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Effective Momentum and Heat Flux Models for Simulation of Stratification and Mixing in a Large Pool of Water

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Abstract

Performance of a boiling water reactor (BWR) containment is mostly determined by reliable operation of pressure suppression pool which serves as a heat sink to cool and condense steam released from the core vessel. Thermal stratification in the pool can significantly impede the pool's pressure suppression capacity. A source of momentum is required in order to break stratification and mix the pool. It is important to have reliable prediction of transient development of stratification and mixing in the pool in different regimes of steam injection. Previously, we have proposed to model the effect of steam injection on the mixing and stratification with the Effective Heat Source (EHS) and the Effective Momentum Source (EMS) models. The EHS model is used to provide thermal effect of steam injection on the pool, preserving heat and mass balance. The EMS model is used to simulate momentum induced by steam injection in different flow regimes. The EMS model is based on the combination of (i) synthetic jet theory, which predicts effective momentum if amplitude and frequency of flow oscillations in the pipe are given, and (ii) model proposed by Aya and Nariai for prediction of the amplitude and frequency of oscillations at a given pool temperature and steam mass flux. The complete EHS/EMS models only require the steam mass flux, initial pool bulk temperature, and design-specific parameters, to predict thermal stratification and mixing in a pressure suppression pool. In this work we use EHS/EMS models implemented in containment thermal hydraulic code GOTHIC. The POOLEX/PPOOLEX experiments (Lappeenranta University of Technology, Finland) are utilized, to (a) quantify errors due to GOTHIC's physical models and numerical schemes, (b) propose necessary improvements in GOTHIC sub-grid scale modeling, and (c) validate our proposed models. Specifically the data from POOLEX STB-21 and PPOOLEX STR-03 and STR-04 tests are used for validation of the EHS and EMS models in this work. We show that the uncertainty in model prediction is comparable with the uncertainty in the experiments. The capability of the EHS/EMS model to predict thermal stratification and mixing in a plant scale pressure suppression pool is demonstrated. Finally, a new series of PPOOLEX experimental tests is proposed to reduce experimental uncertainty and to validate more accurately the sub-models used in the EMS model.

Key words

BWR pressure suppression pool, thermal stratification, mixing, effective models, GOTHIC

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Research report

Effective Momentum and Heat Flux Models for Simulation of Stratification and Mixing in a Large Pool of Water

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2012

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Executive Summary

Performance of a boiling water reactor (BWR) containment is mostly determined by reliable operation of pressure suppression pool which serves as a heat sink to cool and condense steam released from the core vessel. Thermal stratification in the pool can significantly impede the pool's pressure suppression capacity. A source of momentum is required in order to break stratification and mix the pool. It is important to have reliable prediction of transient development of stratification and mixing in the pool in different regimes of steam injection. Previously, we have proposed to model the effect of steam injection on the mixing and stratification with the Effective Heat Source (EHS) and the Effective Momentum Source (EMS) models. The EHS model is used to provide thermal effect of steam injection on the pool, preserving heat and mass balance. The EMS model is used to simulate momentum induced by steam injection in different flow regimes. The EMS model is based on the combination of (i) synthetic jet theory, which predicts effective momentum if amplitude and frequency of flow oscillations in the pipe are given, and (ii) model proposed by Aya and Nariai for prediction of the amplitude and frequency of oscillations at a given pool temperature and steam mass flux. The complete EHS/EMS models only require the steam mass flux, initial pool bulk temperature, and design-specific parameters, to predict thermal stratification and mixing in a pressure suppression pool. In this work we use EHS/EMS models implemented in containment thermal hydraulic code GOTHIC. The POOLEX/PPOOLEX experiments (Lappeenranta University of Technology, Finland) are utilized, to (a) quantify errors due to GOTHIC's physical models and numerical schemes, (b) propose necessary improvements in GOTHIC sub-grid scale modeling, and (c) validate our proposed models. Specifically the data from POOLEX STB-21 and PPOOLEX STR-03 and STR-04 tests are used for validation of the EHS and EMS models in this work. We show that the uncertainty in model prediction is comparable with the uncertainty in the experiments. The capability of the EHS/EMS model to predict thermal stratification and mixing in a plant scale pressure suppression pool is demonstrated. Finally, a new series of PPOOLEX experimental tests is proposed to reduce experimental uncertainty and to validate more accurately the sub-models used in the EMS model.

1 INTRODUCTION AND BACKGROUND

1.1 Motivation

The pressure suppression pool (PSP) is central for safety of Boling Water Reactors (BWRs). It was designed to serve as a heat sink to prevent containment pressure buildup by cooling and condensing the steam released from the reactor vessel during loss of coolant accident (LOCA) or in normal operation of pressure relief valves. Steam released from the reactor vessel is vented into the PSP through the blowdown pipes and/or spargers.

If the steam injection flow rate is small, it provides mainly a source of heat which causes development of thermal stratification in the pool above the steam injection point. Consequently, the stratification significantly impedes the pool's pressure suppression capacity. In a post-accident long-term cooling process, partial steam pressure in the wetwell gas space is defined by the pool surface temperature which increases as thermal stratification starts to develop. An increase of the pool surface temperature due to stratification can lead to a significant increase in containment pressure [1]. If water in the layer above the pipe outlet reaches saturation temperature, the injected steam cannot condense in this layer. The pool is also a source of water for the emergency core cooling system (ECCS). If local temperature at the location of the ECCS strainers increases due to stratification, then net positive suction head (NPSH) might be insufficient to avoid cavitation in the ECCS pumps.

If a source momentum is introduced into the pool it can erode stratified layer by mixing of the pool. The source of momentum can be provided e.g. by higher steam flow rate, or due to periodic oscillations in the blowdown pipes caused by unstable direct contact condensation, or by return nozzles of the pool cooling system.

Different thermal hydraulic codes have been developed in the past for containment analysis using different levels of resolution (from lumped models to 3D CFD analysis). Yet, an accurate and computationally efficient prediction of the transient pool thermal-hydraulics, affected by thermal stratification and mixing, presents a computational challenge. Main difficulties are: (i) large span of the length and time scales for the important phenomena which govern pool behavior; (ii) lack of adequate simulation methods for resolving direct contact condensation upon steam injection into a subcooled pool, (iii) limited experimental data for code development and validation.

1.2 Goals

The main objective of our work is to develop and validate accurate and computationally efficient models to simulate transient phenomena of thermal stratification and mixing caused by steam injection.

Specific tasks for the present work are:

(i) to examine the state-of-the-art understanding of multiphase flow phenomena that govern pressure suppression pool dynamics;
(ii) to assess capability of existing tools (codes and models) in predicting key behaviors and parameters of suppression pools;
(iii) to develop new effective models for prediction of stratification and mixing in a pressure suppression pool;
(iv) to validate the new models against available experimental data including tests in the POOLEX and PPOOLEX facilities;
(v) to address with simulations plant scale phenomena related to mixing and stratification;
(vi) to provide an evaluation of, and analytical support for, the related experimental program conducted at Lappeenranta University of Technology (LUT) on condensation pools, namely POOLEX and PPOOLEX experiments.

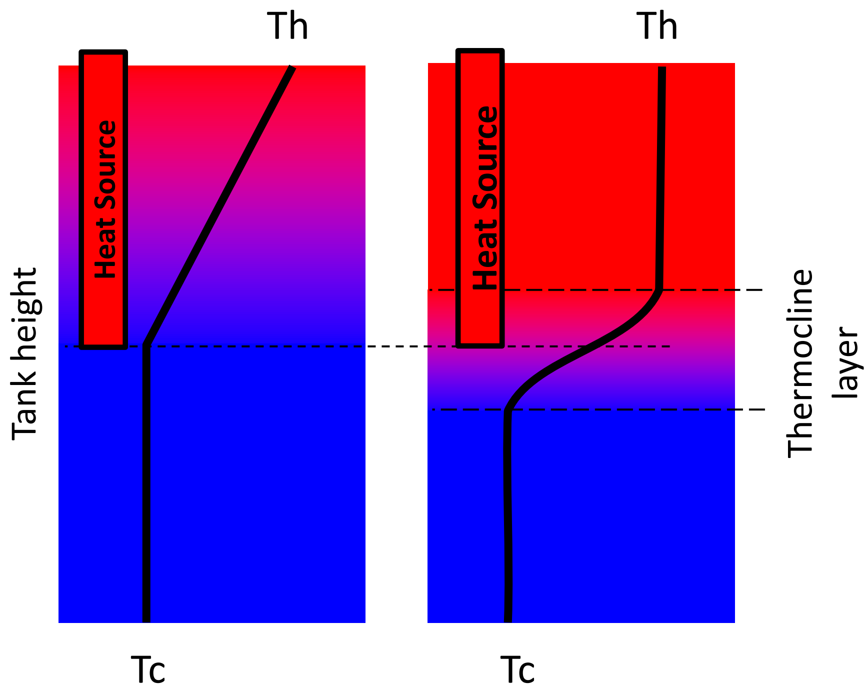
As a specific task, the work aims to validate the GOTHIC code for prediction of thermal stratification and mixing in a pressure suppression pool. In the present work we focus on validation of GOTHIC against data provided in POOLEX test STB-21 [2]. Model validation against PPOOLEX experimental data STR-03 and STR-04 are also included in the report.

The goal of the validation activity is to clarify the deficiencies in the present code simulation models for prediction of safety important phenomena:
(a) development of thermal stratification at low mass flow rate of steam, and
(b) time scale for mixing of a stratified pool.

1.3 Overview of Stratification and Mixing in Water Pools: Phenomena and Simulation Approaches

Thermal stratification in a large water pool is a well-known physical phenomenon which is responsible for the formation of horizontal liquid layers with different densities. Thermal stratification is an important factor in the environmental and biological sciences (e.g., stratification in lakes and oceans) and is also widely applied in various kinds of sensible heat storage systems [3].

Configuration of the stratified layers generally depends on location of the heat source and history of transient heat transfer in the pool (heating and cooling phases). In the present work we consider scenarios of thermal stratification development caused by a heat source immersed into the pool at a certain depth. Such configuration is motivated by the focus of the present work on BWR pressure suppression pool operation. Two typical transient stratification configurations presented in Figure 1 are considered. Specifically we are interested in (i) the rate of thermal stratification development with a continuous increase of water temperature in the layer of the pool above the bottom of the heat source and a constant temperature of cold water *Tc* below the heat source (Figure 1a), and in (ii) formation of the top isothermal layer at temperature *Th* separated from the bottom layer of cold water by relatively thin thermocline layer, where temperature is changing rapidly from *Tc* to *Th* (Figure 1b).



a) b)

Figure 1: Typical configurations of thermal stratification in a tank:
a) developing stratification; b) thermocline layer.
Note: Th – temperature of hot liquid; Tc – temperature of cold liquid.

A breakdown of thermal stratification in the pool can be achieved by mixing. Mixing of a stratified pool takes some time which generally depends on the momentum injected in the pool. The time which is necessary to achieve mixing determines how fast suppression pool capacity can be restored. Therefore, the characteristic time scale of mixing is considered as an important parameter of the pool's operation. Condensation of steam in the subcooled pool also plays an important role in determining the resultant momentum of the steam jet and thus affects dynamics and characteristic time scales of mixing and thermal stratification development.

Thus, there is a need for reliable and computationally efficient methods that can predict mixing and stratification phenomena. These methods are necessary for safety analysis of the pressure suppression pool operations.

State of the art in suppression pool stratification and mixing research can be summarized as follows:

(i) Numerous experimental studies were performed in the past on stratification and mixing in a pool, but only few are full or large scale tests. Westinghouse methodology for addressing pool stratification is based on a series of blowdown tests performed in the Nordic BWR suppression pools. However, not all experimental data is available and suitable for validation of codes and models.

(ii) POOLEX/PPOOLEX [2, 4] is a relatively large scale experiment which provides the most complete set of data necessary for code validation.

(iii) Lumped-parameter and 1D models based on scaling approaches [5-10] were developed and successfully utilized for prediction of a number of tests problems. Unfortunately, applicability of these methods is limited to stably stratified or well mixed conditions. In addition, the time scale of breakdown of a stratified layer has not been addressed in these models.

(iv) Direct application of high-order accurate CFD (RANS, LES, DNS) methods are not practical due to excessive computing power needed to calculate 3D high-Rayleigh-number natural convection flows [11], and direct contact condensation of the steam [12].

(v) The need for development in GOTHIC code of effective subgrid models and approaches to prediction of thermal stratification development and mixing is identified in the present work (see also [13, 14, 15]). Validation and feasibility studies of proposed approaches are also discussed in the present work and in [13, 14, 15]. The key elements in the proposed approach are concepts of “Effective heat source” (EHS) and “Effective momentum source” (EMS) generated by steam injected into a subcooled water pool. The effective momentum defines the time scale for mixing of an initially stratified pool. In order to determine the effective momentum, one has to combine knowledge about (a) flow regimes of steam injection into a subcooled pool [16] and (b) models for analysis of heat and momentum transfer caused by direct contact condensation [17-30] in each flow regime, and (c) design specific parameters. These models are implemented in the codes to enable computationally efficient and sufficiently accurate prediction of stratification and mixing phenomena.

A more detailed review of previous work can be found in [31]. Intensive research has been done in the past on suppression pool behavior during the blowdown phase of a loss-of-coolant accident (LOCA). The tests were performed at the Pressure Suppression Test Facility (PSTF) at different scales [32, 33, 34].

Stratification and mixing phenomena in a large pool of water with a heat source have been studied experimentally and analytically [14-35]. Strong stratification above a heat source submerged in a water pool was observed in different tests [2, 4, 35, 36, 37, 38, 39, 40]. Kataoka et al. [36] found that heat transfer into layer below the heat and momentum source is limited by thermal conduction. Thus stratification limits the available heat sink capacity of the pool. The region below the source of momentum and heat remains inactive as a heat sink [2, 4, 35, 36, 37, 38, 39, 40].

Two most recent experimental efforts on study of thermal stratification and mixing in relatively large pools are worth mentioning. Namely, experiments performed in the PUMA facility [39] systematically addressed effects of vent opening submergence depth, pool initial pressure, steam injection rate, and volume fraction of non-condensable gases on thermal stratification in suppression pool. Unfortunately, information provided in [39] is not sufficient to perform independent validation of codes and models against PUMA data.

Another large experimental program that is partially motivated by investigation of thermal stratification development and mixing in a relatively large pool [2, 4] includes POOLEX (POOL EXperiment) and PPOOLEX (Pressurized POOLEX) experiments performed at Lappeenranta University of Technology (LUT, Finland).

Scaling approaches for prediction of thermal stratification and mixing in pools and in large interconnected enclosures were developed and applied by Peterson and coworkers at UC Berkeley [5-10]. A 1D simulation code BMIX/BMIX++ was also developed at UC Berkeley to simulate stratification development [8]. It was validated against a number of experimental tests [7, 8, 9, 10]. However, BMIX++ is applicable only for the stably stratified conditions or well-mixed volumes. Details of transition from stratified to mixed conditions and specifically the time scale for such process were not addressed.

Gamble et al. [1] studied post-accident long-term containment performance in case of passive SBWR containment and found that surface temperature of the pressure suppression pool is an important factor in determining the overall long-term containment pressure. Analytical models were developed and implemented into a system simulation code, TRACG, and used to model thermal stratification behavior in a scaled test facility [1]. The main idea of the proposed model is based on analysis of the effect of injected momentum in each computational cell. The analytical models were used to model thermal stratification behavior in a scaled test facility and good agreement with the experimental data was reported.

Condensation and mixing phenomena during a loss of coolant accident in a scaled down pressure suppression pool of simplified boiling water reactor were also studied in [40]. Results of the experiments [40] were compared with the TRACE code predictions and showed deficiency in the code capabilities to predict thermal stratification in the pool. Specifically uniform temperature distribution was predicted with TRACE while experiments performed at the same conditions showed significant stratification [40].

Experimental investigation of steam condensation and CFD analysis of thermal stratification and mixing in subcooled water of the In-containment Refueling Water Storage Tank (IRWST) of the Advanced Power Reactor 1400 (APR1400) were performed by Song et al. [41], Kang and Song [42] and Moon et al. [43]. The IRWST is, in fact, a BWR SP technology adopted in a PWR designs to reduce the containment failure risk by condensing steam in a subcooled pool. Contemporary CFD codes do not have a standard model for direct contact condensation analysis. Therefore a lumped volume condensation region model [42] was used to provide boundary conditions for temperature and velocity of the condensed steam and the entrained water in the CFD simulations. Similar approach to modeling of steam injection was initially proposed by Austin and Baisley [44]. A comparison of the calculated and experimentally measured temperature profiles [43] shows some disagreement in the vicinity of the sparger. The main reason for this disagreement is claimed to be caused by the difference in the test and simulating conditions at the tank wall. However, away from the sparger, the rate of temperature increase becomes similar to that in the experiment [43]. In addition, only the stable flow condensation regime was addressed [42, 43].

Hydrodynamic flow regimes of steam injection into a subcooled water pool at different conditions were studied intensively in the past [16, 45, 46, 47, 48]. Figure 2 depicts a flow regime map.

Unlike condensation oscillations, chugging [16, 49] can result in large oscillations of the steam-liquid interface which can enhance mixing [1]. Apparent influence of chugging on mixing in the pool was observed in POOLEX experiment [2]. Steam flow rate in the POOLEX STB-20 and STB-21 was kept below certain limit to prevent mixing in the pool by steam flow pulsations. Aya and Nariai [50, 51] proposed analytical models for prediction of the dynamics of chugging phenomena depending on the steam flow rate, pool temperature and steam line characteristics. These models can be used to predict frequency and amplitude of chugging in a blowdown pipe. However, the models were validated against relatively small-scale experiments [50, 51]. The applicability of the models for simulation of the phenomena at larger scales still has to be established.

It is clear that an important element in the development of the models for predicting stratification and mixing in the BWR pressure suppression pool is how to take into account direct contact condensation of steam jet in a subcooled pool. The problem of direct contact condensation has been addressed in a number of studies [17-30]. Different approaches have been developed to predict the distance required for complete condensation of the steam and pressure oscillations. Furthermore, different idealized shapes (conical, ellipsoidal and divergent) of the pure steam jet plume in a subcooled pool of water were considered based on experimental observations, where the plume shape and length were found to depend on the injection diameter, injection orientation and pool subcooling, and steam mass flux.

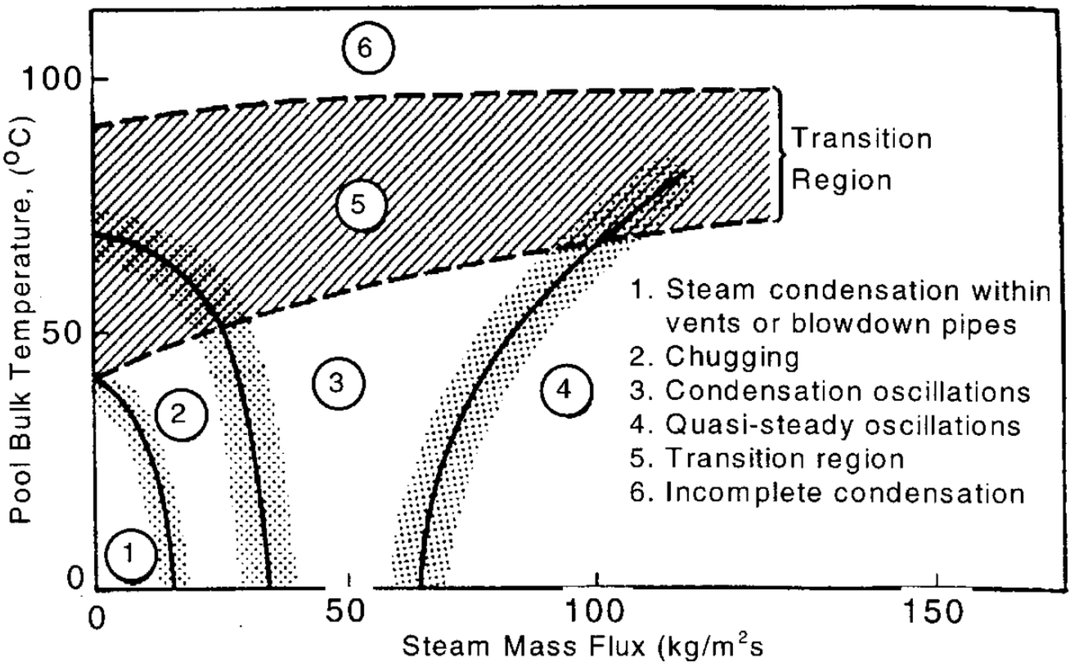


Figure 2: Regime map of steam condensation [16].

Direct application of high-order accurate CFD (RANS, LES, DNS) methods to plant scale analysis is usually impractical due to excessive computing power needed to calculate 3D high-Rayleigh-number natural convection flows [11], and direct contact condensation of the steam [12], especially in long transients and in real geometry of the BWR pressure suppression pool [13]. Therefore, a CFD-like model of the general purpose thermal-hydraulic code GOTHIC [52, 53] is selected as a computational vehicle in the present study. GOTHIC provides a middle-ground approach between a lumped parameter and pure CFD models. In each cell of a 3D grid, GOTHIC uses lumped parameter type closures and correlations for simulation of heat, mass, and momentum transfer at subgrid scales. With such an approach the computational efficiency can be dramatically improved in comparison with pure CFD methods due to the much less strict demands for necessary grid resolution. For example, there is no need in GOTHIC to resolve near wall boundary layers, because heat and mass transfer is resolved by subgrid scale models based on boundary layer theories or experimental correlations. At the same time, 3D resolution of the flow field in GOTHIC is a big advantage for the study of phenomena such as mixing and stratification, and it provides much greater flexibility than in 0D and 1D models.

Extensive validation of the GOTHIC has been performed in the past [52] including the simulation of Marviken tests, which are unique full scale experiments on the venting through a pressure suppression pool in the wetwell [54]. GOTHIC has also been validated against experiments performed in the large scale PANDA facility on mixing of air, steam and helium [55, 56].

GOTHIC version 7.0 was used to model five tests that were conducted in the Nuclear Power Engineering Corporation facility in Japan [57]. The tests involved steam and helium injection into a scaled model of a pressurized water reactor dry containment. The focus of simulation is on gas and steam temperatures and concentrations distribution in the containment.

GOTHIC 3.4 was used to evaluate performance of passively cooled containment of integrated pressurized water reactor [58]. The focus was on development of thermal and concentration stratification in the gas space of the containment. Two experiments were carried out; one to test the performance of the external moat, and one to verify the code's ability to predict thermal-stratification inside the containment.

As far as the authors are concerned, no validation of GOTHIC has been found in the open literature against the problem of thermal stratification and mixing in case of steam injection into a large water pool.

In [13, 14] and in the present work the GOTHIC CFD-like option is used to simulate POOLEX [2] and PPOOLEX [4] experiments to validate GOTHIC's physical and numerical models, and to identify the need for improvement of the models. One of the main reasons for selection of POOLEX/PPOOLEX data for the code validation is the detailed description of experimental conditions and accessible results provided in the research reports [2, 4].

The objective of the present work is to propose a method for reasonably-accurate and computationally affordable simulations of thermal stratification and mixing transients in BWR suppression pools.

As it has been discussed above, direct contact condensation (DCC) phenomena including different oscillatory flow regimes of steam injection into a subcooled pool are important for development of stratification or mixing in the pool.

Inspired by the ideas proposed by Austin and Baisley [44] and developed further by Kang and Song [42], we propose to use subgrid models in GOTHIC to predict DCC **effect** on development of thermal stratification and mixing (see also [13, 14]), instead of attempting "direct" CFD-type simulations of DCC phenomena based on first principles.

We postulate that steam injection affects stratification and mixing by two main mechanisms:

I) Local heat source in the pool due to steam condensation.

II) Local momentum source induced by steam injection (by motion of steam water interface and by buoyancy plum of steam bubbles escaping the blowdown pipe).

In order to resolve the effect of steam condensation on mixing and stratification in the pool one has to provide models for the heat source and for the momentum source induced by steam injection. Fortunately characteristic time and space scales of DCC phenomena are much smaller than the characteristic time and space scales of development of thermal stratification and global circulation and mixing in the pool. Such scale separation suggests that computationally affordable "effective" models for assessment of the "net effects" of steam injection do not need to resolve details of DCC phenomena. We call such models "Effective Heat Source" (EHS) and "Effective Momentum Source" (EMS) approaches to emphasize that these models are dealing with the **effect** of steam condensation on stratification and mixing.

The structure of this report is organized as follows. The concepts of "Effective heat source" (EHS) approach to modeling of stratification at small steam flow rate and "Effective momentum source" (EMS) approach to modeling of mixing at high steam flow rate are introduced in Chapter 2. In Chapter 3, validation of the effective models against POOLEX STB-21 test is presented. Next in Chapter 4, the effective models are also validated against PPOOLEX STR tests, in particular, STR-04 and STR-06 tests. In addition, preliminary results of a plant scale analysis using EHS/EMS is discussed in Chapter 5. In Chapter 6, a summary is given and further steps on the development, implementation, and validation with EHS/EMS are outlined.

2 DEVELOPMENT OF EHS/EMS MODELS

Steam injected into a pool with subcooled water creates a source of (i) heat and (ii) momentum in the pool. The pool state (mixed or stratified) is determined by the competition between the heat and momentum sources. The heat source is determined by the steam enthalpy and flow rate, while momentum depends on the flow regime. Direct contact condensation of steam on steam-water interface is the key mechanism which defines regime of steam injection into subcooled pool. Simulation of direct contact condensation is a challenging task for contemporary CFD codes due to the multi-scale nature of the phenomena involved. Large scale rapid motions of the free surface and local micro scale interplay between turbulent heat transfer and condensation at the interface have to be resolved accurately. Even if accurate models which could resolve micro-scale heat and mass transfer would be available, the grid and time resolution necessary for plant scale applications would lead to computational costs which are far beyond affordable.

In this work we propose an alternative to direct simulation approach based on development of effective models which can provide necessary accuracy and affordable computational efficiency. In the development of the effective models we employ the fact that there is a gap between time and space scales important for direct contact condensation oscillations and thermal stratification and mixing in the pool. Indeed, the characteristic time for oscillations of water-steam interface is of the order of 1 second, while the large scale circulation and development of stratification in the pool have characteristic time scales of the order of 100-1000 seconds. It is hard to imagine that large scale (~tens of meters) flow structure is still following each individual oscillation of the free surface in the blowdown pipe. Therefore we believe that the influence of individual oscillations is lost in the time and space scale gaps. In the PSP safety analysis we are mostly interested in the large scale phenomena, while details of small scale direct contact condensation phenomena are less important. Therefore we aim to resolve only integral (quasi-steady) effects of the steam-water interface oscillations and heat transfer on the large scale flow and temperature fields in the pool.

Specifically we propose the Effective Heat Source (EHS) model which is developed to provide the integral, quasi steady **effect** of steam injection on the pool heat transfer as a distributed heat source; and the Effective Momentum Source (EMS) model which is developed to provide the integral, quasi steady effect of steam-water interface oscillations on the large scale circulation in the pool as a local source of momentum.

2.1 Effective Heat Source (EHS) model

The purpose of EHS model is to provide conservation of mass and thermal energy. Time averaged mas flow and enthalpy of the steam define the effective heat source. The spatial distribution of the effective heat source can be adjusted depending on the condensation regime. For example, if all steam is condensed inside the blowdown pipe, the effect of steam injection is modeled with a heat flux uniformly distributed on the outer surface of the blowdown pipe. Thus, only hot saturated water flows out of the blowdown pipe to keep the mass balance.

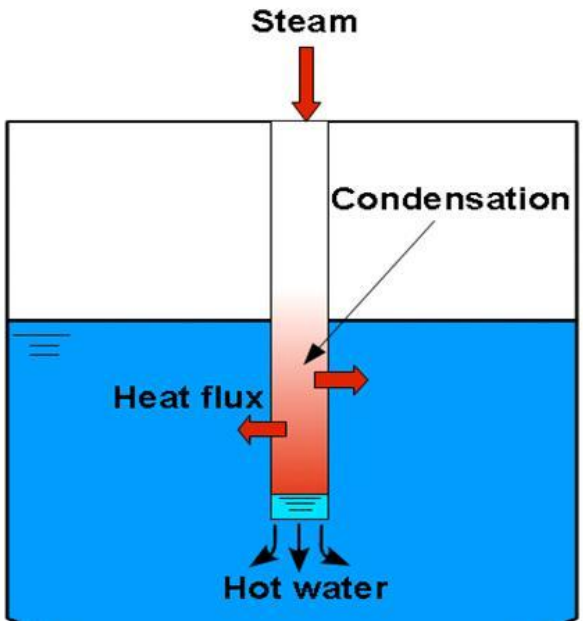


Figure 3: Schematic of Effective Heat Source (EHS) model.

Figure 3 shows the schematic of the EHS model. The heat flux through the pipe wall surface is uniformly distributed and is directed towards the liquid part of the pool. The effective heat flux is calculated by Eq.1.

$$H_{eff} = \frac{1}{\Delta T}\int_{t}^{t+\Delta T} H(t)\,dt \qquad \text{Eq. 1}$$

The EHS model can be further improved by considering actual time averaged distribution of the heat flux due to steam condensation on the inner surface of the pipe.

2.2 EMS (Effective Momentum Source) model

At large steam mass flow rates, initially stratified pool can be mixed. The momentum induced by steam injection governs the transition from stratification to mixing. The goal of the EMS model is to provide momentum source due to steam injection which can reproduce time scale for mixing of different layers in an initially stratified pool.

2.2.1 Steam injection into subcooled pool

The calculation of the effective momentum should take into account the condensation regime. As mentioned in Chapter 1, the condensation regime map is divided into 6 regions depending on the injected steam flow flux and pool bulk temperature, as shown in Figure 2. The mechanism of producing momentum due to steam injection for each condensation regime is different. For instance, the momentum induced into the pool in the chugging or condensation oscillation regime at smaller steam mass flow rates can be higher than in the quasi-steady condensation regime.

2.2.2 Model for prediction of momentum

Kang et.al has provided a way to calculate the momentum from the holes of blowdown pipes, when steam injection is in a quasi-steady condensation regime [42]. The momentum introduced into the pool can be calculated by defining the steam condensation region and solving the momentum equation in this region, where the steam flow rate and pool temperature are involved. A similar approach can be used for calculating the momentum in the condensation regime, which has no oscillations in the pool. For example, in condensation regime with steam completely condensed inside the blowdown pipe, the momentum is produced only by hot condensate out of the pipe, which has the same mass flow rate as an injected steam. With this approach, the effective momentum can be easily obtained, since the steam mass flow rate already quasi stationary.

However, the momentum cannot be calculated in a straightforward manner when oscillation occurs during the steam injection. An example is the chugging phenomenon that occurs at relatively low steam mass flux and low pool temperature. As observed in the experiment, the momentum induced by chugging is larger than in other condensation regime and can results in faster mixing in the pool [2]. The calculation of momentum for chugging and oscillation regime is a significant step in the implementation of EMS model.

The study on synthetic jet gives the idea for calculation of momentum caused by oscillation through the blowdown pipe. A synthetic jet is a time-averaged fluid motion generated by sufficiently strong oscillatory flow with zero time averaged mass flow [59]. Early experiments by Smith and Glezer [60] have shown that a low Reynolds number synthetic jet has many characteristics that resemble continuous higher Reynolds number jets. The study of Mallinson has also shown that the far-field behavior of round synthetic jets is closer to that of conventional (turbulent) round jets, i.e., the centerline velocity decays like 1/x [61].

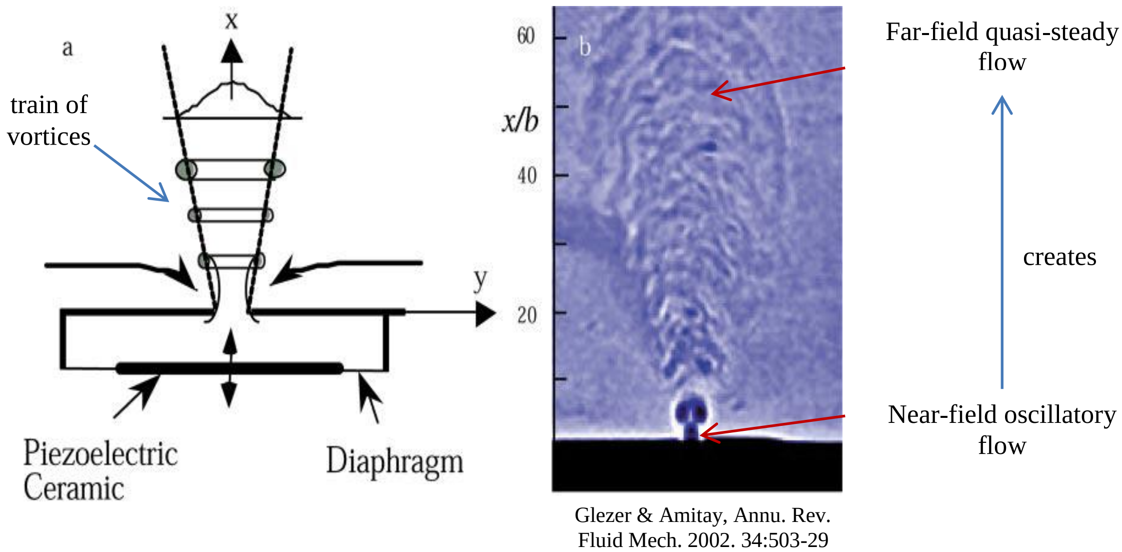


Figure 4: Synthetic jet [60].

Based on the synthetic jet theory, the large scale circulation is not oscillatory, i.e., it does not follow high frequency oscillations of the free surface. The corresponding velocity induced at far field by oscillation can be calculated by Eq.2.

$$U_0 = \sqrt{2}fL \qquad \text{Eq. 2}$$

where f is the frequency of oscillation in [1/s], and L is the amplitude of oscillation in [m].

Then the momentum can be calculated with Eq.3.

$$M = \frac{\pi}{4}\rho U_0^2 d^2 \qquad \text{Eq. 3}$$

where ρ is the liquid density, in [kg/m^3], and d is the diameter of blowdown pipe, in [m].

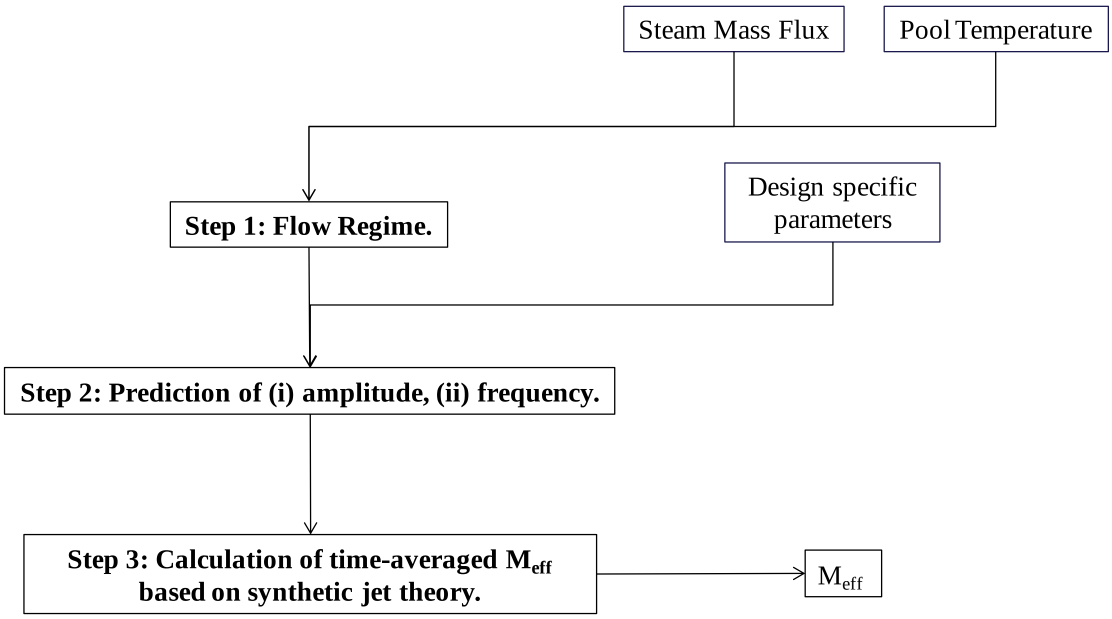


Figure 5: EMS calculation diagram.

The necessary steps to calculate the effective momentum source with the chugging and condensation oscillation regime are provided in Figure 5. The first step is to determine the condensation regime according to the steam mass flux and pool temperature. Once the oscillation regime or chugging regime is determined, the amplitude and frequency is obtained given the design specific parameters. Finally, the effective momentum is calculated based on the synthetic jet theory.

2.2.3 Model for prediction of amplitude and frequency of oscillation

To get the amplitude and frequency of oscillations through the blowdown pipe, either an experimental data or an analytical model can be used. In the experiment, these can be obtained from water-level measurements with level meters. An alternative way is to use sufficient number of thermocouples to capture indirectly the water-level from the temperature profiles.

Aya and Nariai studied experimentally and analytically the frequency and pressure amplitude in chugging regime of steam injection [30, 50, 51]. They proposed a model for a one-dimensional motion of water column in the vent tubes which was able to reproduce satisfactorily wave shape of pressure oscillation and the interface movement in chugging regime.

Figure 6 shows a sketch of the analytical model for chugging [30]. The water level in the blowdown pipe can be expressed by Eq. 4.

$$z(t) = C\sin\omega_c t - \frac{D}{\omega_c^2} t \quad \text{Eq. 4}$$

in which

$$\omega_c^2 = \frac{g}{\bar{z} + l_m}\left(1 + \frac{\pi \kappa P_{s0} d^2}{4 \rho_L g V_s}\right) \quad \text{Eq. 5}$$

$$D = \frac{\pi \kappa G_0 P_{s0} d^2}{4 \rho_L \rho_{s0} \left(\bar{z} + l_m\right) V_s} \quad \text{Eq. 6}$$

where:
$\bar{z}$: the averaged water level, $\bar{z} = 0.5z_{max}$, m;
ρ_L, ρ_s: the density of liquid and steam, kg/m^3;
G_0: the steam mass flow rate, kg/s;
d: the diameter of blowdown pipe, m;
V_s: the volume of header, m^3; and
l_m: the water length outside of the blowdown pipe for inertia force, m.

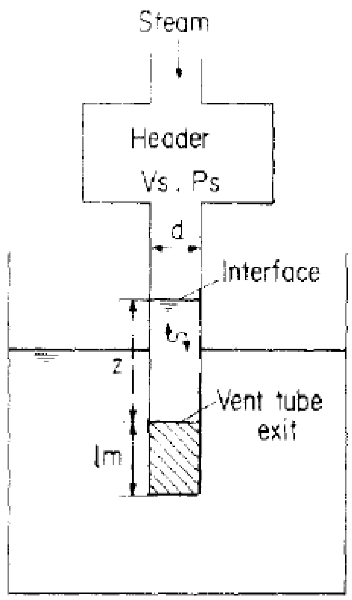


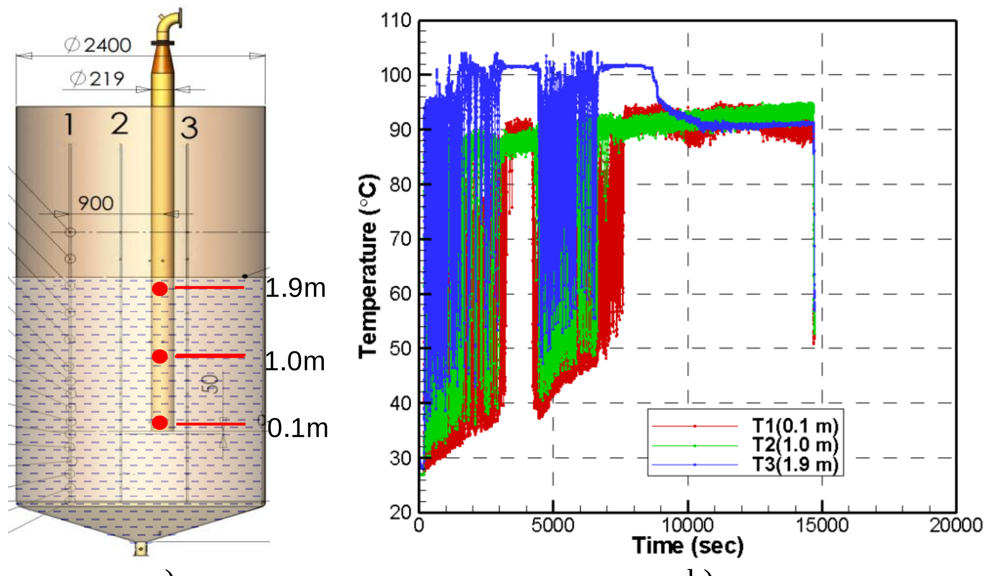
Figure 6: Analytical model for large chugging [30].

3 VALIDATION OF EFFECTIVE MODELS AGAINST POOLEX STB-21 TEST

In this chapter, the STB-21 experimental data of the POOLEX facility will be used for validation of the EMS model. The validation is divided into two separate parts. The first part is validation of EMS based on synthetic jet theory with the amplitude and frequency of oscillation estimated from the temperature readings in the blowdown pipe during the experiment. The second part is validation of EMS based on synthetic jet theory with the amplitude and frequency of oscillation calculated analytically using the Nariai and Aya model [30].

3.1 Validation of EMS model using TC readings

In the STB-21 experimental test, oscillations are observed in the blowdown pipe, when steam is injected into the pool. The condensation regime for this oscillation is determined as chugging, based on the condensation map and the injection condition, i.e., steam mass flux and pool temperature. In the POOLEX facility, three thermocouples (denoted by T1, T2, and T3) are installed inside the blowdown pipe, as shown in Figure 7a. The space interval between them is 0.9 m. Figure 7b shows the measured temperatures in the blowdown pipe in the STB-21 test exhibiting the oscillations of the water level at certain time windows. These thermocouple (TC) readings are used to determine the amplitude and frequency of oscillations of the water level at different time periods.

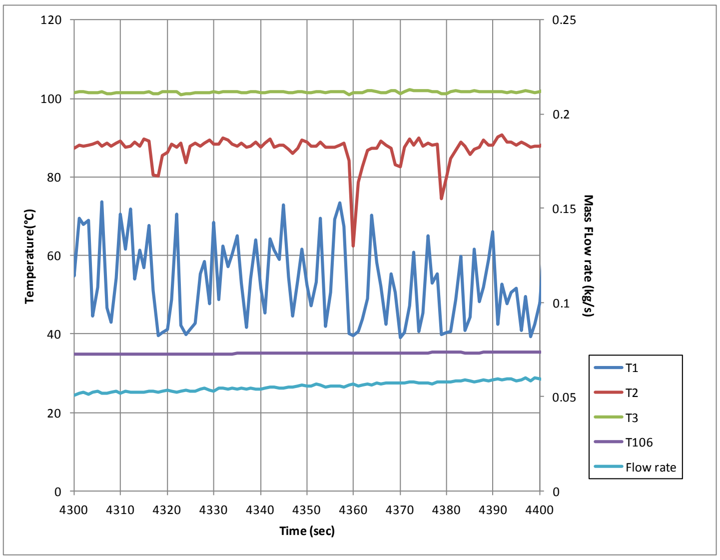


a) b)

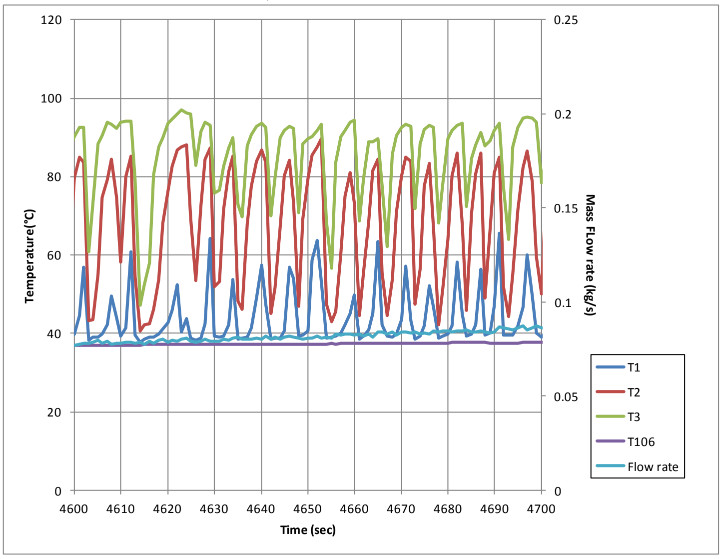
Figure 7: a) Location of thermocouples T1 (at 0.1 m), T2 (at 1.0 m), and T3 (at 1.9 m) installed in the blowdown pipe in POOLEX facility and b) temperature readings in STB-21 test [2].

3.1.1 Calculations of effective momentum based on synthetic jet theory

The TC readings in the blowdown pipe in STB-21 test are shown in Figure 9. The T106 is the temperature close to the pipe outlet. The steam mass flow rate is also shown in the figures. Note that the oscillation pattern is different depending on the pool temperatures and steam mass flow rates. However, for each oscillation pattern, it is assumed that the water level oscillation has constant amplitude and frequency. These parameters can be estimated from the temperature profiles.



a) t=4300-4400 s



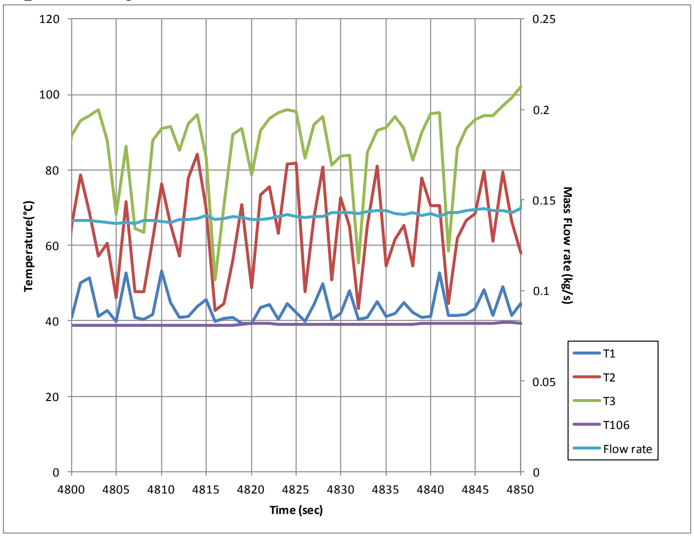
b) t=4600-4700 s

Figure 8: Oscillation pattern in STB-21 at different time periods (a) 4300-4400 s and (b) 4600-4700 s.

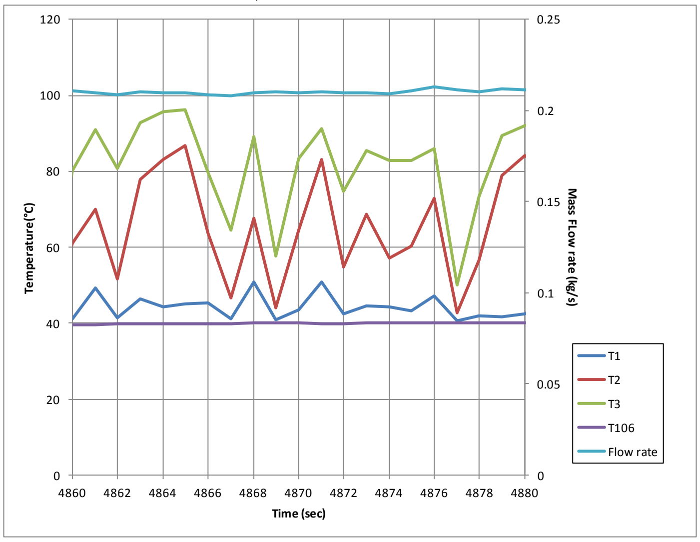
The temperature profile that is shown in Figure 9a is from 4300 seconds to 4400 seconds with a steam mass flow rate of about 0.05 kg/s. Negligible changes in TC readings at T3 and still high TC readings at T2 (compared to T1 and the pool temperature) suggest that the water level oscillates mostly below T2 (at 1.0 m) thus setting the maximum possible amplitude at 1.0 m, and above T1 (at 0.1 m) thus setting the minimum possible amplitude at 0.1 m. By estimating the number of cycles of oscillation in the given time frame, the maximum frequency of oscillation is determined to be 0.4 Hz, while the minimum frequency is determined to be around 0.303 Hz.

The same approach is applied to other time frames. The oscillations from 4600 seconds and 4700 seconds are shown in Figure 9b. The temperature at T3 varies significantly. Since there is no oscillation detected by flow meter above the top of the pipe, it is assumed that the maximum water level can only reach the top of the pipe (about 3.8 m) but not over. The minimum amplitude of oscillation is above T3 (at 1.9 m). The frequency of oscillation is determined to be about 0.18-0.25 Hz, by counting the number of cycles at different periods.

The amplitude and frequency of oscillations at periods from 4800 seconds to 4850 seconds and from 4860 seconds to 4880 seconds can be determined from Figure 9a and Figure 9b, respectively.



a) t=4800-4850 s



b) 4860-4880 s

Figure 9: Oscillation pattern in STB-21 at different time periods (a) 4800-4850 s and (b) 4860-4880 s.

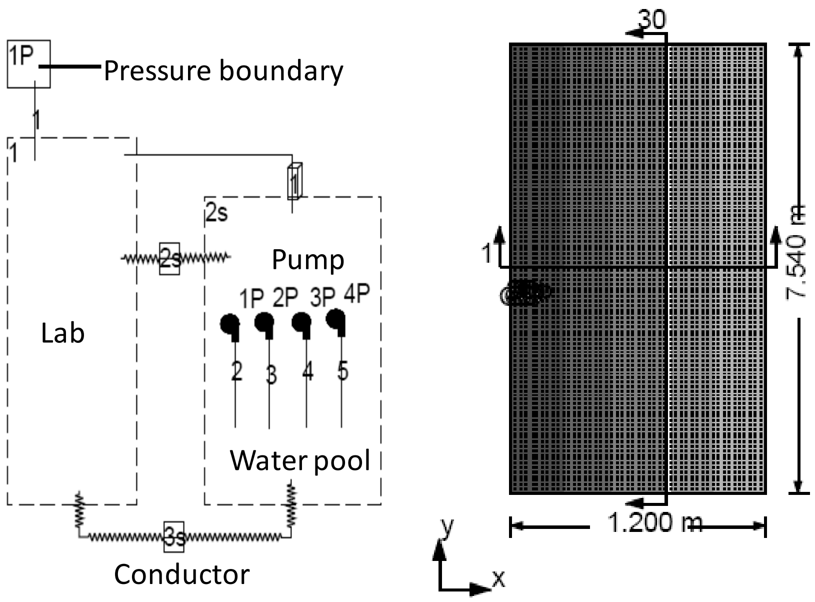
The values of frequency and amplitude of oscillations at different periods are summarized in Table 1. The quasi-steady flow velocity induced by oscillation is also calculated based on synthetic jet theory and is shown in the table. The range of estimated effective momentum is also shown. Cases 1 and 3 are the minimum and maximum effective momentum based on estimated amplitude and frequency, respectively. The effective momentum in case 2 is somewhere in between.

Table 1: Momentum rates (calculated based on synthetic jet theory) at different time frames in STB-21 test.

Estimated Frequency and Amplitude from TC measurements in STB-21					**Momentum rate**		
Time(s)	Period (s)	Frequency (Hz)	Amplitude (m)	Velocity (m/s)	Momentum (kg-m/s^2)		
					Case 1	Case 2	Case 3
4300-4400	2.5-3.3	0.303-0.4	0.1-1.0	0.043 – 0.57	0.066	10.32	11.5
4600-4700	4-5.6	0.18-0.25	1.9-3.8	0.48 – 1.36	8.43	54.4	67
4800-4850	2.5-3.3	0.3-0.4	1.9-3.8	0.81 – 2.18	23.4	151	171.5
4860-4880	2-3.1	0.33-0.5	1.9-3.8	0.88 – 2.73	27.55	177.7	268

3.1.2 GOTHIC modeling with EMS

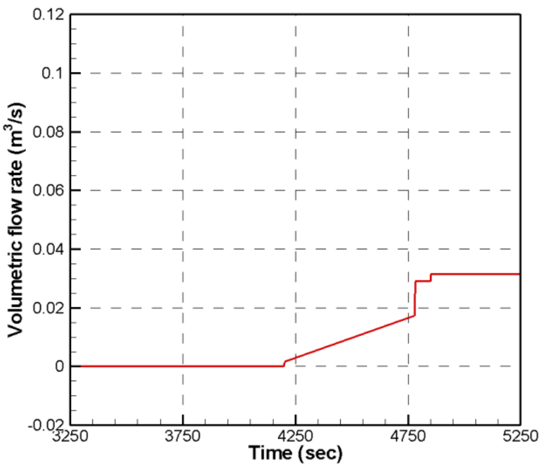
The scheme for modeling of POOLEX with EMS is shown in Figure 10a. The grid for pool tank is 48×114 and the vapor space is also modeled. The pumps are used to connect two vertically adjacent cells in the pool and impose the momentum. Since the outlet of the blowdown pipe is resolved with 4 cells, four pumps are needed on the corresponding cell surfaces as shown in Figure 10b. The heat loss through the bottom and side wall is modeled by two conductors. One spanned conductor is used to supply the heat source equivalent to steam condensation. One 3D connector is used to model the open orifice on the top of tank.



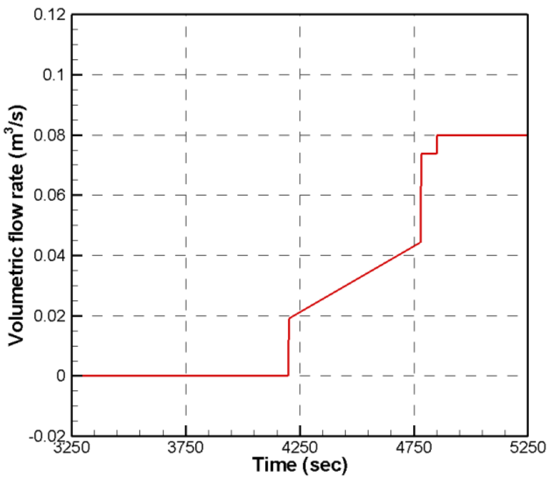
a) b)

Figure 10: GOTHIC code model used for simulations with effective momentum simulated by pump. a) GOTHIC schematic diagram, b) grid resolution on XY plane.

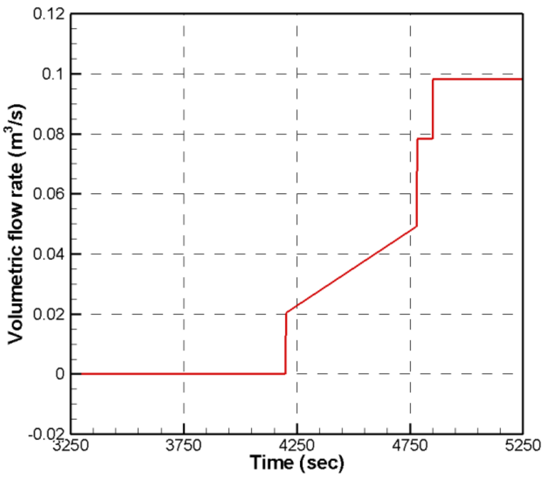
Three cases are performed with different momentum source, which are estimated from the experimental data, as shown in Table 1. The volumetric flow rates of the pumps are shown in Figure 11. It is assumed that the momentum change is linear from 4200 seconds to 4780 seconds. The momentum in other time periods is assumed to be constant. The first order upwind differencing scheme is used for GOTHIC simulations.



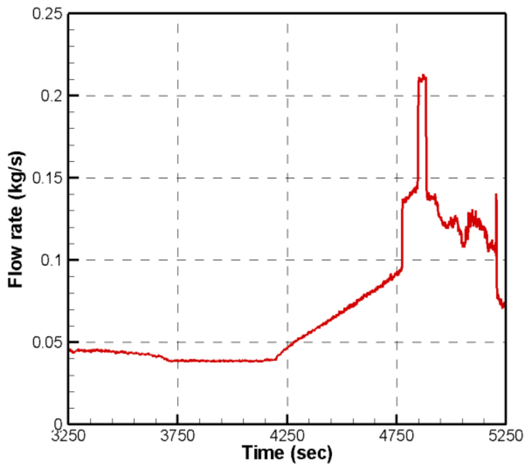
a) case 1



b) case 2



c) case 3



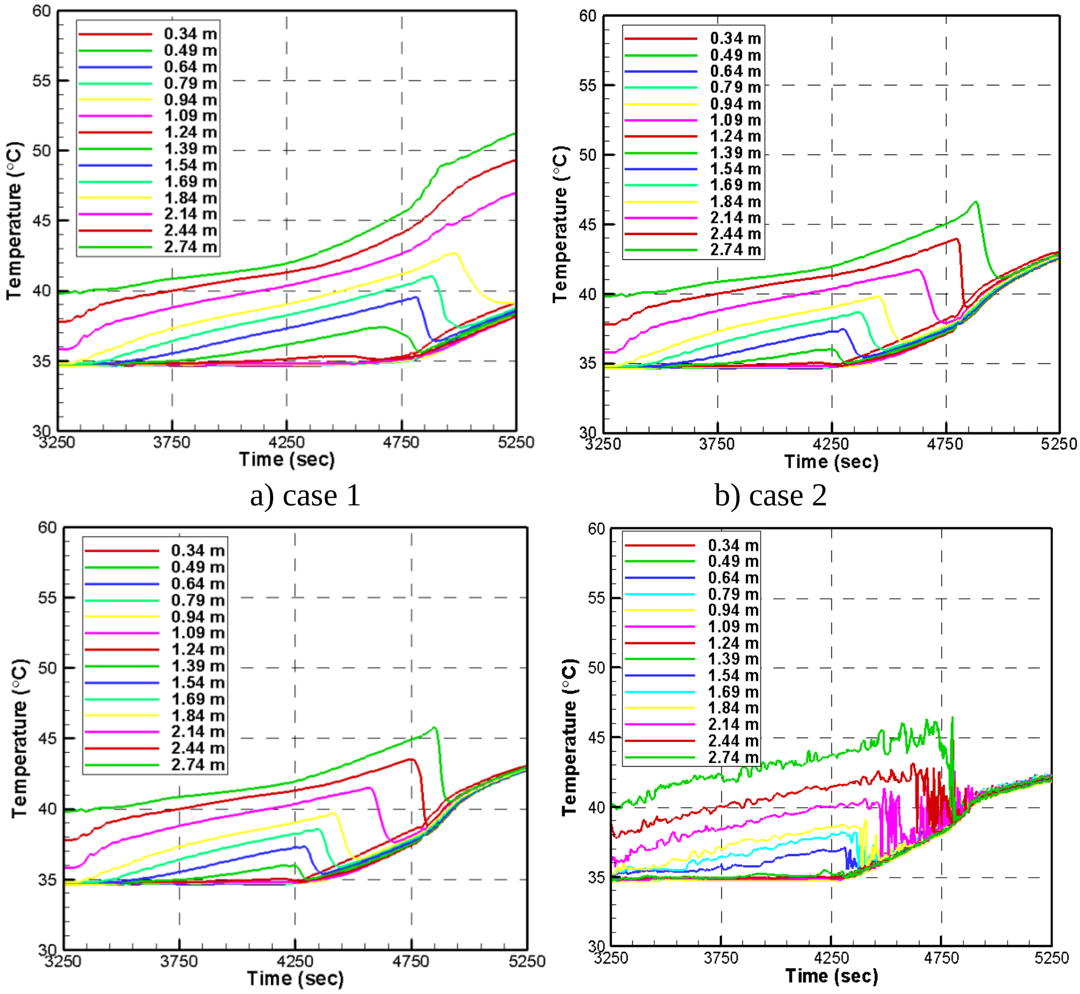
d) measured steam mass flow rate

Figure 11: Pump volumetric flow rate used in the GOTHIC simulation and steam mass flow rate measured from experiment.

The comparison between the three simulation cases using GOTHIC against the experimental data is shown in Figure 12. It can be seen that the temperature trends in the simulations are similar to those in the experiment. The stratification development before 4250 seconds is predicted in the simulations, and then the mixing starts from the bottom. In case 1 with minimum estimated momentum, the parts of layer below 1.84 m are mixed step by step from the bottom and the complete mixing of the pool is not predicted at 5250 seconds. In case 2 with values between the minimum and maximum estimated momentum, a complete mixing is obtained at about 5000 s. The mixing times for all layers are longer than those in the experiment and the time scale for complete mixing is about 800 seconds. In case 3 with maximum momentum, although the time scales of mixing for some layers are longer than that in the experiment, complete mixing is obtained at 4900 seconds and the time scale for complete mixing is around 700 seconds, which agrees with the experiment.

The comparisons verify that the detailed mixing behavior observed in the experiment can be predicted when variable effective momentum is used. The momentum used in the simulation is under-estimated; however, the way to obtain the effective momentum by measured temperatures in the pipe is feasible.

Since in POOLEX experiment, only three thermocouples are installed in the blowdown pipe and measurement frequency is 1 Hz. Both the space and time interval are not enough to accurately estimate the oscillation amplitude and frequency.



a) case 1 b) case 2

c) case 3 d) measured temperature

Figure 12: GOTHIC simulation results and experimental data

3.2 *Validation of EMS model based on analytical estimation of amplitude and frequency*

Aya and Nariai have proposed an analytical model for the prediction of frequency and amplitude of oscillation in the blowdown pipe during steam injection [30]. The specific analytical model for chugging is included in their models. The velocity and momentum calculated based on the Aya and Nariai model and comparison to the momentum estimated by experimental data are summarized in Table 2.

In the analytical model, the parameter C is determined by the experiment and it depends on the steam injection conditions and pool condition. For STB-21, the parameter C is adjusted to match the maximum and minimum amplitude estimated by the experimental data.

As shown in the table, the difference of momentum between analytical value and experimental value is rather large. It is instructive to note that the analytical model is derived based on the experimental data from small scale facility with adiabatic drywell above the blowdown pipe. Further development of the analytical model for prediction of oscillation at larger scales (e.g. POOLEX facility and plant blowdown pipes) is necessary.

Table 2: Comparison of amplitude and frequency calculated by the analytical model and estimated from the experimental measurements

	Calculated Frequency and Amplitude with analytical Model for STB-21			**Estimated Frequency and Amplitude from TC measurements in STB-21**		
Time(s)	Period (s)	Frequency (Hz)	Amplitude L (m)	Period (s)	Frequency (Hz)	Amplitude L (m)
4300-4400	0.152-0.34	6.6-2.9	0.1-0.99	2.5-3.3	0.303-0.4	0.1-1.0
4600-4700	1.05-1.414	0.95-0.71	1.94-3.79	4-5.6	0.18-0.25	1.9-3.8
4800-4850	0.403-0.56	2.48-1.79	1.97-3.78	2.5-3.3	0.3-0.4	1.9-3.8
4860-4880	0.381-0.55	2.62-1.82	1.91-3.79	2-3.1	0.33-0.5	1.9-3.8

4 VALIDATION OF THE EFFECTIVE MODELS AGAINST PPOOLEX STR TESTS

Several experiments on thermal stratification and mixing are also performed in the PPOOLEX facility [4]. The main difference between the POOLEX and the PPOOLEX facility is that the PPOOLEX has a drywell. During a steam injection from, part of the steam condenses in the drywell first and the rest of the steam rushes into the wetwell through the vertical blowdown pipe. Because of this effect, the numerical simulation of PPOOLEX tests is more complex than that for POOLEX facility.

The development of thermal stratification is obtained in tests STR-03 and STR-04 with low steam mass flow rates. The main difference between the two tests is that the upper layers are isothermal in STR-03 (thermocline is formed during the steam injection) while stratification layer is formed in STR-04 with considerable temperature gradient in the upper layers.

The schematic illustration of the steam condensation inside the blowdown pipe is shown in Figure 13. Steam directed through the blowdown pipe can condense on the walls and on the free water surface which translate local heat fluxes on the walls and on the free surface close to the outlet. Two limiting approaches to the implementation of the EHS model with respect to distribution of a total heat flux Q_{total} are (i) the total heat flux is distributed on the walls, $Q_{eff-wall} = Q_{total}$, or (ii) the total heat flux is applied at the free surface, $Q_{free-surface} = Q_{total}$. A more realistic case is a combination of these approaches. Implementation of such model is a subject for further study.

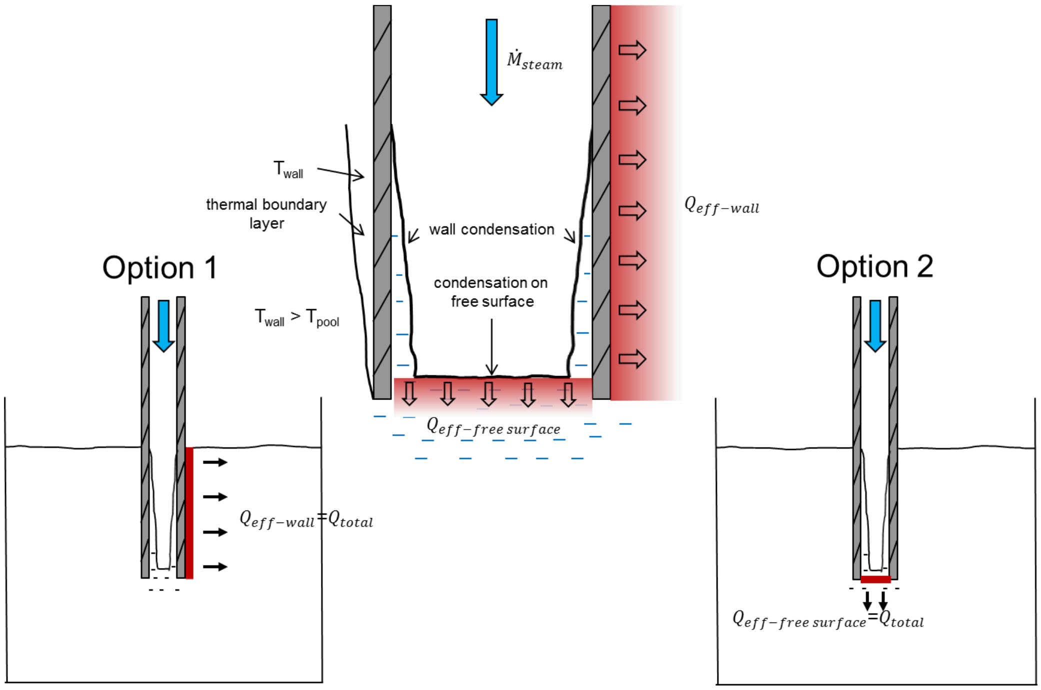


Figure 13: Simple approaches to the implementation of the EHS model.

4.1 Validation of EHS model against STR-03 with stratification development

The steam mass flow rate in STR-03 measured in the steam line is shown in Figure 14. The steam mass flow rate increases to a peak of 0.1 kg/s around 3000 s, then decreases slowly to 0.05 kg/s around 10000 s. Finally, it fluctuates around 0.06 kg/s until 14000 s. Respectively, as shown in Figure 15, the condensation regime goes from region 1 (steam completely condensed inside the blowdown pipe) to region 5 (transition region). Although it passes through the chugging regime, the water level oscillations in the blowdown pipe are not apparent in the temperature measurements, as shown in Figure 16. A possible reason is that the oscillation amplitude is so small and the water-level is always below the thermocouples that are installed. Another possible reason is that only the hot condensates are involved in the chugging and this chugging cannot be detected by thermocouples. In any case, it is reasonable to assume that the momentum from the pipe outlet is negligible and only the effective heat source model can be used for simulation.

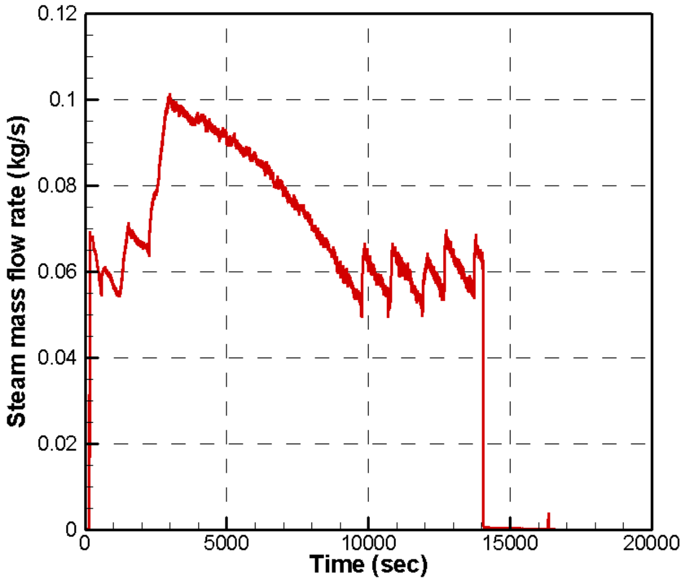


Figure 14: Steam mass flow rate measured in STR-03 test.

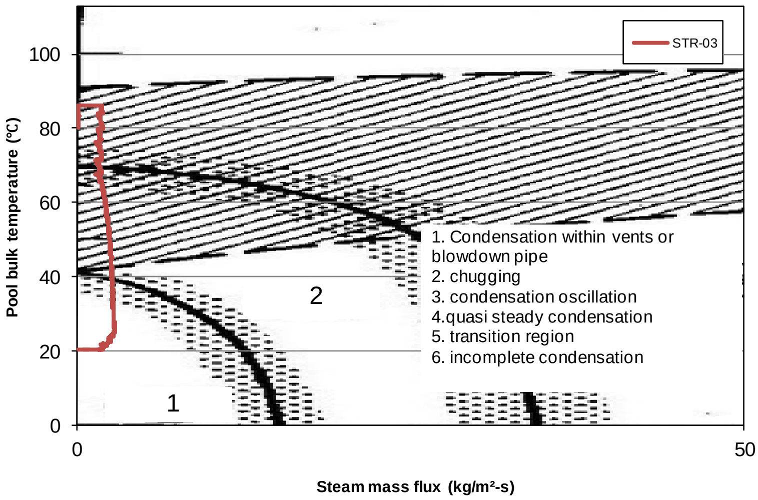


Figure 15: Condensation regime in STR-03 test.

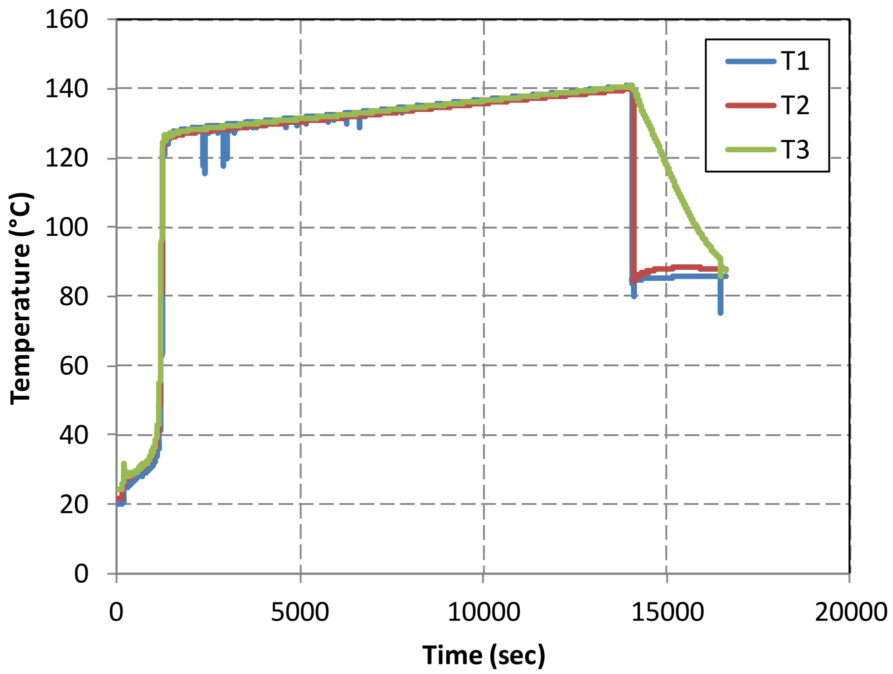


Figure 16: Temperature measured in the blowdown pipe.

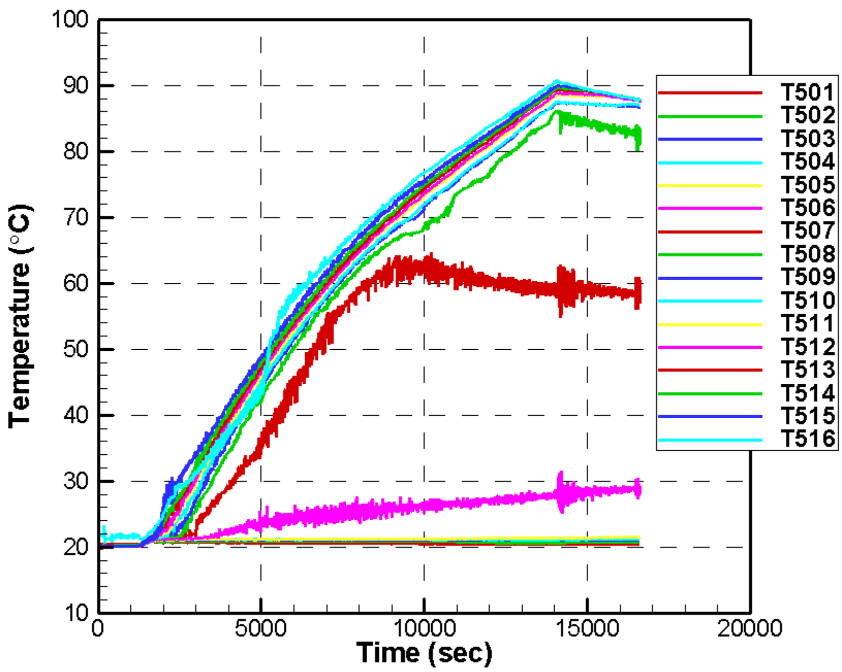


Figure 17: Pool temperature profile measured in STR-03 test.

The temperature measured in the pool in STR-03 at different levels is shown in Figure 17. Mixing is obtained during the first 1500 s attributed to air clearing from the drywell to the wetwell. Then thermal stratification starts to develop until about 14000 s in the upper part of the water pool in the wetwell. It can be seen that the upper part of the water pool is almost completely isothermal during the stratification development. This behavior is different to STB-20 where significant temperature gradients are observed in the pool. The temperature at T507 in STR-03 (near the level of the pipe's outlet) has also increased during the stratification development before 9000 seconds, while it is relatively constant at the beginning of stratification development in STB-20. The possible reason for such differences is that in STR-03, a higher steam mass flow rate, about 0.1 kg/s, is used from 3000 seconds. Most of the steam condensation with such injection flow rate occurs rather at the exit of the pipe, than on the surface of the pipe wall. If most of the heat is provided at the pipe exit, then the layer above the steam injection point will be isothermal. The layer below the pipe exit is heated due to the stronger convection at higher steam flow rate.

4.1.1 GOTHIC modeling with EHS

In PPOOLEX tests, the steam mass flow rate is measured in the steam line, but not in the blowdown pipe. Before the steam is injected into the wetwell pool in PPOOLEX facility, part of the steam is condensed in the drywell. Thus, the actual steam mass flow rate through the blowdown pipe is unknown. This quantity is important for the EHS model since the effective heat source is calculated based on it. Since GOTHIC has models to simulate the steam condensation on the walls, it is possible to use GOTHIC lumped models to calculate the steam condensation rate in the drywell and the steam mass flow rate through the blowdown pipe. Therefore, a lumped simulation is performed first to obtain the needed boundary conditions for 2D simulation with the EHS model.

4.1.1.1 Lumped simulation

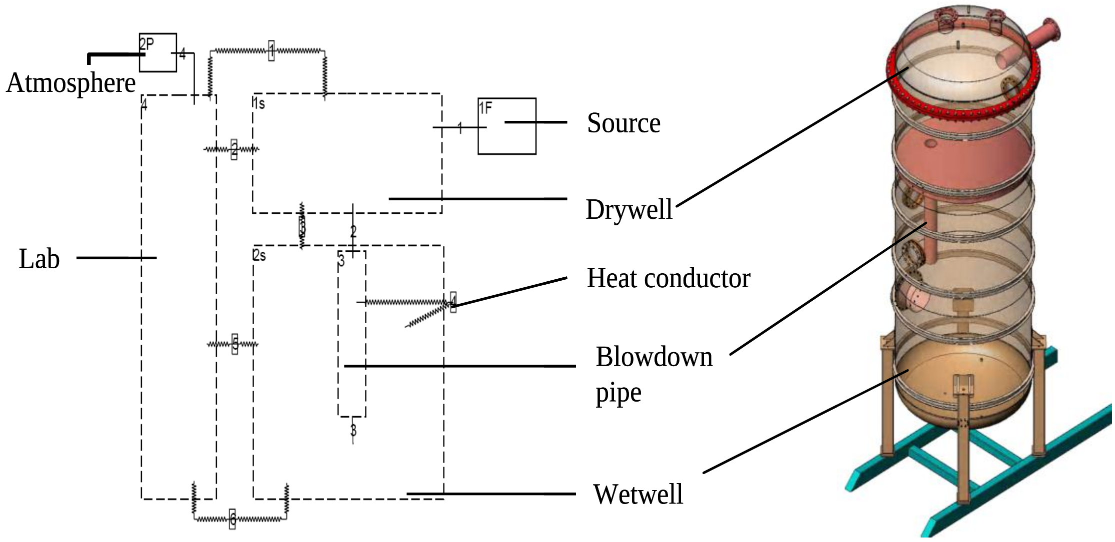


Figure 18: GOTHIC Lumped modeling for PPOOLEX facility

GOTHIC lumped model is shown in Figure 18. The drywell, wetwell, blowdown pipe and lab are all modeled with lumped volumes. The flow boundary, 1F, supplies the steam for injection into the drywell. The pressure, temperature, and steam mass flow rate measured in the experiment are input parameters in the corresponding flow boundaries. One pressure boundary, 2P, is used to keep a constant condition in the lab. The lab temperature is not measured during the experiment, but here it is assumed to be 20 °C in all the STR tests.

The heat transfer through all the solid structures, for example, the intermediate floor between the drywell and wetwell, and the tank walls, are all modeled by thermal conductors. The initial temperatures for these conductors are taken from the experimental data.

The pool liquid temperature predicted by GOTHIC lumped model is compared to the averaged liquid temperature in the experiment. As shown in Figure 19, the pool temperature is over-predicted in the simulation, which can imply that more steam is injected into the wetwell through the blowdown pipe in the simulation than in the experiment. A possible reason is that the condensation rate in the drywell is under-predicted. Another possible reason is that the lumped model cannot predict thermal stratification. Further study will be performed to investigate this discrepancy.

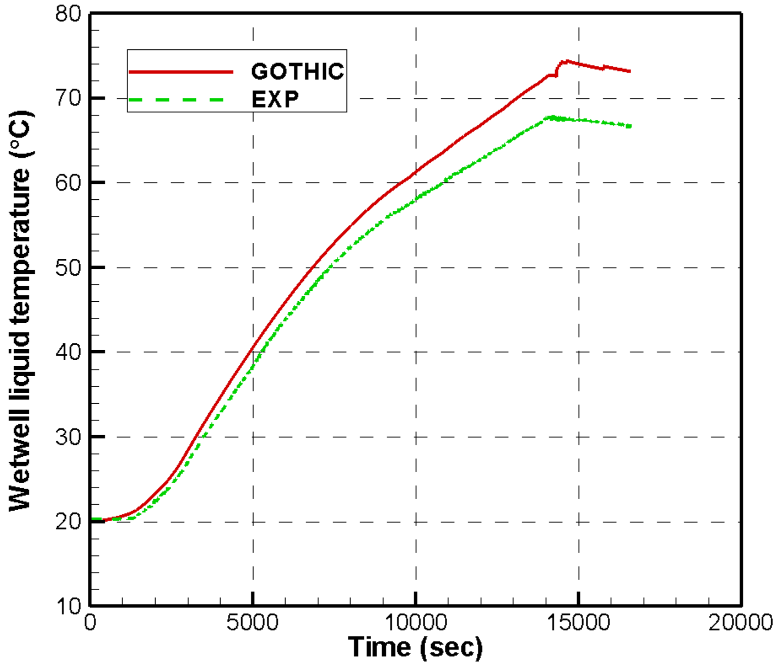


Figure 19: Comparison of predicted pool liquid temperature to averaged liquid temperature in the experiment.

The comparison of the predicted drywell pressure to the measured value in the experiment is shown in Figure 20. The first 1500 s in the experiment is the clearing phase, that is, when the air in the drywell is pushed into the wetwell. In the simulation, the clearing phase corresponds to the first 2500 s, during which the drywell pressure has increased from around 1 bar to 2.6 bars. The reason for this delay in the simulation is attributed to the deficiency of lumped modeling. With the lumped model, it is always assumed that the steam injected into the drywell is well-mixed with air remaining in the drywell. In reality, the air from the drywell is not completely mixed, especially at the beginning, and large portion of it is pushed by steam like a piston into the wetwell. This behavior can be resolved by using a 3D volume for the drywell. The part after 9000 seconds in the experiment has lower pressure than that in the simulation, because the temperature of pool surface with thermal stratification in the experiment is higher than in the simulation.

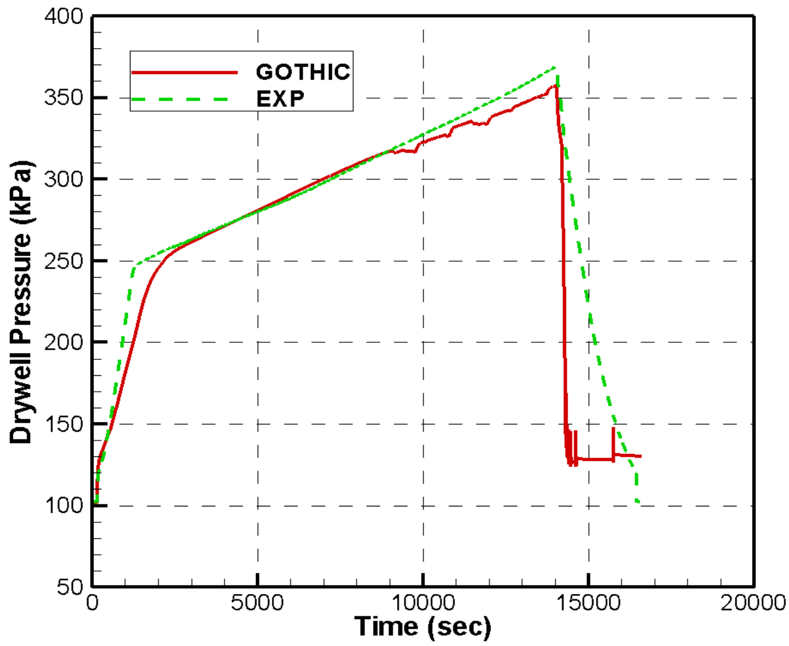


Figure 20: Comparison of drywell pressure predicted by GOTHIC simulation against experiment.

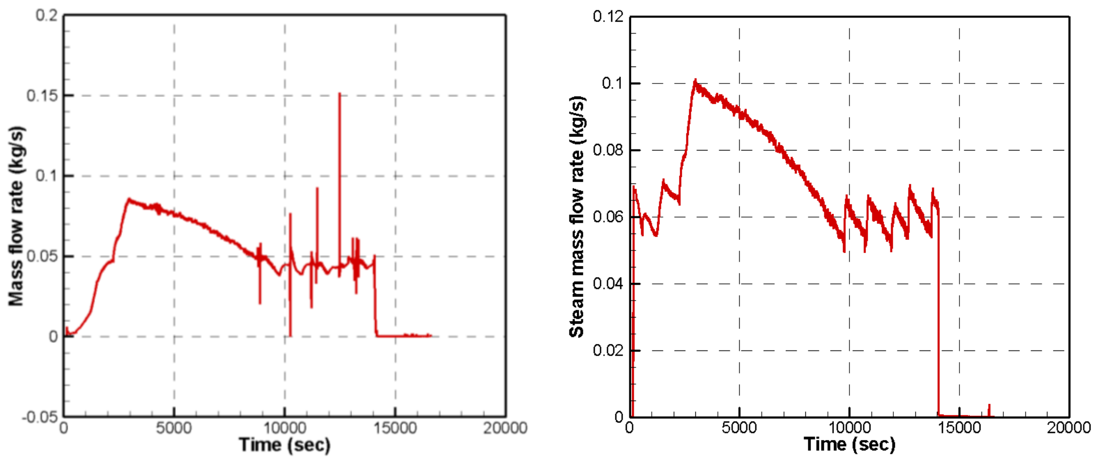


Figure 21: a) Calculated steam mass flow rate through the blowdown pipe from the GOTHIC lumped model, b) measured in experiment.

The steam mass flow rate through the blowdown pipe in the simulation is shown in Figure 21a. Compared to the measured injected steam mass flow rate shown in Figure 21b, the calculated flow rate through the pipe is lower and has some jumps which are attributed to numerical instabilities. However, the averaged mass flow rate through the pipe is reasonable compared to the injected steam mass flow rate. In the 2D simulation with EHS model, it is assumed that all steam which flows into the blowdown pipe is completely condensed inside the pipe and only the hot condensates flows out. The momentum introduced by jumps of condensate flow rate in the calculation is assumed to have negligible effect on the thermal behavior in the pool. The effective heat source, $Q_{in} = G_s H_{latent}$, is calculated which is based on steam mass flow rate through the blowdown pipe. The value of heat source is shown in Figure 22. This effective heat source is used as an input in the 2D simulation discussed in the next section.

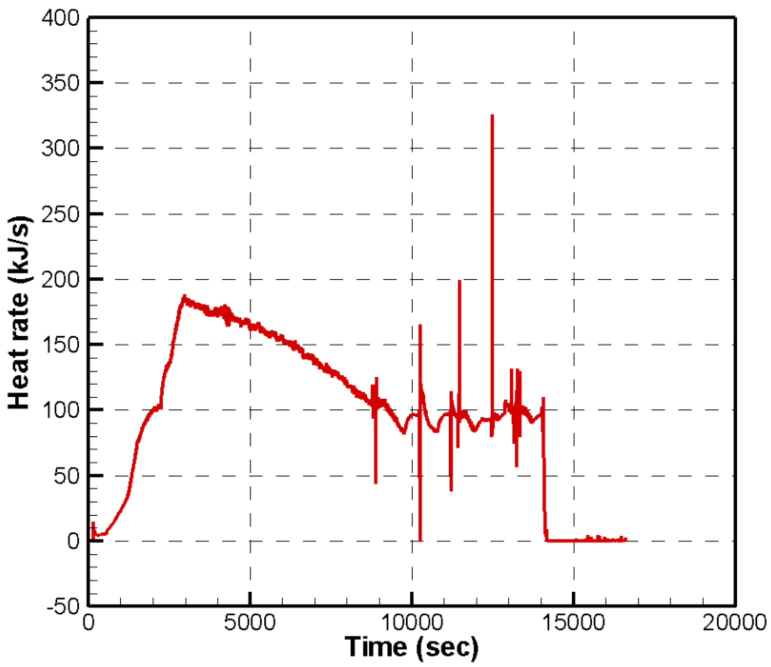


Figure 22: The effective heat source based on steam flow rate through the blowdown pipe.

4.1.1.2 2D simulation

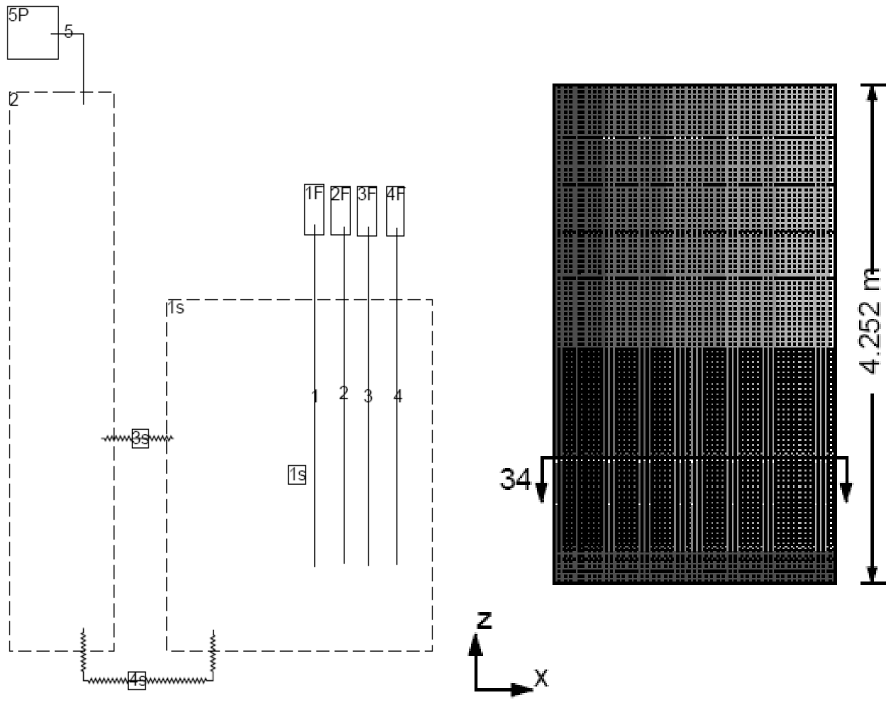


Figure 23: GOTHIC 2D modeling and grid resolution for wetwell.

The GOTHIC 2D modeling is shown in Figure 23a while the grid resolution is shown in Figure 23b with grids 48×70 for the liquid part and 48×5 for the vapor part. Only the wetwell is modeled with a 2D volume and the rest is lumped. Four flow boundaries are used to supply the water source out of the blowdown pipe, since the diameter of the pipe is occupied by four cells. The lab is modeled with a large lumped volume connected to a pressure boundary with atmospheric conditions. Two thermal conductors are used to model the heat loss through the side wall and bottom of the wetwell. The heat transfer through the plate separating the wetwell and the drywell is obtained from the lumped simulation.

The effective heat source calculated in lumped simulations is imposed on the thermal conductors in the blowdown pipe. Two distribution schemes are used in the simulation (see Figure 13 for illustration). In case 1, the heat source is uniformly distributed on the surface of submerged pipe part. It is assumed that all steam is condensed on the pipe walls. For case 2, the heat source is located at the end of the pipe. In this case, we assume that the steam is condensed near the end of the pipe on the free steam-water interface. For both cases, the bounded second order upwind difference scheme is used in the GOTHIC calculation.

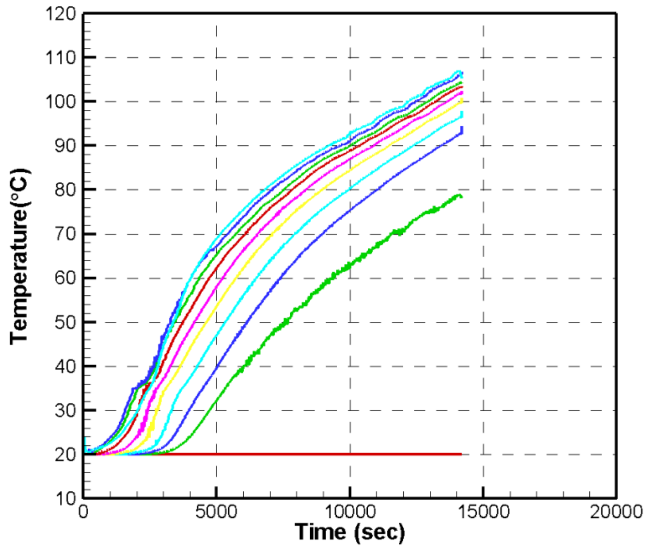
The predicted temperature of the pool in case 1 with uniformly distributed heat source on the surface of blowdown pipe is shown in Figure 24a. It can be seen that the thermal stratification is predicted in the simulation. Only the temperature in the part above the pipe outlet has increased during the transient while the remaining lower part is constant. Compared to the experimental data shown in Figure 24c, the temperature difference in the upper part of case 1 is higher and the top surface has a higher temperature at any given time. For example at 14000 s, the temperature difference in the upper layer is about 25 °C in case 1 with a peak temperature of about 106 °C while is about 5 °C in the experiment with a peak temperature of about 90 °C.

With case 2 where the heat source is located at the end of pipe, the temperature profile agrees better with the experimental data, as shown in Figure 24b. The predicted temperature of the upper part is almost mixed in the simulation. The temperature at the location of T507 has also increased in the simulation, which is similar to that in the experiment.

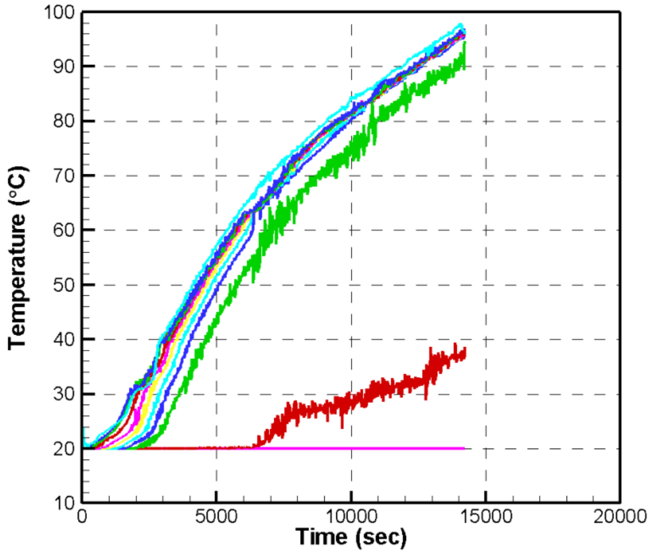
The comparison implies that in STR-03, most of the steam could have condensed close to the end of the blowdown pipe, since the steam mass flow rate is a little higher than that in STR-04. It also implies that for different regimes, such as, chugging, condensation oscillation, etc., the EHS model has to be modified. In addition to the simple limiting cases (as illustrated in Figure 13 as Option 1, Option 2) we need more mechanistic approaches which would provide heat source distribution based on the distribution of steam condensation in the pipe.

It is noted that the mixing phase at the first hundreds of seconds is not well predicted because the momentum created by air injection in the clearing phase is not considered in the simulation. Generally, the air injection will cause a strong buoyancy force and will enhance mixing in the pool.

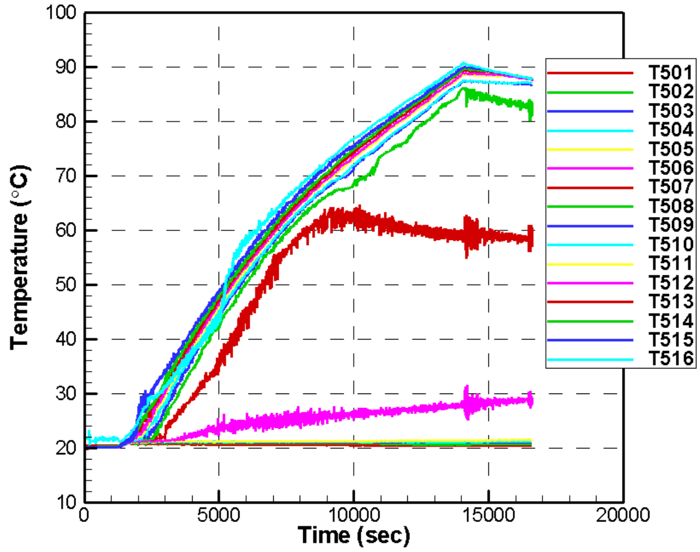
Figure 25 shows the temperature in the gas space of the wetwell. Compared to the experimental data, the predicted gas temperature is 10°C higher. However, the thermal stratification in the gas space is predicted, even though a coarse grid is used in the gas space.



a) case 1

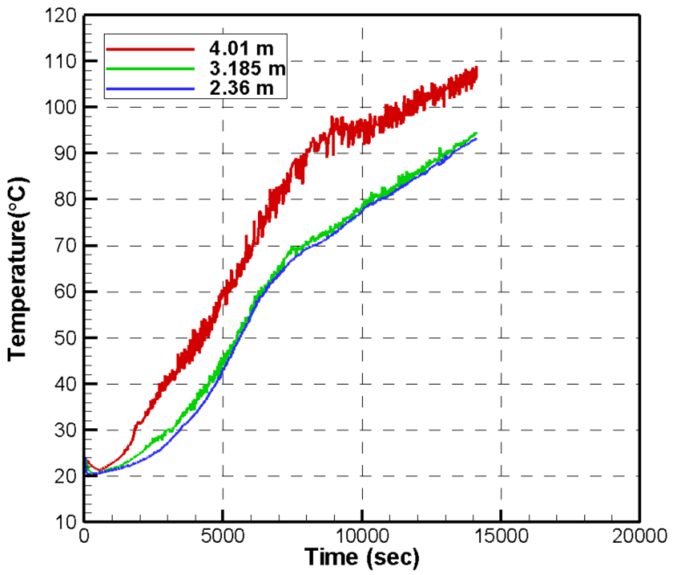


b) case 2

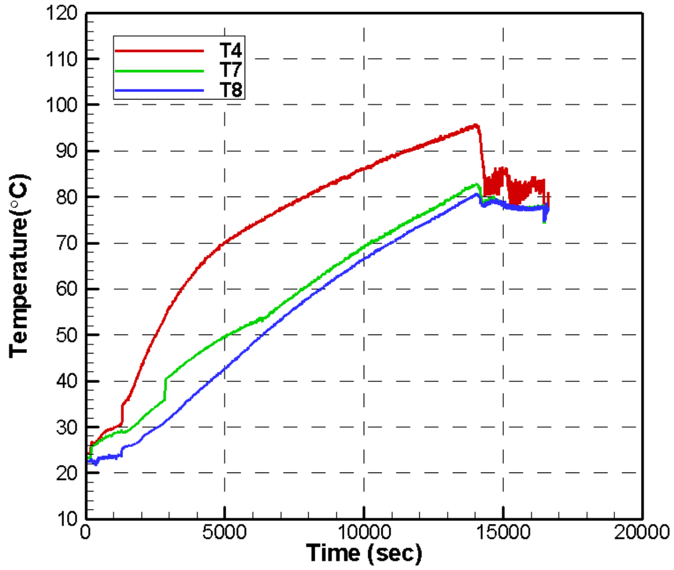


c) Experiment

Figure 24: Pool temperature in a) case 1 with uniform heat source on the pipe surface, b) case 2 with heat source at the end of the pipe



a) case 2



b) measured temperature

Figure 25: Temperature in wetwell gas space in a) case 2 with heat source at the end of the pipe, b) experiment (T4: 4.01 m; T7: 3.185 m; T8: 2.36 m) [4]

4.1.1.3 Simulation with 3D drywell

As mentioned previously, the lumped simulation predicts a longer clearing phase due to equilibrium model in lumped volume. In reality, when steam is injected into the upper part of the drywell the steam is accumulated there and pushes the air from the upper part to the bottom. Only the air, but not mixture is pushed into the wetwell in the first phase of the blowdown. As it was mentioned, earlier, the clearing affects the mixing in the water pool at the beginning of the transient. A possible approach to modeling of the clearing phase is to simulate the drywell with a 3D volume, in which the air and steam concentration distribution are taken into account. Figure 26 shows the grid resolution used in the simulation. The drywell is divided into 10×10×10 cells.

Blockages are used to have cylindrical geometry and cap ceiling. The thermal conductors are spanned on the subvolumes in the drywell.

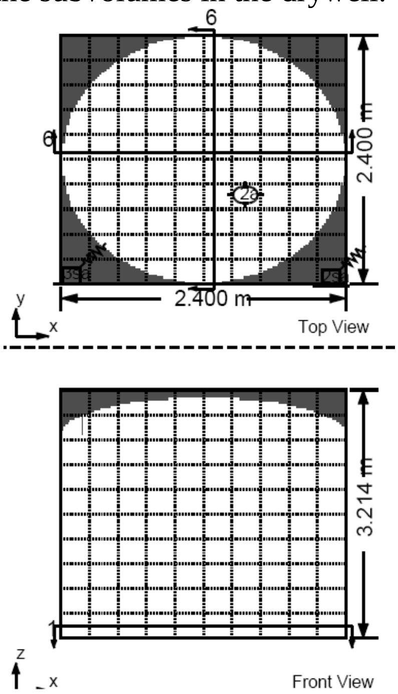


Figure 26: Grid configuration for 3D drywell

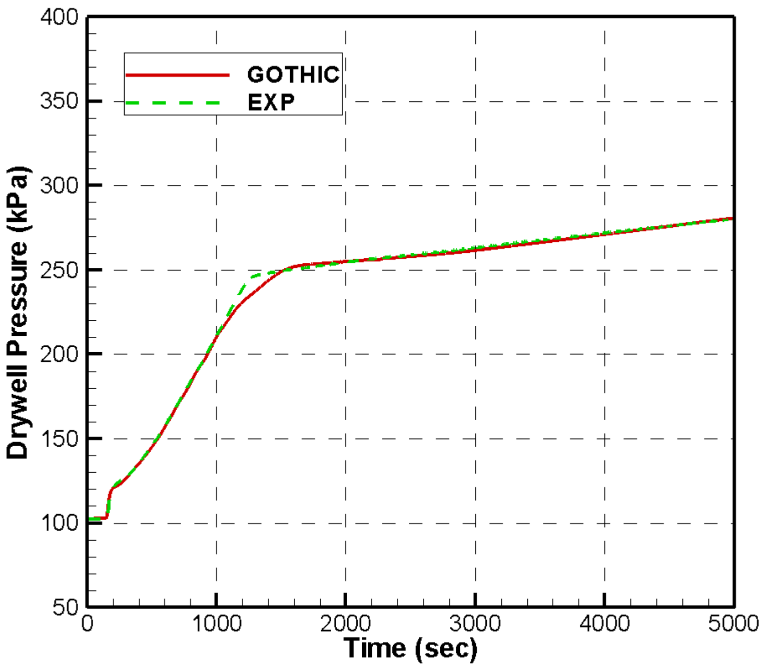


Figure 27: Comparison of predicted drywell pressure with 3D drywell and measured value

The comparison of predicted drywell pressure with 3D drywell to experimental data is shown in Figure 27. Compared to the lumped simulation, the drywell pressure in the simulation with 3D drywell has significantly improved during the clearing phase. The air mass fractions with different levels (totally 10 levels on z direction) are shown in Figure 28. The results show that the air at upper part (Level 9) is pushed first by steam down to the bottom part, and the air fraction at the bottom cell (Level 1) goes to zero the latest.

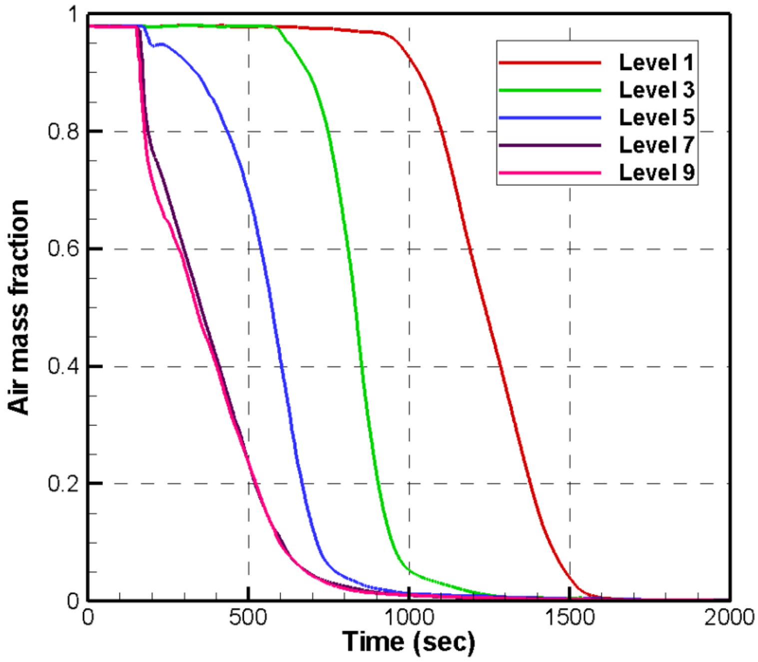


Figure 28: The air mass fraction at different levels

4.2 Validation of EHS model against STR-04 with stratification development

The small steam mass flow rate measured from the steam source line in STR-04 test is shown in Figure 29. The steam mass flow rate is kept at the 0.05 kg/s level except for an abrupt peak around 0.1 kg/s at 2000 s. The temperature profiles at different levels are shown in Figure 30. The temperature below the level of T508, which is close to the pipe outlet, remained relatively flat during the steam injection, while thermal stratification is observed in the part above the T508.

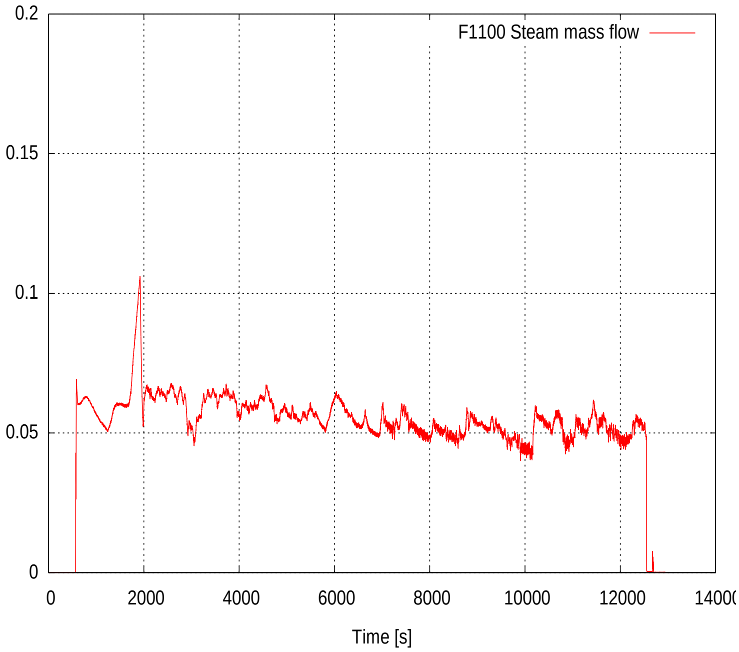


Figure 29: Steam mass flow rate measured in the experiment

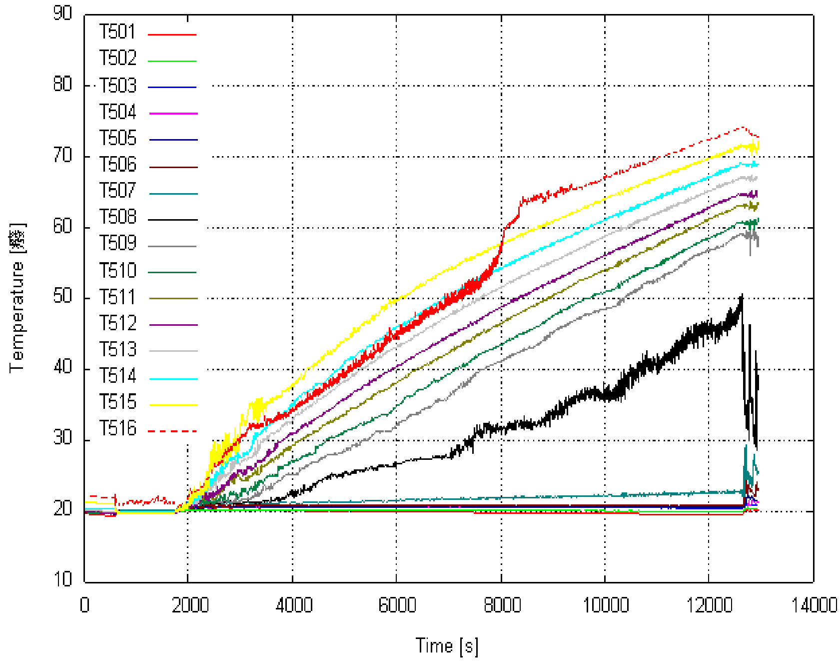


Figure 30: Pool temperature in the experiment

4.2.1 GOTHIC modeling with EHS

Similar to the approach for STR-03, a lumped simulation is used first for STR-04 to get additional boundary conditions for the 2D simulation. The lumped modeling in GOTHIC is similar to STR-03 with the schematic diagram shown in Figure 18. The steam mass flow rate, steam temperature and pressure imposed on the flow boundary are taken from experimental measurements.

4.2.1.1 Lumped simulation

A comparison of the drywell pressure between the lumped simulation and experiment is shown in Figure 31. The clearing phase is longer in the lumped simulation compared to the experiment; a behavior similar to the lumped simulation of STR-03. The calculated pressure after 5000 s is lower than the measured data, mainly because the stratification cannot be predicted by the lumped model.

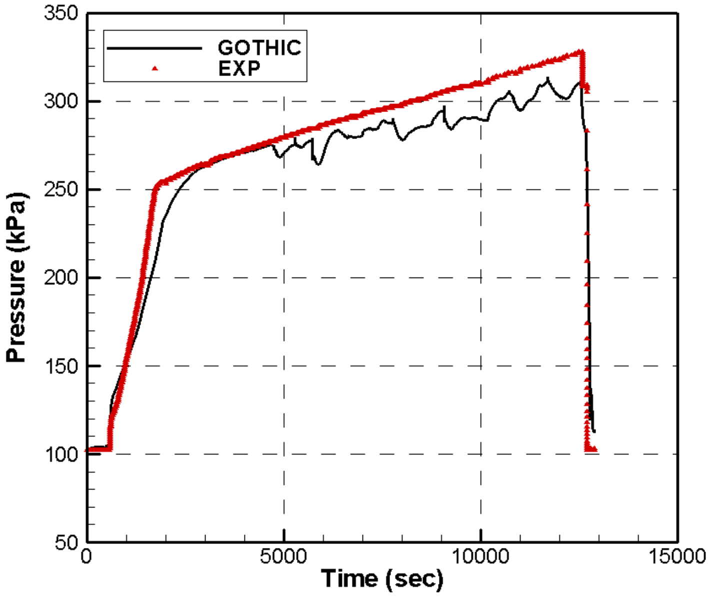


Figure 31: Drywell pressure in GOTIHC simulation and experiment

The calculated liquid temperature in the wetwell is higher than the averaged liquid temperature in the experiment, as shown in Figure 32. The final maximum deviation between the experiment and simulation is almost 5°C. The reason for this temperature difference is the under-prediction of condensation rate in the drywell, as also mentioned in the simulation against STR-03.

The vapor and liquid mass flow rate through the blowdown pipe is then obtained from lumped simulation, as shown in Figure 33. The jumps shown in the figure are due to numerical problem, which is not observed in the experiment. However, such jumps did not affect the prediction of thermal stratification, as shown later in 2D simulation. The total latent heat generated by steam through the blowdown pipe is shown in Figure 34. It is the effective heat source for 2D simulation with EHS model.

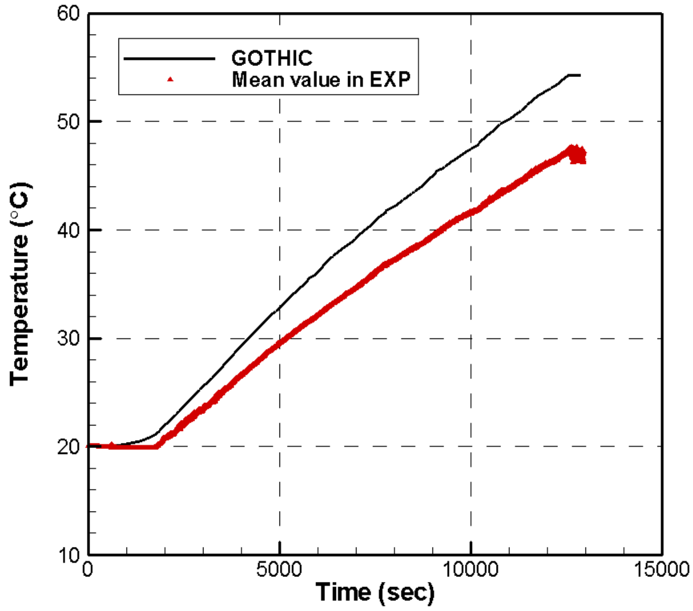


Figure 32: Predicted wetwell liquid temperature and measured averaged liquid temperature in wetwell.

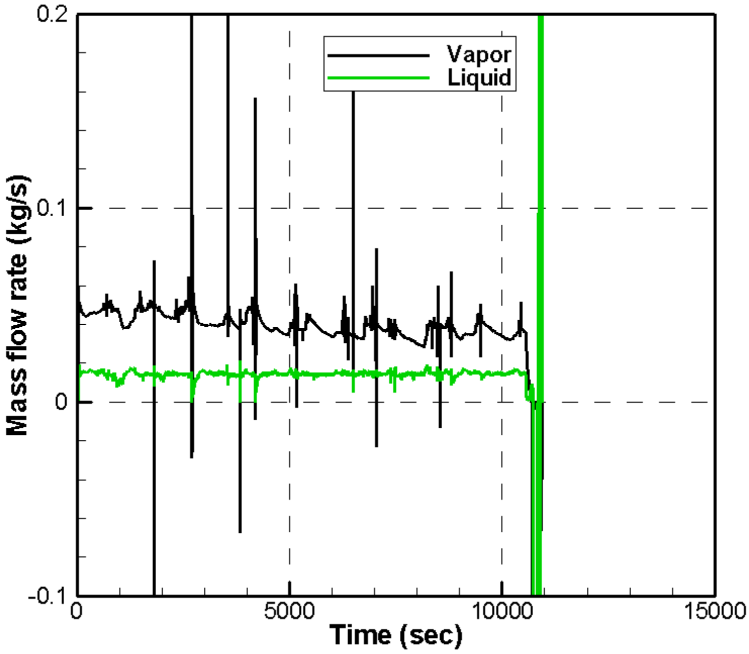


Figure 33: Mass flow rate through the blowdown pipe from the GOTHIC lumped simulation

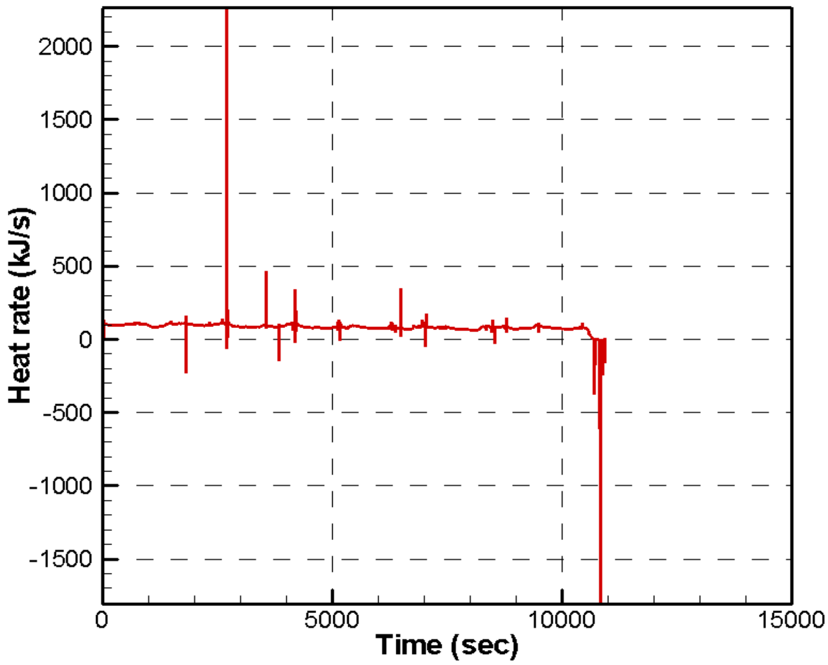


Figure 34: Calculated effective heat source based on steam flow rate through the blowdown pipe

4.2.1.2 2D simulation

The 2D modeling approach is the same as in the STR-03 test validation. The heat source is uniformly distributed on the surface of submerged part of blowdown pipe. Since the clearing phase is not accurately predicted by the lumped simulation, this phase is not considered in the 2D simulation. As observed in the experiment, the clearing phase has lasted about 2000 s. Therefore, only the transient time after 2000 s is simulated in the calculation.

The result of simulations for distribution of the temperature in the pool is shown in Figure 35. Comparison with the experimental data suggests that stratification can be reasonably well predicted by 2D simulation with the EHS model. Since the heat sources used in 2D simulation is the same as in the lumped simulations, the calculated pool temperature at the upper part is higher than that in the experiment.

Figure 36 shows the temperature profile vs. height in the simulation and experiment. The deviation between simulation and experiment can be observed clearly. The temperature increases linearly along the height at the upper part in the experiment, while it increases non-linearly in the simulation. The reason for this difference is under investigation. A possible reason is the influence of the clearing phase at the initial stage of the experiment which is not taken into account in the simulation.

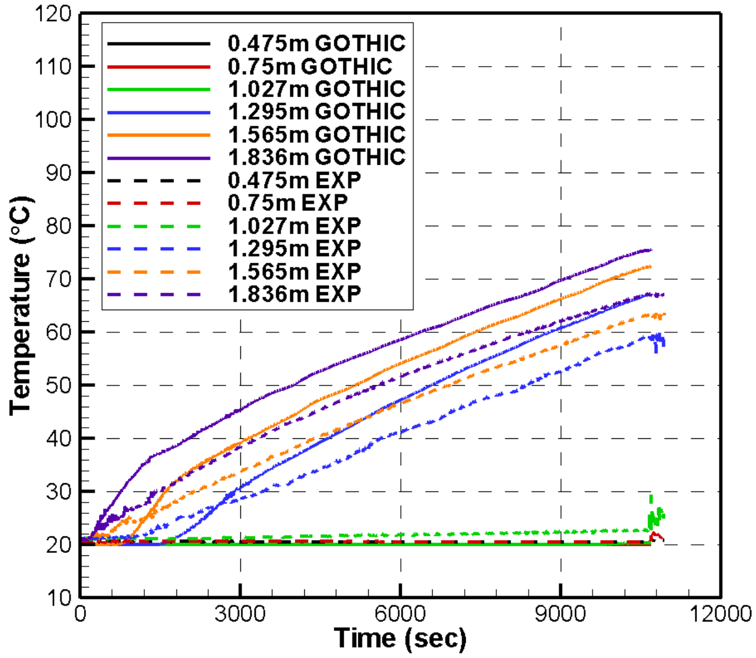


Figure 35: Comparison of temperature profile between simulation and experiment

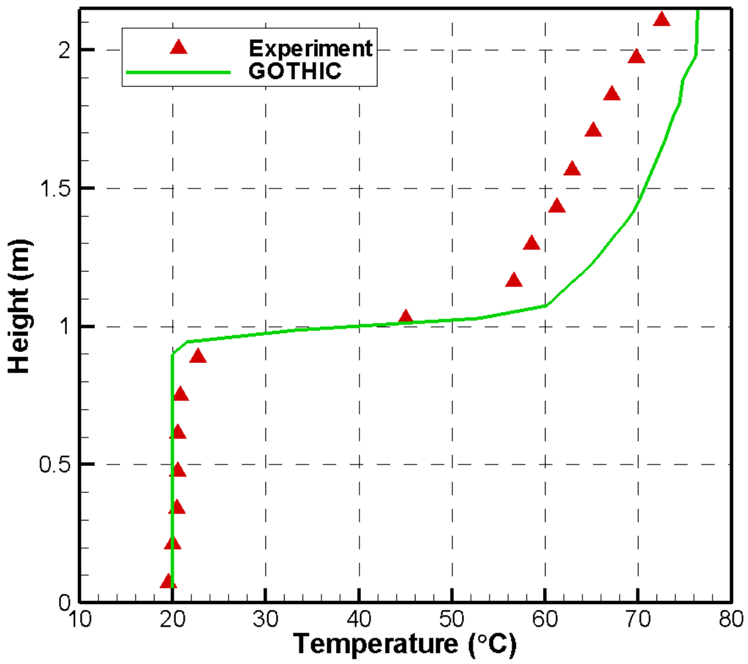


Figure 36: Temperature vs. height in simulation and experiment

5 Plant scale analysis

In this chapter, the capability of the EHS/EMS model to predict thermal stratification and mixing in a plant scale suppression pool is discussed.

5.1 Introduction to plant scale tests

It is assumed in this plant scale test that steam is directly injected into the wetwell pool water through vertical pipes with spargers. Several pipes are circumferentially distributed in the water pool. The spargers are grouped by four pipes controlled by one pressure relief valve. At about few meters above the pipe outlet, a load reduction ring is installed. The holes on the sparger surface have relatively small diameters and the steam is released out from the holes in the horizontal radial direction. The holes of the spargers and the load reduction ring are submerged in the water. During the test, the valve is open and steam is released through only four pipes to the wetwell. In this case, the steam injection is not axisymmetric. The steam mass flow rate is about 10 kg/s and it lasts for 1000 seconds. Then the residual heat removal (RHR) pump starts to supply the 200 kg/s from the strainer to the nozzle mixer in the pool, until the mixing is obtained.

5.2 GOTHIC simulation with EHS/EMS

The simulation has several assumptions for cylindrical water pool experiment with steam injection.

- The pool walls are thermally insulated.
- The complex structure in the water pool is not considered and only the cylindrical geometry is modeled by a blockage in GOTHIC.
- Heat exchange through the pipe wall of the sparger is ignored. Most heat of steam is transferred to the water outside the sparger by direct contact condensation.
- The condensation map and relevant experiments shows that the steam is condensed in quasi steady flow regime in near vicinity of exit holes. The momentum induced by steam injection through the sparger is not considered in the simulation.
- The mass influx due to steam injection is ignored in the simulation, since it is small compared to the inventory of the water in the pool.

The schematic of the GOTHIC simulation and pumps arrangement are shown in Figure 37a. The diameter of the tank is 20 m and height of the tank is 19 m with 6 m height of water. Blockages are used to generate a cylindrical shape for the tank. The grid of volume 1 is shown in Figure 37b. A uniform grid of 20×20 is used in the XY plane and 19 levels are used in the Z direction, 12 for water and 7 for vapor.

The Effective Heat Source model is implemented with two heaters. The heaters supply the equivalent heat source to the injected steam and are located at the same level as the pipe outlet.

The nozzle mixer is modeled by a pump located on the flow path. The flow path has the same flow area as the nozzle and the pump can supply the 200 kg/s water. The pump is also located at the level of the pipe outlet.

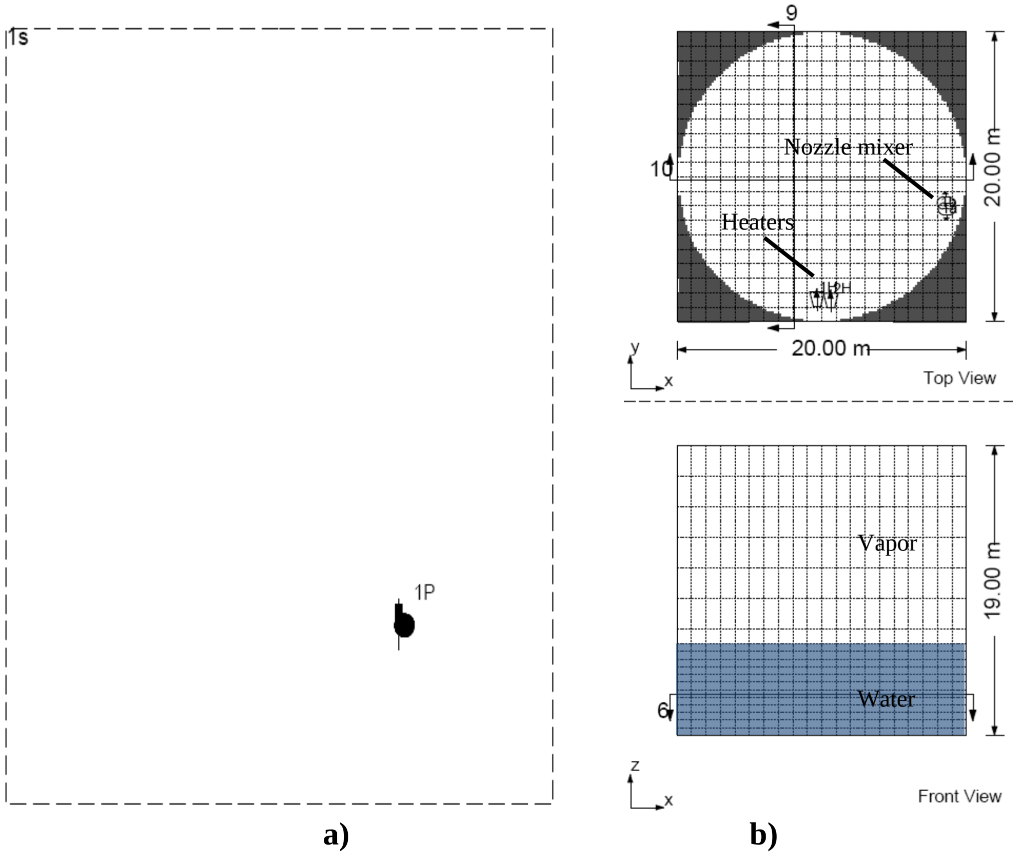


Figure 37: GOTHIC simulation. a) schematic, b) grid configuration.

5.3 Results and discussion

Figure 38 shows the temperature change at the center of different levels in the simulation. It can be seen that thermal stratification is predicted in the first 1000 seconds. The temperature in the part below the pipe outlet (z=1 to 6) is not changing, while the temperature in the upper part (z=7 to 12) has increased. The temperature at the top water layer has reached about 28.5°C. After 1000 s, the steam injection stopped, and then the momentum introduced by the nozzle mixer starts to mix the pool. The temperature in the upper part decreases to around 23°C while the temperature in the lower part increases to the same value. At about 2600 seconds, temperatures in both upper and lower layers remain at 23°C, indicating a complete thermal mixing in the pool.

Figure 39 shows the temperature fields with superimposed velocity profiles on the XZ and YZ planes that intersect at the center of the pool. In Figure 39a at 1000 s, the temperature and velocity plots indicate that hot water flows up and spreads on the water surface and along the side walls, and then the lower part is heated up by conduction from top. The velocity direction shows that the water circulation in the pool is from the location of the heaters to the top, and then back to the bottom.

The temperature and flow fields during the mixing phase are shown in Figure 39b and Figure 39c. When the heaters are turned-off, the water pool starts to mix. The velocity fields also show the unsteady behavior of the global circulation that effectively results in thermal mixing of the pool.

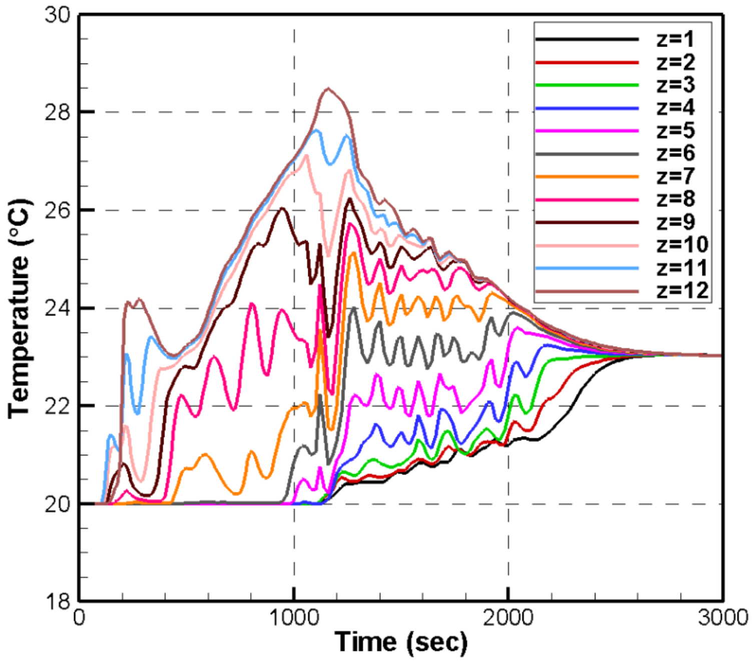
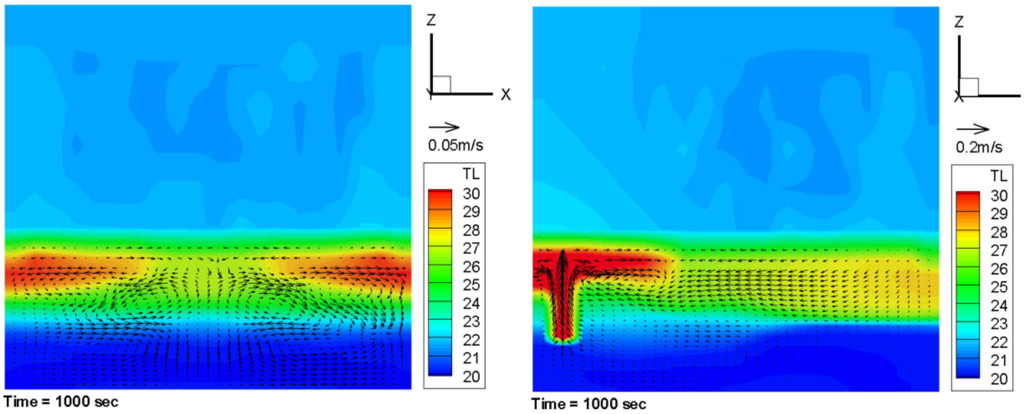
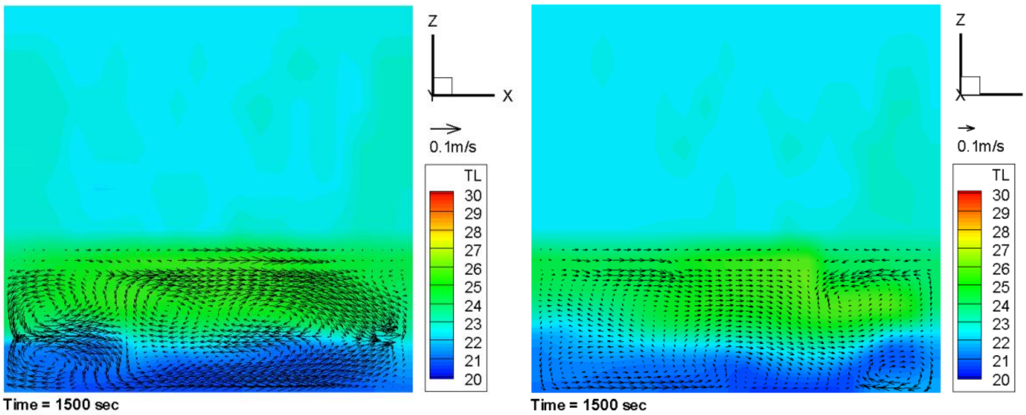


Figure 38: Liquid temperature history at different levels (z=1 to 12) predicted with EHS/EMS model by GOTHIC

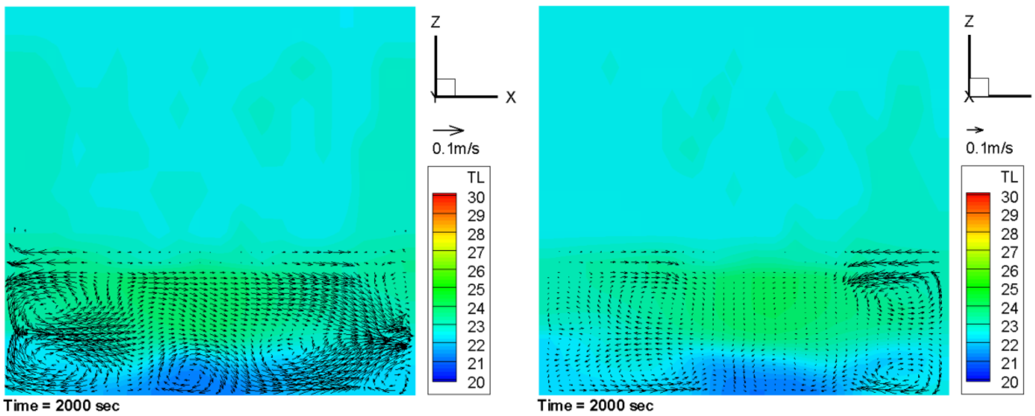
Figure 40a shows the water circulation in the pool at 1000 seconds. The liquid particle trajectories start from the heater location, as indicated by the red dot, and follow streamlines vertically to the top and then showing a complex flow structure in the pool. This pattern of the circulation is due to buoyancy forces induced by the effective heat sources. At 1500 s and 2000 s, a global large scale circulation is established in the pool. The flow is driven by the pump, which supplies the effective momentum source with a horizontal direction, as shown in Figure 40b and Figure 40c. This global circulation results in complete thermal mixing in the pool



a)

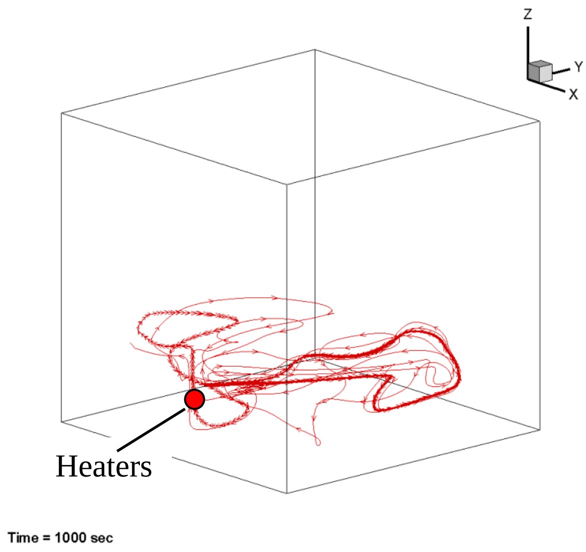


b)

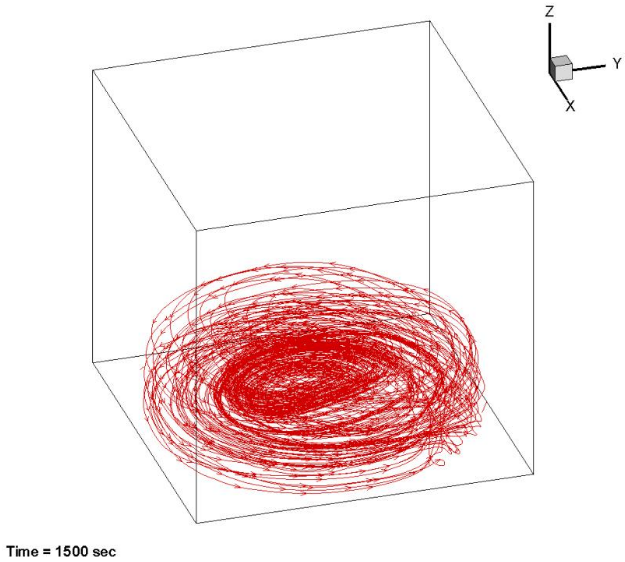


c)

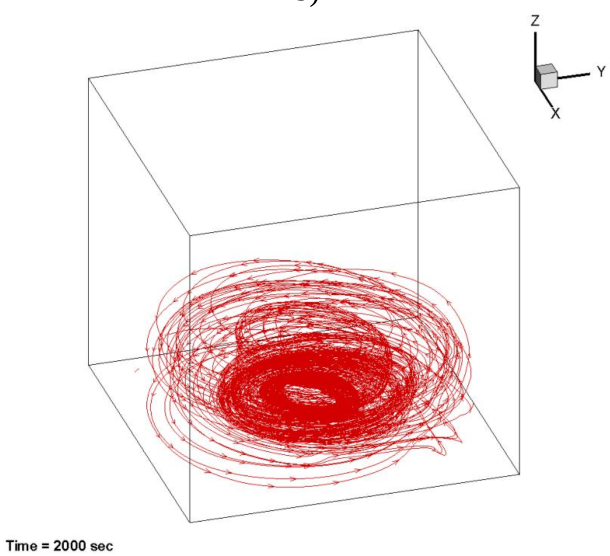
Figure 39: Temperature fields with superimposed velocity profiles at a) 1000 s, b) 1500 s, c) 2000 s.



a)



b)



c)

Figure 40: A sampled set of streamlines at a) 1000 s, b) 1500 s, c) 2000 s.

6 SUMMARY AND OUTLOOK

Main results of the present work can be summarized as follows:

(i) The reliable and computationally affordable prediction of time scales for development of thermal stratification and mixing in case of steam injection into a large subcooled pool is a challenging problem for contemporary simulation methods. Major problems are due to long time of the plant transients, complex geometry, complex physics of mixed (forced/natural) turbulent convection at high Rayleigh numbers, and potential instabilities in direct contact condensation of steam in different flow regimes.

(ii) The effective heat source (EHS) model and the effective momentum source (EMS) model are proposed and further developed for prediction of thermal stratification and mixing dynamics in the pool. The EHS model is used to provide thermal effect of steam injection on the pool, preserving heat and mass balance. The EMS model is used to simulate momentum induced by steam injection in different flow regimes. The EMS model is based on the combination of (a) synthetic jet theory, which predicts effective momentum if amplitude and frequency of flow oscillations in the pipe are given, and (b) model proposed by Aya and Nariai for prediction of the amplitude and frequency of oscillations at given pool temperature and steam mass flux (see Chapter 2 for details). The models are used in the containment thermal-hydraulic code GOTHIC.

(iii) The data from POOLEX STB-21 and PPOOLEX STR-03 and STR-04 tests carried out at Lappeenranta University of Technology (LUT) were used for validation of the EHS and EMS models. A separate effect validation strategy was applied to synthetic jet and Aya and Nariai models. First, the frequency and amplitude of oscillations in the blowdown pipe were estimated based on the measurements of the temperatures at different elevations in the pipe. Second, the amplitude and frequency were used (a) to calculate the effective momentum according to synthetic jet model and to validate prediction of stratification and mixing with the estimated momentum, and (b) to validate Aya and Nariai model for prediction of the amplitude and frequency itself.

(iv) Unfortunately, we found that estimations of the amplitude and frequency based on available experimental data from POOLEX STB-21, and PPOOLEX experiments STR-03 and STR-04 have too large uncertainties due to poor space (~1m) and time (~1s) resolution of the temperature measurements in the blowdown pipe. Nevertheless, the results demonstrated that simulations with variable effective momentum which is selected within the experimental uncertainty have provided reasonable agreement with test data on transient temperature distribution in the pool. For the improvement of the Aya and Nariai model more accurate experimental data on the dynamics of the free surface is necessary.

(v) The validation of EHS/EMS models against PPOOLEX experiments STR-03 and STR-04 includes prediction of the steam flow in the drywell. A lumped simulation is performed first to obtain boundary conditions for the steam flow from the drywell to the wetwell in 2D simulation. We found that modeling the drywell with 3D instead of 2D or lumped can improve the prediction of the air clearing phase, which in turn can affect the ensuing stratification development. In general, results of 2D wetwell simulation have shown that stratification development can be predicted with the EHS model.

(vi) We found that different approaches to the implementation of the EHS model can change temperature distribution in the stratified layer. Specifically, we obtain uniform temperature distribution in the upper layer of the pool if effective heat source is imposed at the outlet of the blowdown pipe and gradient of the temperature in the stratified layer if the heat flux is distributed uniformly on the side wall of the blowdown pipe. In reality, spatial distribution of heat fluxes on the walls and at the pipe's outlet depend on the steam mass fluxes and pool conditions. Implementation of the EHS, which can take into account dynamics of the steam condensation inside the blowdown pipe and condensation regimes, is a subject for further study.

(vii) The EHS and EMS models are used for analysis of plant scale pool behavior with steam injection through the spargers and activation of mixing nozzle. Time scales for development of stratification and forced mixing in the pool have been assessed.

6.1 Proposal for new tests in PPOOLEX facility

Currently, the possibility to reduce uncertainty in the simulations with EHS/EMS models is limited by the experimental data uncertainty. There it is proposed to modify the experimental procedures and measurements system in the PPOOLEX facility in order to reduce the uncertainty. Figure 41 shows a flow regime map description of the proposed test in PPOOLEX. First, a small mass flow rate is used for steam injection to produce the stratified layers in the water pool. The steam should be totally condensed in the blowdown pipe. Once the temperature difference, say, around 15 °C, is obtained between the top and the bottom layer, the steam mass flow rate should be adjusted to a large value to have an oscillation in the blowdown pipe which will result in a well-mixed pool. The well-mixing can be obtained in the chugging regime.

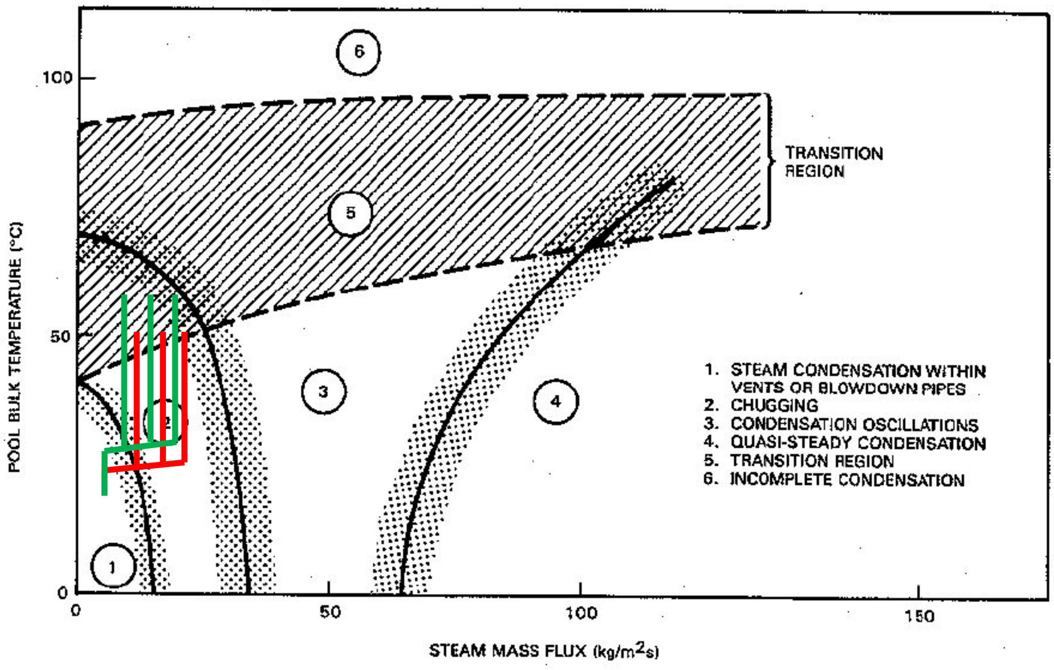


Figure 41: Condensation regime change during the proposed test.

The trend of steam mass flux change in the test is shown in Figure 42. In the tests, the steam mass flux can be changed rapidly from low value for stratification to high value for mixing. The steam mass flux is desired to be constant during chugging, in order to get a stable character of the oscillation.

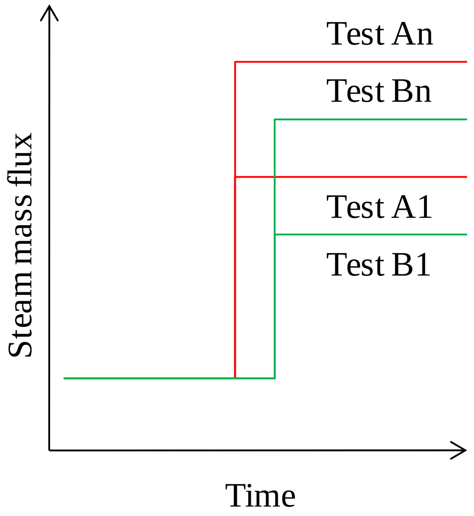


Figure 42: Steam mass flux change in proposed tests.

Table 3: Proposed PPOOLEX Test Conditions

Test NO.	Initial pool level (m)	Initial pool uniform temperature (°C)	Stratification phase			Mixing phase	
			Steam mass flow rate (g/s)	Transient time (s)	Maximum temperature difference, (°C)	Steam mass flow rate(g/s)	Transient time (s)
A-1	2.14	20	~60	~3000	15	~325	Until complete mixing achieved
A-2	2.14	20	~60	~3000	15	~375	Until complete mixing achieved
A-3	2.14	20	~60	~3000	15	~425	Until complete mixing achieved
B-1	2.14	20	~60	~4300	22	~300	Until complete mixing achieved
B-2	2.14	20	~60	~4300	22	~350	Until complete mixing achieved
B-3	2.14	20	~60	~4300	22	~400	Until complete mixing achieved

Six tests with different steam mass flow rates and transient times are proposed (see Table 3). The low initial pool temperature is needed to make sure that there is enough time for thermal stratification development and also to achieve complete-mixing in the chugging regime. The steam mass flow rate of 60 g/s is used for the phase of stratification development. This value is the same with that in STR-04 test. The transient time for stratification phase is different for tests A and tests B so the maximum temperature difference in stratified layers is also different, which in turn affects the mixing time. The steam mass flow rate for mixing phase is set in order to have a sufficient time for chugging regime.

The mixing phase of stratified layers in the tests is important for the development of EMS model as well as the phase of stratification development since the pool temperature after stratification phase will affect the condensation regime in the mixing phase. If the pool temperature is too high, it is possible that the condensation goes to transition region quickly right after a steam mass flux increase almost skipping the chugging regime (see Figure 41). Therefore, the test is preferable to have a low pool temperature, especially at the outlet of pipe. In STR-04 the stratified layers have about 23 °C of maximum temperature difference at 5000 s. The temperature of T508, where the pipe outlet is located, is about 25 °C. Since the large steam injection can cause rapid increase of pool bulk temperature and may change the condensation regime, the lower temperature of T508 will allow the condensation regime to stay longer in chugging regimes when steam mass flux changes to a large value.

Based on the previous PPOOLEX tests, the steam mass flow rate proposed for the mixing phase, which is around 0.3-0.425 kg/s, can effectively result to a complete mixing.

A fine resolution both in space and time for TC measurement is needed to get an accurate effective momentum. Similar to STR 09-11 tests, the recommended space interval for thermocouples is between 0.05-0.2 m, and the TC acquisition rate is higher than 10 Hz. Assuming that the liquid-air oscillation in the blowdown pipe follows a sinusoidal pattern (say, elevation=amplitude*sin(frequency*time)) with typical values from the experiment, amplitude = 1 m and frequency = 0.6 Hz, the norm error between the analytical velocity and the calculated velocity (with TC acquisition rate of 10 Hz and 0.1 m TC space interval) is 0.08 which is about 4% average error in velocity measurement.

Additional TCs are proposed to be placed about 0.05 m and 0.1 m down from the outlet of the pipe. The goal is to measure pool temperature at the outlet of the pipe to determine condensation regime. Additionally, this should be able to determine large scale oscillation of the free surface outside of the pipe which is important in determining the amplitude of the oscillations. Heat flux sensors would be very useful in determining non-uniformity of the heat flux distribution on the outer surface of the pipe submerged in to the pool. If possible 4-5 sensors would give better idea about the heat flux distribution.

Preheating of the drywell is desired. Since this will reduce the steam condensation in the drywell during the clearing phase. And the assumed steam flow rate in the blowdown pipe (which is used as a boundary condition for the GOTHIC simulations) is close to the measured steam flow rate from the steam source, thus reducing the uncertainty in the modeling. The measured parameters, including pressure, temperature of each part (steam line, lab, drywell, blowdown pipe, wetwell), steam flow rate from steam line are also needed in the simulation. In addition, measurements of velocity under the pipe outlet, in far field (single phase) would be interesting as confirmatory data for oscillations in the pipe. PIV measurements of the flow structure in the pool (far from the pipe outlet) would be interesting for validation of the synthetic jet model.

7 ACKNOWLEDGEMENT

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Title	Effective Momentum and Heat Flux Models for Simulation of Stratification and Mixing in a Large Pool of Water
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Abstract	Performance of a boiling water reactor (BWR) containment is mostly determined by reliable operation of pressure suppression pool which serves as a heat sink to cool and condense steam released from the core vessel. Thermal stratification in the pool can significantly impede the pool's pressure suppression capacity. A source of momentum is required in order to break stratification and mix the pool. It is important to have reliable prediction of transient development of stratification and mixing in the pool in different regimes of steam injection. Previously, we have proposed to model the effect of steam injection on the mixing and stratification with the Effective Heat Source (EHS) and the Effective Momentum Source (EMS) models. The EHS model is used to provide thermal effect of steam injection on the pool, preserving heat and mass balance. The EMS model is used to simulate momentum induced by steam injection in different flow regimes. The EMS model is based on the combination of (i) synthetic jet theory, which predicts effective momentum if amplitude and frequency of flow oscillations in the pipe are given, and (ii) model proposed by Aya and Nariai for prediction of the amplitude and frequency of oscillations at a given pool temperature and steam mass flux. The complete EHS/EMS models only require the steam mass flux, initial pool bulk temperature, and design-specific parameters, to predict thermal stratification and mixing in a pressure suppression pool. In this work we use EHS/EMS models implemented in containment thermal hydraulic code GOTHIC. The POOLEX/PPOOLEX experiments (Lappeenranta University of Technology, Finland) are utilized, to (a) quantify errors due to GOTHIC's physical models and numerical schemes, (b) propose necessary improvements in GOTHIC sub-grid scale modeling, and (c) validate our proposed models. Specifically the data from POOLEX STB-21 and PPOOLEX STR-03 and STR-04 tests are used for validation of the EHS and EMS models in this work. We show that the uncertainty in model prediction is comparable with the uncertainty in the experiments. The capability of the EHS/EMS model to predict thermal stratification and mixing in a plant scale pressure suppression pool is demonstrated. Finally, a new series of PPOOLEX experimental tests is proposed to reduce experimental uncertainty and to validate more accurately the sub-models used in the EMS model.
Key words	BWR pressure suppression pool, thermal stratification, mixing, effective models, GOTHIC

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