Nordic nuclear safety research

NKS-284
ISBN 978-87-7893-359-1

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

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June 2013

Abstract

The pressure suppression pool is the most important feature of the pressure suppression system in a Boiling Water Reactor (BWR) that acts primarily as a passive heat sink during a loss of coolant accident (LOCA) or when the reactor is isolated from the main heat sink. The steam injection into the pool through the blowdown pipes can lead to short term dynamic phenomena and long term thermal transient in the pool. The development of thermal stratification or mixing in the pool is a transient phenomenon that can influence the pool's pressure suppression capacity. Different condensation regimes depending on the pool's bulk temperature and steam flow rates determine the onset of thermal stratification or erosion of stratified layers. 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 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. The data from PPOOLEX STR-06, STR-09 and STR-10 tests are used for validation of the EHS and EMS models in this work. We found that estimations of the amplitude and frequency based on available experimental data from PPOOLEX experiments STR-06, STR-09, and STR-10 have too large uncertainties due to poor space and time 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. In order to reduce uncertainty in both experimental data and EHS/EMS modeling, additional tests and modifications to the experimental procedures and measurements system in the PPOOLEX facility were proposed. Pre-test simulations were performed to aid in determining experimental conditions and procedures. Then, a new series of PPOOLEX experimental tests were carried out. A validation of EHS/EMS models against MIX-01 test is presented in this report. The results show that the clearing phase predicted with 3D drywell can match the experiment very well. The thermal stratification and mixing in MIX-01 is also well predicted in the simulation.

Key words

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

NKS-283
ISBN 978-87-7893-359-1

Electronic report, June 2013
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NKS-ENPOOL
NORTHNET-RM3

Research report

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

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Executive Summary

The pressure suppression pool is the most important feature of the pressure suppression system in a Boiling Water Reactor (BWR) that acts primarily as a passive heat sink during a loss of coolant accident (LOCA) or when the reactor is isolated from the main heat sink. The steam injection into the pool through the blowdown pipes can lead to short term dynamic phenomena and long term thermal transient in the pool. The development of thermal stratification or mixing in the pool is a transient phenomenon that can influence the pool's pressure suppression capacity. Different condensation regimes depending on the pool's bulk temperature and steam flow rates determine the onset of thermal stratification or erosion of stratified layers. 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 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. The data from PPOOLEX STR-06, STR-09 and STR-10 tests are used for validation of the EHS and EMS models in this work. We found that estimations of the amplitude and frequency based on available experimental data from PPOOLEX experiments STR-06, STR-09, and STR-10 have too large uncertainties due to poor space and time 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. In order to reduce uncertainty in both experimental data and EHS/EMS modeling, additional tests and modifications to the experimental procedures and measurements system in the PPOOLEX facility were proposed. Pre-test simulations were performed to aid in determining experimental conditions and procedures. Then, a new series of PPOOLEX experimental tests were carried out. A validation of EHS/EMS models against MIX-01 test is presented in this report. The results show that the clearing phase predicted with 3D drywell can match the experiment very well. The thermal stratification and mixing in MIX-01 is also well predicted in the simulation.

1 INTRODUCTION AND BACKGROUND

1.1 Motivation

The pressure suppression pool (PSP) was designed to have the capability as a heat sink to cool and condense steam released from the core vessel and/or main steam line during loss of coolant accident (LOCA), or opening of safety relief valve in normal operation of BWRs. For the case of small flow rates of steam influx, thermal stratification could develop on the part above the blowdown pipe exit and significantly impede the pool's pressure suppression capacity. The pressure of containment, which is determined by the temperature of free surface of water pool in the wetwell, will increase rapidly with development of thermal stratification and cause safety issue in the containment.

Experimental study showed that once steam flow rate increases significantly, momentum introduced by the steam injection and/or periodic expansion and collapse of large steam bubbles due to direct contact condensation can erode stratified layers and lead to mixing of the pool water. However, accurate and computationally efficient prediction of the pool thermal-hydraulics with thermal stratification, mixing, and transition between them, presents a computational challenge, because the direct contact condensation, which dominates in such phenomena during the steam injection, is not fully understood and cannot be modeled correctly.

The main objective of our work is to develop and validate proposed models which can be used to simulate thermal stratification and transition to mixing phenomena during a steam injection, in a sufficiently accurate and computationally efficient manner.

1.2 Project Goals

This work implements part of the NORTHNET Roadmap 3 (Containment Thermal Hydraulics) Project goals at KTH. It contributes to the development of capability and sustenance of expertise in the area of containment thermal-hydraulics. Objectives of the current project 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 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 model Validations against PPOOLEX experimental data STR-06, STR-09 and STR-10 are performed. The new MIX-01 test with more thermocouples installed inside the blowdown pipe in the PPOOLEX facility is used for validation.

The goal of validation activity is clarification of 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 stratified pool.

1.3 Stratification and Mixing in Water Pools

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 [1].

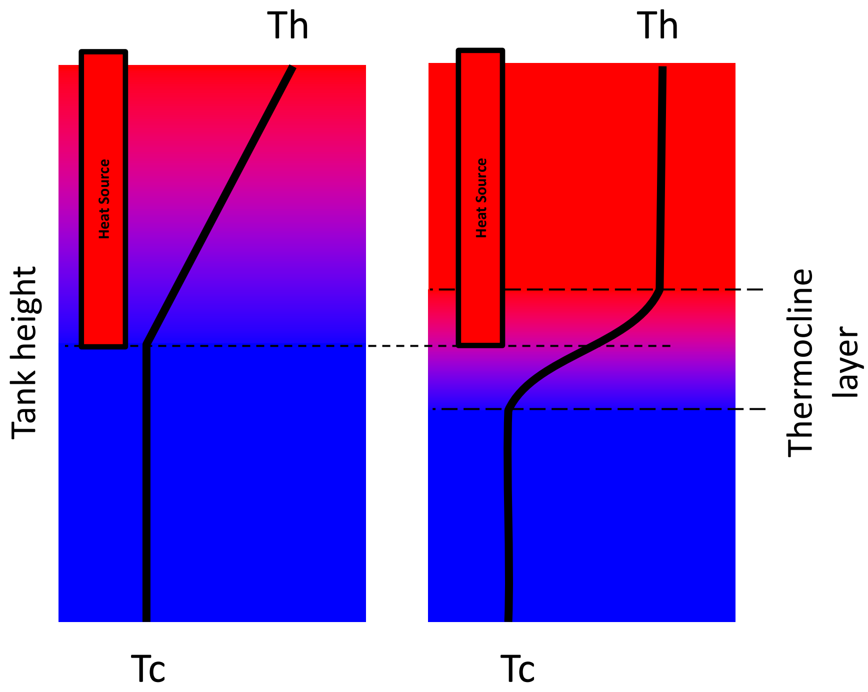


Figure 1: Typical configurations of thermal stratification in a tank:
a) developing stratification; b) thermocline layer.
Note: Th – temperature of hot liquid; Tc – temperature of cold liquid.

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 continuous increase of water temperature in the layer of the pool above the bottom of the heat source and 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 T_c to T_h (Figure 1b).

A pressure suppression pool is an important part of a BWR reactor containment safety system. It serves as a heat sink and steam condenser to prevent containment pressure buildup during loss of coolant accident (LOCA) or during safety relief valve opening in normal operations. Steam flowing out of the reactor vessel or out of the main steam line is vented through the blowdown pipes and condenses in the pressure suppression water pool. Weak mixing in the pool, such as in the case of relatively small mass flow rate of steam, may be insufficient to prevent the development of thermal stratification. As a result, the temperature of the pool surface can increase significantly. This can lead to a reduction of 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's surface temperature. An increase of the pool's surface temperature due to stratification can lead to a significant increase in containment pressure [2]. If water in the layer above the pipe outlet reaches saturation temperature, the injected steam cannot condense in this layer.

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 the suppression pool's capacity can be restored. Therefore, the characteristic mixing time scale 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's 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 [3, 4] is relatively large scale experiment which provides most complete set of data necessary for code validation.

(iii) Lumped-parameter and 1D models based on scaling approaches [2, 5, 6, 7, 8, 9, 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 stratified layer breakdown transient 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, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30] in each flow regime, and (c) design specific parameters. These models are implemented in the code 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 [2, 3, 4, 5, 6, 7, 8, 9, 10, 13, 14, 35, 36, 37, 38, 39, 40,]. Strong stratification above a heat source submerged in a water pool was observed in different tests [3, 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 [3, 4, 35, 36, 37, 38, 39, 40].

Two recent experimental efforts on the 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 [3, 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 co-workers at UC Berkeley [2, 5, 6, 7, 8, 9, 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. [2] 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 [2]. 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 scaled experimental test data was reported.

Condensation and mixing phenomena during loss of coolant accident in a scaled down pressure suppression pool of simplified boiling water reactor were also studied in [40]. Results of 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 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, 49]. Figure 2 depicts a flow regime map.

Unlike condensation oscillations, chugging [16, 50] can result in large oscillations of the steam-liquid interface which can enhance mixing [2]. Apparent influence of chugging on mixing in the pool was observed in POOLEX experiment [3]. 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. The analytical model, proposed by Aya and Nariai [51, 52] showed that the characteristic of chugging phenomena, in terms of frequency and amplitude of chugging in the pipe, can be predicted well.

Therefore an important element in development of models for predicting stratification and mixing in the BWR pressure suppression pool is how to take into account direct contact condensation of steam jet discharged into a subcooled pool. The problem of direct contact condensation has been addressed in a number of studies [17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 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.

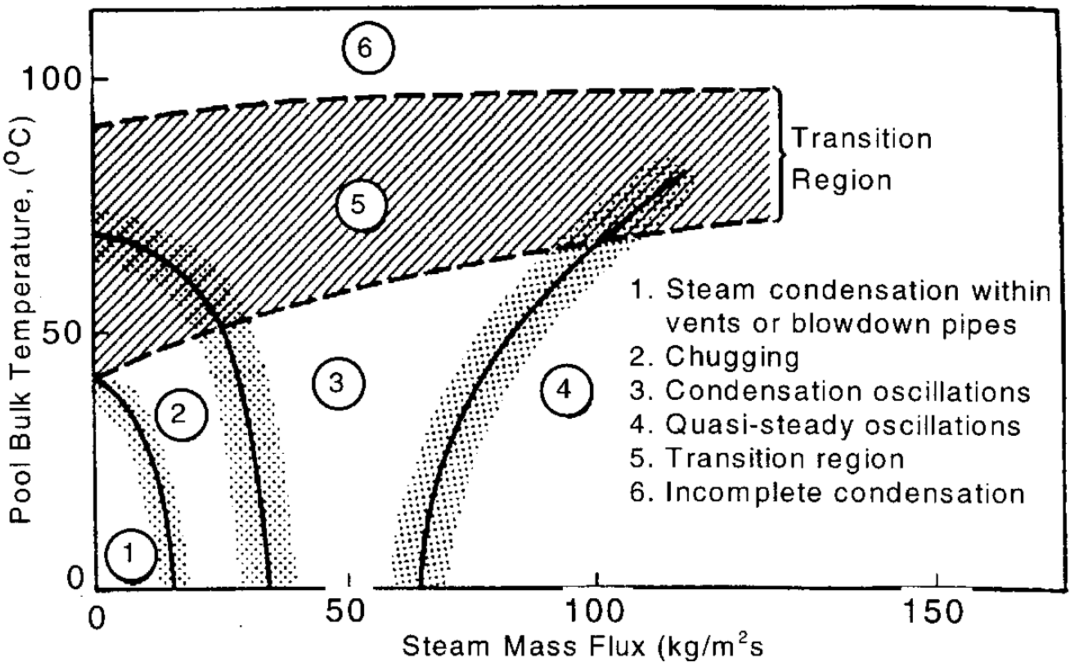


Figure 2: Regime map of steam condensation [16].

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 [53, 54, 55] 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 standard 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 [53] including the simulation of Marviken tests, which are unique full scale experiments on the venting through a pressure suppression pool in the wetwell [56]. GOTHIC has also been validated against experiments performed in large scale PANDA facility on the mixing process in the drywells gas space, initially filled with air, during the start of steam purging transient [57, 58].

GOTHIC version 7.0 was used to model five tests that were conducted in the Nuclear Power Engineering Corporation facility in Japan [59]. 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 [60]. 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 another 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 [3] 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 [3, 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.

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

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

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

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

Thus, 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 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, a review of available experimental data is presented. Then Chapter 4 provides details of the validation of the effective models against PPOOLEX STR tests, in particular, STR-06, STR-09, and STR-10. Next in Chapter 5, the effective models are also validated against new PPOOLEX MIX tests, specifically MIX-01. Finally a summary is given in Chapter 6.

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 mass 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 and condensation region. For example, if the steam mass flow rate is relatively low and 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. With a higher steam mass flow rate, the steam condensation along the blowdown pipe is not uniform, thus the effect the steam injection is modeled with a heat flux having a non-uniform distribution on the outer surface of the blowdown pipe. When the steam mass flow rate is high and most of steam condenses in the vicinity of the blowdown pipe outlet, a heat source in the vicinity of the pipe outlet is also assumed.

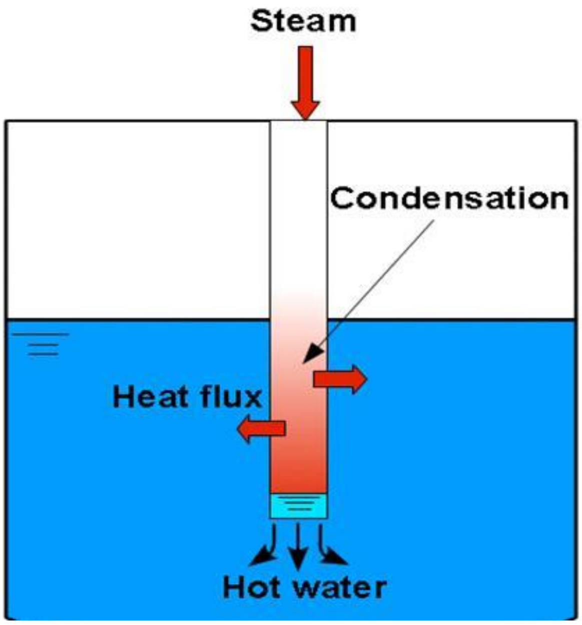


Figure 3: Schematic of Effective Heat Source (EHS) model.

Figure 3 shows the schematic of the EHS model when the steam has completely condensed inside the blowdown pipe. The heat flux through the pipe wall surface is distributed along the pipe and is directed towards the liquid part of the pool. The effective heat flux is calculated by Eq.1.

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

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 and Song [42] have provided a way to calculate the momentum from the holes of blowdown pipes, when steam injection is in a quasi-steady condensation regime. 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 is 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 [3], the momentum induced by chugging is larger than in other condensation regime and can result in faster mixing in the pool. 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 [61]. The injection phase of the small scale oscillatory flow creates a train of vortices which has enough thrust to propagate and not destroyed during the suction phase. The resulting (synthetic) jet is responsible for the far-field quasi-steady flow. Early experiments by Smith and Glezer [62] 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 [63].

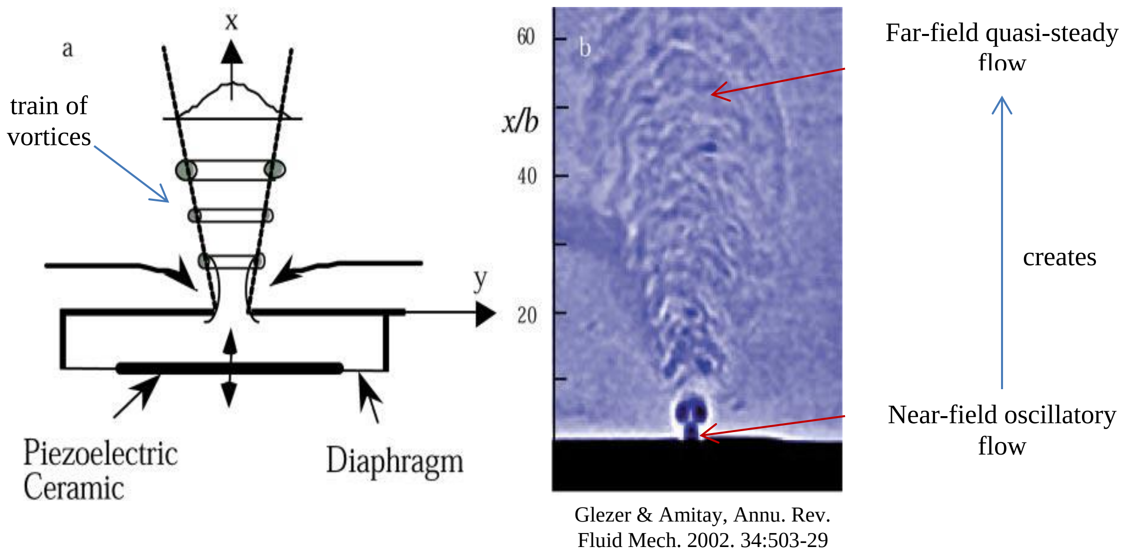


Figure 4: Synthetic jet [62].

Based on the synthetic jet theory [64], 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 rate 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].

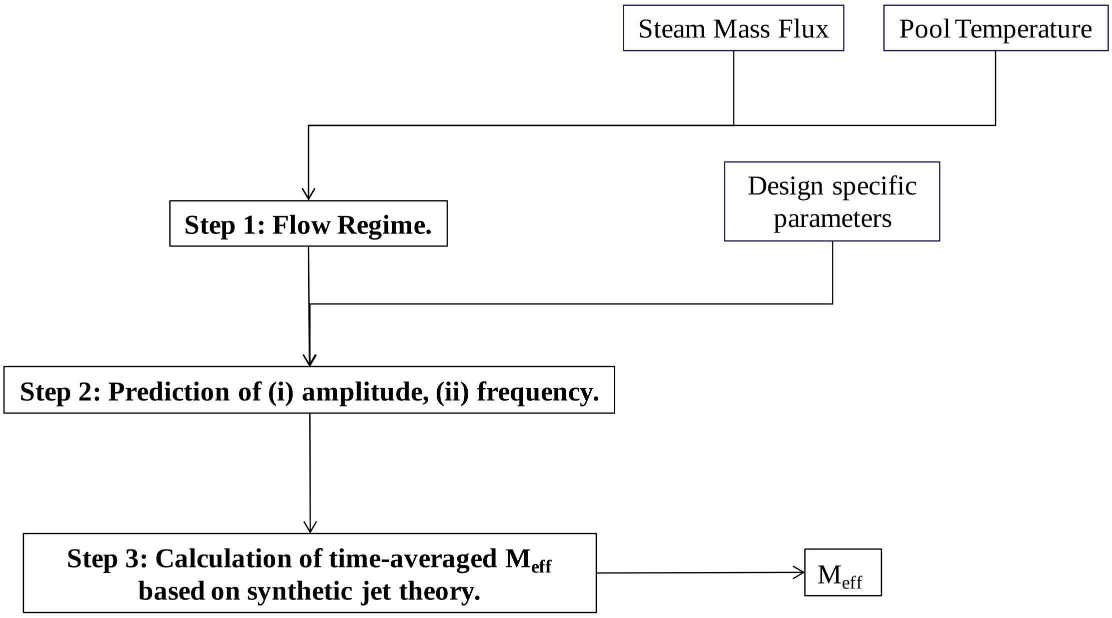


Figure 5: EMS calculation diagram.

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, 51, 52]. 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.

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

in which

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

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

where:
$\bar{z}$: the averaged water level, $\bar{z} = 0.5 z_{max}$, 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.

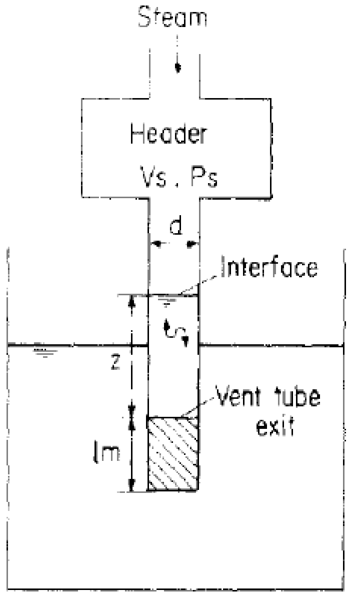


Figure 6: Analytical model for large chugging [30].

3 REVIEW OF AVAILABLE EXPERIMENTAL DATA

Several experimental tests on thermal stratification and mixing have been performed in the POOLEX and PPOOLEX facilities at LUT. The tests covered a range of mass flow rates up to almost 800 g/s and pool temperature reaching 100 °C.

3.1 POOLEX experiments

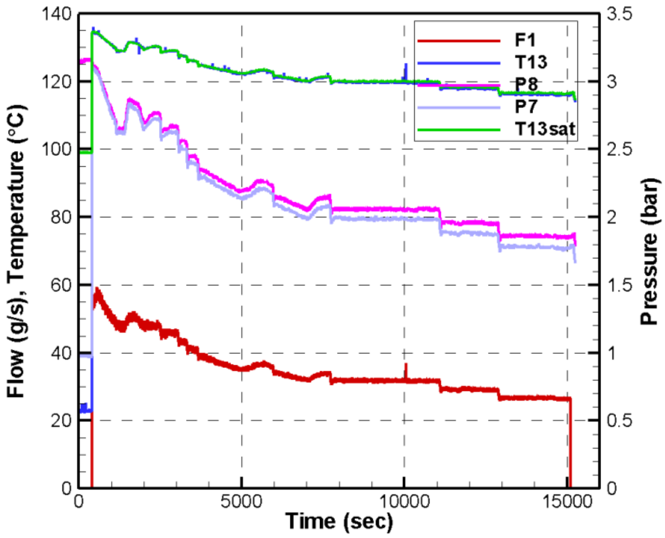
In the POOLEX experiment, steam is injected downwards into a top-open cylindrical tank through a vertical blowdown pipe [3]. The pipe is installed close to the central axis of the tank. Forty eight thermocouples are installed and distributed on three vertical rods to measure the temperature distribution at different elevations. There are 3 thermocouples installed inside the blowdown pipe, with 0.9 m space interval. Two tests were performed for investigation of thermal stratification and mixing. The measurements frequency is 1 Hz for these tests.

3.1.1 STB 20

Development of thermal stratification is observed in test STB-20. Figure 7a shows the steam conditions injected from the steam source. The steam mass flow rate is around 60 g/s to 25 g/s during the injection, in order to condense the steam completely inside the blowdown pipe. The water level in the pipe is observed to be close to the pipe outlet.

The temperature history measured by 14 thermocouples during the steam injection is shown in Figure 7b. The temperatures of the thermocouples T101 to T105, which are located below the pipe, have maintained their initial values until the end of the transient. The temperatures of the thermocouples above the pipe outlet have increased and at the end of the transient the temperature difference between the top thermocouple, T114, and the bottom thermocouple, T101, is over 35 °C.

The experimental data measured in the test STB-20 indicates the feasibility to model it with the EHS model, since the momentum induced by the hot condensate is so small and can be negligible. All the latent heat released from the injected steam can be assumed to be transferred through the pipe wall.



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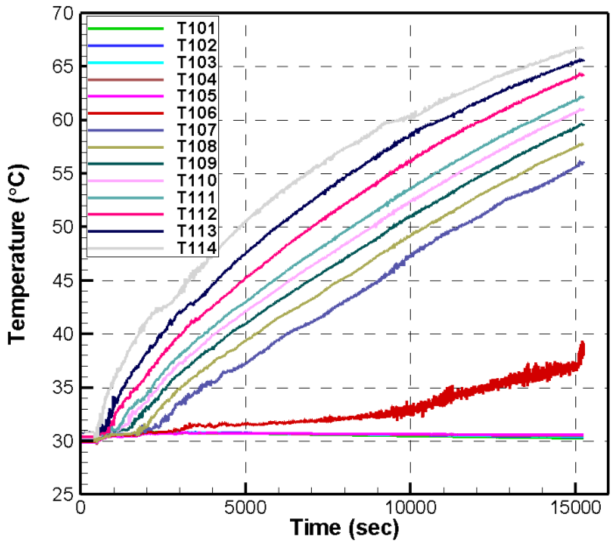


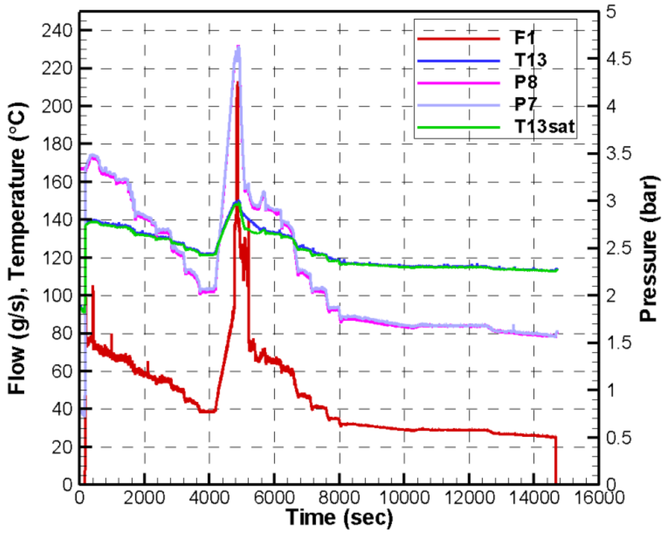
b)

Figure 7: The measured data in STB-20, a) steam conditions; b) temperature history for heating phase with steam injection.

3.1.2 STB-21

The main purpose of STB-21 is to investigate the mixing of stratified layers in the POOLEX. The steam condition is shown in Figure 8a. The steam mass flow rate decreases from 75 g/s to about 40 g/s, in order to have stratification development in the pool. Once the mass flow rate is increased rapidly to over 200 g/s, thermal mixing is obtained in about 700 seconds. After that, the mass flow rate is decreased again to allow development of thermal stratification.

Figure 8b shows the temperature measured in the blowdown pipe at three levels. The temperature oscillation implies that the water level moves up and down inside the blowdown pipe. There is no significant oscillation between 3000 s to 4000 s and high temperature is measured for the three thermocouples. This means that the water level is close to the pipe outlet and remains stable.



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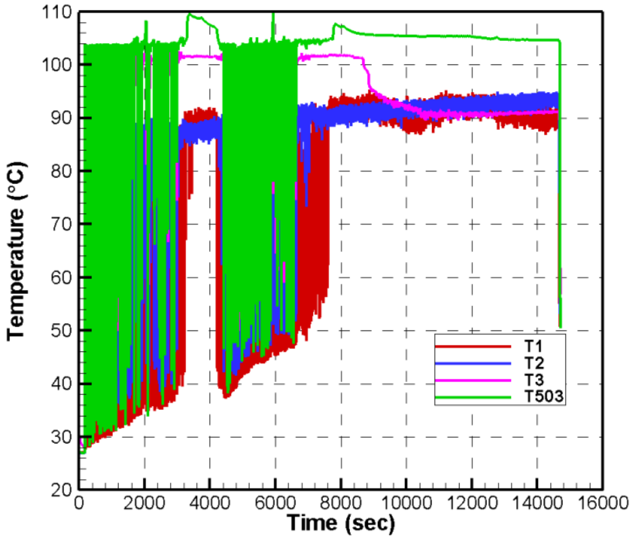

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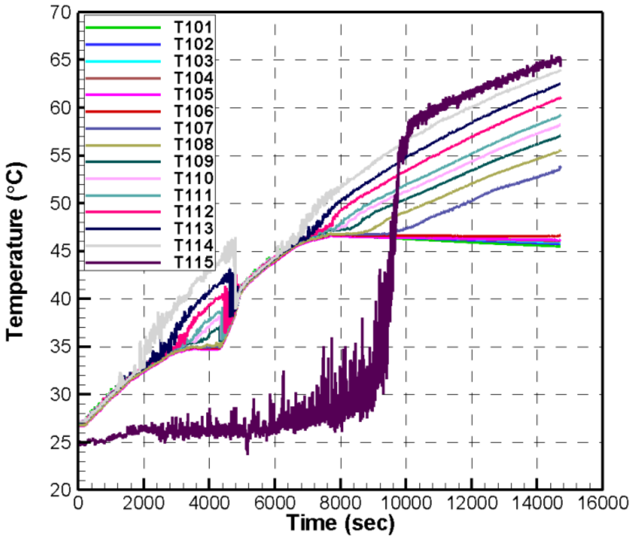


c)

Figure 8: The measured data in STB-21, a) Steam conditions; b) temperature in the blowdown pipe; c) temperature history during steam injection.

The temperature readings of 15 thermocouples are shown in Figure 8c. It shows the transition between mixing and stratification. At high steam mass flow rates, mixing is observed in the pool. With decreasing flow rates after 2000 s, stratification develops. The second mixing phase starts about 4200 s when steam mass flow rate jumps to a high value and complete mixing is obtained at 4900 s. The second stratification phase starts around 7000 s with about 45 g/s mass flow rate.

The modeling and simulation of test STB-21 can be performed with the EHS and EMS models. For the stratification part, only the EHS model is implemented, since the momentum out of the pipe is negligible. For the transition to mixing, both the EHS and EMS models are implemented that supply the heat and momentum sources, respectively.

3.2 PPOOLEX experiments

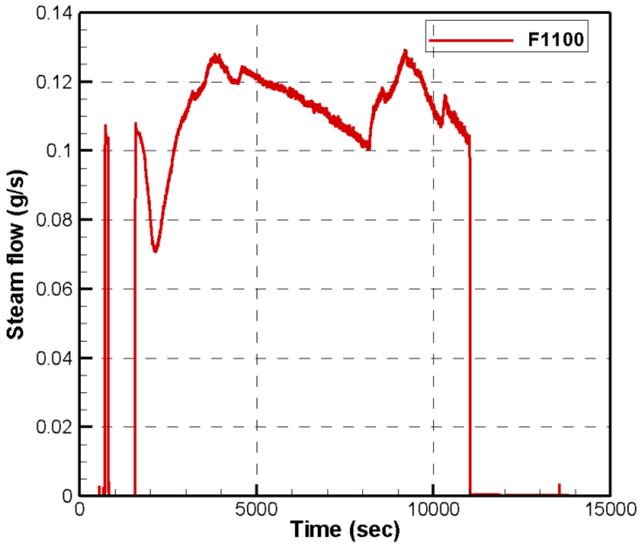
PPOOLEX has both the drywell and the wetwell, which is closer to a containment of BWRs as compared to POOLEX [4]. First, steam from the steam generator is injected through the horizontal inlet plenum, then into the drywell of PPOOLEX tank, and finally discharges into the wetwell through the vertical blowdown pipe, which is installed close to the central axis of the tank. The vacuum valve is installed between the drywell and the wetwell, in order to balance the pressure between them once the steam discharge is stopped. A total of 11 tests, STR-01 to STR-11, have been performed in PPOOLEX to investigate thermal stratification and mixing in a pool of water. STR-01 test focus was on cooling phase, during which no steam is injected. A total of 48 thermocouples are installed in the wetwell at different elevations to measure the temperature distribution in the pool. In the STR-01 to STR-08 tests, only three thermocouples are installed in the blowdown pipe with a 0.9 m interval and a measurements frequency of 1 Hz. In the STR-09 to STR-11 tests, four more thermocouples are installed in the blowdown pipe and the minimum interval of the thermocouples is 0.225 m. The frequency for data acquisition in the tests STR-09 to STR-11 is 10 Hz.

3.2.1 STR-02, STR-03 and STR-04 with stratification

The aim of tests STR-02 to STR-04 is to get data on the development of thermal stratification in the water pool. The steam mass flow rates were controlled in the tests in a way to have all steam condense inside the blowdown pipe.

Figure 9 shows the measured data in STR-02. As shown in Figure 9a, steam is injected (but shortly) around 1500 seconds with a mass flow rate of just over 0.1 kg/s. For the next 500 seconds, the steam mass flow rate is decreased to 0.07 kg/s. After that, the steam mass flow rate is maintained above 0.1 kg/s until the end of the steam injection phase. After 11000 seconds, a cooling phase is initiated in which steam injection has been halted.

In the heating phase with steam injection (see Figure 9b), the temperature in the part below the pipe is relatively constant, as shown by thermocouples T501 to T505. T506 is a thermocouple right below the pipe outlet and the temperature there increases a few degrees at the end of the transient. For the thermocouples above the pipe outlet, T507 to T516, the temperatures measured are relatively close to each other and they increase to around 90 °C at the end of the steam injection. Such thermal profile is called a thermo-cline layer.



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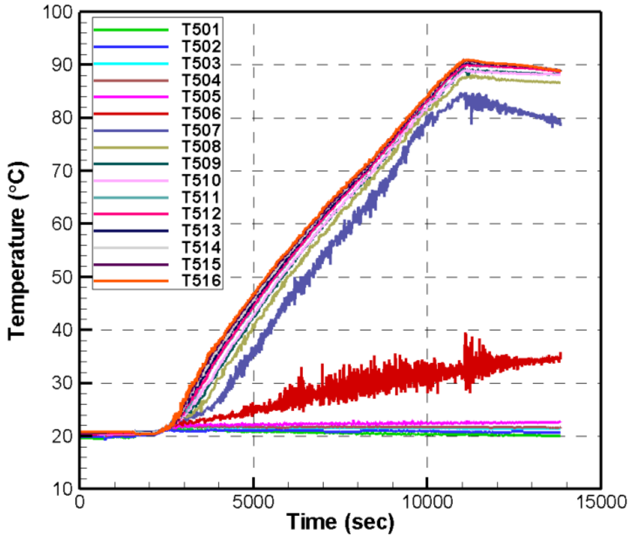
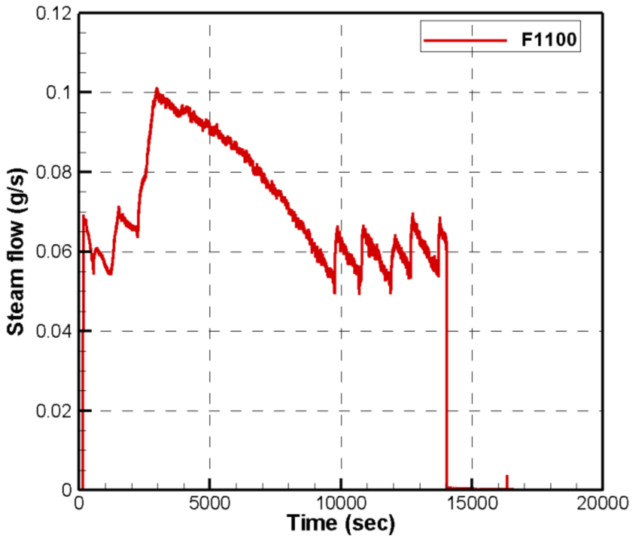


b)

Figure 9: The data in test STR-02, a) steam mass flow rate; b) temperature history

A thermocline layer is also observed in the STR-03 test, as shown in Figure 10. Figure 10a shows the steam mass flow rates in STR-03. The steam mass flow rate increases from 0.06 kg/s to 0.1 kg/s and decreases slowly to 0.06 kg/s again at 10000 seconds. After that it is maintained around 0.06 kg/s until the end of the steam injection around 14500 seconds.

Figure 10b shows the temperature history in STR-03 tests. It is similar to that in STR-02, except for the temperature at T507, where it increases and stays around 60 °C until the end of the transient.



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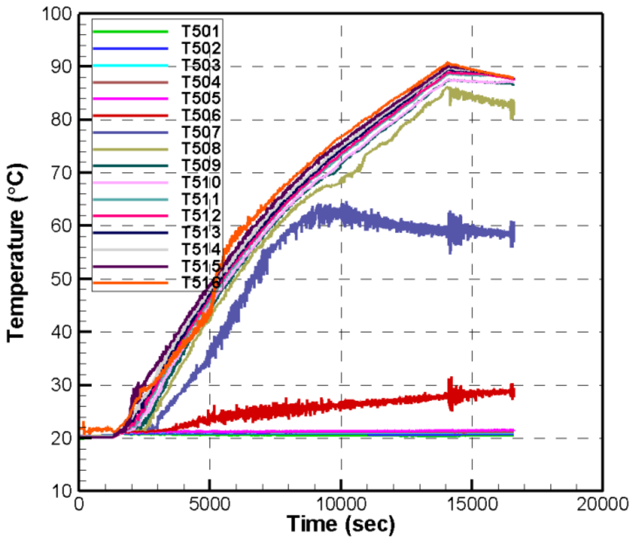
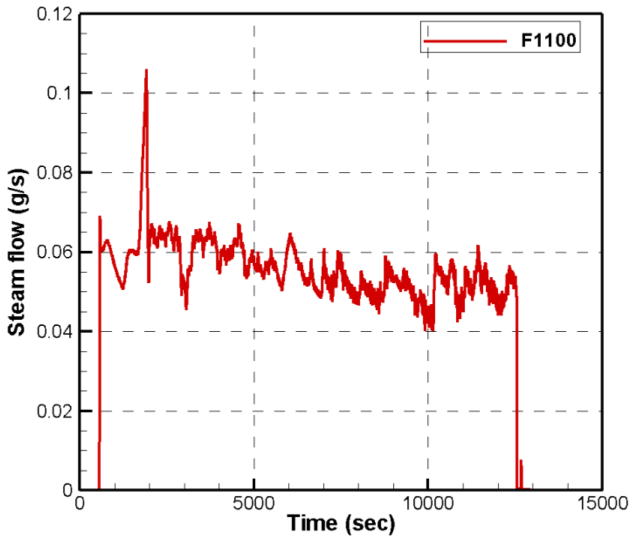


b)

Figure 10: The data in test STR-03, a) steam mass flow rate; b) temperature history

The development of thermal stratification is observed in STR-04, where low steam mass flow rates around 0.06 kg/s is maintained during the steam injection, except for a short-period peak value at 2000 seconds. Figure 11b shows the temperature history measured by thermocouples T501 to T516. The part below the pipe has a constant temperature during the injection phase while the temperatures above the pipe outlet increase along with time.



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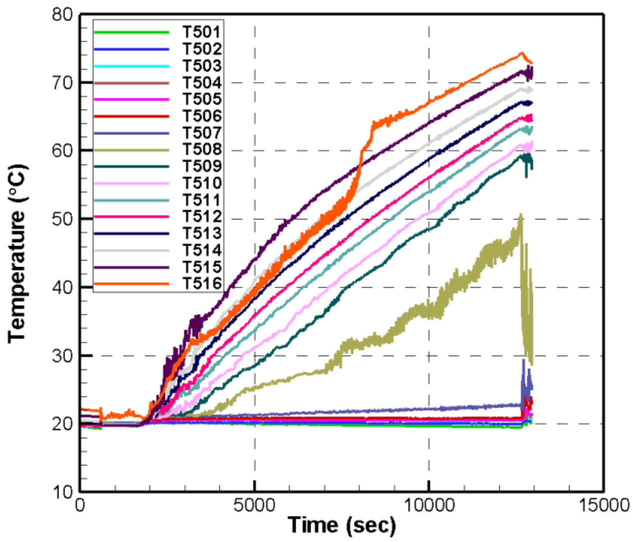


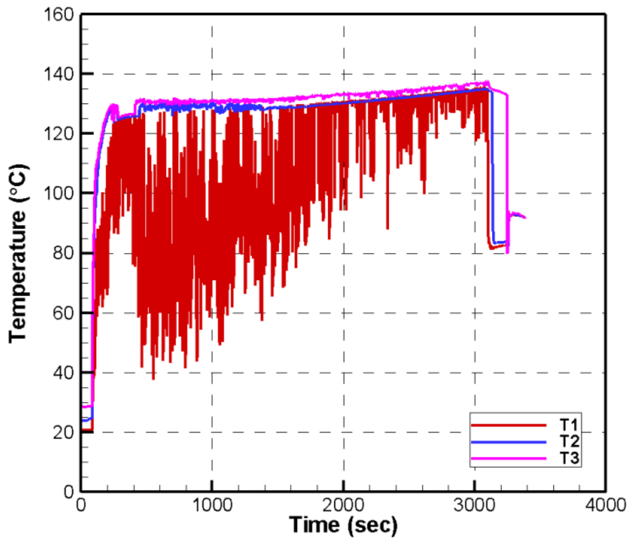
b)

Figure 11: The data in test STR-04, a) steam mass flow rate; b) temperature history

In the tests STR-02 to STR-04, it is observed that all steam entering the blowdown pipe is condensed almost completely inside the pipe. Thus, it is suitable to use the STR-02 to STR-04 data to validate the EHS model, since the momentum out of blowdown pipe is assumed to be negligible.

3.2.2 STR-05 and STR-06 with stratification after mixing

In the tests STR-05 and STR-06, oscillation of the steam-water interface is observed in the blowdown pipe and consequently mixing is achieved in the pool. Figure 12a shows the temperatures measured in the blowdown pipe in STR-05. The temperature at T1 that is located 0.1 m above the pipe exit oscillates strongly, especially before 2000 seconds. After 2000 seconds, the oscillation stops for some periods which is attributed to the transition from chugging to condensation regime. As shown in Figure 12b, all thermocouples have almost uniform temperature before 2000 seconds, and then stratification starts to develop in the pool.



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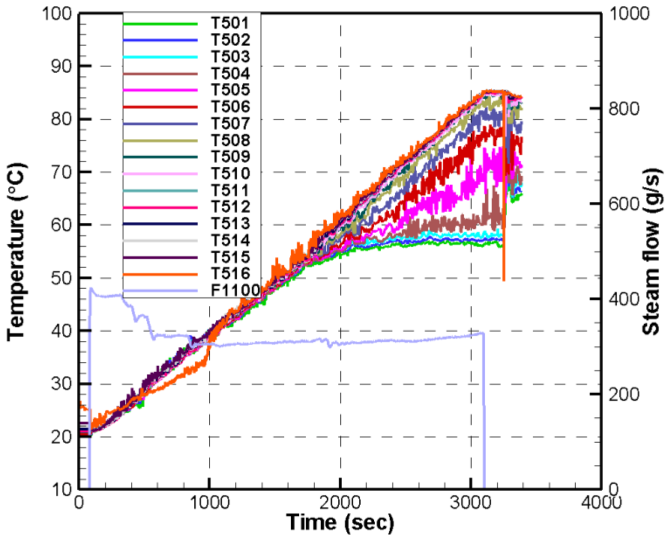

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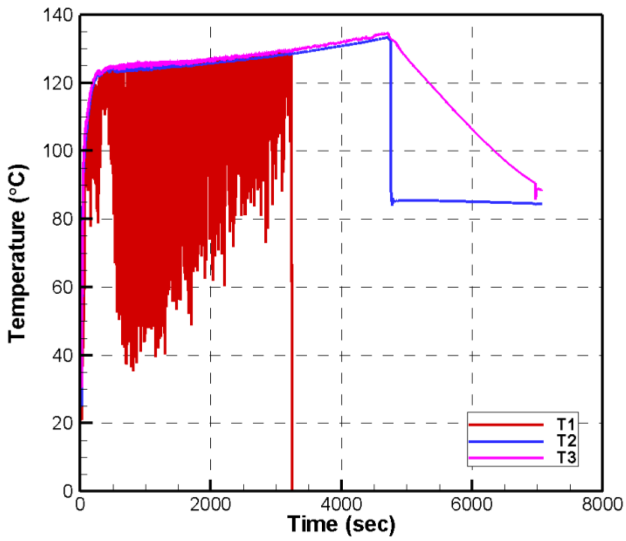
Figure 12: The data in test STR-05, a) temperature in the pipe; b) temperature history and steam flow

The transient behavior in STR-06 is generally similar to that in STR-05. The main difference is that the steam mass flow rate in the STR-06 test is maintained at around 0.2 kg/s for a long period during the mixing phase, as compared to around 0.3 kg/s in the STR-05 test. Figure 13a shows the temperatures measured in the pipe. Strong oscillations are measured at T1. However, no temperature data has been recorded for T1 after 3200 seconds, most likely because the thermocouple has been broken. It can be seen from Figure 13b that stratification starts to develop after 2000 seconds. Then steam injection is stopped at about 4500 seconds. Finally, the cooling phase without steam injection has lasted 2500 seconds.



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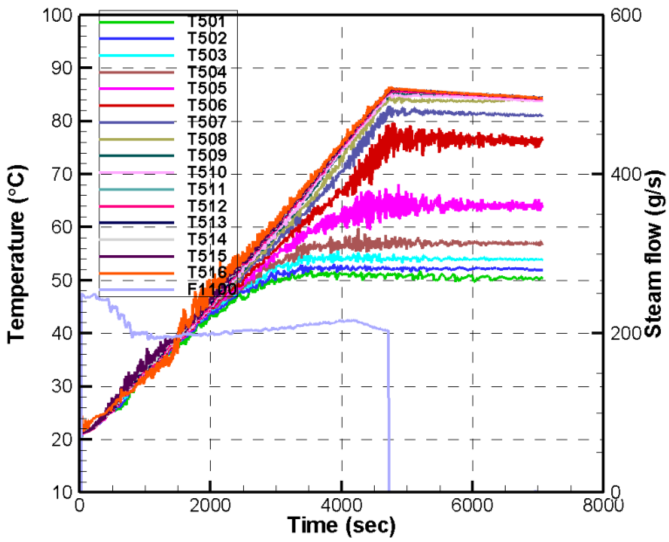


(b)

Figure 13: The data in test STR-06, a) temperature in the pipe, and b) temperature history and steam flow. The thermocouple T1 has been broken (most likely) after 3200 seconds, so no data has been recorded from this time until the end of the test.

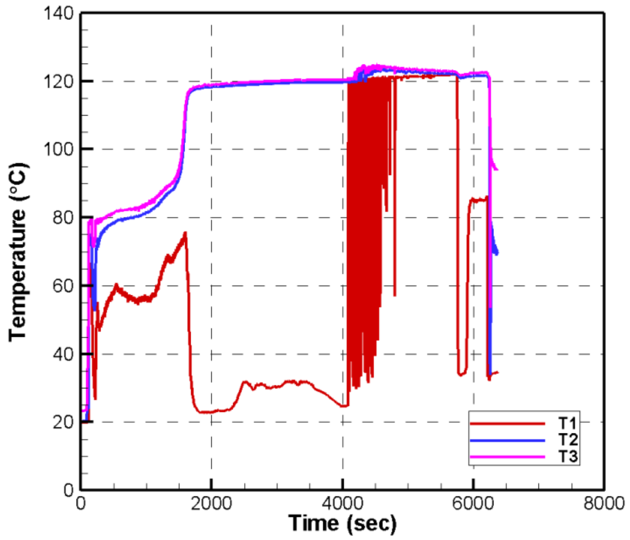
The data from STR-05 and STR-06 can be used for validation of both EMS and EHS models. For the mixing phase, the EMS and EHS models can be implemented to supply the momentum and heat sources, respectively. For the stratification phase, the EHS model can be implemented to supply the heat source.

3.2.3 STR-07-11 tests

The goal of STR-07 to STR-11 tests is to investigate the process from thermal stratification to mixing. Generally, a small steam mass flow rate is imposed to develop thermal stratification, and then the mass flow rate is increased to introduce a large momentum, in order to break up the stratification and can result in a well–mixed pool.

Figure 14 shows the temperatures measured in the test STR-07. As seen from Figure 14a, T2 and T3 have temperatures over 120 °C while T1 has low temperature before 4000 s. It indicates that T2 and T3 are surrounded by steam and T1 is submerged in the water. The water level in the blowdown pipe is located between T1 and T2, and the steam has condensed completely inside the blowdown pipe. After 4000 s, the temperature oscillation is measured by T1 indicating a water level oscillation in the pipe. At about 5000 s, all three thermocouples have temperatures over 120 °C, which means that steam flows out of the pipe and condenses in the pool.

Figure 14b shows the temperature history in the pool. Thermal stratification develops before 4000 s, and then the pool starts to mix. However, complete mixing is not achieved and thermal stratification starts to develop again at about 4500 s.



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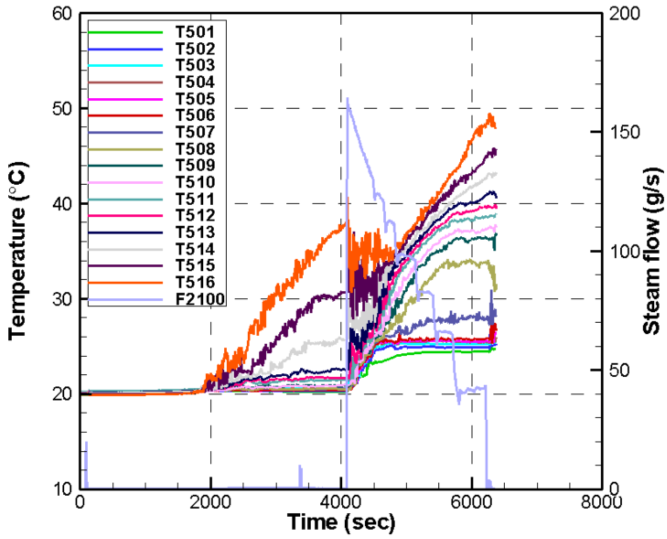


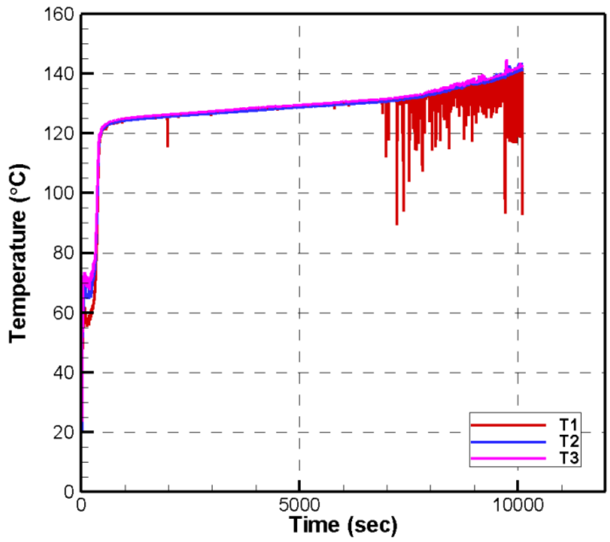
b)

Figure 14: The data in test STR-07, a) temperature in the pipe; b) temperature history and steam flow

In test STR-08, a thermocline layer is obtained first at about 6500 s. It can be seen from Figure 15a that all thermocouples in the blowdown pipe show high temperatures.

It implies that some steam could have escaped out of the pipe and condenses in the water pool. After that, oscillation is observed at T1 until the end of the test.

Figure 15b shows the temperature measured in the water pool. A thermocline layer develops from the beginning until 6500 s. The pool starts to mix when oscillation occurs in the pipe. However, complete mixing is also not achieved and the test is terminated due to some problems encountered during the experiment.



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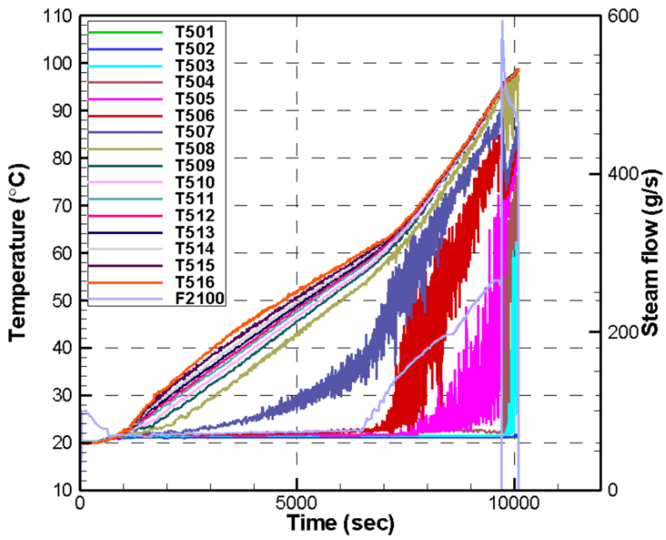

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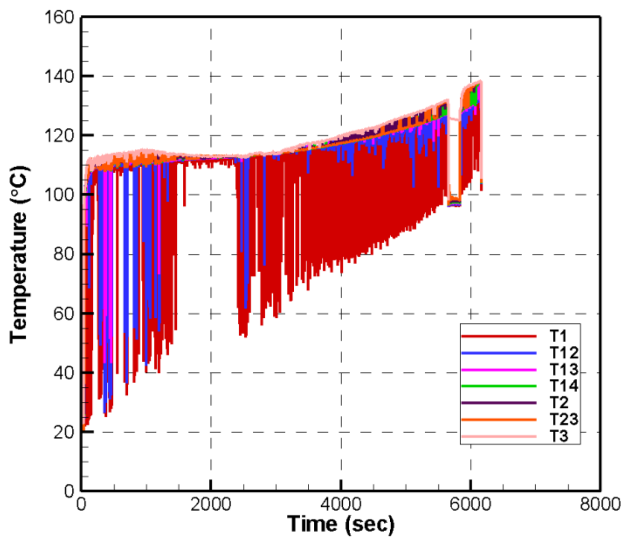
Figure 15: The data in test STR-08, a) temperature in the pipe; b) temperature history and steam flow

Four more thermocouples are installed in the blowdown pipe in test STR-09 to STR-11, in order to determine more accurately the water level inside the pipe. The frequency of measurements is also increased from 1 Hz to 10 Hz.

Figure 16a shows the temperature measured in the blowdown pipe in STR-09. At the beginning of the steam injection, the temperature oscillations are recorded at T11 and T121, which is located at 0.1 m and 0.325 m above the pipe exit, respectively. At around 1500 s, the oscillations disappear and all thermocouples indicate a high steam temperature. At about 2500 s, strong oscillation is measured at T11 until the end of the test except for a few short interruptions due to a non-monotonic increase of the steam mass flow rates (see Figure 16b).

The measured pool temperature in STR-09 is shown in Figure 16b. The first 500 s mixing is due to air injection in the clearing phase. Then the thermal stratification starts to develop. After 2500 s, mixing begins to propagate from the top of the pool water to the bottom. However, complete mixing is not achieved at the end of the test; even though high steam mass flow rates were imposed.



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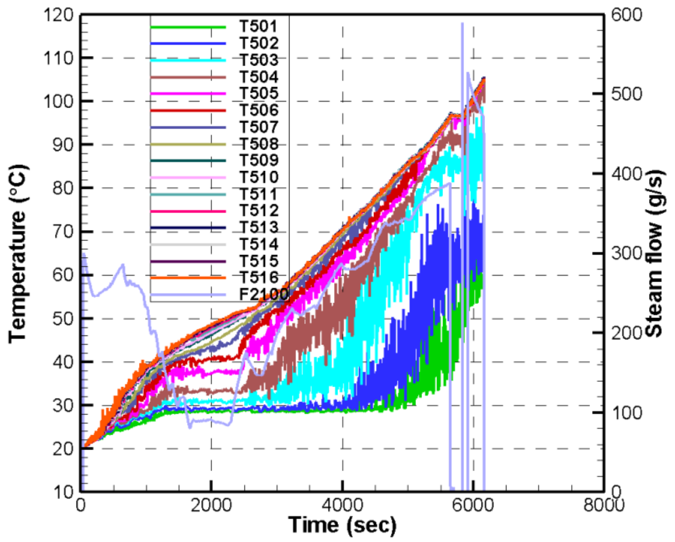
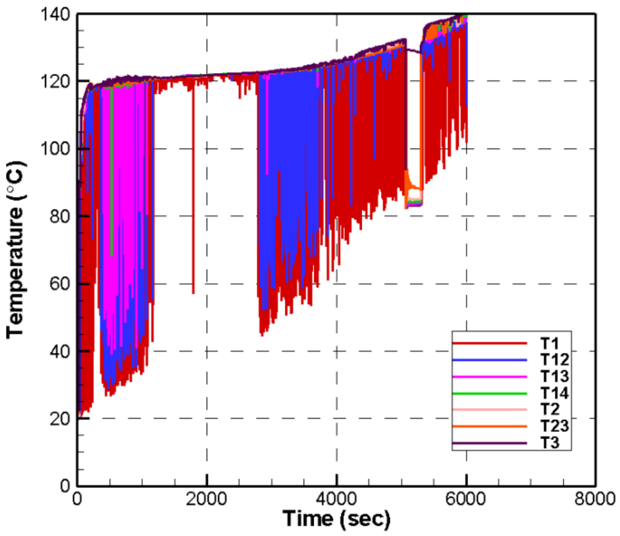


b)

Figure 16: The data in test STR-09, a) temperature in the pipe; b) temperature history and steam flow

The test STR-10 has similar test transients to test STR-09. As shown in Figure 17, oscillations are observed in the blowdown pipe. The pool temperature history shows that mixing in the clearing phase is obtained until 1200 s. Then stratification develops until about 2800 s, which is then followed by incomplete mixing. Finally, stratification starts to develop again around 3600 s until the end of the transient.

The main reason for the incomplete mixing in the tests STR-09 and STR-10 is attributed to the non-monotonic increase of the steam mass flow rates and sudden switching off of the steam flow. The STR-11 test demonstrates this quite well, see Figure 18. From a steam mass flow rate of 0.1 kg/s, a non-monotonic increase (up to 0.7 kg/s) with sudden start-stop of the steam flow is imposed. The general thermal behavior of the pool is similar to STR-10.



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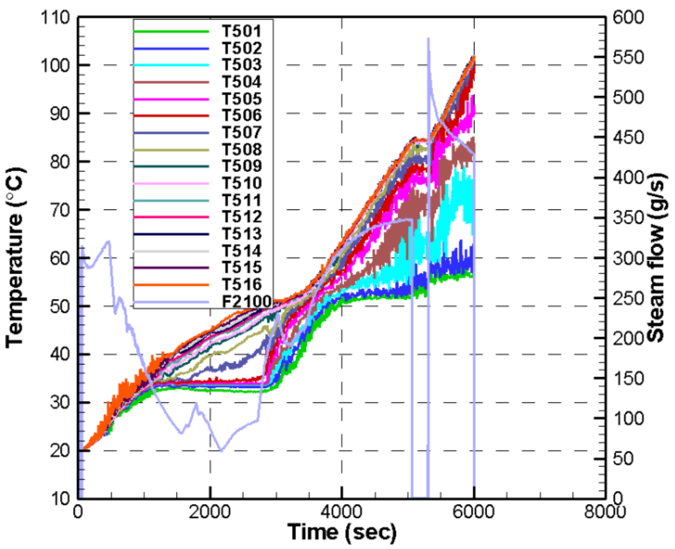

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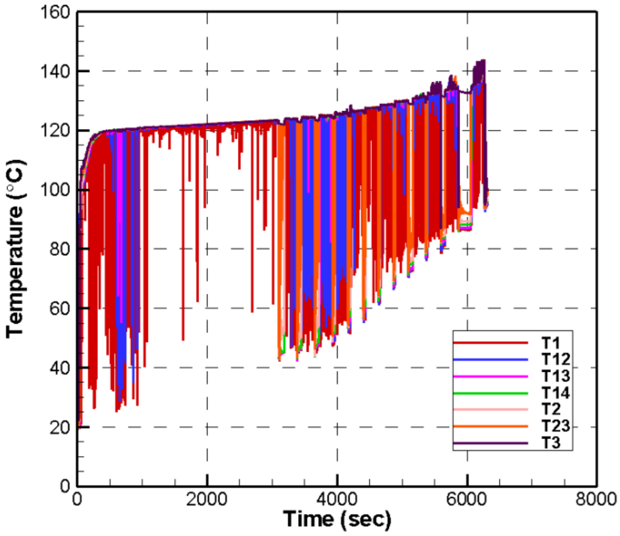
Figure 17: The data in test STR-10, a) temperature in the pipe; b) temperature history and steam flow

The EHS and EMS models can also be validated with experimental data from tests STR-07 to STR-11. The heat source produced by the steam condensation can be modeled with the EHS model and the momentum induced by steam injection can be modeled with the EMS model. The effective momentum can be estimated more accurately with these tests than the previous tests since more TC readings with higher measurement frequencies were implemented.



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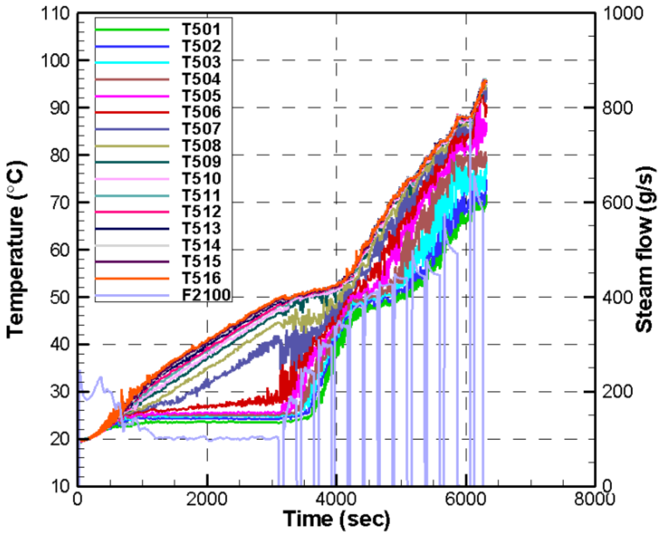

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Figure 18: The data in test STR-11, a) temperature in the pipe; b) temperature history and steam flow

4 VALIDATION OF 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 in PPOOLEX, part of the steam condenses in the drywell first and the rest of the steam rushes into the wetwell through the vertical blowdown pipe. Hence the measured steam mass flow rate from the steam source is a reduced steam mass flow rate in the blowdown pipe that is directly affecting thermal stratification and mixing. The steam mass flow rate in the blowdown pipe is not measured in the experiment and has to be estimated. With this additional complexity, the numerical simulation of PPOOLEX tests is more involved 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 (a thermocline layer has formed during the steam injection) while a stratification layer has formed in STR-04 with considerable temperature gradient between the upper layers. For both cases, validation of the EHS model is performed.

Three additional experimental tests are included in this section, STR-06, STR-09, and STR-10. In these cases, the TC readings inside the blowdown pipe indicate a period of water-level oscillations in the pipe which is a source of momentum that can erode stratification layers in the pool. Thus, both the EHS and EMS models are implemented to predict the thermal behavior of the water pool.

The schematic illustration of the steam condensation inside the blowdown pipe is shown in Figure 19. Steam directed through the blowdown pipe can condense on the walls and on the free water surface which results in 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.

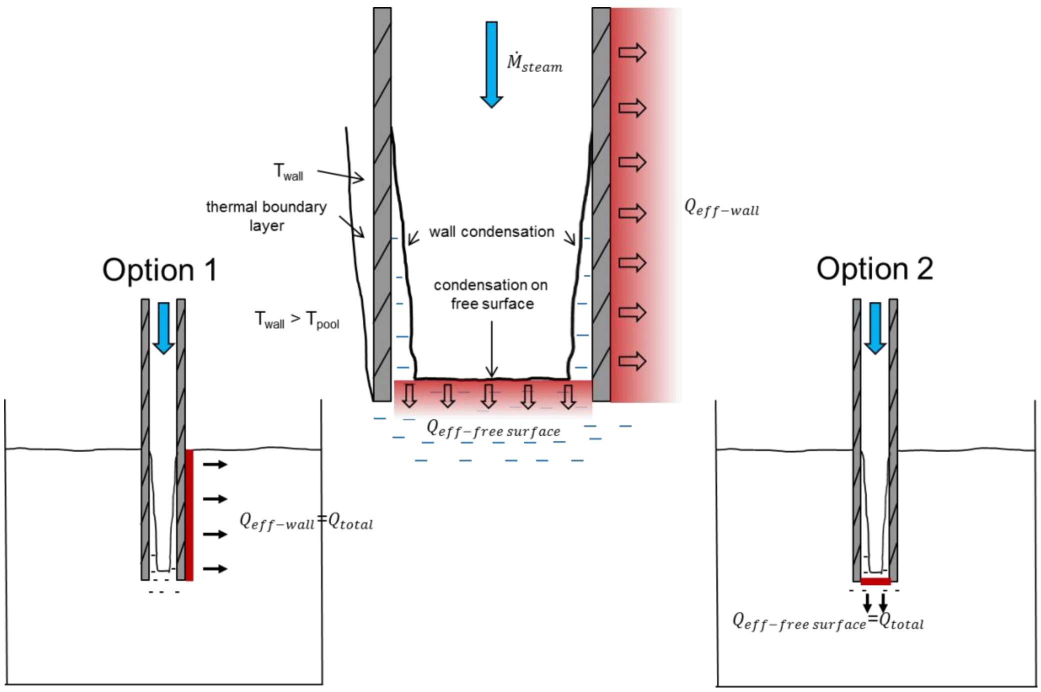


Figure 19: Simple approaches to the implementation of the EHS model.

4.1 Validation of model against STR-06

The injected steam mass flow rates imposed in test STR-06 is shown in Figure 20. A mass flow rate of 0.25 kg/s is used for clearing phase before 1000 s. After that, a mass flow rate is kept around 0.2 kg/s. Finally, steam injection is terminated at about 4700 s.

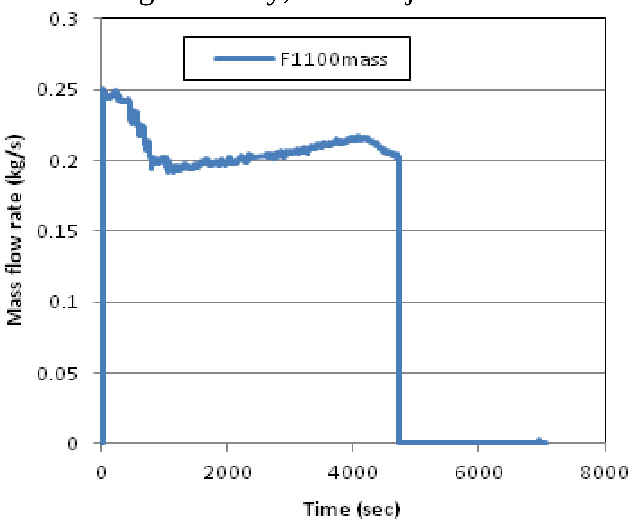


Figure 20: The steam mass flow rate used in STR-06

4.1.1 Validation of model based on synthetic jet

4.1.1.1 Momentum calculated based on synthetic jet

Figure 21 shows the condensation regions in the STR-06 test. The condensation regions in the test changes from low pool bulk temperature to high pool temperature.

It goes from region 1 (condensation within vents of pipe), to region 2 (chugging), and then to region 5 (transition region). The condensation regime map is a good indicator of the condensation regimes during an experimental test. However, the boundaries between regions or grey areas are only considered qualitative, since certain regimes can be observed in certain periods even though the corresponding conditions indicate an almost different regime, such as the early part of STR-06 test with the chugging regime.

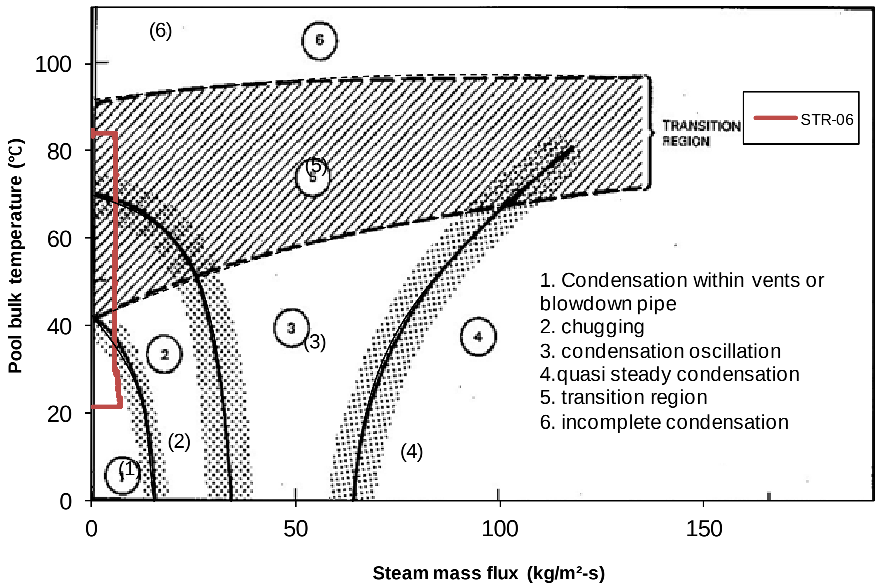


Figure 21: Condensation regime in test STR-06

The amplitude and frequency of oscillation can be estimated from the measured temperature in the blowdown pipe. As shown in Table 1, the maximum and minimum momentum rates are calculated based on the synthetic jet theory.

Table 1: Estimated momentum for different periods

Estimated Frequency and Amplitude from TC measurements in STR-06				**Momentum rate estimated with synthetic jet model**		
Time(s)	Period (s)	Frequency (Hz)	Amplitude L (m)	(m/s)	(kg-m/s^2) Min	(kg-m/s^2) Max
610-620	2-3	0.5-0.333	0.1-1.0	0.0047-0.707	0.08	18
3215-3225	2-3	0.5-0.333	0.1-1.0	0.0047-0.707	0.08	18

4.1.1.2 GOTHIC modeling with EHS/EMS

4.1.1.2.1 Lumped simulation

The corresponding GOTHIC lumped model of PPOOLEX is shown in Figure 22. 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 the wetwell, and the tank walls, are all modeled by thermal conductors. The initial temperatures for these conductors are taken from the experimental data.

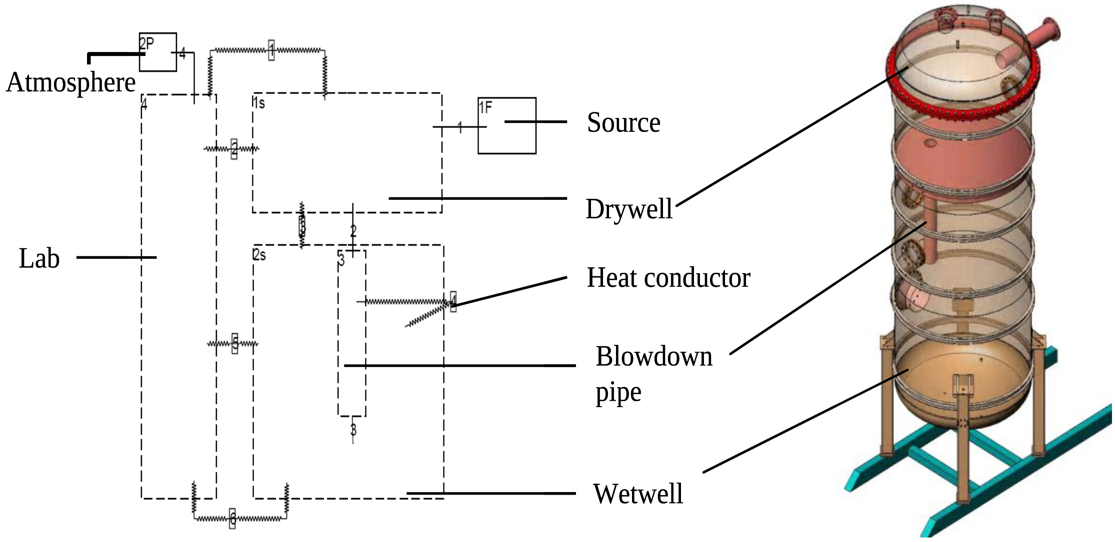


Figure 22: GOTHIC Lumped modeling for PPOOLEX facility

Figure 23 shows the comparison of averaged liquid temperature in the wetwell between the experiment and simulation. The black line is a result from a lumped GOTHIC simulation while the red dots are averaged liquid temperature measured in the experiment. In the simulation, the initial pool temperature is 20 °C which is adopted from the report [4], but the measured averaged liquid temperature is actually about 22 °C. Nevertheless, the differences in liquid temperature between the simulation and experiment throughout the transient are considered small.

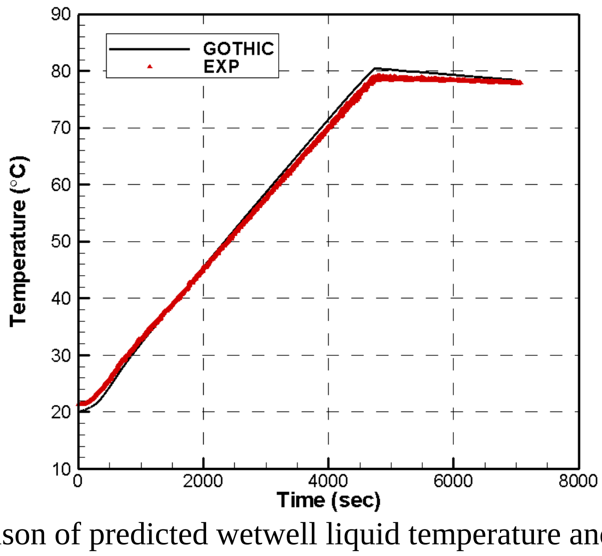


Figure 23: Comparison of predicted wetwell liquid temperature and experimental data

Figure 24 shows the predicted vapor and liquid mass flow rates through the blowdown pipe. The vapor mass flow rate is slightly lower than the injected steam mass flow rate, since some of the steam condenses in the drywell. The condensation in the drywell is indicated by the liquid mass flow rate. The oscillation on the liquid mass flow rate is observed after about 4500 s. Since the vacuum breaker is not modeled in the simulation, water can flow reversely from the wetwell to the drywell, and can cause the observed oscillation. However, the results prior to 4500 s can still be used as a boundary condition for the 2D simulation.

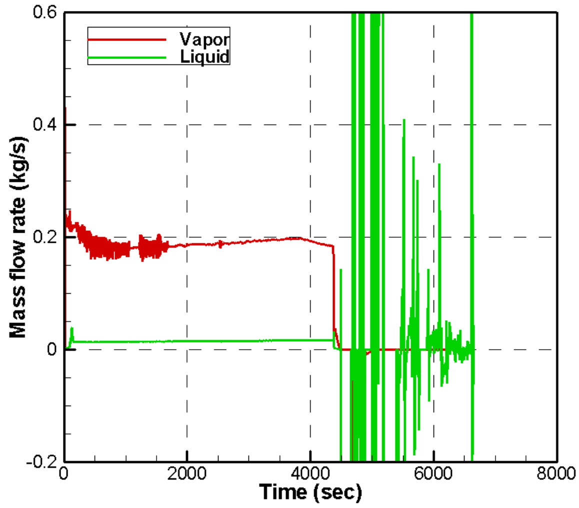
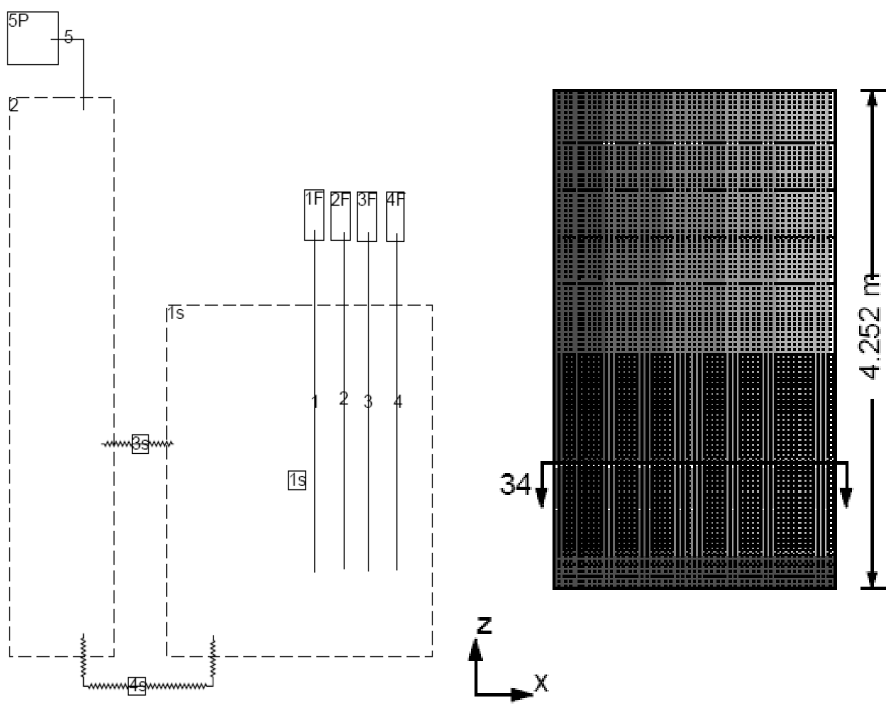


Figure 24: The mass flow rate predicted by lumped simulation

4.1.1.2.2 2D simulation



a) b)

Figure 25: GOTHIC 2D modeling and grid resolution for wetwell.

The GOTHIC 2D modeling is shown in Figure 25a while the grid resolution is shown in Figure 25b 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. A total of 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.

A thermal conductor is used to supply the heat source, which is equivalent to the steam condensation inside the pipe. Figure 26 shows the heat rate imposed on the thermal conductor. It is calculated based on the steam mass flow rate through the blowdown pipe and the latent heat of the steam.

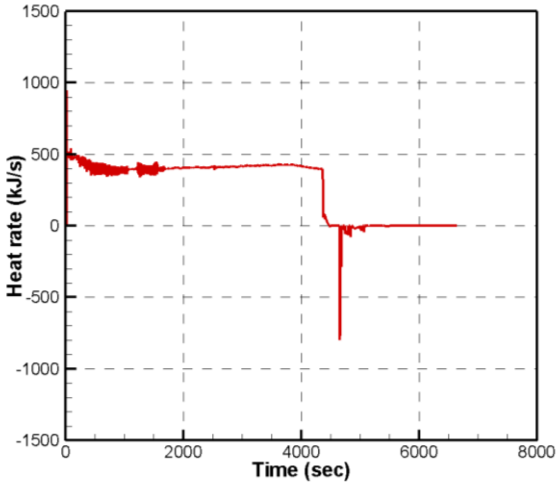


Figure 26: The heat source based on steam mass flow rate through the blowdown pipe

A pump is used to impose the momentum rate at the outlet of the pipe, with a downward direction according to the synthetic jet model. Figure 27 and Figure 28 show the simulation results with the estimated minimum momentum rate and estimated maximum momentum rate, respectively.

With an estimated minimum momentum rate, see Figure 27, the development of thermal stratification starts right in the beginning, in contrast to the thermal mixing observed in the experiment (see Figure 13b). The behavior at the end of the transient is due to the reverse flow of water from the wetwell to the drywell.

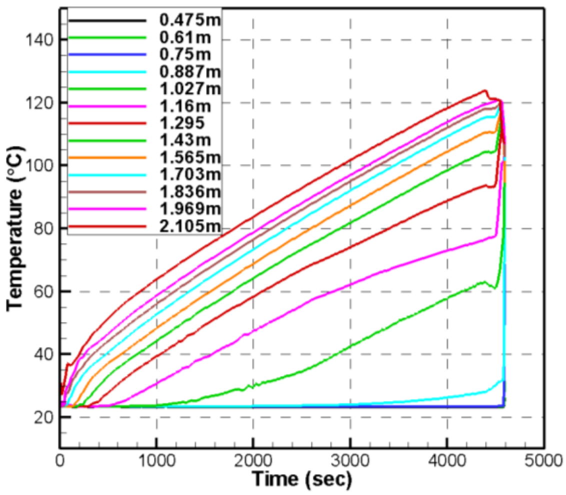


Figure 27: Simulation with minimum estimated momentum

With an estimated maximum momentum rate, as shown in Figure 28, the pool can be divided into two sub-regions, the lower part stays mixed with increasing temperature while the upper part develops a stratified sub-layer with also increasing temperature. This thermal behavior in the pool does not agree with the experiment (as shown in Figure 13b). The disagreement between the experiment and simulation is attributed to the inaccurate estimation of the momentum and assumed constant momentum for the whole transient.

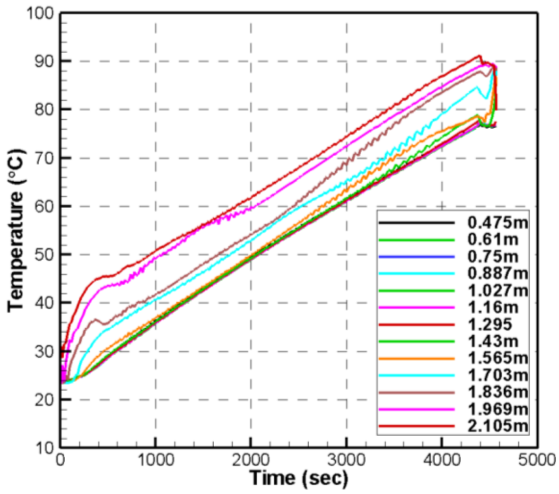


Figure 28: Simulation with maximum estimated momentum

4.1.2 Validation of model based on analytical estimation of amplitude and frequency

Table 2 shows the comparison of frequency and amplitude of oscillation in the blowdown pipe. The left part is the data calculated by Nariai model using the conditions in STR-06 while the right part is the value estimated from the measured temperature in the pipe. It shows that the calculated frequency by Nariai model is higher than the estimated value.

Table 2: Comparison of frequency and amplitude

Calculated Frequency and Amplitude with Nariai Model given the conditions in STR-06				**Estimated Frequency and Amplitude from TC measurements in STR-06**		
Time(s)	Period (s)	Frequency (Hz)	Amplitude L (m)	Period (s)	Frequency (Hz)	Amplitude L (m)
610-620	0.37-0.75	**2.7-1.33**	0.106-0.99	2-3	**0.5-0.333**	0.1-1.0
3215-3225	0.364-0.746	**2.75-1.34**	0.1-0.99	2-3	**0.5-0.333**	0.1-1.0

4.2 Validation of model against STR-09

Figure 29 shows the steam mass flow rate injected from the inlet plenum in STR-09 test. A high steam mass flow rate of 0.3 kg/s is imposed during the clearing phase and then lowered gradually to develop the thermal stratification. After that, the steam mass flow rate is increased again to induce mixing in the pool. For some reason, the steam injection is stopped several times around 5700 s to 5900 s.

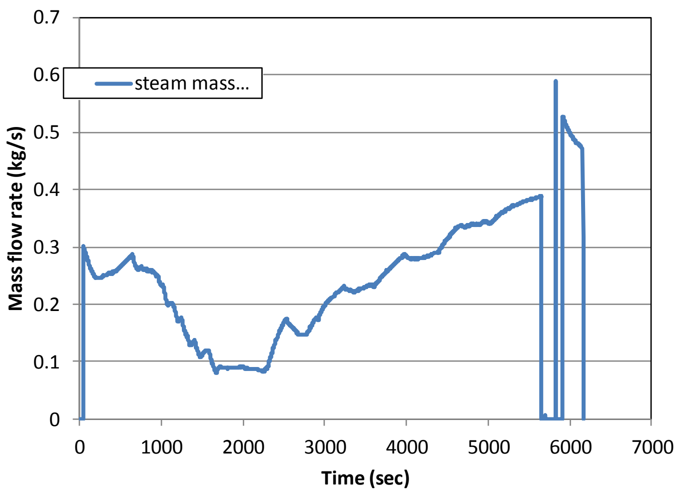


Figure 29: The steam mass flow rate used in STR-09

4.2.1 Validation of model based on synthetic jet

4.2.1.1 Momentum calculated based on synthetic jet

Figure 30 shows the condensation regimes in STR-09. It goes from region 1, to region 5 and then to region 6. For some time, the condensation regime is located on the boundary between regions 1 and 2. The measured temperature in the blowdown pipe shows that water-level oscillations exist in this period. The oscillations are also observed when the condensation regime is located in region 5. Thus, the EMS model is implemented in all periods with oscillations to calculate the momentum rate.

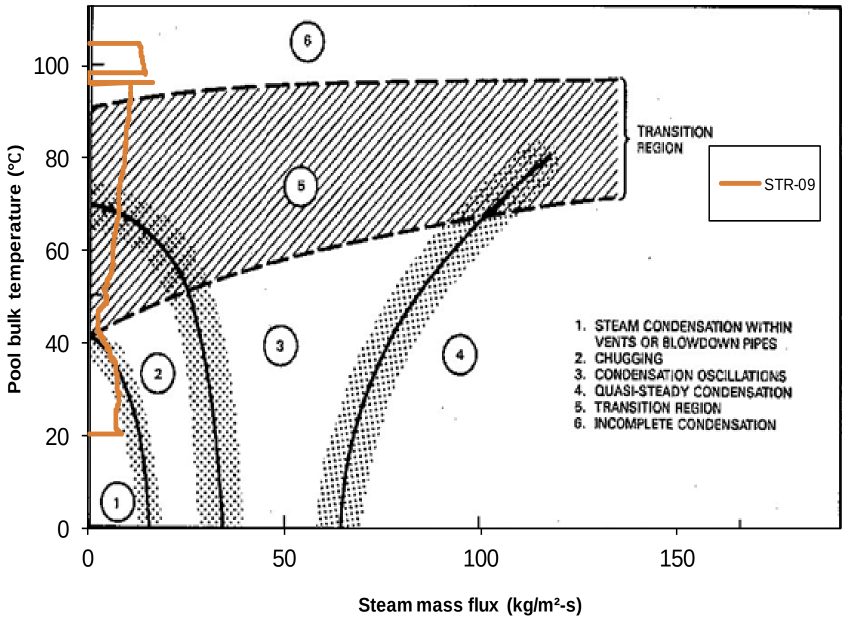


Figure 30: Condensation regime in test STR-09

4.2.1.2 GOTHIC modeling with EHS/EMS

4.2.1.2.1 Lumped simulation

Figure 31 shows the comparison of predicted drywell pressure and measured drywell pressure. The drywell pressure is over-predicted compared to the measured value. One possible reason is that the initial humidity in the drywell and wetwell, which is not measured in the test, is higher in the simulation. The predicted pressure increases faster than the measured pressure during the transient time. This is due to the assumption in the lumped simulation of a well-mixed water pool of the wetwell.

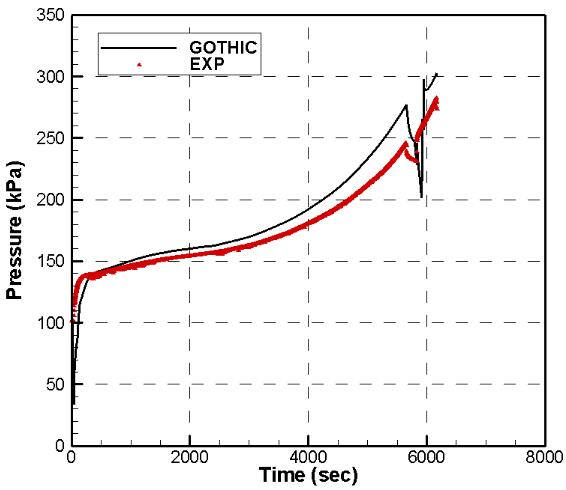


Figure 31: Comparison of calculated and measured drywell pressure.

Figure 32 shows the calculated liquid temperature in the wetwell water pool with lumped GOTHIC simulation, compared to the measured liquid temperature. The calculated liquid temperature in the simulation agrees well with the measured data.

Since the drywell is pre-heated in the experiment, most of the steam condenses in the wetwell. This might be the reason for the good agreement on the liquid temperature in the wetwell water pool.

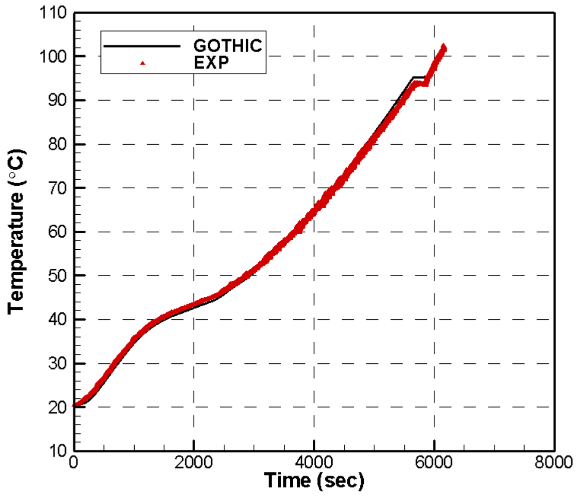
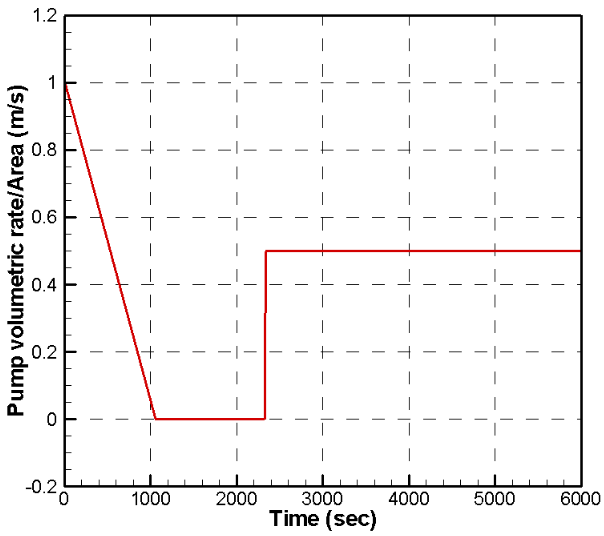


Figure 32: Comparison of calculated and measured liquid temperature in the wetwell pool.

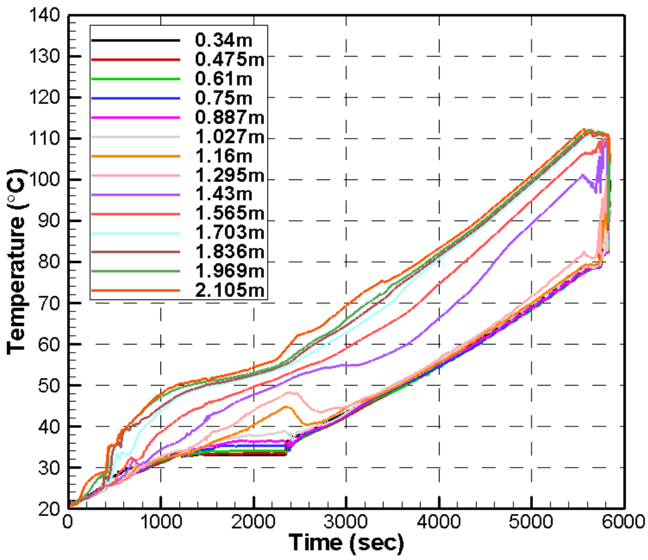
4.2.1.2.2 2D simulation

In 2D simulation, three cases with different pump rate behaviors are performed. In case 1, as shown in Figure 33a, the pump decreases linearly from a high value down to 0 at 1000 s, which is the time when water-level oscillations in the blowdown pipe disappear in the test. At about 2400 s, the pump rate increases from 0 to a high value when the oscillations occur inside the blowdown pipe. The pump value is calculated based on the measured temperature inside the blowdown pipe.

Figure 33b shows the 2D simulation results with such pump behavior. Compared to the measured pool temperature (see Figure 16b), the first mixing phase due to the clearing phase is predicted by the 2D simulation. Also the thermal stratification in the experiment is well predicted. However, the mixing part in the experiment is not predicted by the simulation, which means the imposed momentum rate used in case 1 for that period is under-predicted.



a)

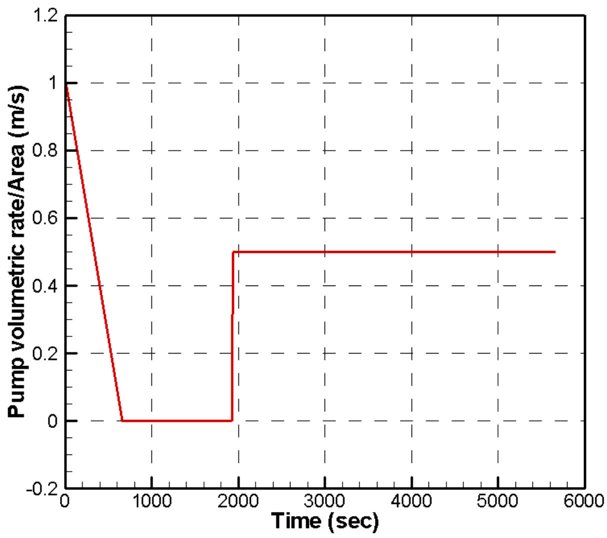


b)

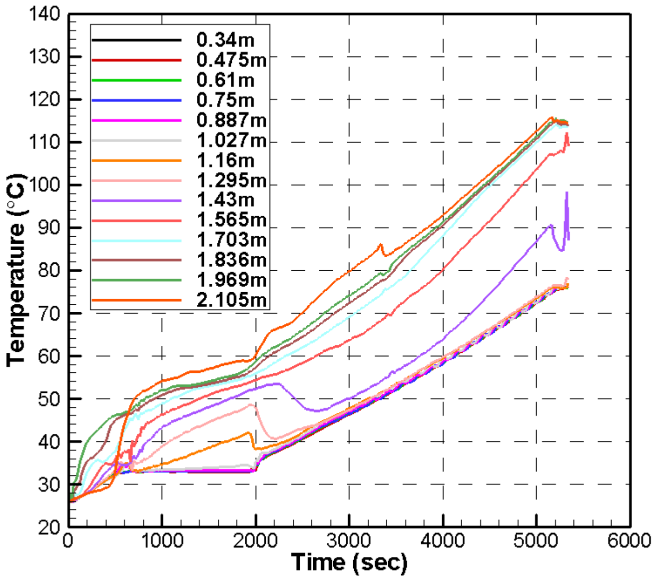
Figure 33: a) pump speed used in case 1 and b) the simulation results

Figure 34 shows the pump behavior and simulation results in case 2. The pump rate in case 2, as shown in Figure 34a, is similar to that in case 1, but the clearing phase is not considered in case 2. It means that air injection for the first 400 s is neglected. At about 600 s, the pump rate decreases to 0.

The simulation result of case 2 is shown in Figure 34b. The first mixing phase due to clearing phase is not predicted. Other parts predicted is similar to that in case 1, since the momentum rates imposed are the same.



a)

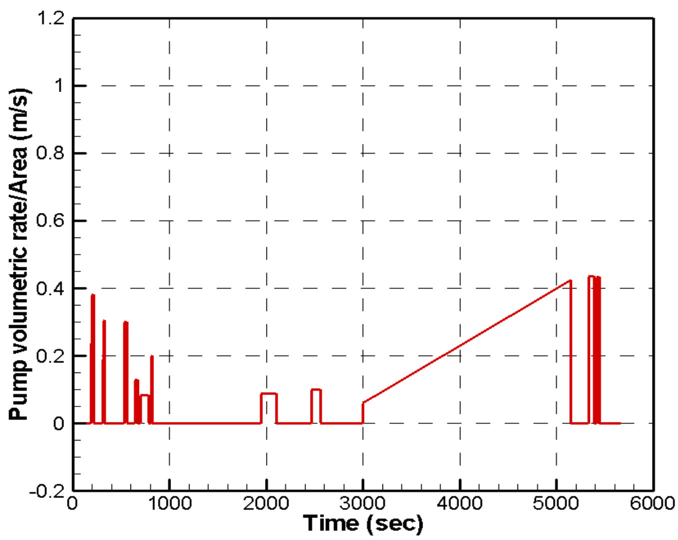


b)

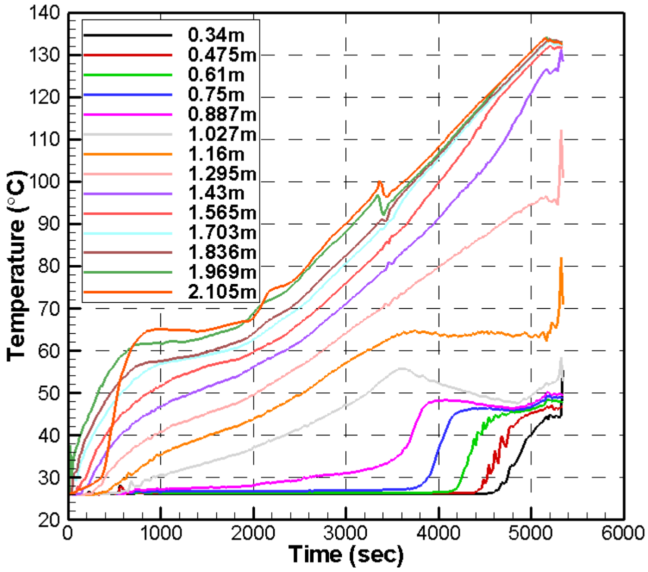
Figure 34: a) pump speed used in case 2 and b) the simulation results

In case 3, the pump rate varies along with time based on many time windows of oscillations. As shown in Figure 35a, a linearly increasing pump rate is used after 3000 s, to supply the increased momentum rate. The clearing phase in case 3 is not considered either.

Figure 35b shows the simulation result of case 3. The first mixing phase is not predicted, since the clearing phase is neglected. After that, thermal stratification develops until the end of transient. Thermal mixing after 3000 s is only achieved at the bottom part of the wetwell water pool. The result implies that the momentum imposed is lower than the actual momentum induced by oscillations in the pipe.



a)



b)

Figure 35: a) pump speed used in case 3 and b) the simulation results

4.2.2 Validation of model based on analytical estimation of amplitude and frequency

Based on the measured conditions in the test STR-09, the Nariai model is used to calculate the frequency and amplitude of oscillation in the experiment. Table 3 shows the comparison of frequency and amplitude calculated by the analytical model and estimated from measured temperature in the pipe. It can be seen that the calculated frequency is only about twice than the estimated frequency.

In STR-09, the measurement frequency for the thermocouples in the blowdown pipe increases from 1 Hz to 10 Hz. However, there are still only three thermocouples installed in the blowdown pipe and the space interval is 0.9 m.

Table 3: Comparison of frequency and amplitude

Calculated Frequency and Amplitude with Nariai Model given the conditions in STR-09				Estimated Frequency and Amplitude from TC measurements in STR-09		
Time(s)	Period (s)	Frequency (Hz)	Amplitude L (m)	Period (s)	Frequency (Hz)	Amplitude L (m)
4007.5-4017.5	0.348-0.491	**2.87-2.04**	0.102-0.323	0.6-1	**1.67-1**	0.1-0.325
5006.1-5016.1	0.332-0.472	**3.01-2.12**	0.1-0.316	0.6-0.8	**1.67-1.125**	0.1-0.325

4.3 Validation of model against STR-10

The steam mass flow rate measured on the inlet plenum in STR-10 is shown in Figure 36. Similar to STR-09, the steam mass flow rate starts from a high value of 0.3 kg/s for the clearing phase, and then decreases to a low value of 0.1 kg/s for thermal stratification. After that, the steam mass flow rate increases to a high value to induce mixing in the pool. The steam injection is also stopped at about 5000 s and then restarted after about 300 s. The test is finished at about 6000 s.

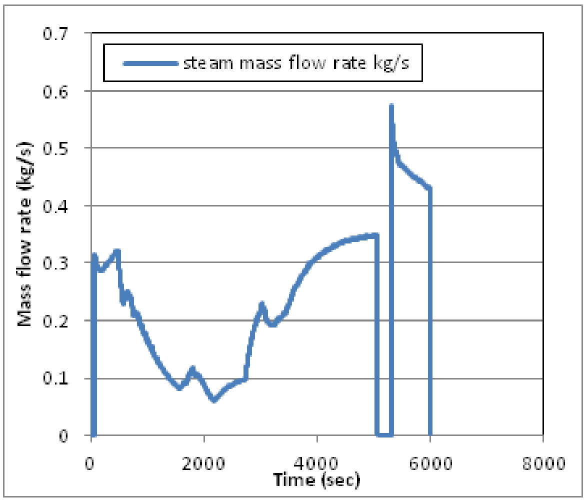


Figure 36: The steam mass flow rate used in STR-10

4.3.1 Validation of model based on synthetic jet

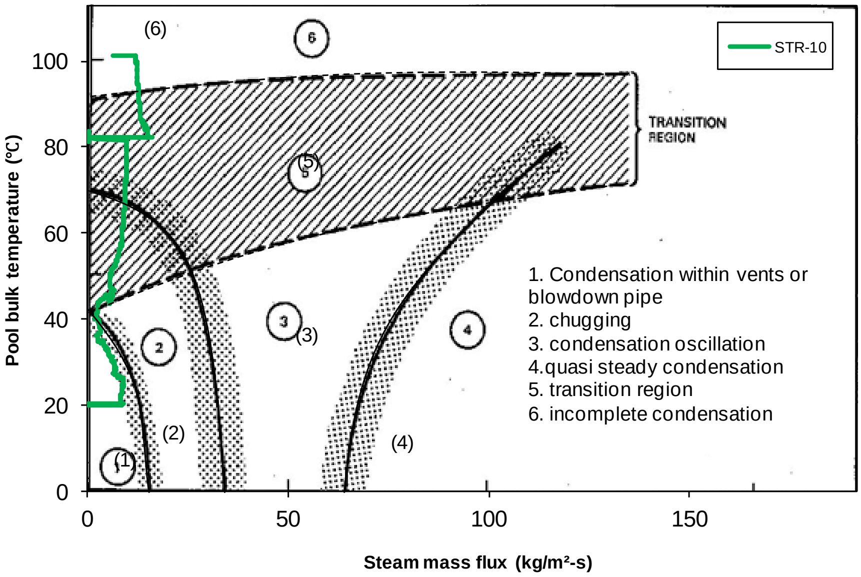


Figure 37: Condensation regime in test STR-10

The condensation regime in STR-10 is also similar to that in STR-09. It goes from region 1, to region5, and then to region 6. Since the condensation regime is located in the grey area close to the boundary between regions 1 and 2, oscillations are also observed in the blowdown pipe.

4.3.1.1 Momentum calculated based on synthetic jet

4.3.1.2 GOTHIC modeling with EHS/EMS

4.3.1.2.1 Lumped simulation

The predicted pressure in the drywell is compared to the measured pressure, as shown in Figure 38. Before the first 3000 s, the predicted pressure matches well with the measured pressure. After 3000 s, the pressure in the lumped simulation is over-predicted. A large jump in pressure occurs around 5000 s and this is due to the reverse water flow from the wetwell to the drywell.

The liquid temperature in the wetwell water pool is shown in Figure 39. Compared to the measured temperature, the predicted temperature is close to the measured value. Since the drywell is preheated, most of the steam injected to the drywell is condensed in the water pool of the wetwell.

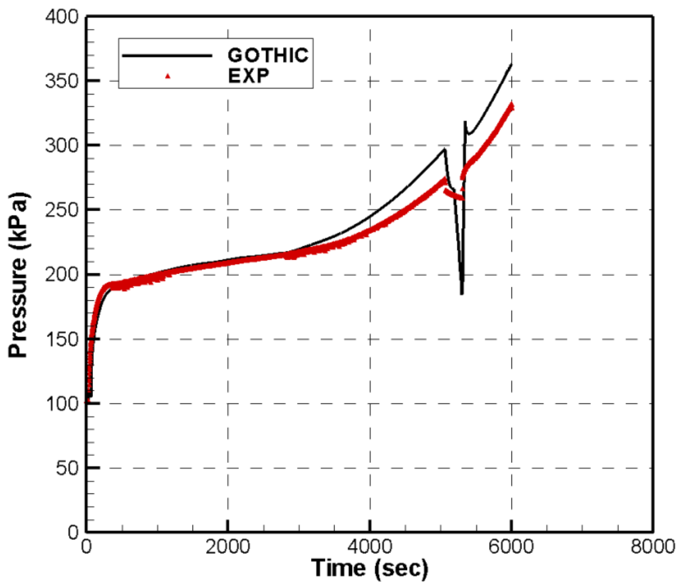


Figure 38: Comparison of predicted drywell pressure to measured pressure

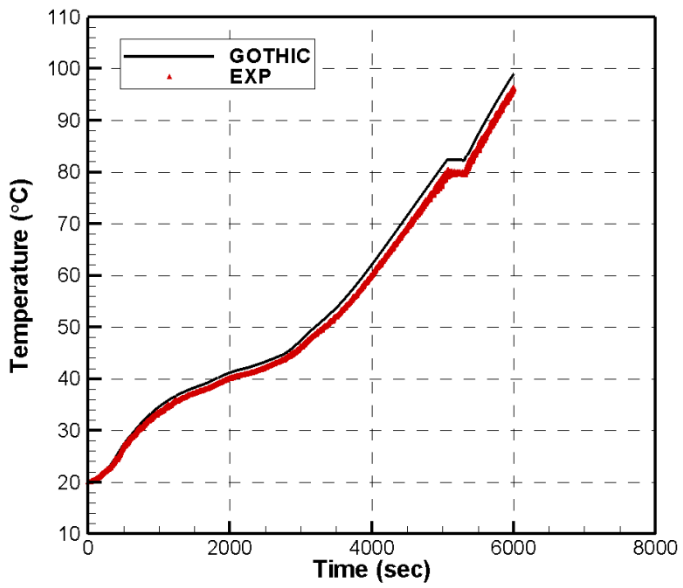


Figure 39: Comparison of predicted wetwell liquid temperature to experimental data

4.3.1.2.2 2D simulation

Most of the boundary conditions used in the 2D simulation are taken from the lumped simulation, the same as for the 2D simulations of other STR tests. Table 4 shows the frequency and amplitude of oscillation estimated based on the measured temperature in the pipe at different periods. The momentum is also calculated based on the synthetic jet theory.

Table 4: Estimated frequency, amplitude and the momentum rate

Estimated Frequency and Amplitude from TC measurements in STR-10				Momentum rate estimated with synthetic jet model	
Time(s)	Period (s)	Frequency (Hz)	Amplitude L (m)	(m/s)	(kg-m/s^2)
34-50	0.94	1.06	0.4375	0.66	15.583
50-95	0.8	1.25	0.2125	0.38	5.076
107-217	0.728	1.37	0.2125	0.41	6.129
350-1084	1.275	0.78	0.4375	0.49	8.470
2816	1.2125	0.82	0.4375	0.51	9.366
3243	1.54	0.65	0.325	0.30	3.204
5030-5065	0.75	1.33	0.2125	0.40	5.775
5375	0.684	1.46	0.2125	0.44	6.943
5930	0.6667	1.50	0.2125	0.45	7.308

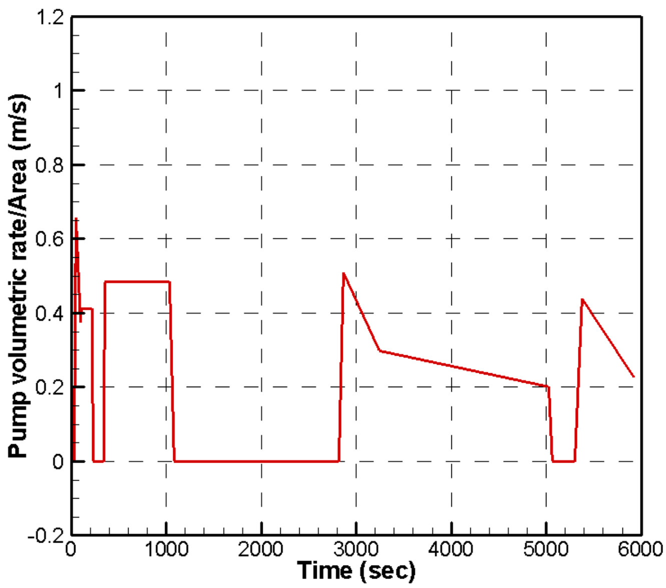


Figure 40: Pump speed used in 2D simulation with EMS model

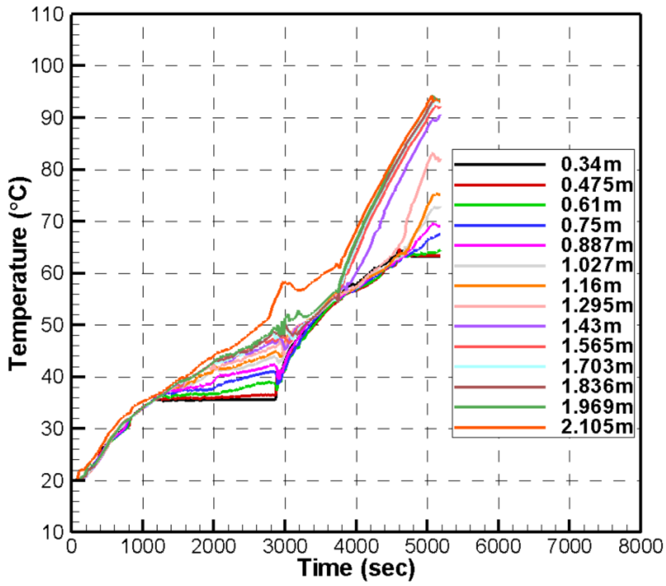


Figure 41: Predicted temperature distribution with GOTHIC

Figure 40 shows the pump rate used in the 2D simulation. It is based on the estimated momentum rate in the Table 4. According to the different oscillation behavior, the momentum varies linearly or rapidly.

Figure 41 shows the simulation result of STR-10. The clearing phase is considered in the simulation. Compared to the measured pool temperature (see Figure 17b), the first mixing phase is predicted well in the simulation. The stratification phase is also predicted in the simulation. After 3000 s, the second mixing phase is also predicted, except for the top layer, which has still a high temperature. After that, the stratification starts to develop again.

5 Pre- and Post- test for new PPOOLEX experiment

The possibility to reduce uncertainty in the simulations with EHS/EMS models is also limited by the experimental data uncertainty. Hence additional tests and modifications to the experimental procedures and measurements system in the PPOOLEX facility were proposed. Details of the proposed tests and modifications, pre-test simulations, and finally post-test simulations, are provided below.

Figure 42 shows a flow regime map description of the proposed test in PPOOLEX. First, steam injection with a small mass flow rate is used 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 is 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.

The schematic of steam mass flux adjustment in the test is shown in Figure 43. In the tests, the steam mass flux can be adjusted rapidly from a low value to develop stratification and to a high value to develop mixing. The steam mass flux is kept constant during chugging, in order to get a stable character of the oscillation.

Six tests with different steam mass flow rates and transient times were proposed. 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 during the chugging regime. A steam mass flow rate of 60 g/s is imposed the development of stratification, which is the same as in STR-04 test. The transient time for stratification phase is different between tests A and tests B so the maximum temperature difference between the 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 to completely mix the pool during the chugging regime.

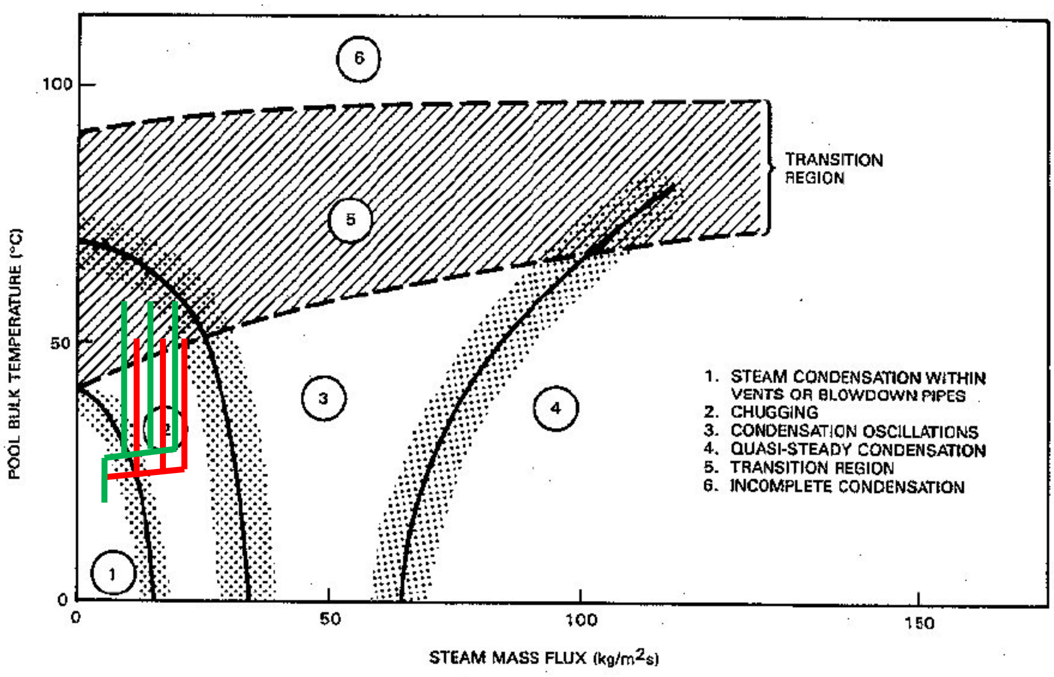


Figure 42: Condensation regimes of the proposed test.

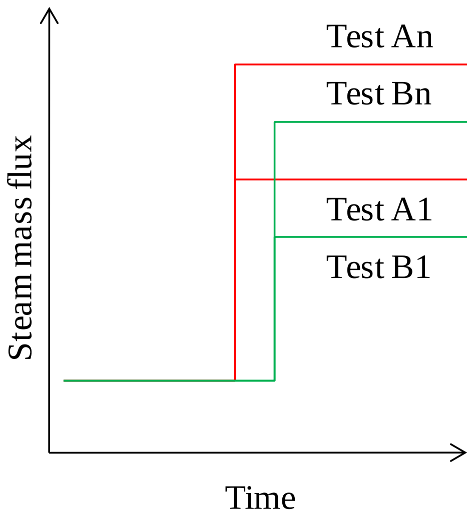


Figure 43: Schematic of the steam mass flux adjustment for the proposed tests.

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 42). Therefore, the test is preferable to have a low pool temperature, especially at the outlet of pipe.

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.

Table 5: 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

Additional TCs were 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. No heat sensors were used, however, during the tests.

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.

5.1 Pre-test simulation for PPOOLEX experiment

5.1.1 Simulation of the clearing phase

Before steam is injected into the wetwell through the blowdown pipe, the air in the drywell and the blowdown pipe is pushed into the wetwell first. Such clearing phase should be simulated accurately, since it affects the succeeding thermal stratification prediction in the wetwell pool.

In this section, the pre-test simulation study of the clearing phase is performed, to estimate the period of the clearing phase and the increase of pool liquid temperature at the end of the phase, with different steam mass flow rates. Figure 44 shows the modeling scheme for the clearing phase. The drywell is modeled by a subdivided volume 1s with grid of 10×10×10. The wetwell and the lab are modeled by lumped volumes, 2s and 4, respectively. The volume for the blowdown pipe is subdivided into 20 cells, in order to simulate reasonable hydraulic dynamics during the steam injection.

Three cases with steam mass flow rates of 200 g/s, 300 g/s, and 400 g/s are performed in this study. The pressure of the steam is 400 kPa and the corresponding saturation temperature is 144 °C. The initial temperature in both the drywell and wetwell is set at 15 °C and the initial pressure is set at 101.325 kPa. The water level of the wetwell pool is 2.0 m.

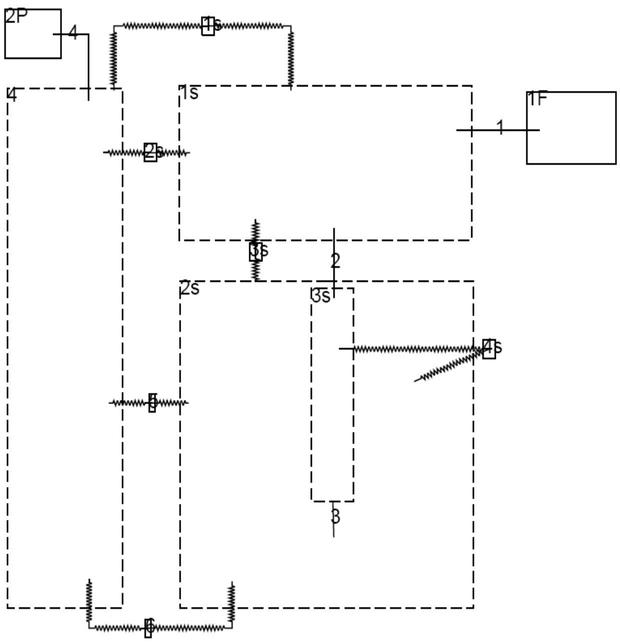
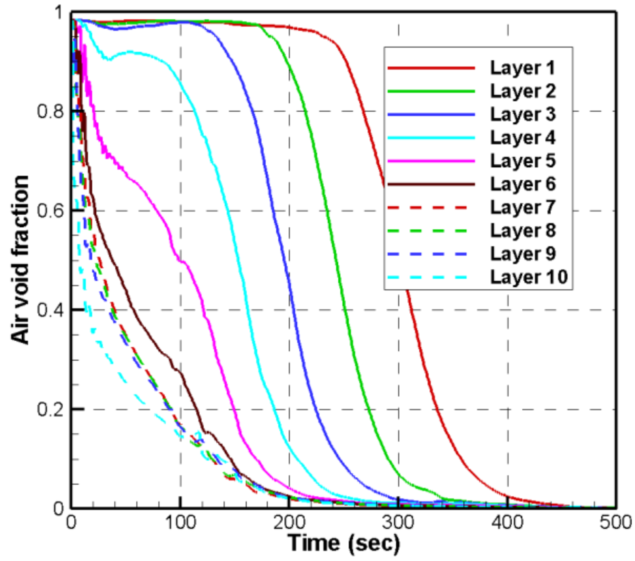
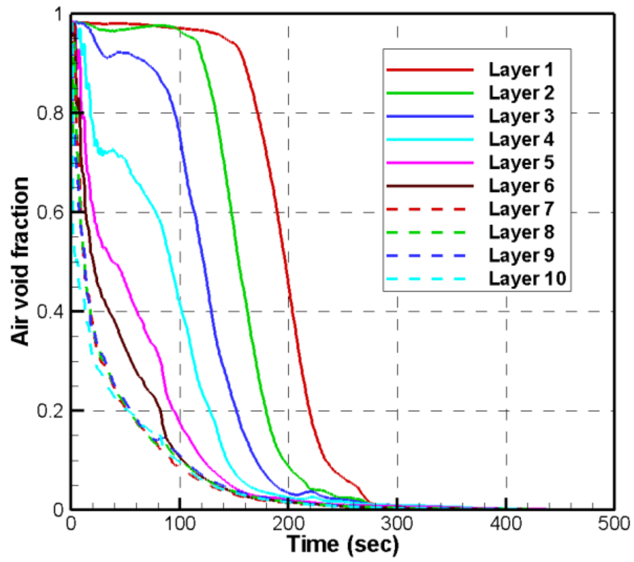


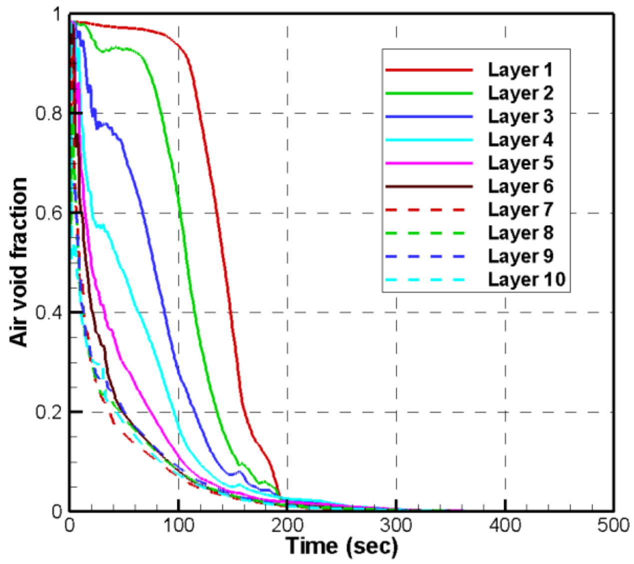
Figure 44: GOTHIC modeling scheme for pre-test simulation of the clearing phase



a) case 1: 200 g/s

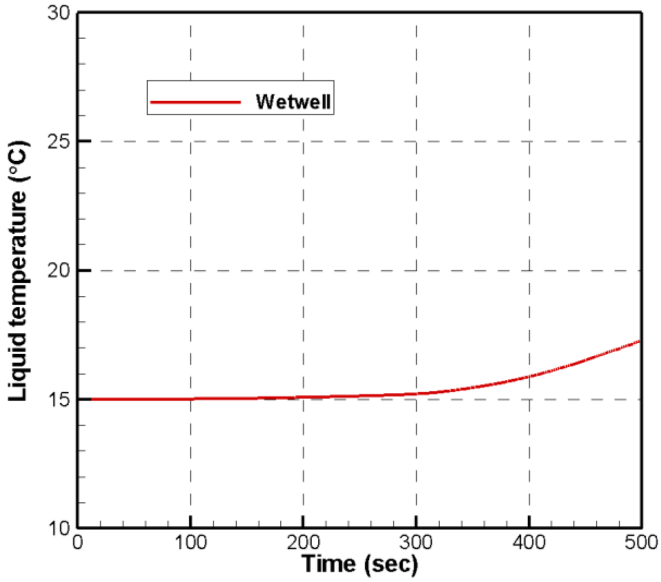


b) case 2: 300g/s

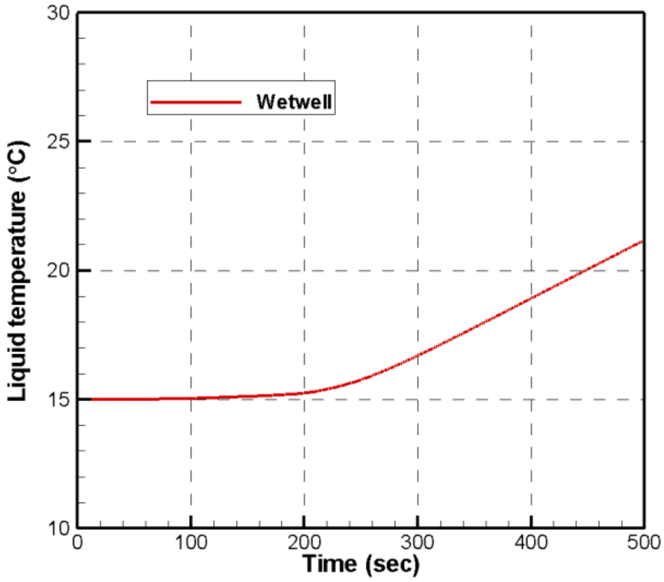


c) case 3: 400g/s

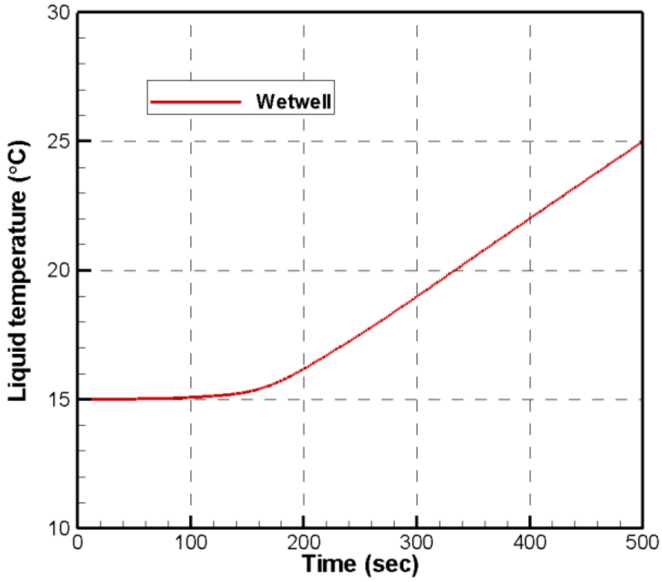
Figure 45: Predicted air fraction in the drywell with different steam flow rates



a) case 1: 200 g/s



b) case 2: 300g/s



c) case 3: 400g/s

Figure 46: Liquid temperature of the pool with different steam flow rates

Figure 45 shows the air fraction in the drywell for different cases. The red solid line (Layer 1) represents the position of the cell connected with the blowdown pipe at the bottom of the drywell. The top layer corresponds to Layer 10 and the numbering follows the order of the height. It can be seen that during the clearing phase, the air in the drywell is pushed by the steam from the top to the bottom. The air fraction in the bottom layer 1 starts to decrease later than other layers. This is because the steam has lower density compared to air and the steam injection inlet plenum is also at the upper part of the drywell. In case 1 with 200 g/s for steam flow rate the clearing phase lasts about 460 s when the air fraction in the bottom layer is 0. The clearing phase is about 400 s for case 2 with 300 g/s and 300 s for case 3 with 400 g/s.

Figure 46 shows the wetwell pool liquid temperature during the clearing phase. In case 1, the liquid temperature increases about 2 °C at about 460 s at the end of the clearing phase, while it increases about 4 °C at 400 s for case 2 and 4 °C at 300 s for case 3. The results show that after the clearing phase, the increase in liquid temperature in the pool is less than 5 °C only.

5.1.2 Pre-test simulation for thermal stratification and mixing

A number of pre-test simulations with EHS/EMS models were done to investigate the thermal stratification and mixing in the pool under the proposed conditions. Only one case is presented here. Several assumptions were made for the pre-test simulation.

- The clearing phase is not considered.
- For thermal stratification, all steam has condensed inside the blowdown pipe.
- For the mixing phase, the condensation regime is chugging and all steam has condensed at the pipe outlet.
- It is assumed that the injected steam temperature is 110 °C for thermal stratification phase and 120 °C for mixing phase. It is based on the measured data in STR-04 test.
- The steam mass flow rate is 60 g/s during the thermal stratification phase and 325 g/s during the mixing phase. The duration for the thermal stratification is 2000 s.
- The mass of water resulting from condensation of the steam in the blowdown pipe is neglected.

With the above assumptions, the heat source for the thermal stratification phase can be calculated as,

$$\mathrm{H} = 0.06 \times (2691.06 - 461.415) = 133.78\,\frac{\mathrm{kJ}}{\mathrm{s}}.$$

The heat source for the mixing phase is calculated as,

$$\mathrm{H} = 0.325 \times (2705.93 - 503.812) = 715.69\,\frac{\mathrm{kJ}}{\mathrm{s}}.$$

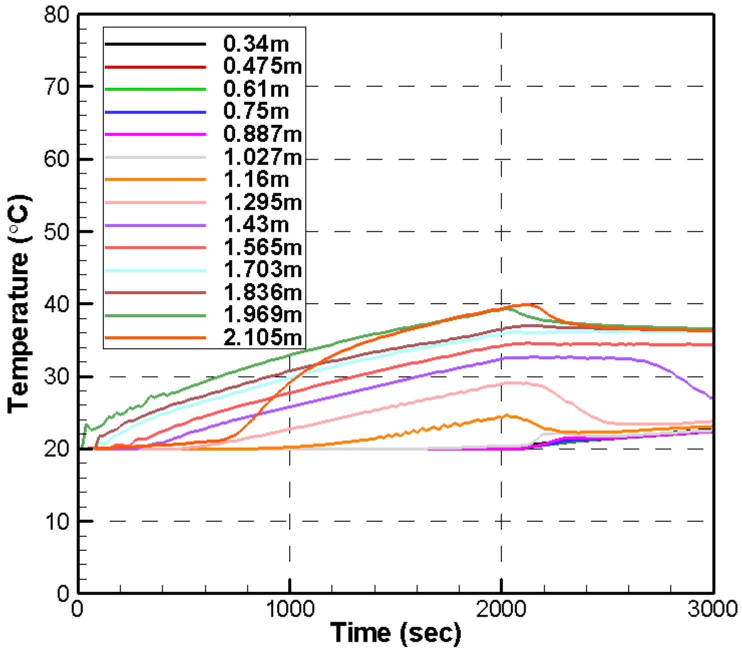
The effective momentum during the thermal stratification phase is assumed to be zero. The effective momentum during the mixing phase is calculated based on the synthetic jet theory where the amplitude and frequency are calculated with the Aya & Nariai model. It is assumed that the drywell and wetwell pressure is constant during the mixing phase, that is, 2.2 bars for the drywell and 2 bars for the wetwell. The assumed pool temperature during this phase is 28 °C. Table 6 shows the calculated minimum and maximum momentum with different C, which can match the maximum and minimum amplitude measured from the experiment. The oscillation amplitude is in the range of 0.07 and 0.92 m, which is based on the measured data in STR-04.

Table 6: **Momentum calculated by analytical model**

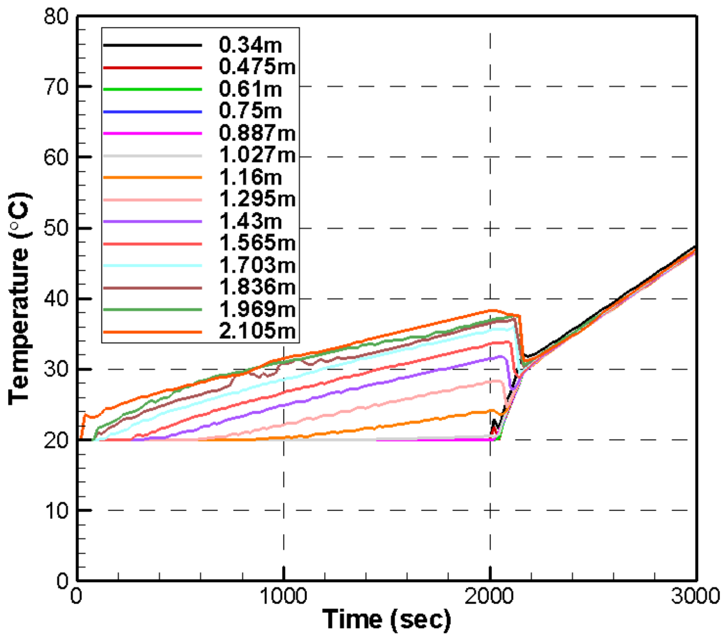
Calculated Frequency and Amplitude with Nariai Model				**Momentum rate estimated based on synthetic jet model**	
C (m)	Period (s)	Frequency (Hz)	Amplitude (m)	Velocity (m/s)	Momentum (kg-m/s^2)
1.14	0.704	1.42	0.9287	1.87	125.19 (max)
0.19	0.31	3.22	0.0748	0.34	4.19 (min)

Figure 47 shows the simulation results with minimum momentum and maximum momentum. Thermal stratification has developed until 2000 s and the temperature increase is about 20 °C. With a steam mass flow rate of 325 g/s and pool temperature of 40 °C, the condensation regime is chugging in the mixing phase. With estimated minimum momentum, thermal stratification continues to develop and mixing is not achieved. With estimated maximum momentum, mixing is obtained after about 200 s.

The temperature and superimposed velocity profiles in the tank at different times is shown in Figure 48. Note that the cell size in the gas space (above z = 2.1 m) is 0.4 m and also the temperature in the gas space is the liquid temperature. The flow pattern during the thermal stratification phase can be seen from Figure 48a and Figure 48b at times t = 250 s and 1500 s, respectively. The heat source through the pipe surface generates the buoyant force and causes the circulation in the clockwise direction. The magnitude of the maximum velocity at t = 1500 s is only 0.0958 m/s and thermal stratification dominates over thermal mixing. Figure 48c and Figure 48d give the flow pattern during the mixing phase at times t = 2020 s and 2100 s, respectively. The momentum imposed by the pump drives the liquid downward to the bottom and the circulation is in counter-clockwise direction in contrast to the thermal stratification phase. The magnitude of the maximum velocity at t = 2100 s is 1.61 m/s and thermal mixing dominates over thermal stratification.

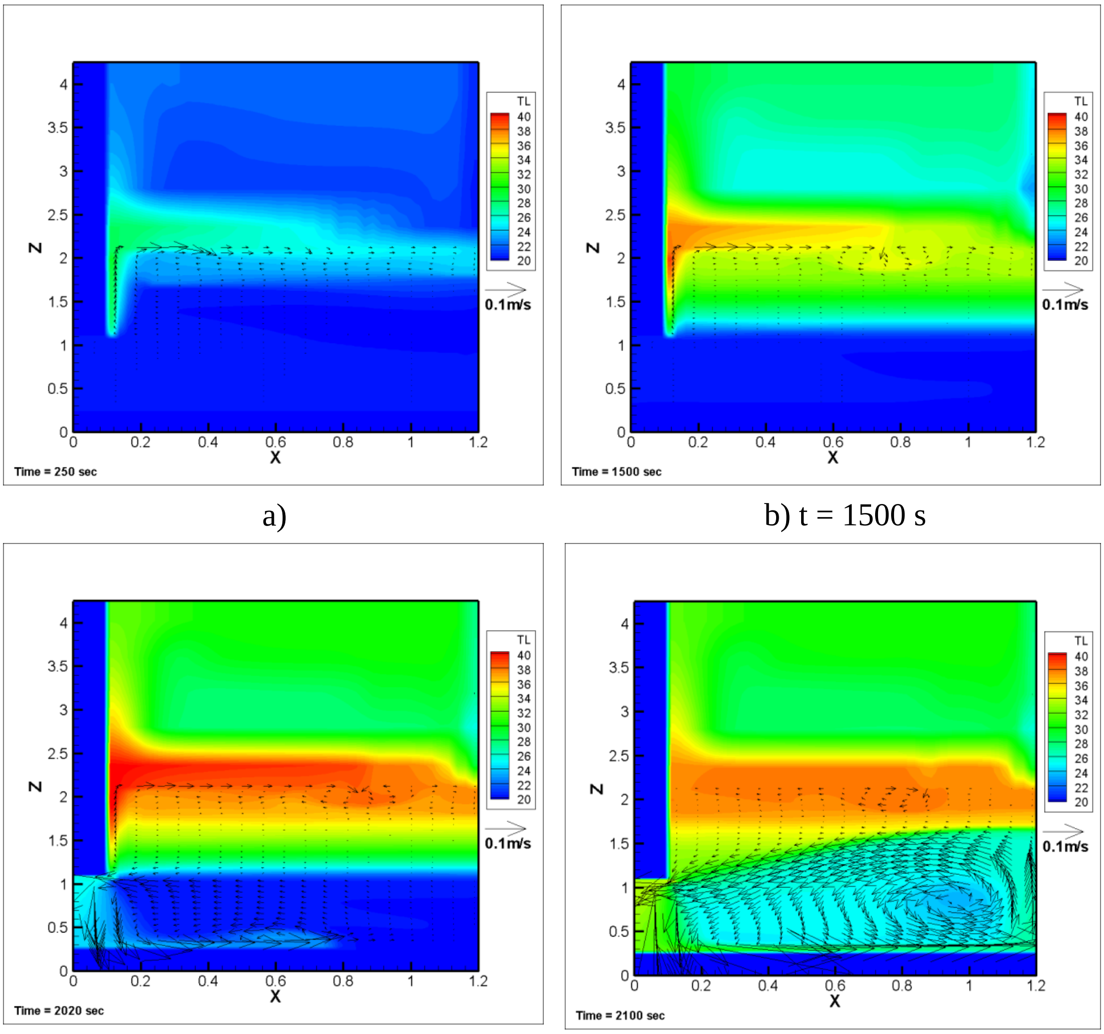


a) with minimum momentum



b) with maximum momentum

Figure 47: 2D wetwell pre-test simulation with estimated momentum



a) b) t = 1500 s

c) t = 2020 s d)

Figure 48: temperature contour and velocity vector in the tank predicted in the simulation.

5.2 Post-test simulation against MIX tests

All 6 tests were performed in the PPOOLEX facility (please see [65] for more details). A total of 17 thermocouples were installed in the blowdown pipe to measure the water level change during the oscillation. The drywell wall is also equipped with insulated material on the outside. Three tests were done according to the proposed group A tests. The difference among them is the steam mass flow rate during mixing phase, which can be seen from Figure 49, Figure 50, and Figure 51. The steam flow rate during the clearing phase is about 200 g/s for the three cases and it takes about 500 s. The steam mass flow rate during the thermal stratification phase is about 90 g/s and the time period is a bit different between the three cases, in order to have same temperature difference between the top and bottom layers.

The pool temperature profiles in MIX-01, MIX-02 and MIX-03 are shown in Figure 52, Figure 53, and Figure 54 [65]. The temperature behavior is similar in all three cases. In case 1 with smallest steam flow rate, the mixing time is around 300 s; while it is about 200 s in case 3 with biggest steam flow rate. In case 2, the mixing time is around 250 s.

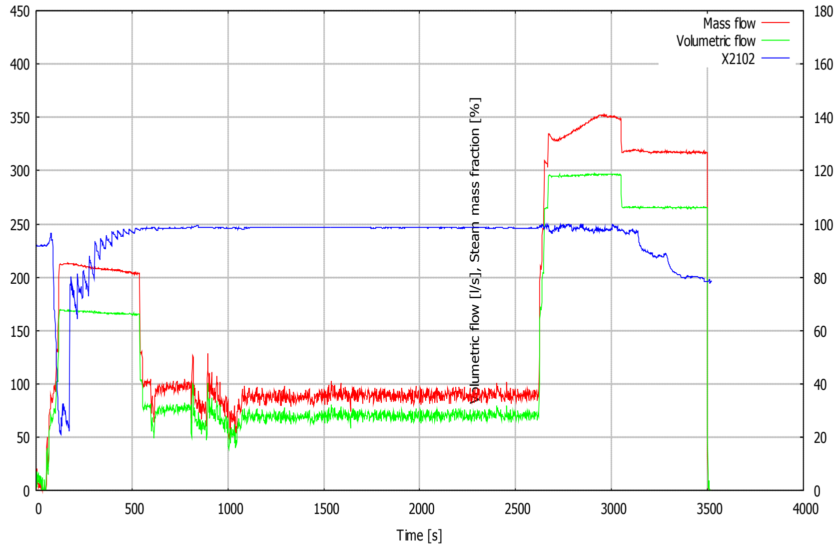


Figure 49: Steam injection conditions in MIX-01

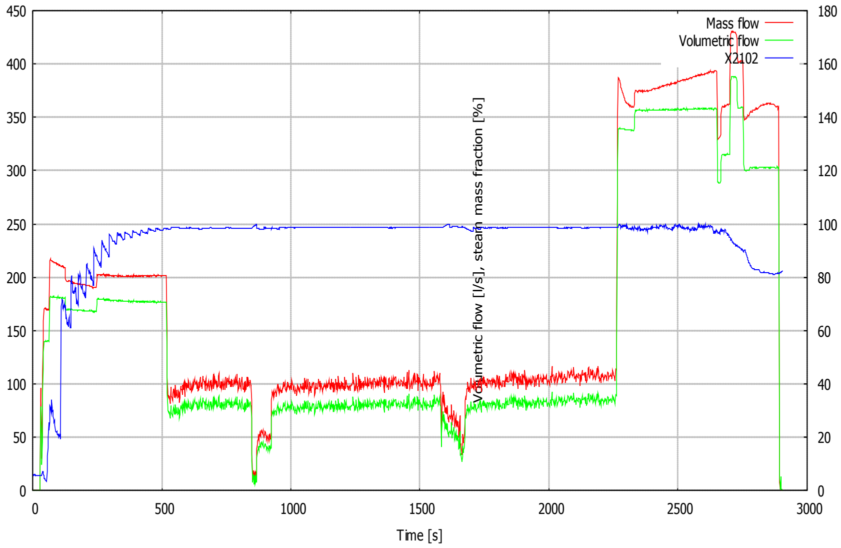


Figure 50: Steam injection conditions in MIX-02

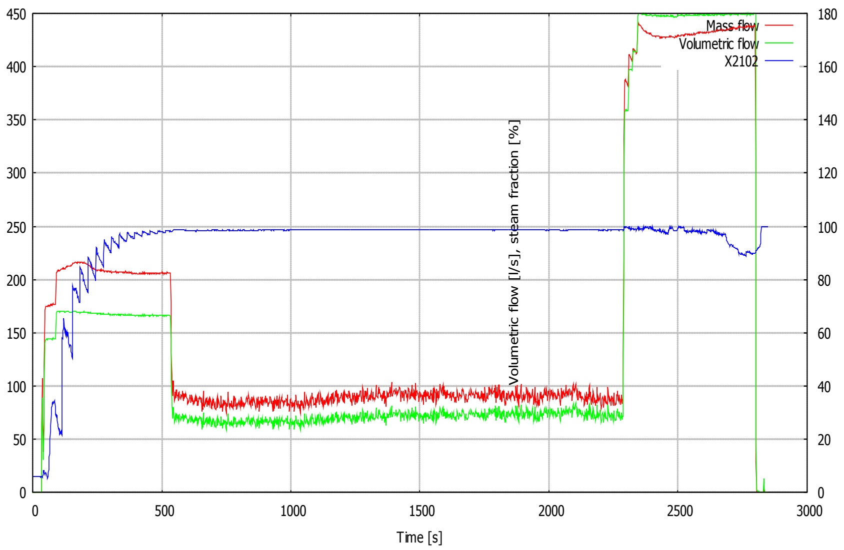


Figure 51: Steam injection conditions in MIX-03

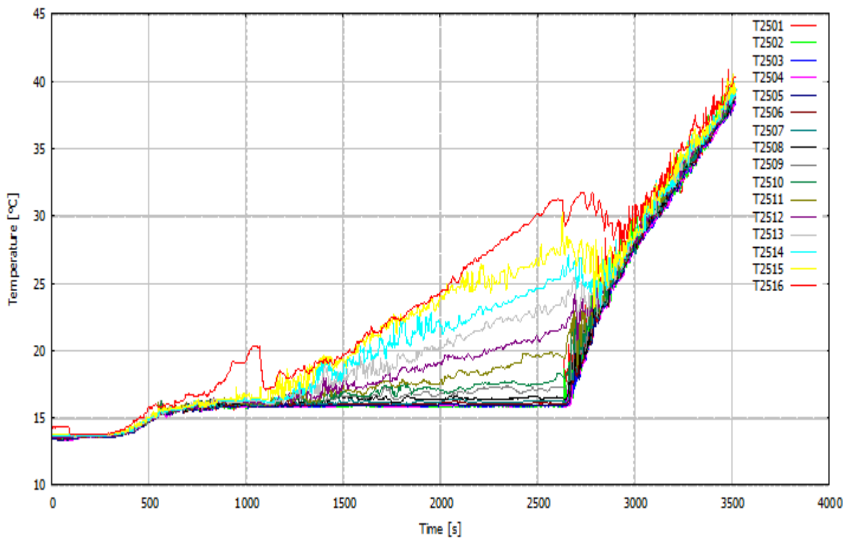


Figure 52: Pool temperature in MIX-01 (Mixing time scale:~300 s)

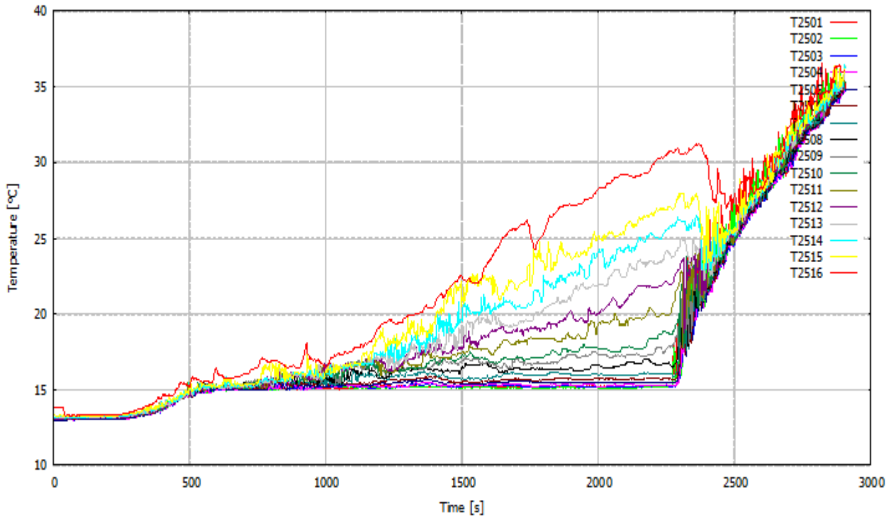


Figure 53: Pool temperature in MIX-02 (Mixing time scale:~250 s)

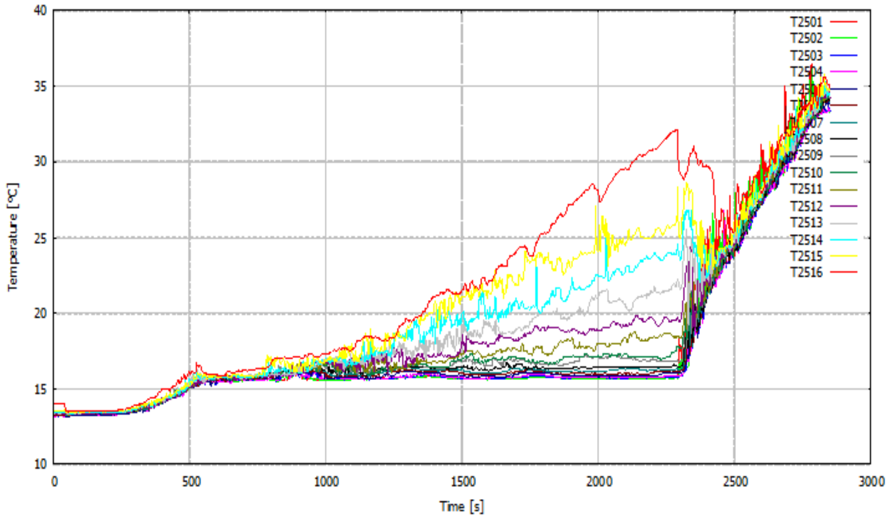


Figure 54: Pool temperature in MIX-03 (Mixing time scale:~200 s)

Figure 55 shows the condensation map in the MIX-01, MIX-02 and MIX-03. The pool liquid bulk temperature is represented by the temperature of T2508, which is located close to the blowdown pipe outlet. The first small part with liquid temperature increasing is the clearing phase. After that, the steam mass flow rate decreases during the thermal stratification phase. Then, the mixing phase starts and the temperature increases from around 17 °C to around 35 °C. Although the map shows that the mixing phase is located in the transition region between regimes 1 and 2, strong oscillation is observed in this phase indicating a chugging behavior.

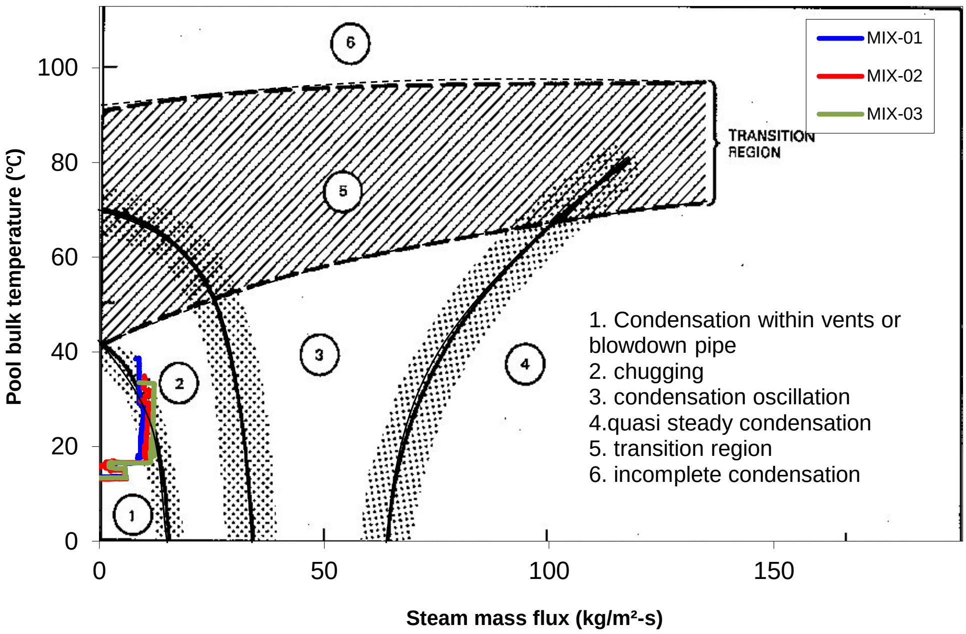


Figure 55: Condensation regimes of MIX-A tests (MIX-01, MIX-02, MIX-03)

The other three cases were done according to proposed group B tests. Compared to group A tests, the temperature difference between the top and bottom layers is larger in group B. In MIX-04, MIX-05 and MIX-06, the temperature difference between the top and bottom layers at the end of the thermal stratification is about 22 °C. After the stratification development, the steam mass flow rate is about 300 g/s for MIX-04, 350 g/s for MIX-05, and about 400 g/s for MIX-06. In MIX-05 and MIX-06, the tests were continued after complete mixing, and development of thermal stratification is observed again. The steam injected conditions and the measured pool temperature are shown in Figure 56-Figure 61.

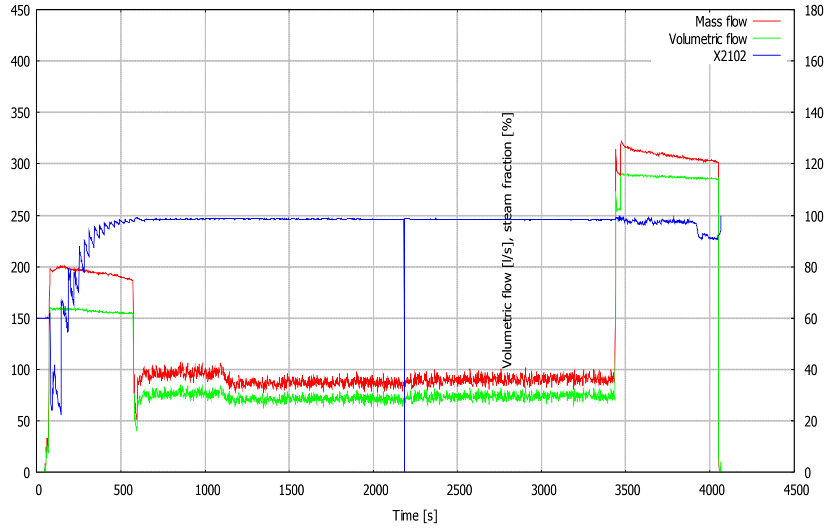


Figure 56: Steam injection conditions in MIX-04

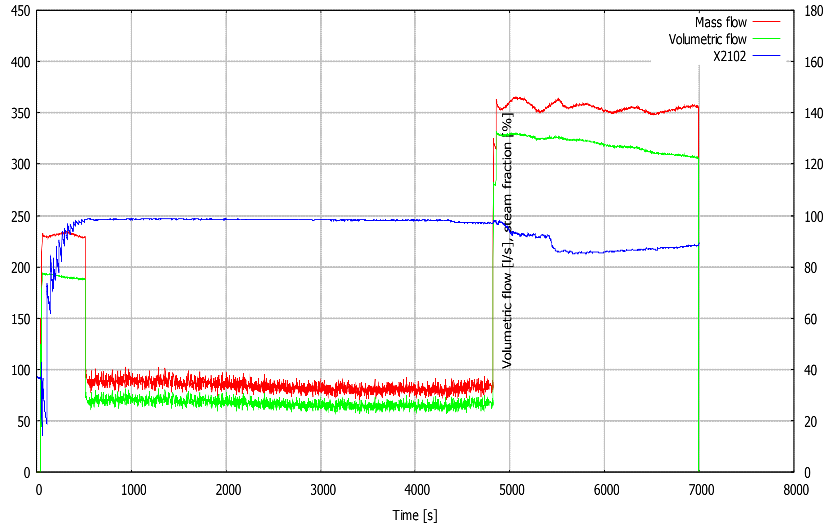


Figure 57: Steam injection conditions in MIX-05

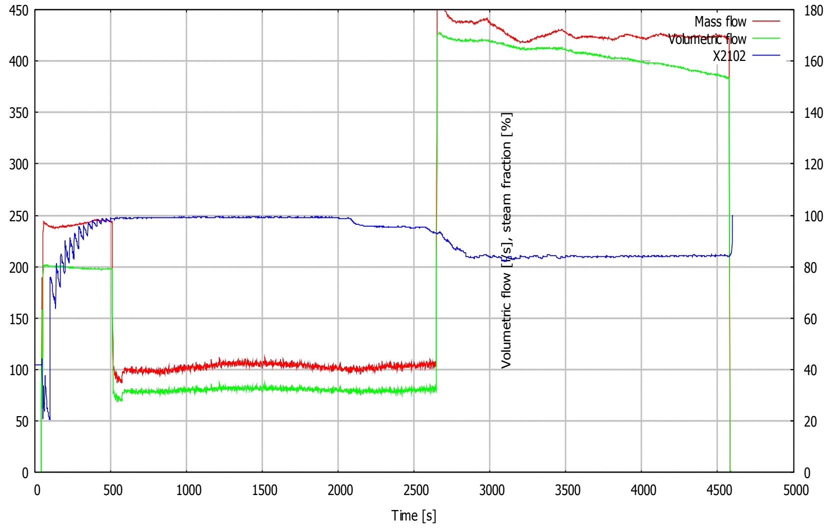


Figure 58: Steam injection conditions in MIX-06

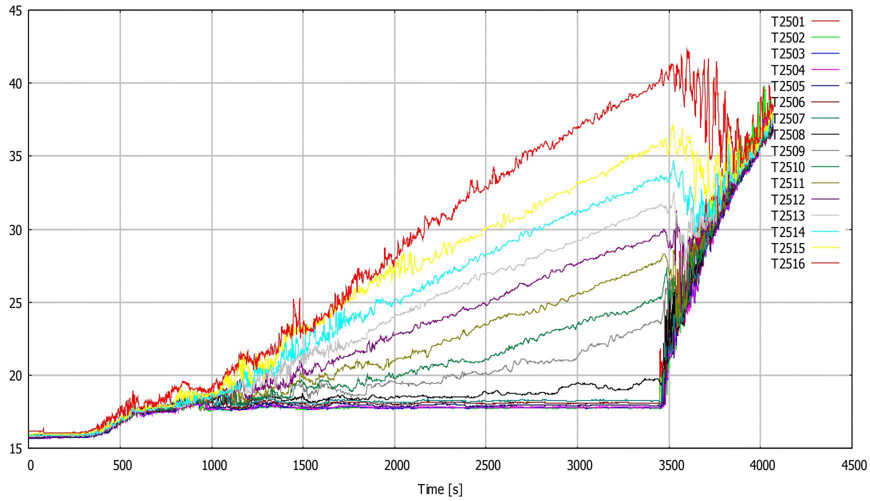


Figure 59: Pool temperature in MIX-04 (Mixing time scale:~450 s)

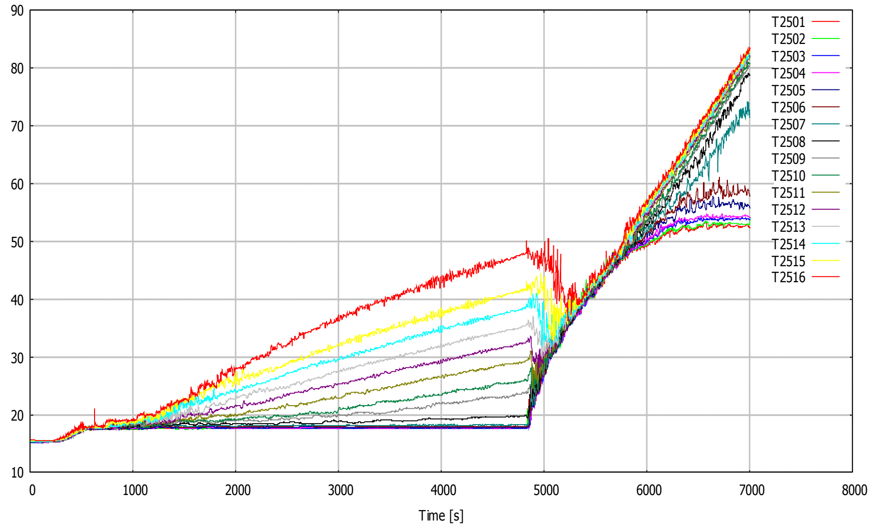


Figure 60: Pool temperature in MIX-05 (Mixing time scale:~500 s)

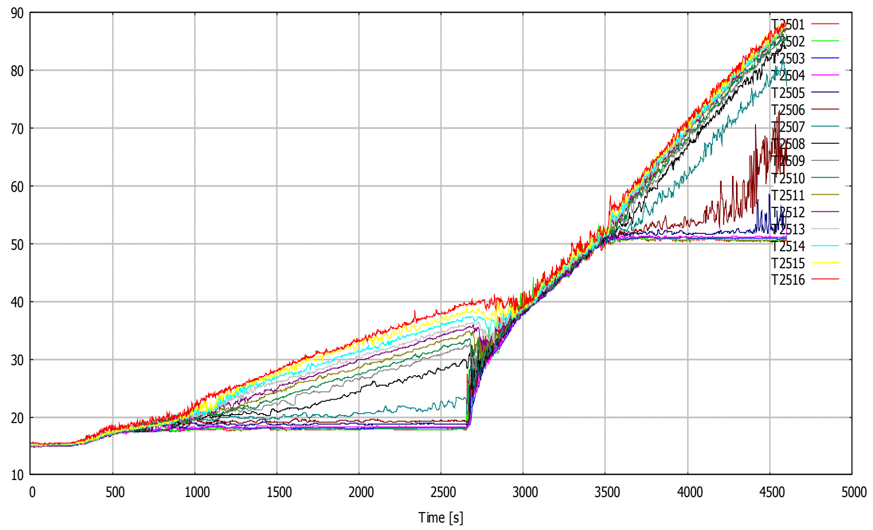


Figure 61: Pool temperature in MIX-06 (Mixing time scale:~300 s)

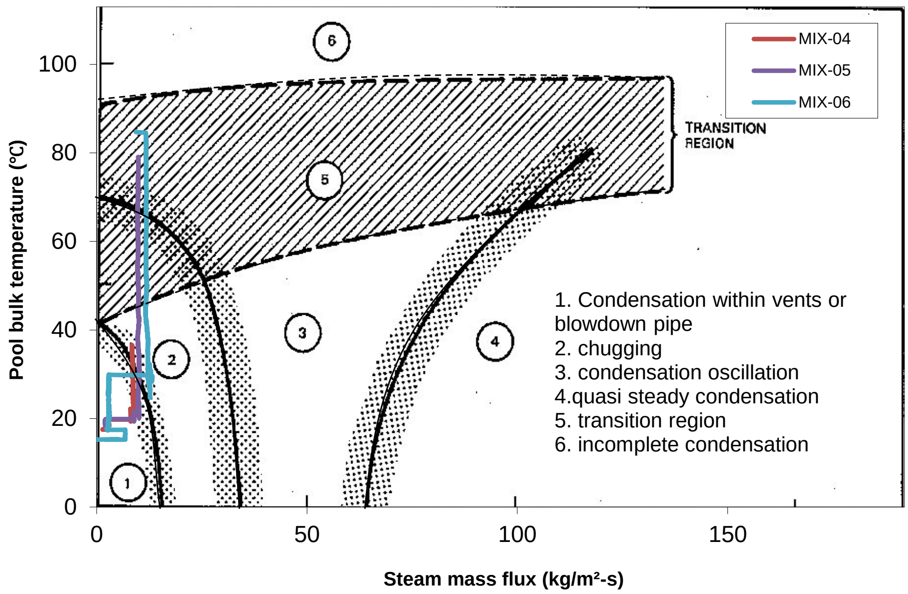


Figure 62: Condensation regimes of MIX-B tests (MIX-04, MIX-05, MIX-06)

Figure 62 shows the condensation map of MIX-04, MIX-05 and MIX-06 tests. In MIX-06, the pool temperature increases to about 30 °C during the thermal stratification phase, while it is less than 20 °C in MIX-04 and MIX-05. Except MIX-04, the other two tests go to the condensation region 5 (transition region) at the end of the mixing phase.

The post-test simulation will be done with measured experimental data. The steam pressure, temperature and the flow rates will be used as boundary conditions in the simulation, and the pressure, temperature in the drywell and the wetwell will be used as initial conditions and for comparison as well.

5.2.1 Post-test simulation of MIX-01

5.2.1.1 Lumped simulation

The input deck for MIX-01 is the same as in the STR tests simulation, except for the boundary conditions of steam and the initial conditions for the drywell and the wetwell. Figure 63 shows the predicted pool liquid temperature compared to the averaged measured pool temperature. The predicted temperature increases much faster than that in the experiment, especially for the thermal stratification phase. The slope of temperature increase for the mixing phase in the simulation is similar to that in the experiment.

A similar behavior is found for the water level of the wetwell pool. As shown in Figure 64, the predicted water level is much higher than that in the experiment. It increases faster in the simulation, especially for thermal stratification phase.

It is then hypothesized that the steam flow rate for thermal stratification measured in the experiment is not accurate. To test this, an analytical calculation is done to estimate the water level increment with measured steam flow rate. It is assumed that all steam mass goes to the water pool. The analytical result also shows higher water level increase than the measured data. Thus it confirms the problem of measurement of the steam flow rate. A possible reason is that the flow meter designed for high flow rates has large measurement error when it is used to measure low flow rates.

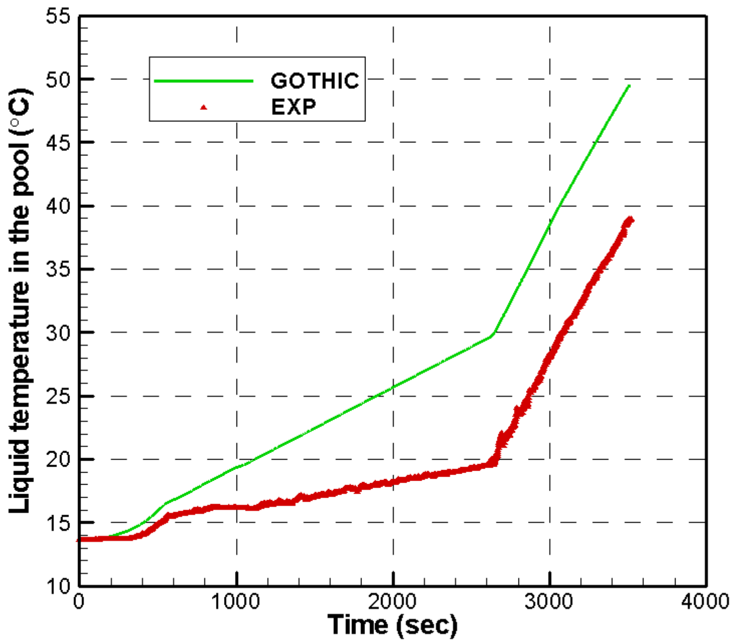


Figure 63: comparison of pool average liquid temperature in GOTHIC and experiment

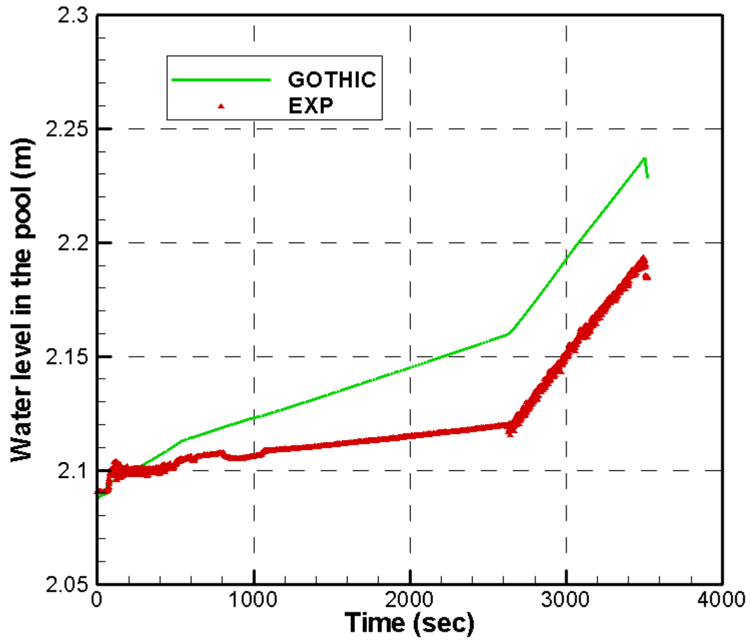


Figure 64: comparison of pool water level in GOTHIC and experiment

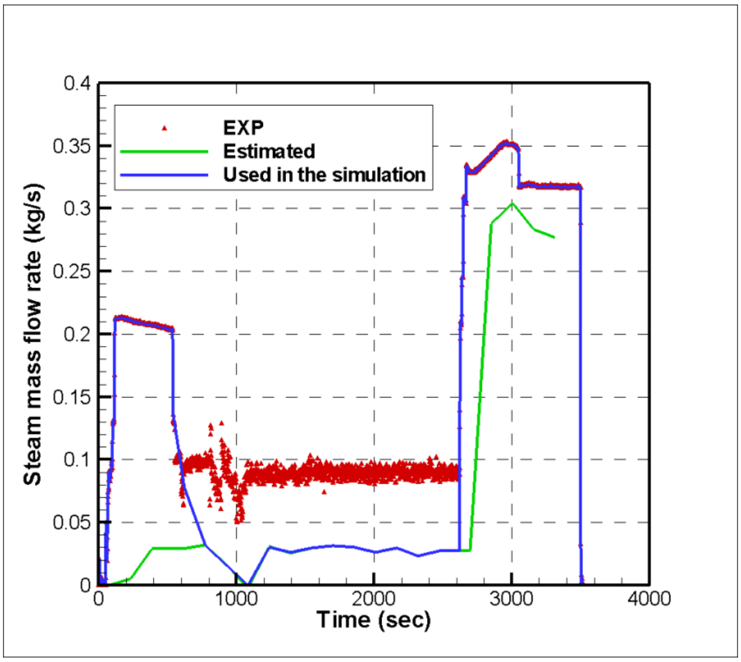
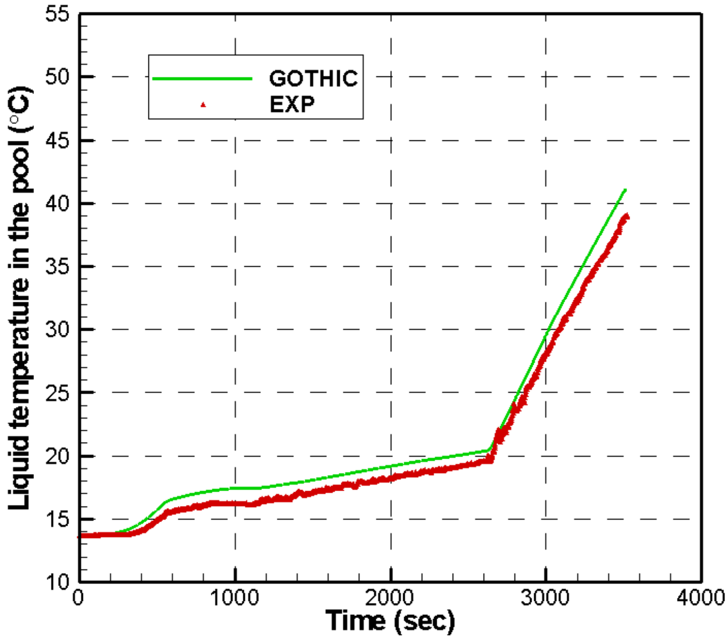


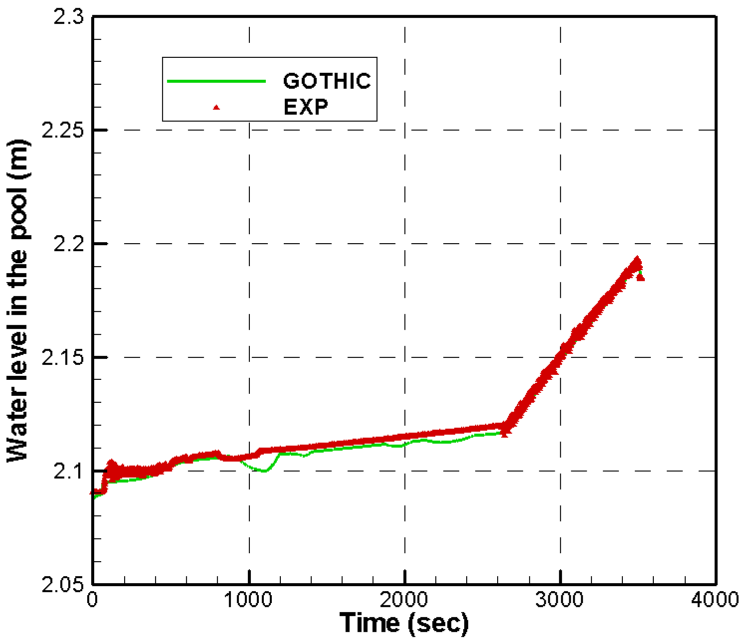
Figure 65: Comparison of steam mass flow measured in the experiment and estimation based on measured pool averaged liquid temperature.

The steam mass flow rate through the blowdown pipe can also be estimated based on the averaged measured pool temperature, if the heat loss through the wetwell wall is ignored. Since the drywell wall is insulated for experiment, it can be considered that the steam mass flow rate through the blowdown pipe equals that injected from the steam line. The steam mass flow rate used for following simulation is shown in Figure 65. It can be seen from figure that only the flow rate for the thermal stratification phase is estimated. The clearing phase and the mixing phase have the same flow rate as measured value. It is because the steam flow rate for the clearing phase cannot be estimated based on the pool temperature change; while for the mixing phase, the heat loss through the wetwell wall is big due to large temperature difference between the pool and the lab and cannot be ignored.

In order to eliminate the measurement error on the thermocouples, the pool average liquid temperature is averaged each 100 time-steps data, to get the reasonable steam flow rate. At about 1100 s, the estimated steam flow rate is negative since the pool temperature decreases in that period for some unknown reason in the experiment.



a)



b)

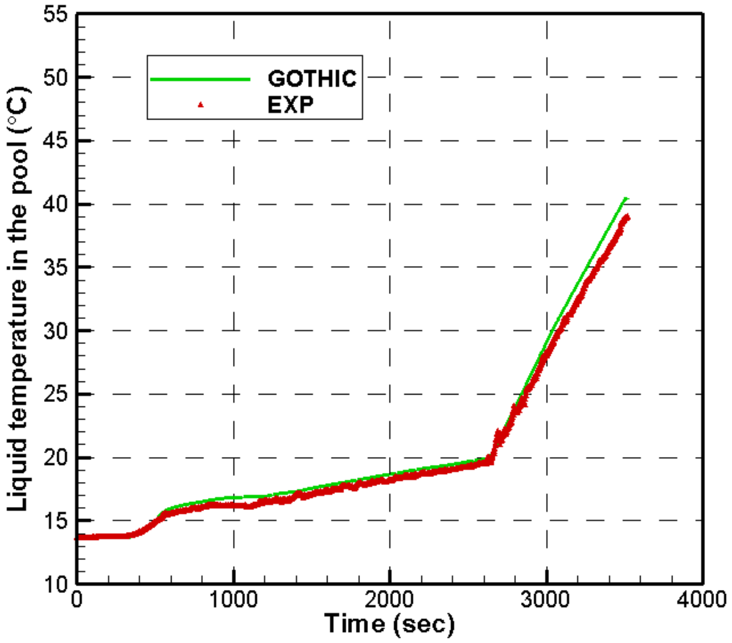
Figure 66: GOTIHC simulation with estimated steam flow vs. measured data. a) for pool liquid temperature, b) for pool water level

A simulation with estimated steam mass flow rate is done and compared to the measured experimental data. It should be pointed out that in the facility the flange connecting the blowdown pipe and the drywell is about 4 cm in height above the drywell floor. This is considered in the simulation by increasing 4 cm for the top elevation of flow path connecting the drywell and the blowdown pipe.

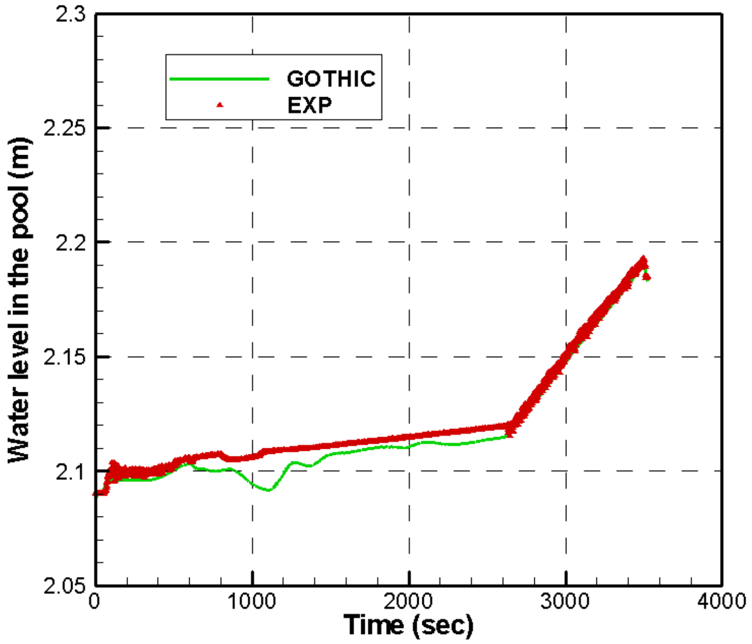
Figure 66 shows the comparison of simulation with estimated steam flow rate and the measured data. The behavior of the liquid temperature and the water level in the simulation can match the measured data well (see Figure 65), although there is slight difference on the magnitude. One reason for over-prediction on the liquid temperature is deficiency of the lumped model during the clearing phase.

5.2.1.2 Simulation with 3D drywell

It is noted that the lumped simulation cannot predict the clearing phase well, since it is assumed that in the lumped model the air and the injected steam are well mixed in the drywell. A simulation with a 3D drywell while the rest is lumped is performed in order to obtain more accurate boundary conditions for 2D wetwell simulation. As described in the pre-test simulation, the volume for the drywell is subdivided into 10×10×10, based on the input deck of lumped simulation.



a)



b)

Figure 67: GOTIHC simulation with 3D drywell vs. measured data. a) for pool liquid temperature, b) for pool water level

Figure 67 gives the comparison of simulation and the experiment on the liquid temperature and the water level in the pool. As shown in Figure 67a, the pool liquid temperature is predicted well for the clearing phase and the thermal stratification phase but there is still a bit of over-prediction in the mixing phase. The water level predicted in the simulation can match the measured data in the clearing phase. It is under-predicted in the stratification phase, as shown in Figure 67b. At about 1100 s, the water level decreases since the steam mass flow decreases to 0 and small part of water is sucked from the pool to the blowdown pipe. However, the water level matches the measured data in the mixing phase well again.

5.2.1.3 Simulation with 2D wetwell

In the MIX tests, more thermocouples are installed inside the blowdown pipe to monitor the water level change during the oscillation in the mixing phase. The measurement frequency is much higher (20 Hz) than before. The temperature inside the blowdown pipe is shown in Figure 68.

It can be seen that in the clearing phase (first 600 s in Figure 68 with TC01), small oscillation occurs near the pipe outlet. In the thermal stratification phase, the oscillation almost disappeared and the water level in the blowdown pipe is maintained below the position of TC01. In the mixing phase, the oscillation is strong due to chugging in the blowdown pipe. Figure 69 shows the temperature change in the blowdown pipe between 3201 s and 3211 s. The water level during the oscillation sometimes can reach the location of TC15, which is about 0.999 m above the pipe outlet. The frequency of oscillation can also be estimated based on this figure.

The temperature measured inside the blowdown pipe can be translated into water level oscillation. The water level change in the blowdown pipe is shown in Figure 70. In the mixing phase, most of the amplitude of oscillation is between 0.492 m and 0.553 m. Hence, the amplitude of oscillation is set as an average value between them, which is 0.5225 m.

The momentum is then estimated based on the synthetic jet model. The value of the velocity and the momentum is shown in Table 7.

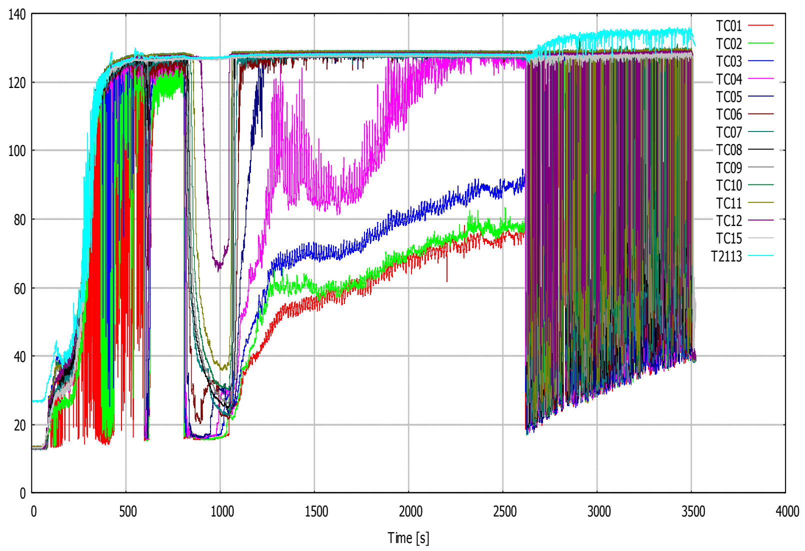


Figure 68: Temperature measured inside the blowdown pipe in MIX-01

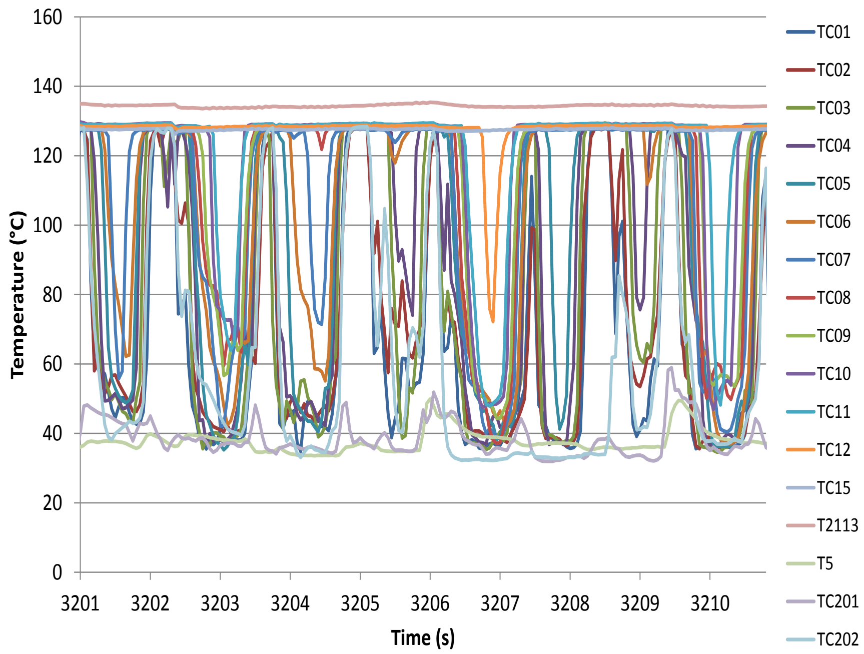


Figure 69: Temperature measured inside the blowdown pipe between 3201 s and 3211 s.

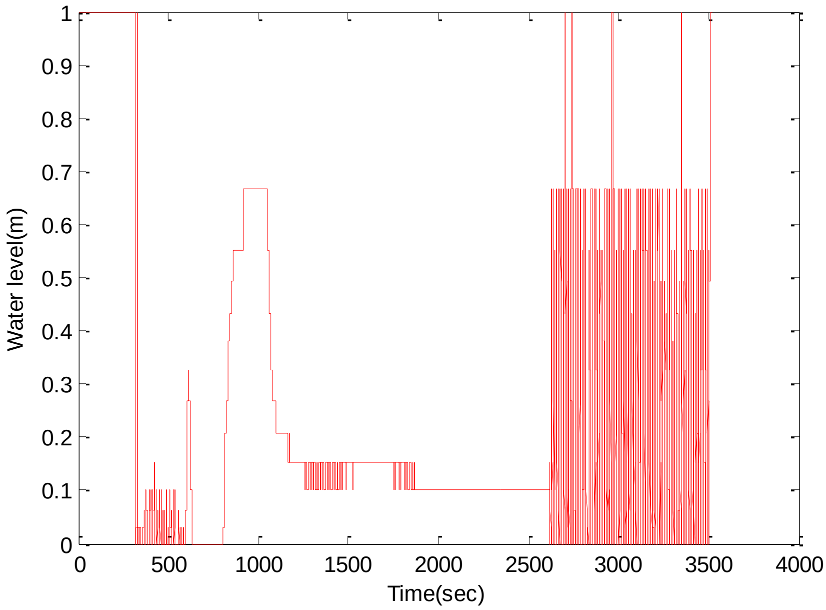


Figure 70: Water level in the blowdown pipe in MIX-01

Table 7: Estimated frequency, amplitude and the momentum rate

Estimated Frequency and Amplitude from TC measurements in MIX-01				**Momentum rate estimated with synthetic jet model**	
Time(s)	Period (s)	Frequency (Hz)	Amplitude L (m)	U (m/s)	M (kg-m/s^2)
2700-3500	1.16	0.86	0.5225	0.635	14.525

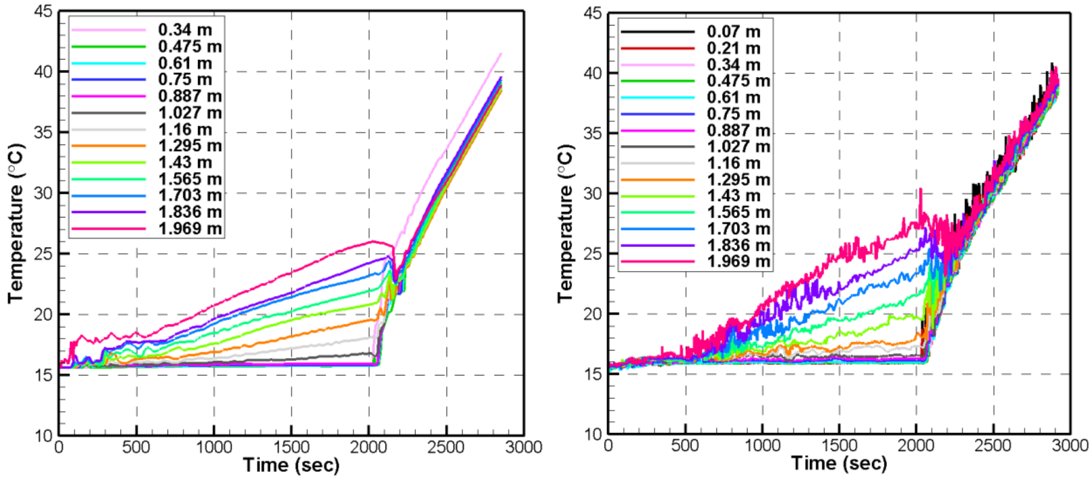
The 3D drywell simulation includes calculation of the heat transfer between the intermediate floor between the drywell and the wetwell, gas, steam and liquid mass flow rate through the blowdown pipe. The heat source is calculated based on the steam mass flow rate from the drywell to the blowdown pipe. All calculations are used to set the boundary conditions in 2D wetwell simulation. The 2D modeling schematic is the same as that for STR test, which is shown in Figure 25.

The clearing phase is not included in the simulation and only experimental part after 600 s is simulated. So the time 0 here corresponds to time 600 s in the actual data, and the figures are adjusted to make better comparison. Figure 71 shows the comparison of pool temperature in the post-test simulation and experiment. It can be seen that in the first 500 s of the experiment, mixing is obtained in the pool, while this is not the case in both post-test and pre-test simulations (Figure 47b). This is attributed to the clearing phase which generated a strong circulation flow responsible for thermal mixing.

At the end of the thermal stratification phase, the top layer temperature in the simulation (1.969 m) is around 25 °C, while the measured temperature in the same level (T2515) is about 28 °C. A possible reason is that the heat transfer through the pipe surface is not uniform in the experiment. It can be seen from Figure 71b that the temperature in the layers below 1.43 m increases less than 3 °C, but it is more than

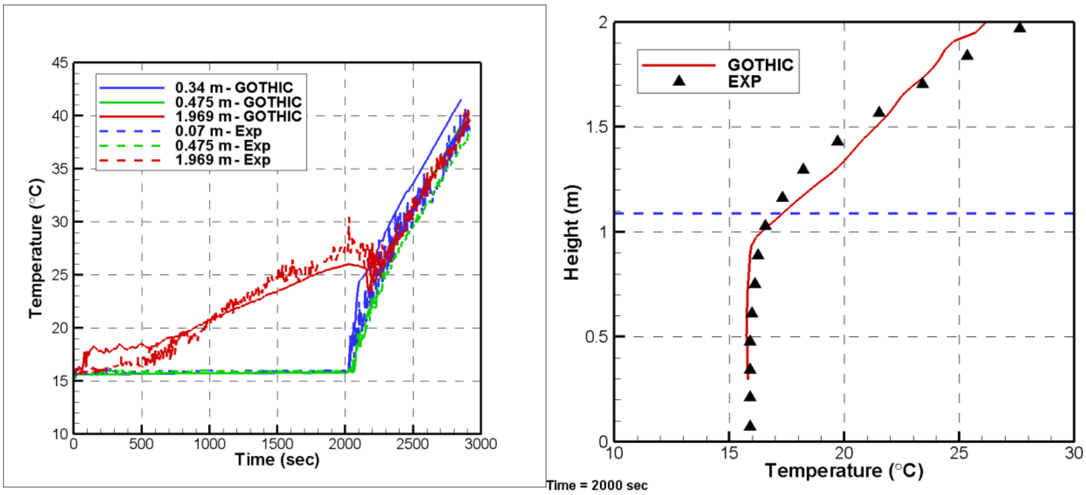
5 °C in the simulation. The heat rate could be higher in the part above 1.43 m than the part below.

Complete mixing is predicted in the simulation and the time for mixing is about 200 s. It is shorter than in MIX-01 which took 300 s to attain complete mixing. Part of the reason is the under-prediction of temperature difference between the top and the bottom layer at the end of the stratification phase.



a) GOTHIC simulation b) experiment

Figure 71: MIX-01 Pool temperature. a) predicted in the post-test simulation; b) measured data provided by LUT.



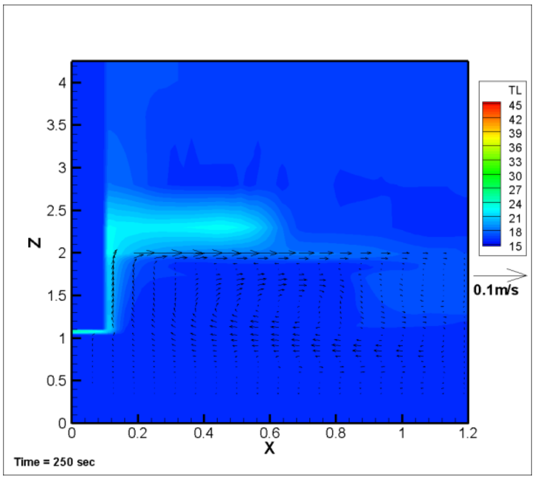
a) temperature distribution b) temperature vs height at t = 2000 s

Figure 72: Comparison of predicted pool temperature in the post-test simulation with measured data provided by LUT.

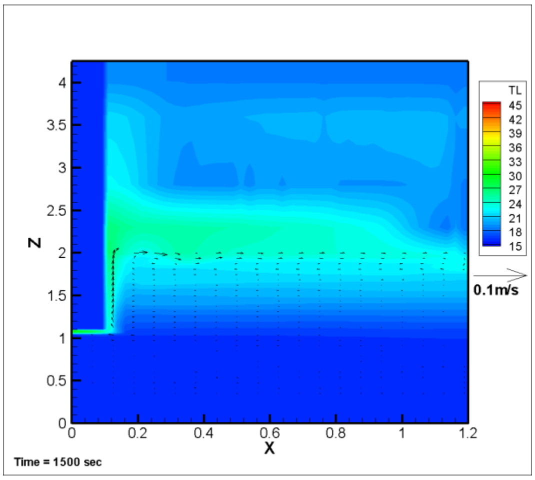
Figure 72a shows comparison of the temperature distribution between the experiment and GOTHIC simulation at three different locations. We found in the simulation that the temperature at 0.34 m during the mixing phase is higher than the rest. This is caused by the downward momentum with heated water from the pipe outlet (see Figure 73d). In the simulation the bottom of the tank is modeled with a flat plate in order to simplify the calculation of the heat transfer between the lab and the bottom wall with GOTHIC built-in model. But in this case the layer at 0.34 m is almost at the bottom of the tank. In the experiment, the bottom of the tank is at 0.07 m, and in this layer we also observed a higher temperature (although fluctuating) than in the layers above it (Figure 72a).

In Figure 72b, the temperature is plotted against height at t = 2000 s which shows that the GOTHIC simulation captures reasonably well the temperature profile from the experiment during the development of thermal stratification.

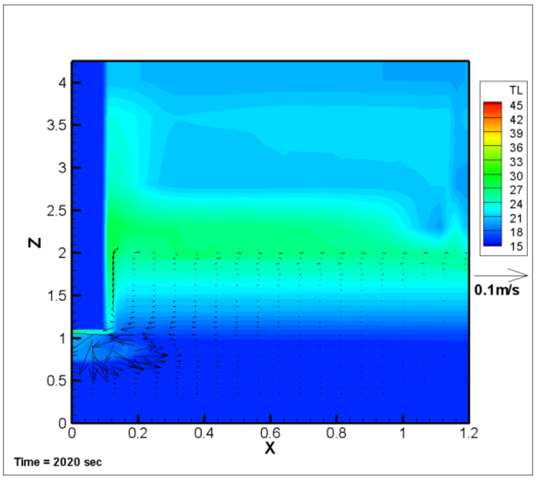
Figure 73 shows the predicted temperature and velocity profiles at different times. The flow pattern during the thermal stratification phase at times t = 250 s and 1500 s can be seen in Figure 73a and Figure 73b, respectively. The circulation is in the clockwise direction with the magnitude of the maximum velocity at 0.07 m/s at t = 1500 s. The flow pattern and temperature profile during the mixing phase at times t = 2020 s and 2100 s can be seen in Figure 73c and Figure 73d, respectively. A high momentum is directed downwards with the magnitude of the maximum velocity at 0.457 m/s at t = 2100 s and the circulation is in the counter-clockwise direction.



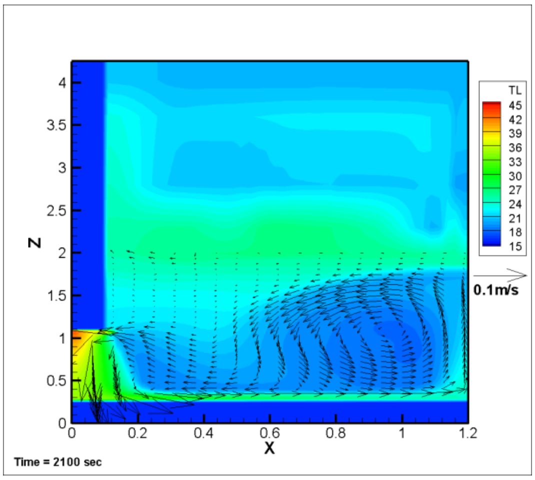
a) t = 250 s



b) t = 1500 s



c) t = 2020 s



d) t = 2100 s

Figure 73: Temperature contour and velocity vector in the simulation at different time.

6 SUMMARY AND OUTLOOK

The presented work contributes to the development of expertise at KTH in the field of modeling of containment thermal-hydraulics under the support of the NORTHNET Roadmap 3 and NKS.

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

(i) The reliable and computationally affordable prediction of thermal stratification development and mixing time scales 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) In this work the Effective Heat Source (EHS) model and the Effective Momentum Source (EMS) model are developed for the 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 estimate 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 provided, 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. The ultimate goal of EMS model is to calculate the effective momentum based on steam mass flux, pool temperature, and design-specific parameters. EMS model implemented in the containment thermal-hydraulic code GOTHIC enables prediction of transient pool behavior and mixing time scales.

(iii) The data from PPOOLEX STR-06, STR-09, and STR-10 tests carried out at Lappeenranta University of Technology (LUT) were used for validation of the EHS and EMS models. Unfortunately, we found that estimations of the amplitude and frequency based on available experimental data from PPOOLEX experiments STR-06, STR-09, and STR-10 have too large uncertainties due to poor space (~1 m) and time (~1 s for early tests and ~0.1 s for late tests) 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 further improvement of the Aya and Nariai model, more accurate experimental data on the dynamics of the free surface would be necessary.

(iv) New set of experiments with high measurement frequency and more thermocouples to be installed in the blowdown pipe were proposed, in order to reduce the uncertainties for both experimental results and analytical model for the prediction of oscillation. The pre-test simulation with 3D drywell shows the temperature increase and time period needed for the clearing phase.

(v) The 6 MIX tests which were carried out at LUT in PPOOLEX facility are used for validation of the EHS/EMS models. It is observed that the measured steam mass flow rate in the MIX-01 experiment could have had a significant uncertainty. Instead of the measured values, steam mass flow rate is estimated based on measured pool temperature. The post-test simulation with estimated steam flow rate can match both the pool average liquid temperature and the pool water level better than the experimentally measured values.

(vi) A 2D wetwell simulation against MIX-01 without the clearing phase is performed and compared to the measured temperature profile of the pool. The simulation can predict the overall temperature behavior in the pool. The results show that the clearing phase has an effect on the first few several hundred seconds of the thermal stratification phase. The temperature difference between the top and the bottom layer is under-predicted in the simulation. A possible reason is that heat rate distribution used in the simulation is uniform, while it is not the case in the experiment. In turn it causes the shorter mixing time in the simulation compared to the experiment.

7 ACKNOWLEDGEMENT

Support from the NORTHNET RM3 and Nordic Nuclear Safety Program (NKS) is greatly acknowledged. Authors are grateful to Markku Puustinen (LUT) and co-workers for very fruitful discussions and unique experimental data which helped a lot in understanding, development and validation of the models.

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Title	Validation of Effective Momentum and Heat Flux Models for Stratification and Mixing in a Water Pool
Author(s)	Hua Li, Walter Villanueva, Pavel Kudinov
Affiliation(s)	Division of Nuclear Power Safety, Royal Institute of Technology (KTH)
ISBN	978-87-7893-359-1
Date	June 2013
Project	NKS-R / ENPOOL
No. of pages	85
No. of tables	7
No. of illustrations	73
No. of references	65

Abstract

The pressure suppression pool is the most important feature of the pressure suppression system in a Boiling Water Reactor (BWR) that acts primarily as a passive heat sink during a loss of coolant accident (LOCA) or when the reactor is isolated from the main heat sink. The steam injection into the pool through the blowdown pipes can lead to short term dynamic phenomena and long term thermal transient in the pool. The development of thermal stratification or mixing in the pool is a transient phenomenon that can influence the pool's pressure suppression capacity. Different condensation regimes depending on the pool's bulk temperature and steam flow rates determine the onset of thermal stratification or erosion of stratified layers. 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 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. The data from PPOOLEX STR-06, STR-09 and STR-10 tests are used for validation of the EHS and EMS models in this work. We found that estimations of the amplitude and frequency based on available experimental data from PPOOLEX experiments STR-06, STR-09, and STR-10 have too large uncertainties due to poor space and time 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. In order to reduce uncertainty in both experimental data and EHS/EMS modeling, additional tests and modifications to the experimental procedures and measurements system in the PPOOLEX facility were proposed. Pre-test simulations were performed to aid in determining experimental conditions and procedures. Then, a new series of PPOOLEX experimental tests were carried out. A validation of EHS/EMS models against MIX-01 test is presented in this report. The results show that the clearing phase predicted with 3D drywell can match the experiment very well. The thermal stratification and mixing in MIX-01 is also well predicted in the simulation.

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

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