. The pool water temperature during Startification period II was significantly higher than in Stratification I, that’s why it was enough to have a lower steam flow rate than in first Stratification period. There was no risk of ending up in chugging. The end of Stratification II period was reached when a temperature difference between water at the bottom and surface reached 26 °C. The values related to this period are shown in table 5.5 (M. Puustinen et al., 2014)

Table 5.5 The main values of Stratification II period during sparger experiment.

Exp.	Time period [s]	Steam flow rate [g/s]	Initial water temperature [°C]	Stratification time [s]	Final water temperature bottom/ surface [°C]	Final temperature difference between bottom and surface [°C]
SPA-T3	5005–10793	95	52	5788	51/77	26

The last period was Mixing II. To start this period the rapid steam flow rate was increased up to 250 g/s. It took about 908 seconds to achieve a full mixing in the pool volume. The values related to this period are shown in table 5.6.

Table 5.6 The main values of Mixing I period during sparger experiment.

Exp.	Time period [s]	Steam flow rate [g/s]	Mixing time	Final temperature [°C]
SPA-T3	10793 – 11701	250	~530	79

5.4 Problems and uncertainties

The main reason of the current POOLEX test uncertainty is immeasurable heat losses from the walls of the vessel, as well as from free surface of the pool to the laboratory atmosphere. There was a proposal of using a method that assumes merging experimental data and lumped parameter simulations for the aim of necessary data recovering to provide boundary conditions and two/three dimension models validation.

The uncontrolled heat and mass exchange between test facility and atmosphere of the laboratory - is a problem of current experiment. This process was solved partially in the PPOOLEX test facility that is an upgraded version of POOLEX.

PPOOLEX is a sealed vessel that is not connected to the atmosphere, in other words there is no mass exchange with atmosphere of the laboratory. The spatial distribution of heat loses through the outer surface of the vessel is hard to be measured during the experiment, because outer surface of vessel is not isolated and heat flux to the laboratory is quite significant (M. Puustinen et al., 2014).

5.5 Validation of EHS/EMS models in SPA-T3 test

Validation - confirmation based on the presentation of objective evidence that the requirements intended for a particular use or application are met, the declared properties and characteristics are confirmed, and the set of goals (the purpose of the system, complex, device, etc.) is achieved.

The validation of the Effective Heat Source and Effective Momentum Source models for a steam sparger was done against two periods of the SPA-T3 test: Stratification I and Mixing I with 5000 s of transient. There were two types of regimes in these transients: oscillatory bubble and cone jet. The reason of choosing for validation purposes SPA-T3 test and the first 5000 seconds is that the mixing was assumed to be produced during oscillatory cone jet regime. In this regime the frequency as well as the amplitude of oscillations of the steam-water interface are especially low. A steady condensation regime was overviewed above 300 kg/m^2s and it was fixed in the condensation regime map. For a proper determination of effective momentum value determination the validation process should be started with oscillatory cone jet regime.

Figure 5.3 Photos of steam jets in suppression pool (M. Puustinen et al., 2014)

At the initial stage of post-test validation, the same model as before the test was used, only with slight modifications accounting for SPA-T3 test conditions. It turned out that the GOTHIC model is not able to predict the vertical temperature distribution during the SPA-T3 test, instead complete water mixing was predicted during the visible long stratification development. Such results are not shown here, but the changes involved in model are shown. In the following stage, the results that were gained by using the improved model will be explained.

The total water mixing predicted in the modelling was caused by an excessive momentum, inducing a significant water circulation in the stratification period, resulted in equal temperature. Effective momentum, appeared due to condensation, has a huge influence on thermal stratification. It has to be determined precisely in order to get a proper agreement in the vertical temperature profiles and time scale of mixing.

The sharp thermocline had appeared during SPA-T3 test in water layers that are close to the bottom but unfortunately, this temperature gradient was not able to be captured by vertical cell, which is 100 mm in size and it used in GOTHIC. With the aim to make GOTHIC predictions more uniform, the decision was made to decrease cell size to 40 mm.

During the continuing model overviewing, a study was conducted in order to define sensitivity to the coefficient of the surface wave damping. In preliminary calculations, this value was set to a limit of 100 to facilitate the limitation of time step for modelling. However, post-test calculations showed that this approach is inaccurate, because the movement of water near the surface of the pool was excessively limited. Then it was decided to decrease value and, it turned out that post-test calculations should have been conducted for the wave dumping surface factor of 10. It can help to get more precise results and still maintain reasonable time step. It was now possible to better reproduce the process of thermal stratification. When the jet hits surface of the pool, surface waves are formed, and the energy of the jet is dissipated. In addition, it was assumed that this value allows to improve the grid at the top. This provided the previous release of a large unphysical temperature drop that occurred when liquid level exceeded the cell. A higher grid resolution at the top allowed to monitor the surface temperature of the pool (Łukasz Filich, 2015).

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6 SPARGER EXPERIMENT MODELING WITH TRACE

6.1 TRACE code overview

Nowadays modeling of processes by software is a very important part of design, development, operation and training at NPPs. The safety and other systems of nuclear reactor operate at a high level of complexity whereby human reasoning and elementary theoretical models are not able to convey a complete understanding of a system's responsiveness to certain perturbation, and it's obvious, that human needs to understand that. During the last thirty years a concerted effort was made on behalf of power engineering companies and other related organizations.

For example, NRC has designed a modern computational tool for modeling some processes in nuclear reactor and containment during normal operation of nuclear power plant or in transients. This tool is used for application of thermal-hydraulic codes for analyzing such scenarios like loss of coolant accident and other accidents that could happen with light water reactors. The NRC together with other nuclear communities has agreed to have a collaboration in technical achievements on thermal-hydraulic safety systems of nuclear reactor and a power plant in whole. According to this collaboration, the NRC supplies other communities with upgraded versions of thermal-hydraulic codes in order to help with evaluation of processes' safety at operating nuclear power plants or new-build projects. To ensure the high quality of tools for analyzing as well as it's confidence, the international partners develop the codes assessments for different applications, improvements and errors fixing. (Bahman Zohuri et al., 2015)

TRACE code considers all the main flow regimes of a two-phase flow, the transition between them is carried out in accordance with a map of flow regimes. The flow regime map defines the realization areas of each mode on the surface, of two parameters characterizing the flow state, most often this is the void fraction and the mass flow rate of the two-phase flow.
It's concluded, that two approaches are used in the codes for describing processes in various elements of NPP equipment: 1) for the volumes in which there is no apparent direction of flow (for example, a vessel with several inputs and outputs), - zero-dimensional (0D), 2)

For the flow in pipelines and channels - one-dimensional (1D). The user of the code determines which thermal-hydraulic module should be used in a certain situation.
TRACE code contains models describing the behavior of non-condensable gases and a liquid absorber, as well as their effect on thermal and neutron physical processes (V.G.Asmolov et al., 2017)

The experiment SPA-T3 with a sparger in the PPOOLEX facility had been modeled by using TRACE thermal hydraulic codes. There were no attempts to model such experiments with the PPOOLEX facility in TRACE or APROS codes before.

Apros is multifunctional software for modelling and dynamic simulation of processes and different power plants. Apros can be used on an ordinary office computer. A dynamic simulation model allows to easily examine the plant and process behaviour. Apros can simulate fast transients and different states of the systems. It provides rigorous dynamic simulation models to support various engineering tasks. It can be used e.g. for safety analysis, process design, training or automation testing.

Apros includes:

- comprehensive plant model covering reactor island, turbine island, balance of plant, electrical and automation systems
- light water reactor types covered: BWR, PWR, VVER
- 1D- and 3D neutronics solvers, incl. two- group nodal kinetic model
- thermal hydraulic solvers incl. six-equation, and three-equation flow models
- complete process component libraries including containment, cooling towers, passive systems, and severe accident management systems
- complete automation model incl. PID controls, interlockings, sequence controls
- plant electrical systems and grid model
- fully graphical user interface for model configuration and simulation
- connectivity to third party software

The whole experiment SPA-T3 was modeled in Model editor, which is based on TRACE code Symbolic Nuclear Analysis Package, which is the result of work sponsored by an agency of the United State Government. The version of used software was 2.5.2. Also animated models were created.

The Model Editor is a graphical interface tool used for development of different models as well as modification, design the input for the analysis code. Also it's used for animating models, for example in current case there's a process of steam discharging in pressure suppression pool. It provides consistent interface for user.

The Configuration tool is used to set up the calculation environment. Job Status shows the propagation of calculation process.

There are some steps of using TRACE code in practice:

- Prepare the input model
- Parameter set, definition of boundary conditions
- Check the model components: if there's an error then it should be corrected, if no errors then submit job and calculate (steady state/transient options)
- If Calculation Completed correctly, then plot the results and analyze
- If not completed correctly, check the output listing for error messages

As a general rule, computational codes like TRACE are really only applicable within their assessment range. TRACE has been qualified to analyse the ESBWR design as well as conventional PWR and BWR large and small break LOCAs (excluding B&W designs). At this point, assessment has not been officially performed for BWR stability analysis, or other operational transients.

TRACE uses a special approach, which is based on components for simulating structures of nuclear reactor. Every mechanical part of equipment in a reactor can be implemented as a certain type of component, and every component is able to be split into certain number of parts (cells) where the equations of fluid, conductivity and kinetics are averaged. There are no any limits for the component amount in the model as well as there are no constrains of connections between objects. Any of reactor components can be simulated in TRACE; the only thing which is setting up some limits is a computer memory. There are a lot of possible varieties of components, but two of them are needed to set up boundary conditions, which is very important in modelling of SPA-T3 test: FILL and BREAK. The boundary conditions are needed to provide calculations: steady-state and transient (U. S. Nuclear Regulatory Commission).

The TRACE is based on a completely non-equilibrium two-fluid model of a two-phase flow. This means that for a steam and for a liquid water separate equations are formulated for saving mass, momentum, and energy, in which exchange terms describing the interaction of the phases are present. In this case, steam and water have a different speed and temperature. Such a model is sometimes called a two-velocity two-temperature model of a two-phase flow. Basically, one-dimensional approximation is used to write the conservation equations. To describe the interphase interactions and interactions with walls (friction, heat transfer, and phase transitions), a system of closing relations is used.

6.2 Geometry of experiment and initial conditions

At the beginning of modeling there was a need to create a proper model of the test facility. So the geometry should had been correct. As it was impossible to insert the pool, which was used in the PPOOLEX experiment, the pipe component was used instead of it. And boundary conditions were introduced. The pool was split into 19 nodes: the water zone was split into 16 nodes and the gas zone into 3 nodes. Four nodes of the water zone were especially small (36 mm in height), because they correspond to sparger holes. All these geometries are shown in Figure 6.1. The aim of such splitting is to overview temperature in each node and get as precise data as possible, especially during stratification period.

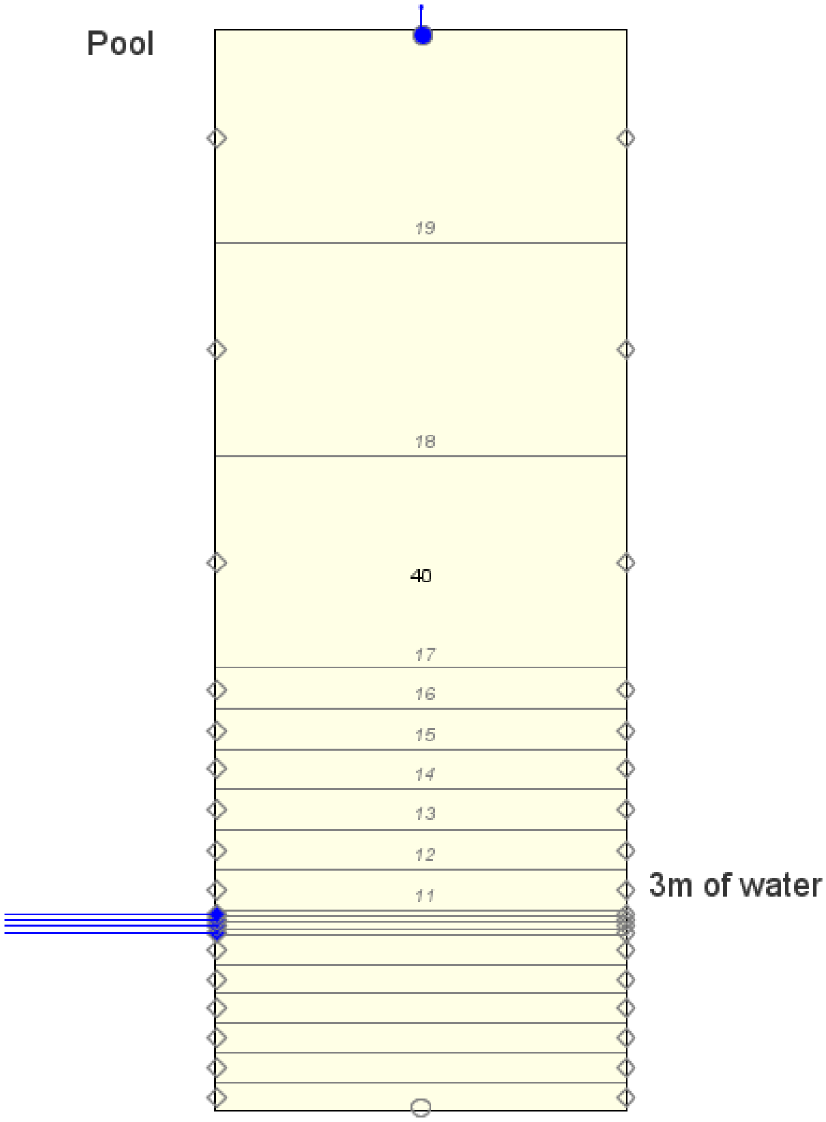

Figure 6.1 PPOOLEX pressure suppression pool in TRACE code model

The height and width of the pool were set up according to the real dimensions of the PPOOLEX facility: height is 7.45 m and diameter is 2.4 m. The walls thickness was not taken into account as it doesn’t effect a lot on the results of the experiment.

The sparger pipe was divided into several nodes as well, because in the test facility it is submerged into the pool, so some parts of the sparger were full of water at the beginning of experiment and other parts were full of air under atmospheric pressure. The pressure suppression pool had also several small nodes which are holes of the sparger head.

It was impossible to put the sparger pipe right inside the pool in this model, so it was decided to set up initial conditions as close to real as possible: water level inside the pipe and location of the sparger head holes were chosen according to the distance between the sparger head outlet and the bottom of the pool, so the submergence depth was 1.8 m, the same as in a real experiment. Sparger geometry was simplified as the point of interests is focused on the head and nozzles. This step is shown in Figure 6.2.

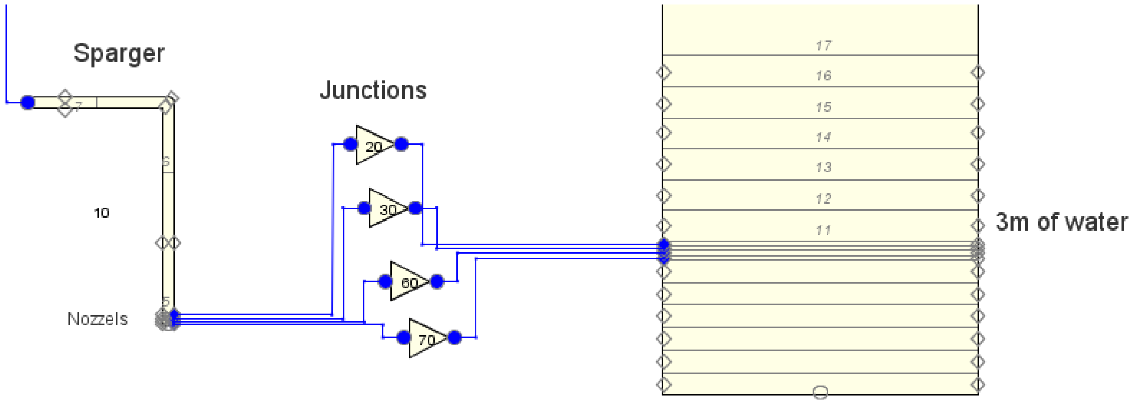

Figure 6.2 Sparger geometry and location

The link between the sparger and the pool was performed by multiple junctions. Each sparger node is connected to a corresponding node of the pool. By such way steam goes through the sparger holes to the pressure suppression pool. The thickness of pipe walls was not taken into account, because it doesn’t affect a lot on the experiment results. The diameter of the pipe was chosen according to the real sparger pipe: 76.1 mm. And the dimensions of the four sparger nodes were the same as the diameter of the holes: 8mm. The reason why there are only four nodes is that TRACE code allows to create one dimensional model, so as there were four rows of holes it’s possible to use only four nodes in pipe and the same amount in pool. The angle of junctions was 90 degrees.

The fill component was used to initiate a steam flow. in experiment SPA-T3. Pressure 0.6 MPa was constant during the whole experiment. The fill was connected right to the sparger pipe.

The valve, which is located on the top side of the pool allows to let the air move out at the beginning of experiment, then it was closed till the end. The break which is connected to the valve was needed to set up boundary condition and prevent any gas or liquid come to the pool. The current model is shown in figure 6.3.

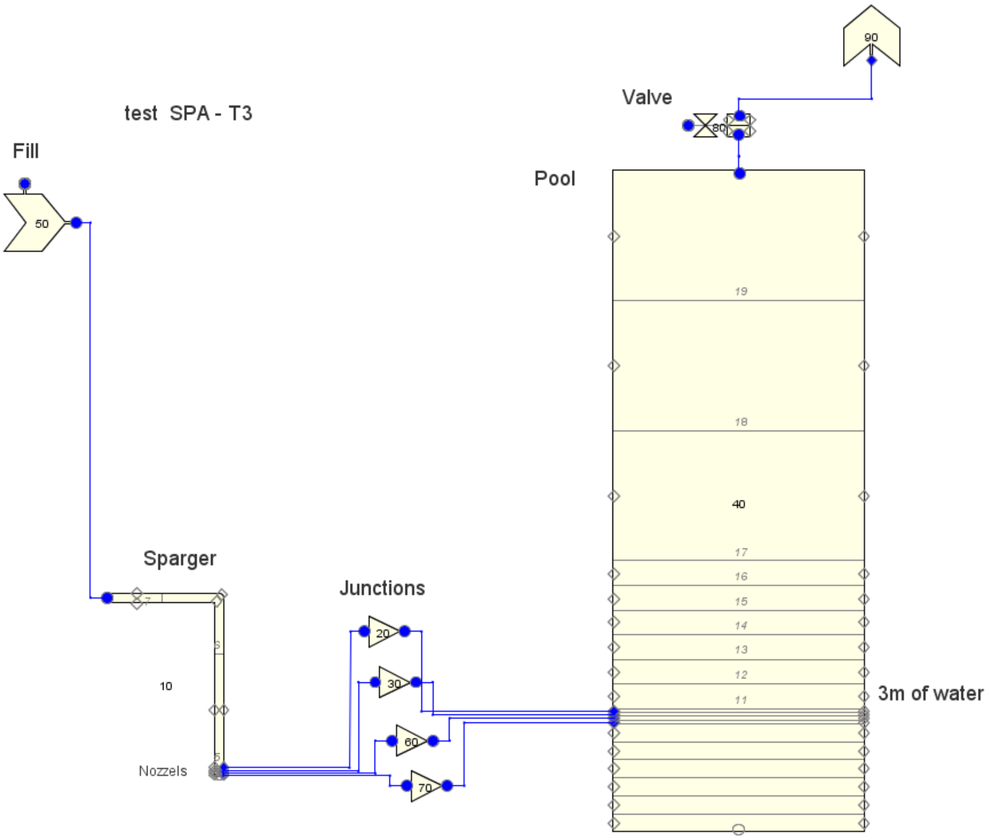

Figure 6.3 TRACE model of PPOOLEX test facility

Initial conditions of the SPA-T3 test were the following: pool water temperature was 20 °C, the whole test facility was under atmospheric pressure as the valve on the top of the pool was open. The water level in the pressure suppression pool was 3 m. The duration of the experiment was 11701 seconds.

6.3 Calculation results

After all the initial conditions were set up and the geometry was corrected, the job stream was started. Together with calculations the animated model was created in order to overview how the process is going.

The process of calculation encountered with several errors, which were related to time steps and abrupt area. So these errors were fixed by changing some parameters: calculation time steps were reduced and the mode of abrupt area allowance was activated, then calculation proceeded.

The pool water temperatures were point of interests, so different graphs of temperature changing with time were plotted. Each node of pool had its individual temperature distribution (Figure 6.4). The first four nodes, that were the closest to the bottom hadn't shown significant changing in water pool temperature. The difference between the initial and final temperature and final was about 1 K or even less, but only one node (number 5) indicated a more significant difference: about 4.5 K. This node was the closest to the outlet of the sparger head.

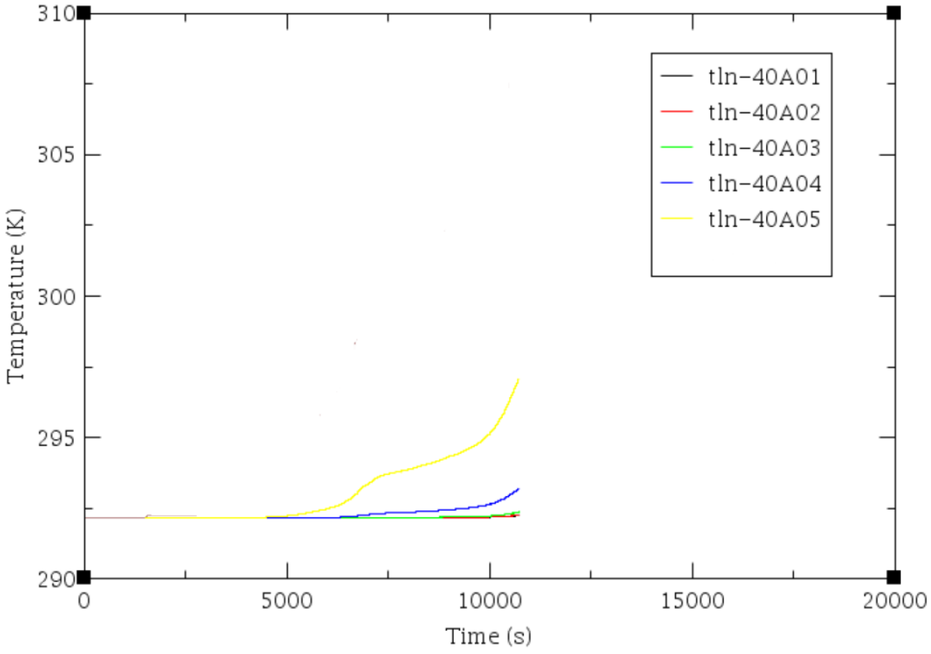

Figure 6.4 Temperature changing over time period of nodes number 1 – 5.

The next four nodes of the pool were located in the sparger head area, where the jets of steam are injected into water. The difference between the temperatures in the beginning of the experiment and in the end was much more significant, than in the previous nodes, that are closest to the pool bottom. This difference is about 48 K.

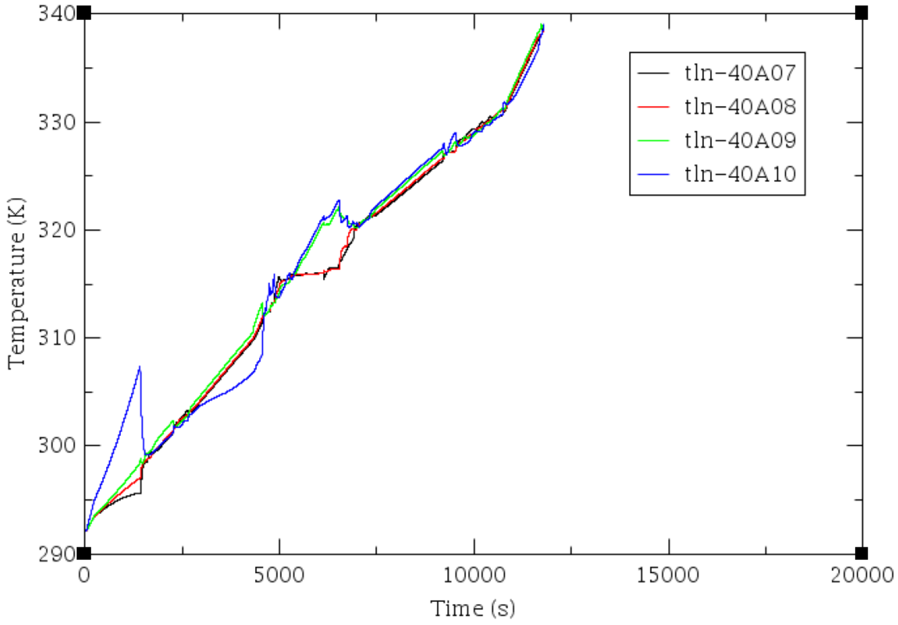

Figure 6.5 Temperature changing over time period of nodes number 7 – 10.

It can be seen from the figure above that temperatures were not constant, but increased quite fast. The Stratification I period was performed from 235 to 4303 seconds, so in a graph the water temperatures of these nodes were more differed from each other during certain time, but not during the whole period from 235 to 4303 seconds. The same situation was observed between 5005 – 10793 seconds, but not during all these seconds again. According to Figure 6.5, the end of stratification was approximately at 7500 second.

The experiment had two mixing periods. Despite the fact that steam flow rate was changed according to the real experiment conditions, the figure 6.5 had shown these periods are not so visible: only slight fluctuation of all temperatures in both cases.

It should be mentioned, that temperatures in the figure above are corresponded only for the four nodes of pool water at the sparger head area, because there are a lot of nodes and temperatures that would be messed up if they're in one figure. It means that other nodes should be overviewed by the same way as well.

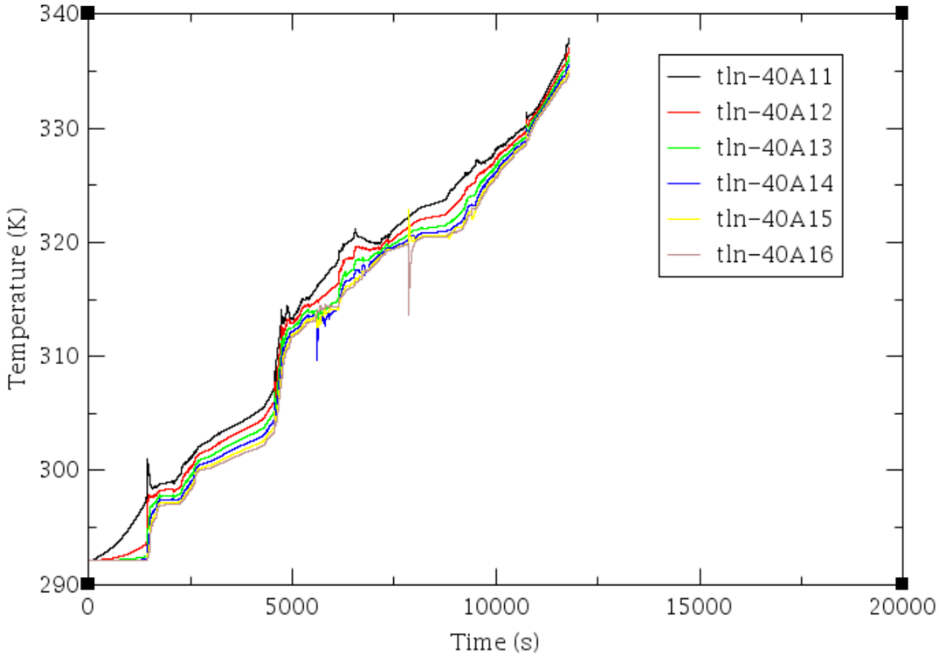

Figure 6.6 Temperature changing over time period of nodes number 11 – 16

In the graph above the stratification and mixing periods are more visible. Especially in the beginning of the test the temperatures are very different, that tells us about thermal stratification during those seconds. The temperatures of water are more different in seconds of Stratification II period, than in other seconds of the experiment, so again this fact approves the existence of stratification in TRACE model of test SPA-T3.

During the time of Mixing period I the pool water temperatures increased rapidly, which could be overviewed in figure 6.6, 4303–5005 seconds of the experiment. In the Mixing period II it's not so visible in the graph above.

There were three nodes for area above the water of pool, but the point of interests is pool water, not gas, so temperatures of these nodes are not overviewed here. Each of the element of the test facility was split for more nodes, than it's shown in the figures above, but it didn't bring significant changes, as well as splitting on several big nodes. The idea was to have equal size nodes in the sparger pipe and in the suppression pool, especially in the region of the sparger head, so it increases the preciseness of model. One of the main factor was to separate divide non-condensable area from water area, and it has been done by these nodes. As an attempt to get more precise results of calculation the surface area of water was splitted on more little nodes together with area of gas, but it didn’t bring any improvements. Finally, the decision to leave normal size nodes was made.

7 COMPARISON OF TRACE MODELING AND REAL EXPERIMENT RESULTS

7.1 Introduction

As one of the main aims of the current master thesis is to model the sparger experiments using TRACE code, with focus on exploring if the observed condensation oscillations in the sparger can be reproduced, then the results should be compared. In other words, we need to validate the model. It’s obvious that results are different, but the question is how big is this difference. Whether TRACE code is enough to model such kind of experiments with a sparger and pressure suppression pool or not.

The processes that are happening in suppression pool during steam injection and its further condensation are not simple, because multi-dimensional flows take place in the pool, and TRACE is a strictly 1D code. These are the reasons of doubts in proper results of modelling by TRACE code. The initial parameters and geometry were chosen according to the real test conditions. So the beginning of the experiment in both cases is the same, but the end is different.

Further comparison will be focused on the temperatures of suppression pool water, because this is the best way to compare results, as pressure was almost constant in both cases and steam mass flow rate was changed manually, it doesn’t depend on any parameters. The geometry was not changed and the pool’s wall thickness was not taken into account as well as the full length of sparger pipe and its walls thickness.

7.2 Temperature changing comparison

In the figures below there are several graphs of pool water vertical temperature changing for Stratification I period and for the entire period. Each figure has TRACE calculated temperature curves and the real experiment temperature curves.

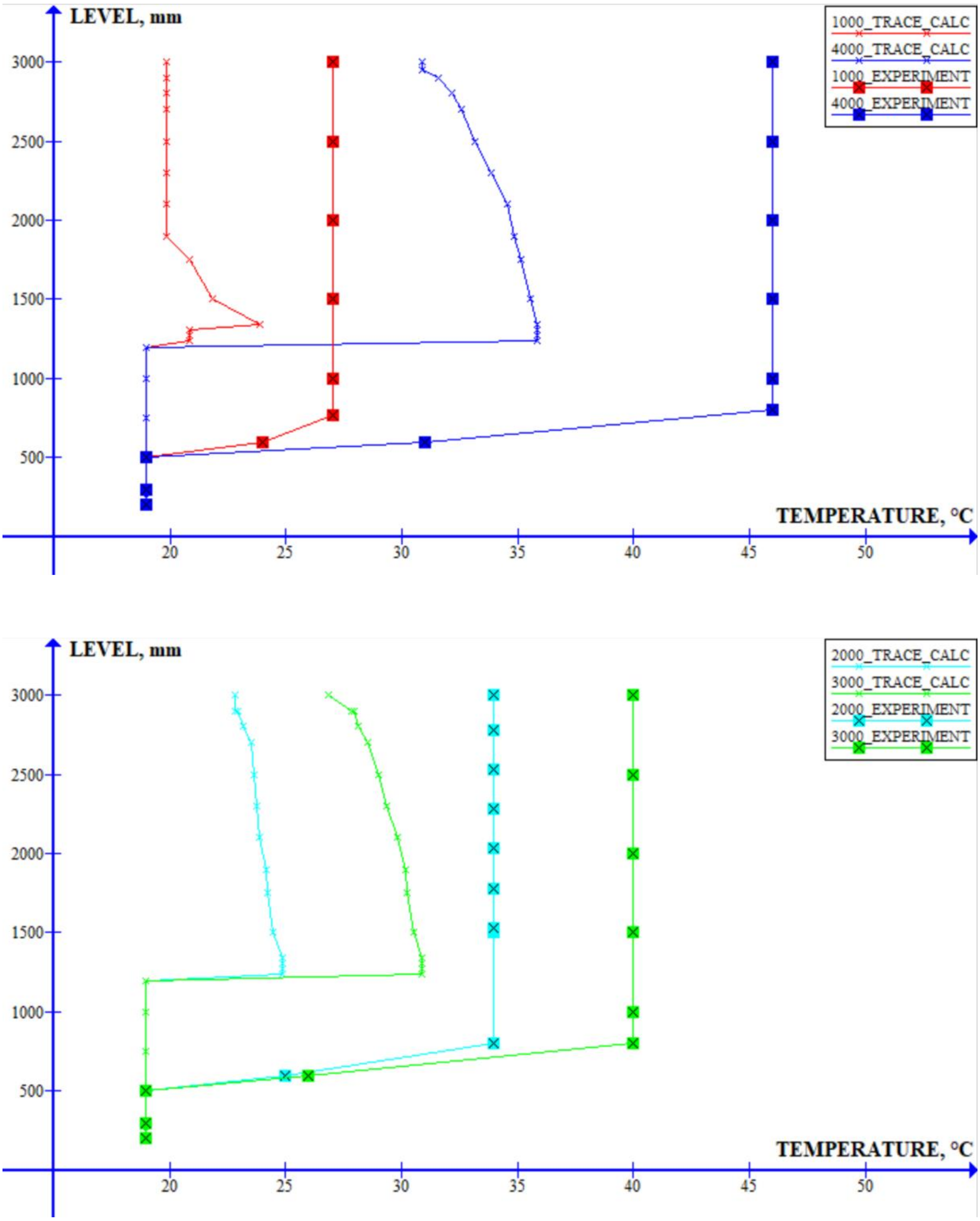

Figure 7.1 Temperature increasing comparison between TRACE calculated results and real test results (Stratification I period)

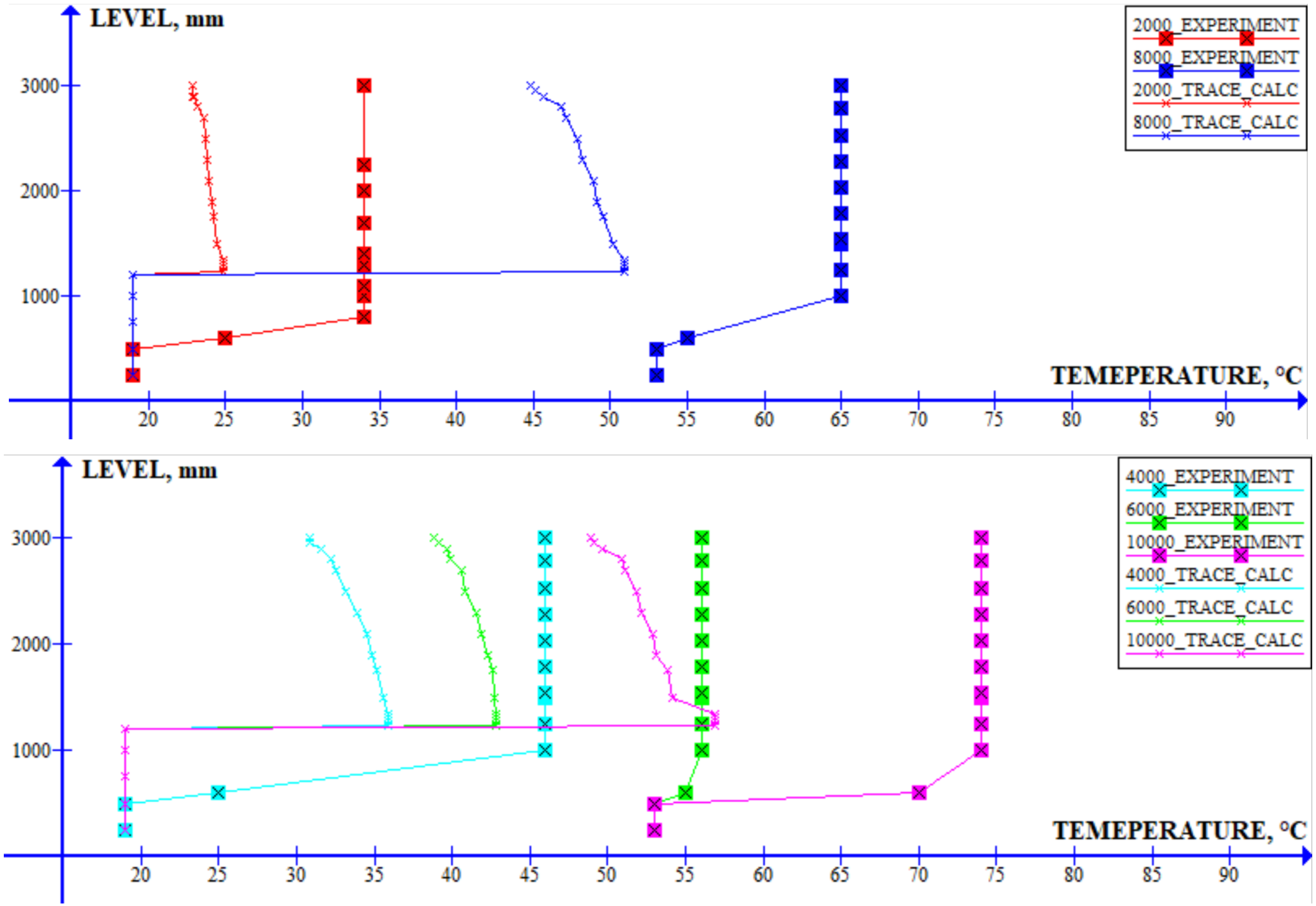

Figure 7.2 Temperature increasing comparison between TRACE calculated results and real test results (The entire experiment)

It can be seen from the figure above, that results of the real experiment and results of the TRACE modelling are different. For more detailed and clearer comparison of the results several time points were overviewed: 1000, 2000, 3000, 4000, 6000, 8000 and 10000 seconds. The pictures show the water temperature changing with time. The plots are different by temperature profiles, the curves of TRACE calculations are not so straight. The curves of temperatures, calculated with TRACE code show decreasing temperatures when the measured temperatures are constant. Perhaps the reason of such difference is that TRACE code does not fully take into account the water mixing during the experiment or there can be an overestimation of heat losses in the TRACE simulation and as a result the top layers of the pool cool down too much in the calculation compared to the experiment. Both the measured results and the calculated by TRACE results have abrupt changes in temperature. In TRACE calculated results this changing is observed at 1200 mm elevation and in measured data it’s observed at 500 mm elevation; the reason of that could be again not fully mixing of the water layers. These temperature peaks related to the holes of sparger head where the steam is discharged and this steam has the highest temperature in the pressure suppression pool. Although the scope of the abrupt temperature increasing is different. The possible reason might be the stratification process, which can’t be same in both calculations and measurements, because the TRACE software is based on 1D code. In other words the 1-dimentional nature of the TRACE code seems to prevent heat-up of the water layers below the sparger head elevation that is seen in the experiment during the stratification period.

The final average water temperature, that was measured in real test is about 83 °C, but according to TRACE calculations it’s only about 64 °C (Figure 7.3), despite the fact that initial conditions and time range were equal. The steam mass flow rate change was equal as well.

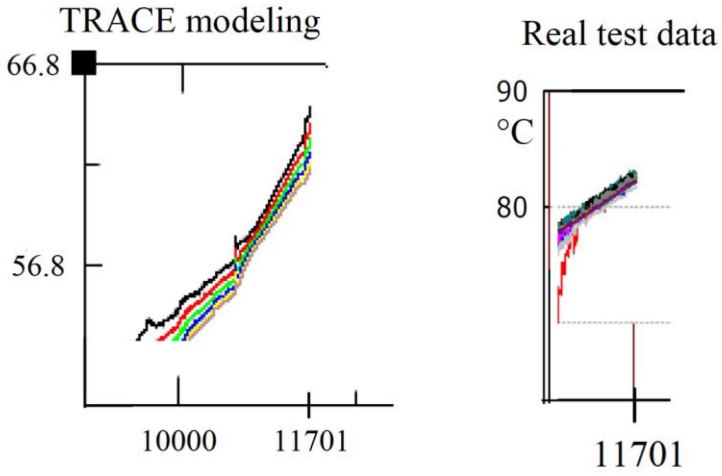

Figure 7.3 Comparison of final temperatures

It’s assumed that TRACE conserves energy. The fact that measured temperature in the middle of the pool was higher than calculated assumes that the pool heating was nonuniform also radially, i.e. that there was radial temperature profile in the pool and colder water somewhere closer to pool periphery.

All the graphs have the thermal stratification and mixing periods, that are visible by temperature differences in case of stratification and fast increasing in case of pool water mixing by steam flow rate changing. Actually, such difference and rapid increasing are not equal among all graphs.

What about water temperatures at the bottom of the pressure suppression pool? In both real and modeled experiment they were changed insignificantly. This can be seen from figure 6.4 and real test description.

The temperature fluctuation in the real test was much more frequent than in the modelled version, but in GOTHIC simulation it was not so frequent as well, which can be observed in the figure below.

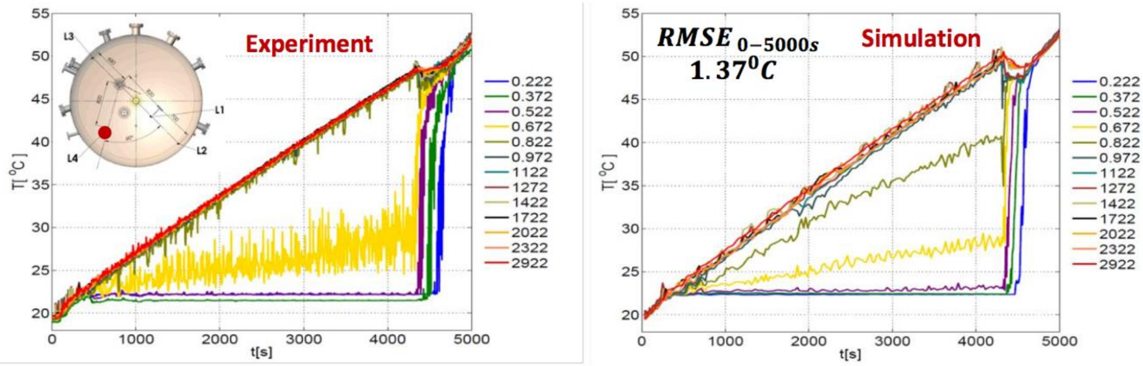

Figure 7.4 Comparison of experimental data with EHS/EMS results - L4 train of TCs (Ignacio Gallego-Marcos et al.)

It could be noticed that the graph with temperatures of the GOTHIC simulation is much more closer to the temperature graph of the real experiment, than the same one of modelled in TRACE. With the aim to make it more similar, the model created by TRACE code Symbolic Nuclear Analysis Package was checked again for errors, but there were no mistakes and initial conditions were as close to reality as possible. In such situation decision was made: instead of one pressure suppression pool, two pools were created that have half of the original pool volume. As the dimension is only 1-D, this decision could give more precise results, than a case with one big pool.

After creating a second pool, changing some dimensions and adding junctions the job was submitted in order to get new results.

7.3 Comparison with a second version of TRACE simulation

The same initial conditions as in the previous version of TRACE model were used in the second version with two pools. This new model is shown in the figure below.

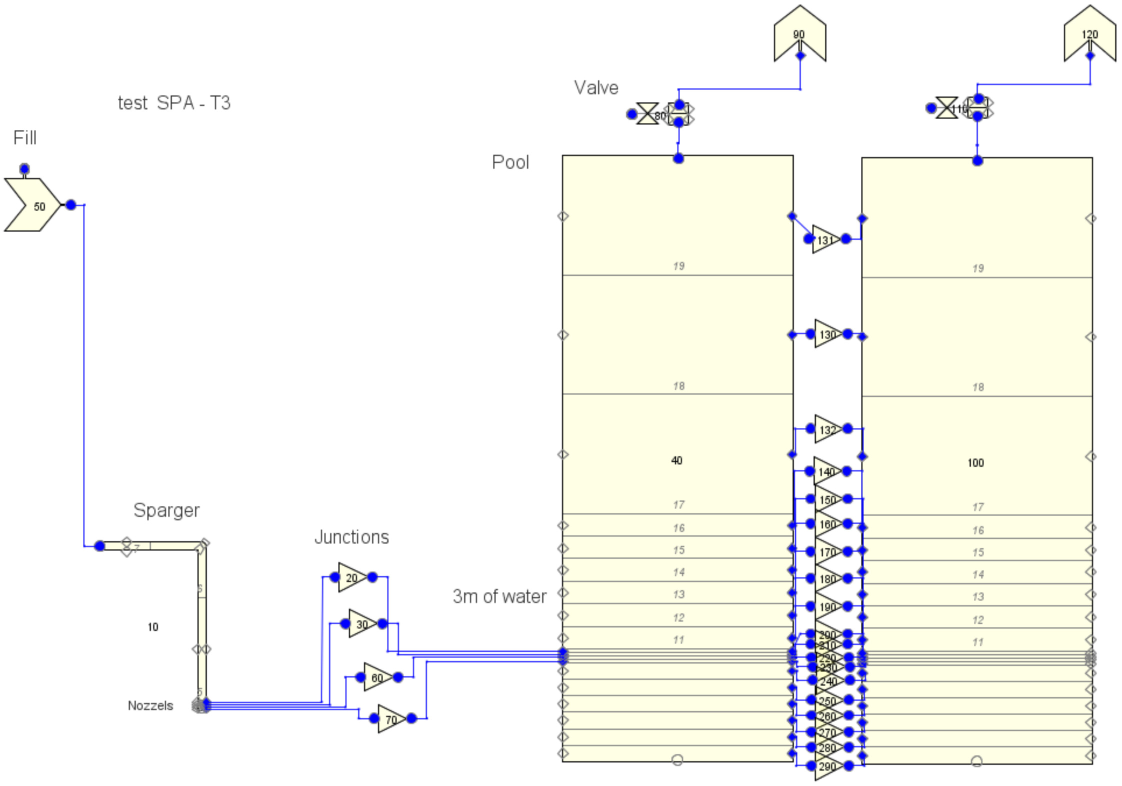

Figure 7.5 Model of PPOOLEX experiment with sparger. Version with two pools

The calculation results for both pools were almost equal, so only one of the pool parameters will be presented further. As it can be seen in the figure 7.5, these two pools are connected to each other by multiple junctions, so all nodes have connection. This procedure was made in order to increase the precision of modelling. The same decision was made in some other thermal hydraulic models, where something is injected inside the vessel with a liquid or air.

This version of modelling had the same periods as the previous version and the real experiment: Stratification I, Mixing I, Stratification II and Mixing II. The results of calculation by Job submitting are shown further and compared with real test measurements.

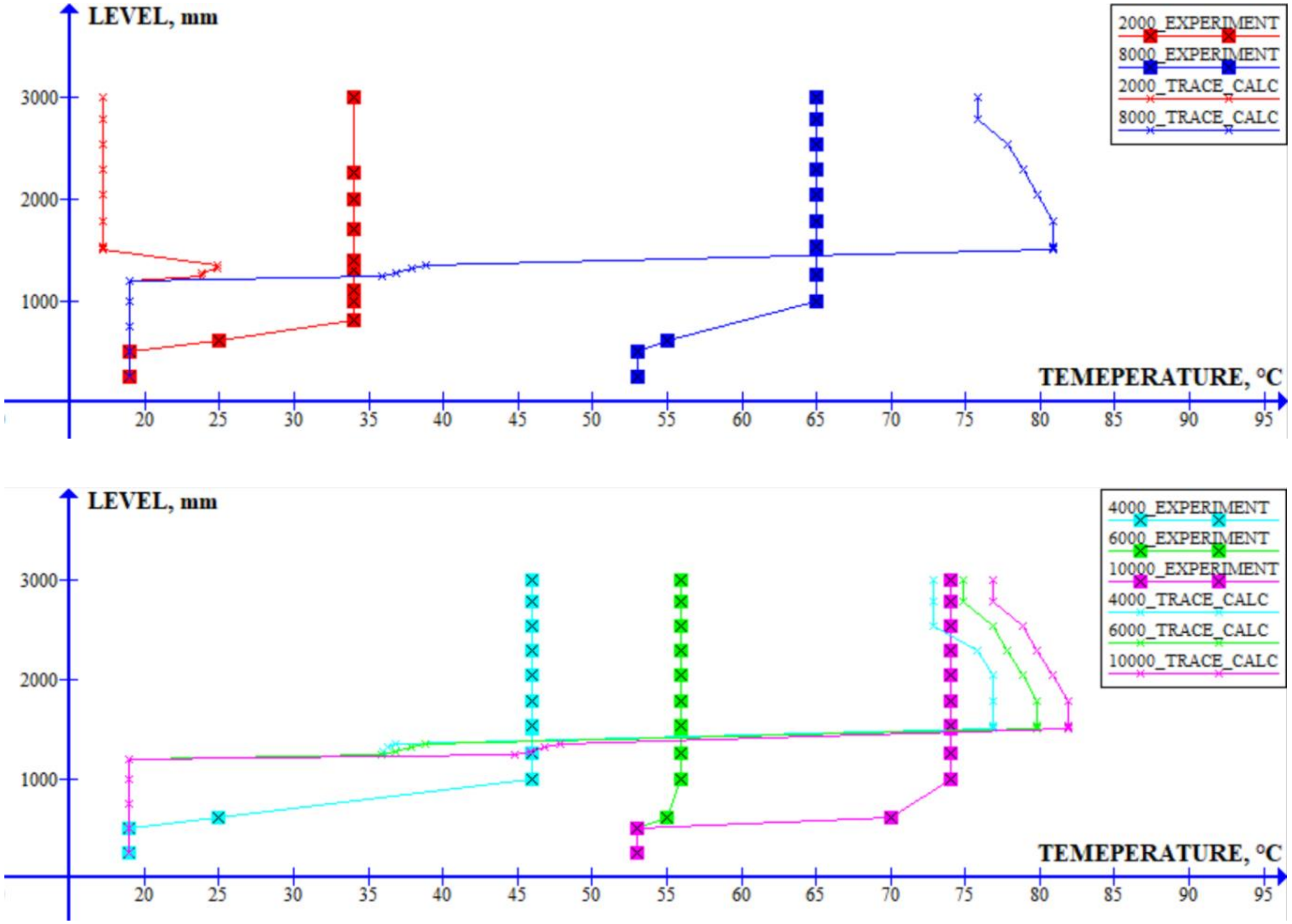

Figure 7.6 Temperatures increasing comparison between TRACE calculations (two pipes) and real test result

The stratification and mixing in TRACE calculations still can be observed by comparison of graphs in figure 7.6 , but not as visible as in previous cases. At the version with two pipes the temperatures increase too fast to more than 75 °C at 4000 s and in other time points even more.

So, according to these facts the conclusion is following: separation of one big pool into two small pools doesn’t give a positive effect in a way to create more precise model.

7.4 Animation model

The animation model was created in order to achieve better understanding of the processes in suppression pool. The model editor allows to use two instruments together: Job Stream and Animation. By connecting all parameters and data the full experiment was modeled with animation. Animation models (or "masks") can be described as Views, that have some visual elements with individual properties, and these properties or parameters may be changed in the Main Property View. Such animation model displays current data from a Calculation Server and shows it visually in some fashion, understandable for everyone. Mentioned data can be received from currently running calculations, or for example finished calculations, imported from some sources EXTData, etc.

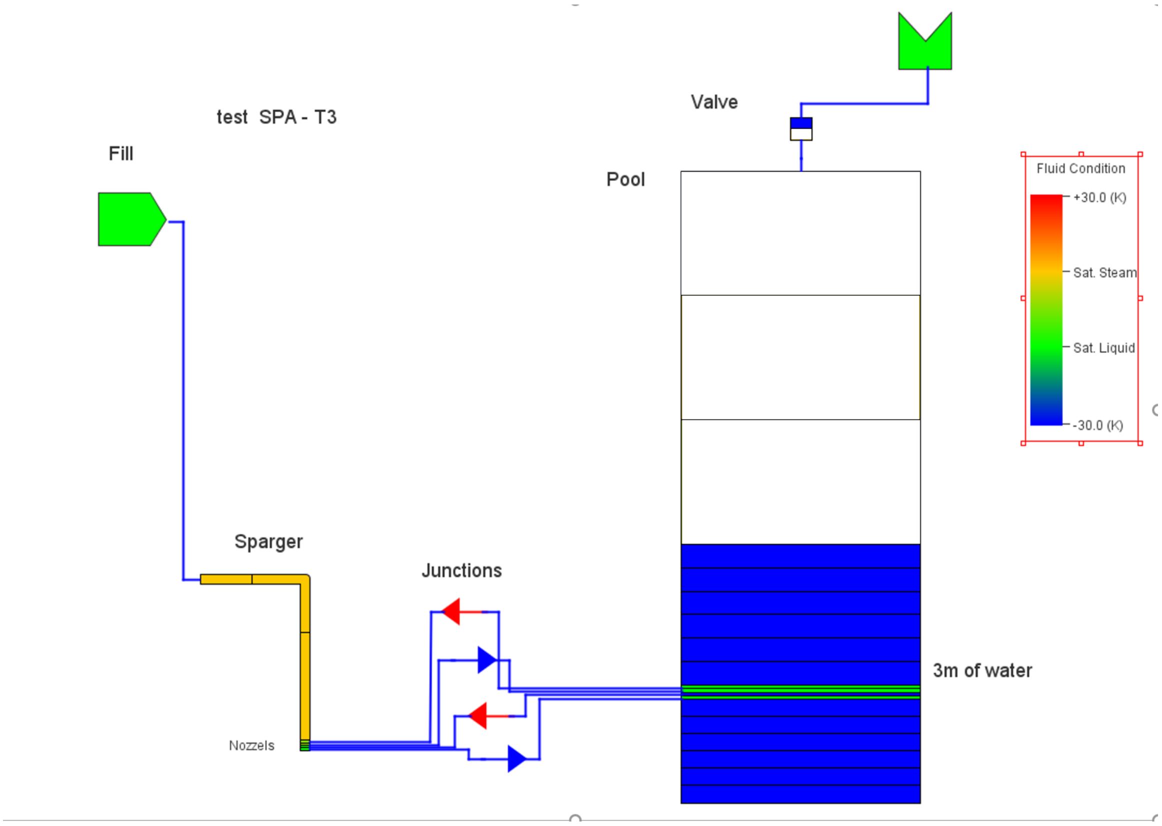

Figure 7.7 Animation model of sparger test with one pool

Obviously it is not possible to show animation here, only static picture, which is shown in figure 7.7. There are different colours in this model, each of them is certain liquid or steam condition.

A Color Map can be changed by user, who defines a colour range and certain values used for showing current animation. In the process of animation usual changes of a display bean is to switch color dependent on the current parameter or value of its suitable data channel. Each color corresponds to certain temperature level and a liquid condition as well. For example, a deep blue color means just a water, not saturated. A green color means saturated liquid. And yellow – saturated steam. During animating these colors are changing with frequency, defined by user.

The figure below has animation model of the SPA-T3 test with an attempt to receive more precise results by dividing one big suppression pool into two.

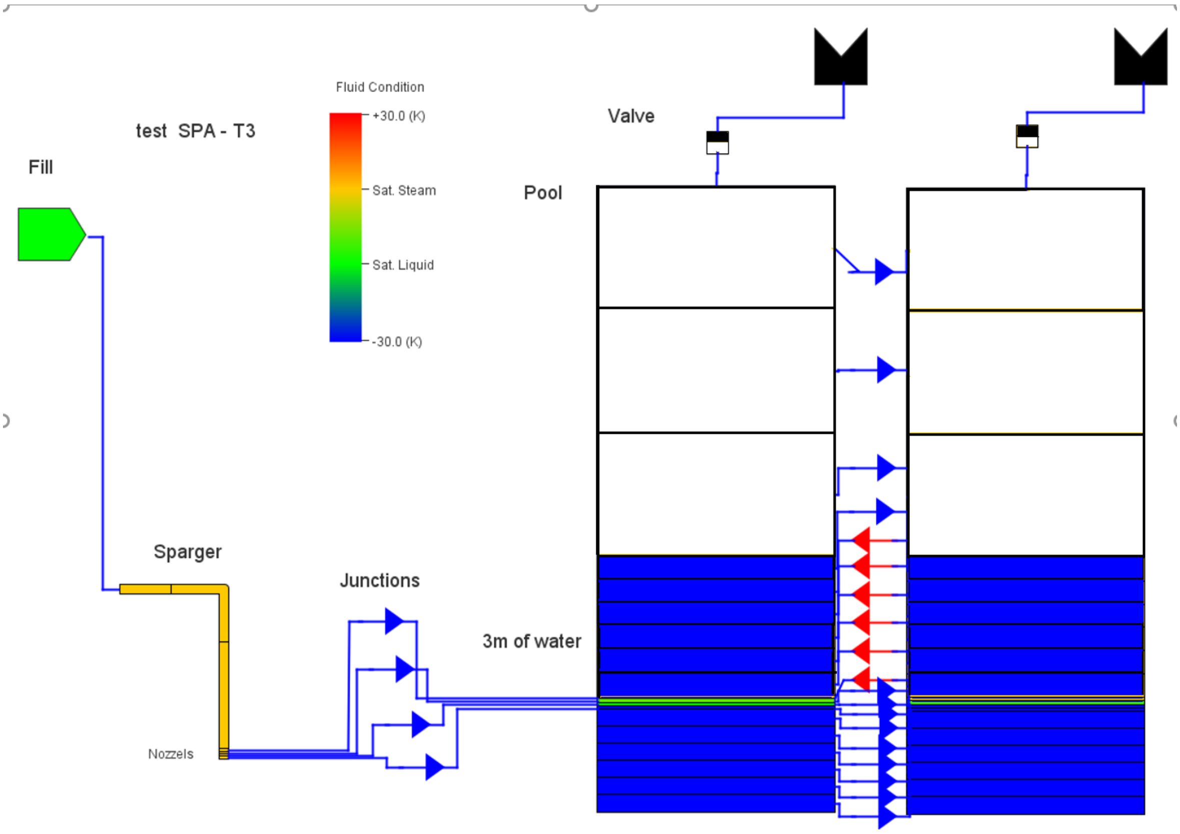

Figure 7.8 Animation model of sparger test with divided pool

It can be seen from both of pictures that the fluid condition of the modelled process corresponds to real test's fluid condition. The sparger pipe has saturated steam inside (yellow color), which is then injected to the water of suppression pool (blue color).

In process of modelling it was assumed that during the whole experiment there's a non-condensable gas above the water of pool. In the beginning of real tests the volume above pool water is filled with non-condensable gas (air). During the tests this gas space heats up due to heat conduction/convection from the pool water and also as a result of compression due to slight pressure increase because the test system is closed. The pool water temperature can be even close to 100 °C on the surface at the end of the longest tests and it therefore heats up the gas space quite effectively. It is possible that some steam injected from the sparger pipe can escape through the water volume without condensing during the final moments of tests when the temperature difference between the steam and pool water was not so large any more. However, it is not known for sure.

8 DISCUSSIONS AND CONCLUSIONS

The final model of the experiment with a sparger and pressure suppression pool has some differences with the real experiment. It can’t be said that the simulated facility is not the same as the real one, but as close to it as possible. The list of consistent results is next:

- Visible stratification in the temperatures changing graph
- Visible mixing in some cases
- Rapid temperature increasing during mixing periods
- Fluid condition

There are some differences:

- The final temperatures are different: in the real SPA-T3 test it was about 83 °C and in the modeled version it was about 63 °C.
- The visibility of stratification and mixing periods do not correspond to each other. In some moments of time when it’s assumed to have stratified temperatures, the model doesn’t have such phenomena, but start to have a little later.

The possible reasons for the differences, that are described above are the following:

- The entire process of modelling had been implemented in 1D, but the process of steam injection and condensation leads to 3D flow patters in the pool.
- The TRACE code is not suitable for simulating those cases in which transfer of momentum has an important role at a localized level. TRACE makes no attempt to capture, in detail, the fluid dynamics in a pipe branch or plenum, or flows in which the radial velocity profile across the pipe is not flat.
- The typical system model cannot be applied directly to those transients in which one expects to observe thermal stratification of the liquid phase in the 1D components. (U. S. Nuclear Regulatory Commission)
- TRACE does not model all cases of momentum exchange involving side junctions. The terms currently in the code were driven by considerations of flow patterns in reactor safety problems, and should not be expected to perform well in all possible flow path topologies. Results presented in the previous section reflect the importance of correct momentum transfer within a jet pump model or in situations where ECCS liquid is being injected into a steam flow through a reactor coolant pipe. (U. S.

Nuclear Regulatory Commission)

There are some recommendations on sparger modelling with system codes: for more precise modelling 3D codes should be used. Also APROS could be used to try to model experiments with sparger in pressure suppression pool under PPOOLEX facility. Another possible software – CFD.

Accurate modeling of phenomenon such as direct contact condensation in a pool with large volume requires at least 2D or even 3D approach.

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