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Thermal Stratification and Mixing in a Large Pool Induced by Operation of Spargers, Nozzles, and Blowdown Pipes

Ignacio Gallego-Marcos, Walter Villanueva, Pavel Kudinov

Division of Nuclear Power Safety
Royal Institute of Technology (KTH)
Sweden

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Abstract

In a Boiling Water Reactor, steam released from primary coolant system is condensed in the pressure suppression pool. Thermal stratification in the pool affects pressure suppression capacity of the pool. Heat and momentum sources generated by the steam condensation define pool behavior. Direct Contact Condensation (DCC) of steam present a challenge for contemporary modeling tools. In previous work, the Effective Heat Source (EHS) and Effective Momentum Source (EMS) models were proposed to simulate development of thermal stratification or mixing induced by steam injection into a large pool of water. These models are computationally efficient and sufficiently accurate in resolving the effect of DCC phenomena on the large scale pool circulation.

In this work, we present the validation of the EHS/EMS models for spargers and mixing nozzles. Validation results with EHS/EMS implemented in GOTHIC and ANSYS Fluent show a good agreement in comparison to the PPOOLEX experiments. The scaling of the PPOOLEX experiments with mixing nozzles was done to preserve prototypical ranges of injection conditions and pool regimes. The experimental results are similar to the pre-test analysis data.

An implementation of the EHS/EMS models for analysis of steam injection into a containment pool was developed. The results of analysis provide a realistic pool behavior. Modeling of direct steam injection showed that without EHS/EMS models the results are severely affected by numerical instabilities.

Key words

Thermal Stratification, Mixing, Pressure Suppression Pool, Spargers, Mixing Nozzles, Containment, Thermal Hydraulic, GOTHIC, BWR

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NKS Secretariat
P.O. Box 49
DK - 4000 Roskilde, Denmark
Phone +45 4677 4041
www.nks.org
e-mail nks@nks.org

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Final Report from the NKS-R COPSAR activity (Contract: NKS_R_2015_114)

Ignacio Gallego-Marcos, Walter Villanueva, Pavel Kudinov

Division of Nuclear Power Safety,
Royal Institute of Technology (KTH),
Roslagstullsbacken 21, 10691

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Stockholm

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Executive Summary

The development of thermal stratification in the pressure suppression pool of boiling water reactors (BWRs) and in-containment refueling water storage tanks (IRWST) of pressurized water reactors (PWRs) is an issue of safety significance since it can (i) affect the operation of the spray and Emergency Core Cooling System (ECCS) in BWRs, and (ii) lead to higher containment pressures. The main systems affecting thermal stratification or mixing of the pool are spargers, mixing nozzles, blowdown pipes, and sprays. Thus, to have an accurate prediction of the pool behaviour during an accident, we need to have models with prediction capability for each one of the aforementioned systems.

Lumped and 1D codes are missing adequate models for simulation of 3D phenomena in the pool, such as mixing and stratification. Application of CFD is too computationally expensive for realistic plant accident analysis. The Effective Heat Source (EHS) and Effective Momentum Source (EMS) models were developed as middle ground approach which provides (i) computational efficiency, and (ii) sufficient accuracy in resolving the safety important phenomena and parameters. The EHS/EMS predict the time and space averaged effect of the small scale direct contact condensation phenomena on the large scale circulation and heat transfer in the pool. EHS/EMS models have been developed and validated for blowdown pipes for flow chugging and internal condensation flow regimes.

In this work, we present the validation of the EHS/EMS models for spargers, mixing nozzles, and the implementation of the EHS/EMS models in a full scale containment model using GOTHIC. In order to account for the effect of steam condensation regime on the momentum a condensation regime coefficient was introduced. The results obtained with the EHS/EMS in GOTHIC 8.1 (QA) showed a good agreement in comparison to the PPOOLEX experiments. Implementation of the EHS/EMS models in ANSYS Fluent 16.2 using a radial mesh gave similar results.

The scaling of the PPOOLEX experiments with nozzles was done to preserve prototypical ranges of injection conditions and pool regimes occurring during a liquid injection through nozzles. Pre-test simulations were done to confirm the mixing capability of the mixing nozzles, and to propose a test matrix. In the experiments, the effects of different injection flow rates, temperatures, pool temperatures, and orientation of the nozzles was analyzed. The experimental results were observed to be very similar to the pre-test predictions.

The implementation of the EHS/EMS models in the containment model using GOTHIC 8.1 (QA) was done to control the heat and momentum injected into the pool, and to minimize the effect of the numerical oscillations at the blowdown pipe outlet by time-averaging them. The results were observed to provide a more realistic pool behavior than the standard direct steam injection approach.

Keywords: Thermal Stratification, Mixing, Pressure Suppression Pool, Spargers, Nozzles, Blowdown pipes, GOTHIC.

1. Introduction

The development of thermal stratification in the pressure suppression pool of BWRs and PWRs is a safety issue since it can (i) affect the operation of the spray and Emergency Core Cooling System (ECCS), and (ii) lead to higher containment pressures than in completely mixed conditions. The main systems responsible for inducing thermal stratification or mixing of the pool are

- spargers, multi hole injection pipes connecting the main steam lines to the wetwell;
- mixing nozzles, high momentum liquid injections into the wetwell pool;
- blowdown pipes, large pipes connecting the drywell to the wetwell; and
- sprays in the wetwell or drywell gas spaces.

Thus, to have an accurate prediction of the pool behaviour during an accident, we need to have models with prediction capability for each one of the aforementioned systems.

Modelling of the pool behaviour during an accident is either too computationally expensive for CFD, or too limited in resolution and modelling approaches for lumped and 1D codes. To solve this issue, Li et al. (2014a) introduced the Effective Heat Source (EHS) and Effective Momentum Source (EMS) models. The general idea behind these models is that, to predict the global pool thermal behavior, the small scale phenomena occurring at the direct contact condensation level does not need to be resolved. Instead, it is the time averaged momentum and heat transferred from the steam to the large scale pool circulation that needs to be provided. Avoiding the direct contact condensation reduces computational time, which is a key factor in analyzing the long-term transients of an accident.

EHS/EMS models have already been developed and validated for blowdown pipes for the condensation regimes of chugging and condensation inside the pipe (Li et al, 2014a, 2014b). In this work, we present the validation of the EHS/EMS models for spargers, the scaling and pre-test of the experiments with mixing nozzles, and the implementation of the EHS/EMS models in a full containment model using GOTHIC.

2. Spargers

Spargers are multi-hole injection pipes which connect the main steam lines to the wetwell pool. Their opening is regulated by the safety and relief valves, which are activated according to the vessel pressure and liquid level (Pershagen, 1996). A low steam flow rate through the spargers can lead to the development of thermal stratification in the wetwell pool, and induce higher containment pressures than in completely mixed conditions. In this section, we present the validation of the EHS/EMS models for spargers.

The validation of the EHS/EMS models for spargers was done with experimental data obtained in the PPOOLEX facility (Laine et al., 2015) where 7 tests were performed to analyze the separate effect of the sparger head and Load Reduction Ring (LRR) during a steam injection. These experiments were scaled to reproduce prototypical ranges of steam injection conditions and pool regimes occurring during a Station BlackOut (SBO) in a BWR. Since all processes and regimes cannot be preserved simultaneously in a reduced scale facility such as PPOOLEX, it is not possible extrapolate the experimental results obtained with the scaled design to predict what would happen in full scale. The experimental results will be mainly used for code validation.

The focus of the scaling was on the unstable condensation regime of oscillatory bubble and chugging occurring at low steam mass fluxes, which were observed to be the dominant regimes during a SBO. Details of the scaling can be found in (Gallego-Marcos et al., 2015). In brief, the processes involved during the SBO were divided into the different levels where they appear: the macro (pool), meso- (sparger pipe), and micro- (injection holes) scales. In the macro and meso-scale, the goals were to preserve similar pool regimes of thermal stratification and mixing and condensation regimes inside the sparger pipe as in the SBO transient. In the micro scale, the goal was to preserve the prototypic dimensions of the injection holes and the micro scale condensation phenomena. To achieve such goals, the design parameters were determined based on previous work done in (Peterson, 1994; Li et al., 2014c; Sonin, 1981; D'Auria & Galassi, 2010).

Pre-test simulations were run to ensure that the pool regimes of thermal stratification and mixing could be achieved with the sparger design obtained with the scaling. The results of these simulations were also used to determine the location of the instrumentation and to design a test matrix. The final design of the sparger used during the PPOOLEX experiments can be found in (Laine et al., 2015; Gallego-Marcos et al., 2015).

2.1. EHS/EMS model for spargers

The effective heat and momentum transferred from the sparger steam jets to the liquid was estimated using the steam condensation region approach used in (Gamble et al., 2001; Kang and Song, 2008, 2010; Moon et al., 2009). This approach solves simplified conservation equations of mass, momentum, and energy in a control volume where the steam jets are expected to condense completely (Figure 1). The obtained condensate and entrainment flows are updated every time step and imposed in the simulation as single-phase liquid boundary conditions. All models found in the literature were developed for stable jets appearing at high steam mass fluxes, typically above 250 kg/(m^2s). However, analysis of a prototypical SBO transient in a BWR showed that stable jets are only expected to appear during the first ~500 s (Gallego-Marcos et al., 2015). The rest of the transient is dominated by unstable condensation regimes such as oscillatory bubble and chugging, Chan and Lee (1982). Thus, the models and experiments presented here will focus on these unstable regimes.

The condensation dynamics of an oscillatory bubble can be divided into three phases. Growth of the bubble, until a critical size is reached; necking, where the tip of the bubble begins to detach from the rest; and fragmentation or collapse of the detached bubble. Prototypical frequencies of this cycle have been measured to be between 50-400 Hz by Chan & Lee (1982) and Yuan et al., (2016). For this regime, the momentum from the bubbles can be transferred to the liquid in the following modes.

"Asymmetric" collapse: Momentum is transferred to the mean flow and turbulence. Video images obtained by Yuan et al., (2016) show that drag forces can induce a pressure gradient along the axis of the detached bubble and deform it to a crescent moon shape. According to the CFD simulations performed by Pan et al. (2012), this causes entrainment of liquid droplets which are then pushed in the axial direction during the fragmentation and collapse of the bubble, inducing a mean flow pattern.

"Symmetric" collapse: Momentum is transferred to turbulence, not to the mean flow. Tang et al. (2015) observed that at high steam flow rates and subcoolings, high levels of turbulence and instabilities developed in the bubble surface, increasing the rate of condensation, and leading to a violent collapse in all directions right after its detachment. This regime was named the *capillary wave regime*. This symmetric collapse does not have a preferred direction, and thus, is not expected to be able to induce a mean flow pattern.

The steam mass fluxes and pool subcooling expected to appear in a BWR sparger indicate that we are in the *capillary wave regime*. However, the PIV data obtained in the PANDA experiments with spargers showed that this condensation regime was able to induce well-defined mean velocity field in the pool (Kapulla et al., 2015). This means that the violent collapse of the bubbles was not "symmetric", it had a preferred direction, probably through the "asymmetric" collapse discussed in the previous paragraphs.

Our initial assumption will be that the detached bubbles transfer *all* of their momentum to the mean flow during their collapse. In terms of force balance, this is equivalent to model the momentum transfer directly at the interface of the non-detached bubble. This hypotheses will be reviewed during the validation process, section 2.3. With this assumption, the momentum transfer at the interphase can be modelled with equation (1), Figure 1b. Here, Γ is the condensation flow rate, and sub-index i represents the fluid properties close to the interface. Given the momentum equation at the interface, the steam and liquid momentum equations in the positive axial direction of the jet are presented in equations (2) and (3) respectively, Figure 1a.

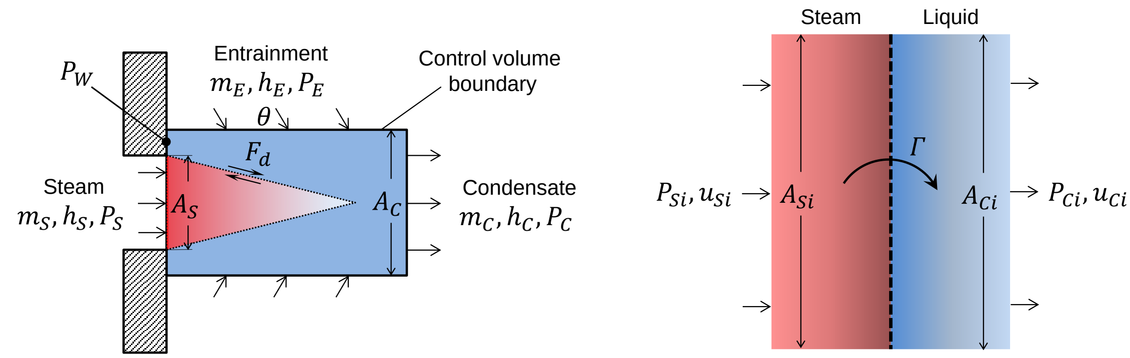


Figure 1: Steam condensation region.

$$\Gamma u_{Si} + P_{Si}A_{Si} = \Gamma u_{Ci} + P_{Ci}A_{Ci} \tag{1}$$

$$-m_S u_S + \Gamma u_{Si} = P_S A_S - P_{Si}A_{Si} - F_d \tag{2}$$

$$m_C u_C - m_E u_E \sin\theta\cos\theta - \Gamma u_{Ci} = -P_C A_C + P_w(A_C - A_S) + P_{Ci}A_{Ci} + F_d \tag{3}$$

In equations (2) and (3) the drag forces F_d should be equal for both phases but with opposite sign. We can also assume that the pressure near the sparger wall P_w is equal to the hydro static pressure of the pool at the injection holes level P_C. Moreover, since we expect the entrainment to be almost perpendicular to the direction of the jet, $\sin\theta$ will drop to a very low value and the magnitude of the entrainment term will be negligible. With these considerations, the summation of equations (2), (3), and (1) leads to equation (4). This equation was used in (Kang & Song, 2008, 2010; Moon et al., 2009) to model sonic jets. However, our steam jets were not at sonic conditions, and the pressure inside the sparger was only increased to overcome the pressure losses along the sparger pipe, and at the injection holes, which, according to Malavasi et al., (2012), can be very significant. Therefore, it will also be assumed that at the exit of the injection holes, $P_S \approx P_C$, leading to a further simplification shown in equation (6).

$$m_S u_S + P_S A_S = m_C u_C + P_C A_S \tag{4}$$

As a result, the EHS/EMS equations of mass, momentum, and energy for the oscillatory condensation bubble condensation regime, applied to the condensation region from Figure 1, are presented in equations (5), (6), and (7) respectively. Validation against experimental data is presented in section 2.3.

$$m_S + m_E = m_C \tag{5}$$

$$m_S u_S = m_C u_C \tag{6}$$

$$m_S h_S + m_E h_E = m_C h_C \tag{7}$$

2.2. Buoyancy effect on turbulence

During a steam injection into a water pool, sharp temperature and density $\rho(T)$ gradients are expected to develop in the vertical direction, at the interface between the cold stratified layer at the bottom of the pool and a hot region above it. It is widely accepted that such gradients tend to suppress mean and turbulent vertical motions by buoyancy effects, reducing the amount of heat and momentum transferred through the interface (Zilitinkevich et al., 2008). Therefore, to have an accurate prediction of the stratified layer thickness and its erosion, such turbulence dissipation must be modelled appropriately.

One possibility to model turbulence dissipation at the interface is to damp the turbulent viscosity when the gradient Richardson number, equation (9), exceeds a critical value. This value was estimated to be 0.25 by Miles (1961) and Howard (1961) for a two-dimensional stratified shear flow, and 1 by Abarbanel et al. (1984) for a three dimensional shear flow with non-linear perturbations. A large body of experimental has confirmed that there is a range between 0.2-1 where turbulence is gradually damped.

Another option would be to include buoyancy terms in the turbulent equations which would reproduce the aforementioned behaviour. An extensive sensitivity study performed by the authors using ANSYS Fluent 16.2 showed that, using the k-Omega turbulence model, the Standard Gradient Diffusion Hypothesis, equation (8), with a $C_{3\varepsilon}$ equal to zero (no buoyancy terms in the dissipation equation) gave the best results, (Gallego-Marcos et al., 2016a). Other models generated too much artificial viscosity at the stratified layer, causing a strong temperature diffusion below the sparger which was not observed in the experiments.

$$G_b = g_i \overline{u_i'\rho'} \approx g_i \left(-\frac{\mu_T}{\rho Pr_T} \frac{\partial \rho}{\partial x_i} \right) = g_i \left(\beta \frac{\mu_T}{Pr_T} \frac{\partial T}{\partial x_i} \right) \tag{8}$$

$$Ri_g = \frac{\beta g \frac{\partial T}{\partial z}}{\left(\frac{\partial U_r}{\partial z} \right)^2 + \left(\frac{\partial U_z}{\partial z} \right)^2} \tag{9}$$

2.3. Validation of the EHS/EMS models using GOTHIC

GOTHIC is a general purpose thermal-hydraulic software package for design, licensing, safety and operating analysis of nuclear power plant containments (GOTHIC, 2014). Its combined lumped and 3D modelling, and the built-in components such as pumps, heat exchangers, etc., make it a very suitable platform to simulate the pool and containment behavior during a long term accident. Therefore, the EHS/EMS models presented in section 2.1 were first implemented in this code, version 8.1 (QA).

During the validation, it was observed that the condensate momentum predicted by equation (6) led to a complete mixing of the pool during the stratification phases. Sensitivity studies with different meshes, turbulence models, and numerical parameters showed similar results. Therefore, this behavior was attributed to the hypothesis from section 2.1, where it was assumed that the bubbles transfer *all* of their momentum to the mean flow. Some of these bubbles could also collapse symmetrically, transferring their momentum to turbulent fluctuations. This would cause a reduction of the momentum transferred to the mean flow.

A condensation regime coefficient C varying between 0 and 1 was used to model this effect, equation (10). This coefficient represents the fraction of steam flow which was not able to transfer its momentum to the mean flow, and instead, dissipated it by generating turbulence. The different values used in the validation are presented in Table 1 and Figure 2. We can see that at low steam mass fluxes and low pool temperatures, where the condensation oscillations are expected to be higher (Yuan et al., 2016), the fraction C of momentum transferred from the steam to the liquid was small. At high steam mass fluxes and pool temperatures, where the condensation regime was more stable (Yuan et al., 2016), the lower amount of detached bubbles allowed the steam to transfer all of its momentum to the condensate liquid; that is, $C = 1$.

$$C = \frac{m_C u_C}{m_S u_S} \tag{10}$$

$$M_{eff} = C m_S u_S \tag{11}$$

During the validation, it was also observed that using a Cartesian mesh, the only available option on GOTHIC, the flow aligned with the mesh axes diffused much less than in other directions. Thus, despite the sparger was modelled with 12 flow paths injecting at 8 different radial directions, the flow was quickly concentrated in the jets aligned with the mesh. In order to clarify the effect of this numerical artifact on the pool behavior, simulations were run using ANSYS Fluent 16.2 and a radial mesh. It was observed that, despite the differences in the flow structure, it was necessary to reduce the momentum of the steam in the Fluent simulation by a similar C coefficient as in GOTHIC. Using a C similar coefficient, the results obtained in GOTHIC and Fluent were also very similar, Figure 8. This observation suggests that, for the case of a steam injection through the sparger head, (i) the development of thermal stratification is not very sensitive to the flow structure but to the total momentum, and (ii) a reduction of the steam momentum is necessary to take into account the effect of the condensation regime for the PPOOLEX test conditions. Details of the implementation of the EHS/EMS models in Fluent, done for the PANDA experiments with spargers, can be found in (Gallego-Marcos et al., 2016a, 2016b).

Table 1: Empirical condensation regime closures used in the simulations of the PPOOLEX SPA-T1, T3, T4, and T7 experiments.

Experiment		Steam mass flux [kg/(m^{2}s)]	Pool temperature [^{o}C]	Condensation regime coefficient C [-]
T1	Stratification	74	15-35	0.1-0.25
	Mixing	305	35-40	1
T3	Stratification	74	20-45	0.25-0.40
	Mixing	162	45-55	0.94
T4	Stratification	80	20-40	0.30-0.36
	Mixing	108	40-60	1
T7	Stratification 1.1	87	15-30	0.41-0.54
	Stratification 1.2	75	30-35	0.46
	Mixing 1	121	35-40	0.86
	Stratification 2	75	40-55	0.76-0.79
	Mixing 2	123	55-60	0.86

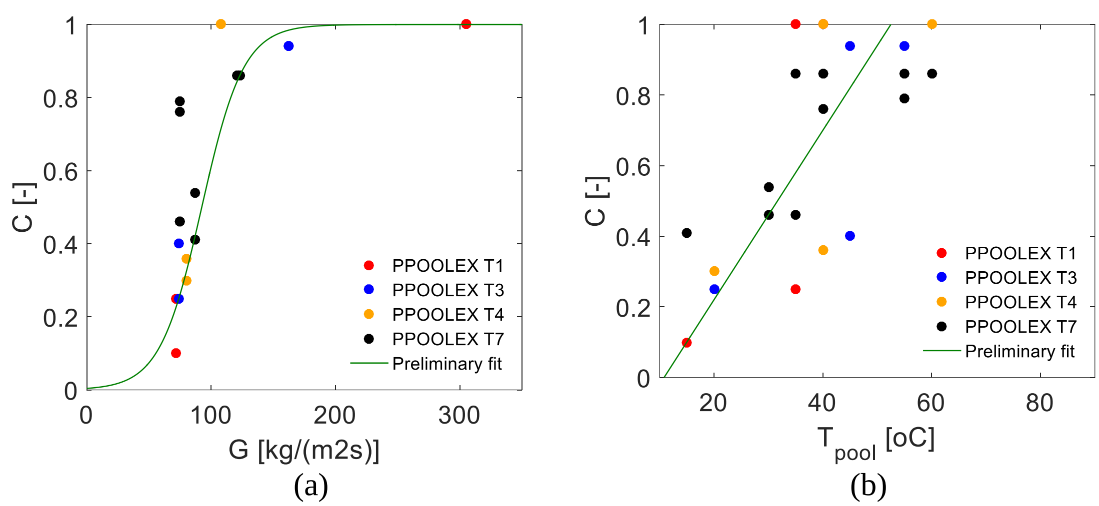


Figure 2: Empirical condensation regime coefficient used in the simulations of the PPOOLEX SPA-T1, T3, T4, and T7 experiments as a function of the (a) steam mass flux through the injection holes and, (b) pool temperature.

2.3.1. Implementation of the EHS/EMS models

Details of the implementation of the EHS/EMS models for sparger is GOTHIC can be found in (Gallego-Marcos et al., 2015). We will only give a short over view of the main modelling parameters used.

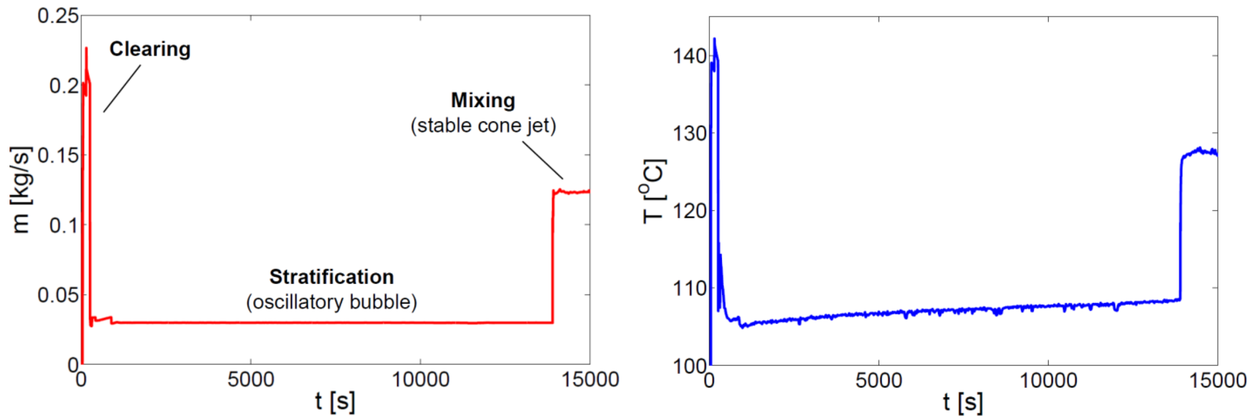
The PPOOLEX wetwell was modelled using three nested control volumes to allow local refinement of the mesh. The cell size was about 100 mm in the horizontal direction and 50 mm in the vertical direction.

The EHS/EMS models for spargers were implemented using boundary conditions which provided the single-phase liquid condensate and entrainment flows. The solution of equations (5), (6), and (7) was computed every time step using Dynamically Linked Libraries (DLLs). Control variables were used to update the pool and steam injection conditions to the DLL functions every time step. Due to the costs of applying the steam condensation region to each one of the injection holes, holes oriented in the same direction were lumped into a single hole.

The standard k-Epsilon turbulence model was used in all of the simulations. In the run control parameters, a second order bounded upwind discretization scheme was used in space and a semi-implicit discretization in time. The pressure equation was solved with the conjugate gradient method until a 1e-7 residual was reached after 4 outer implicit loops with 100 internal iterations each. The minimum time step was set to 1e-7 s and the maximum to 0.05 s.

2.3.2. T1 experiment

The mass flow and temperature of the steam injected into the pool during the first stratification and mixing phases of the T1 experiment is presented in Figure 3. The steam condensation regimes covered were the oscillatory bubble and stable cone jet. Since the steam generation capacity in PPOOLEX was limited to about 0.4 kg/s, the high steam mass flux needed to develop the stable condensation regime was reached by blocking three rings of holes at the sparger head (reduction in injection hole area by a factor of four). Using a desktop computer with i7-4770 processor, 3.4 GHz, and 16 GB RAM, the first 15000 s of the T1 experiment were simulated in about 12 days.



(a) (b)

Figure 3: PPOOLEX-SPA T1 experiment (Puustinen et al., 2016), (a) steam mass flow, (b) average temperature of the 3 TCs located inside the sparger pipe at the injection holes level.

The average pool temperature in PPOOLEX and in GOTHIC was computed as a spatially weighted average of all of the TCs located in the L1, L2, L3, and L4 trains. This value can be a good estimation of the pool conditions; however, it should be noted that it can vary depending on the flow field since it is only computed from specific locations of the pool. We can observe in Figure 4a that the liquid level in the simulation was slightly higher than in the test during the stratification phase, leading to a higher average pool temperature. It has been observed in previous PPOOLEX experiments with blowdown pipes that at low steam mass flows, the flow meter can give significant errors in the measurement. Thus, it is believed that the steam mass flow in the experiment was lower than the measured one. This would explain the over-estimation in liquid level and in pool temperature. Another possibility could be an inadequate modeling of the heat transfer through the vessel walls, which were not insulated. However, we will see in further tests that using the same model the pool temperatures were predicted adequately.

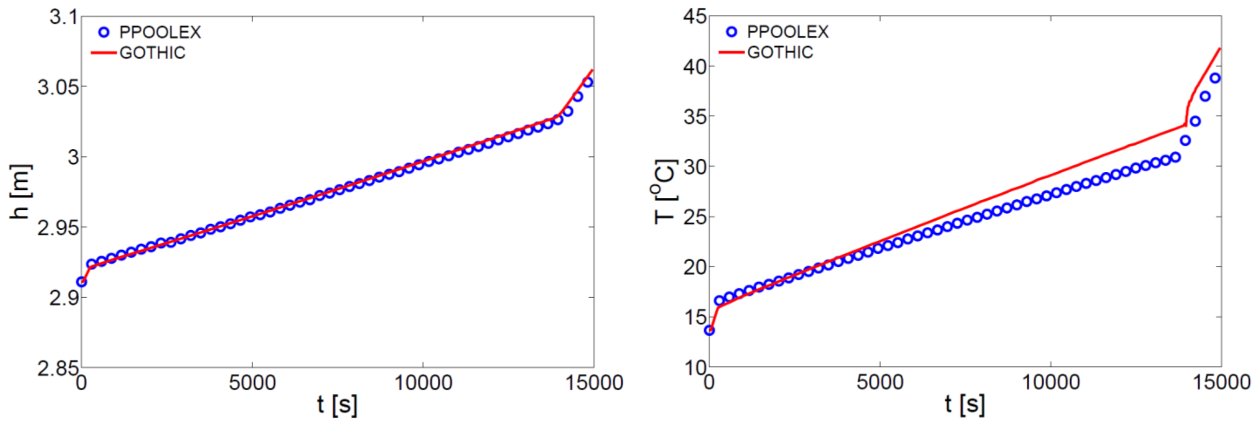
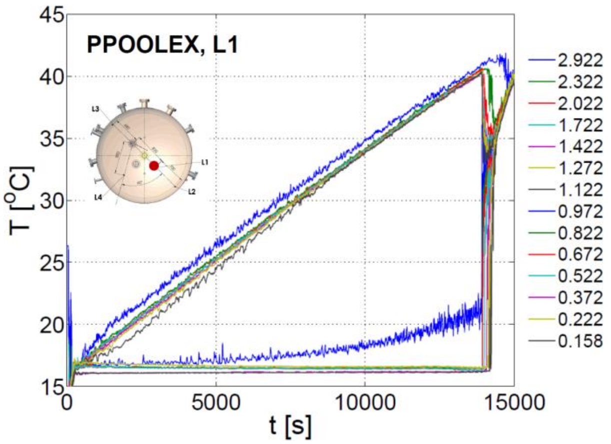


Figure 4: Validation of the EHS/EMS models for spargers against the first 15000 s of the PPOOLEX-SPA T1 experiment. (a) Pool liquid level, (b) pool temperature, obtained as an average of all of the TCs located in the L1, L2, L3, and L4 trains.

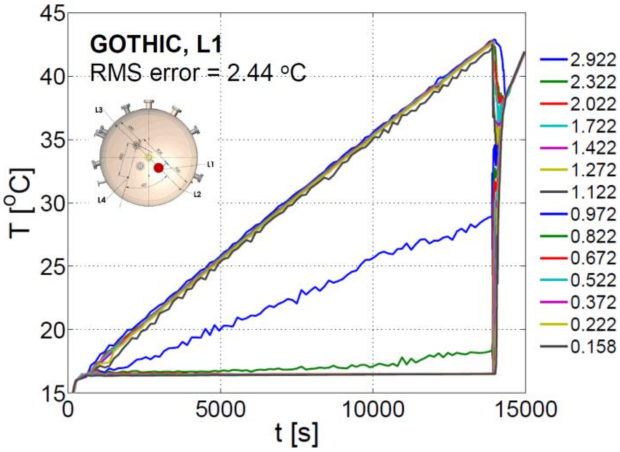
Figure 5 presents the pool temperatures obtained in the experiment and in the simulation. Using a condensation regime coefficient C between 0.1 and 0.25, the thermal stratification phase was well predicted. Such low value of the C coefficient indicates that a significant fraction of the steam bubbles collapsed without transferring their momentum to the mean flow. This is in agreement with the condensation regime, which was oscillatory bubble.

We can see in Figure 6a that during the mixing phase the upper layers of the pool were cooled down at the same time as the bottom layers were heated up. This observation suggests that the high momentum injected into the pool induced a flow pattern which took water from the bottom of the pool and pushed it up towards the hot layers. We will see in further tests that this fast mixing did not occur at lower momentum rates. Instead, the stratified layers were slowly eroded at the surface by other mechanisms.

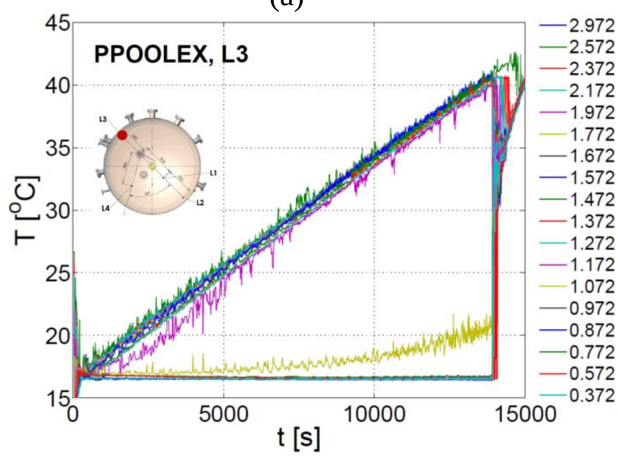
In the mixing phase, since the condensation regime was expected to be stable cone jet, the condensation regime coefficient C was set to 1. That is, all of the steam momentum is transferred to the mean flow. We can see in Figure 6b that, using $C = 1$, the mixing time, stepwise erosion of the stratified layer, and temperature drop at the upper part of the pool, were well predicted in the simulation.



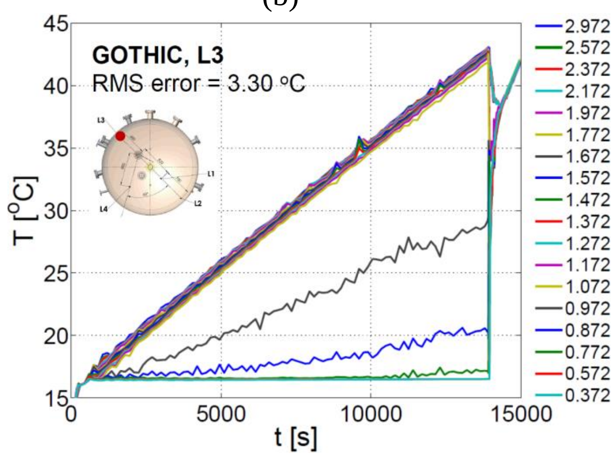
(a)



(b)

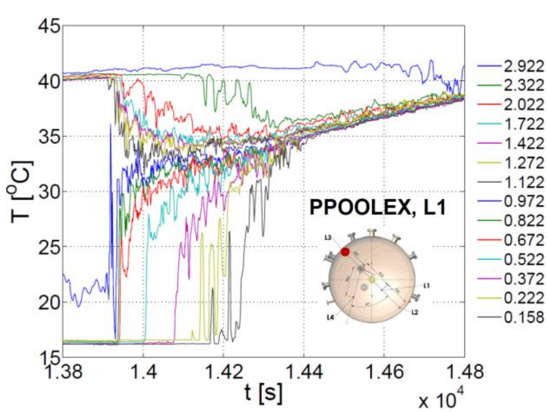


(c)

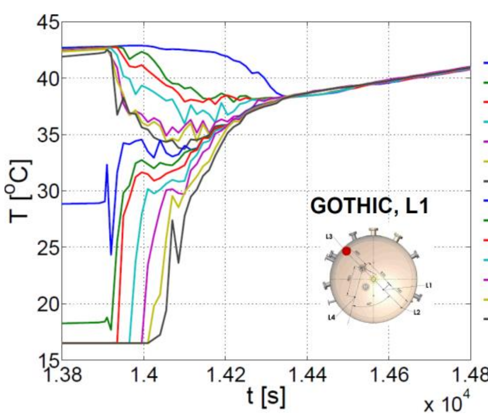


(d)

Figure 5: Validation of the EHS/EMS models for spargers against the first 15000 s of the PPOOLEX-SPA T1 experiment. Pool temperature at the TC locations (a) PPOOLEX measurements, L3 train, (b) GOTHIC results, L3 train, (c) PPOOLEX measurements, L1 train, (d) GOTHIC results, L1 train.



(a)

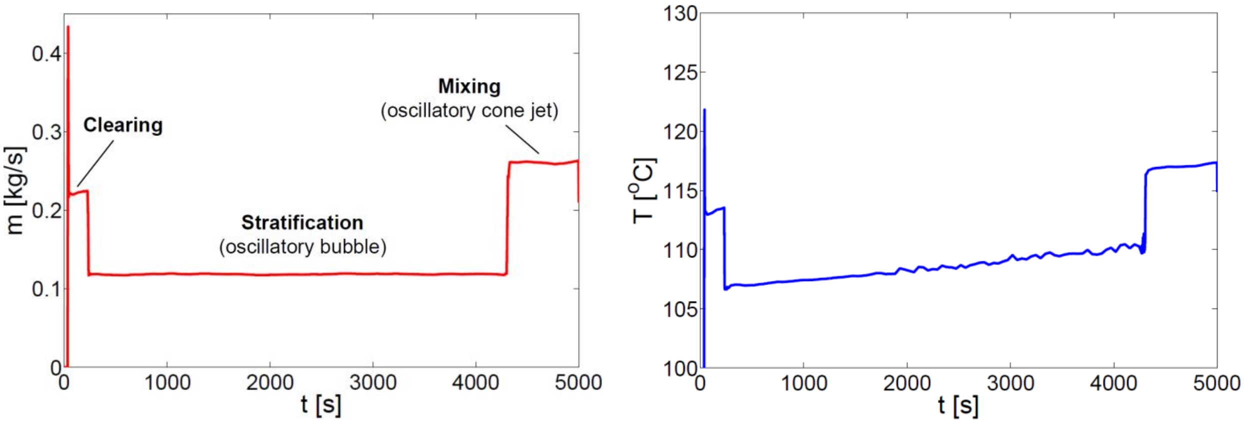


(b)

Figure 6: Validation of the EHS/EMS models for spargers against the first 15000 s of the PPOOLEX-SPA T1 experiment. Pool temperature at the TC locations (a) PPOOLEX measurements, L1 train, detail of the mixing phase, (b) GOTHIC results, L1 train, detail of the mixing phase.

2.3.3. T3 experiment

Details of the validation results of the EHS/EMS models against the T3 experiment can be found in (Gallego-Marcos et al., 2015). The steam condensation regimes covered were the oscillatory bubble and oscillatory cone jet.



(a) (b)

Figure 7: PPOOLEX-SPA T3 experiment (Laine et al., 2015), (a) steam mass flow, (b) average temperature of the 3 TCs located inside the sparger pipe at the injection holes level.

Figure 8 presents the pool temperatures obtained in the experiment and in the simulation. The clearing, thermal stratification, and mixing phases were very well predicted. The condensation regime coefficient C was similar to the one used in the validation of the T1 experiment. That is, small value during the unstable condensation regimes of the stratification phase, and close to unity for the more stable regimes of the mixing phase. The only deviation with the experimental data was observed in the lowest TC at L1 train (Figure 8b, z = 0.222 m), which mixed with the pool 200 s later than in the experiment. This is probably due to a slight under-estimation of the effective momentum. However, since the mixing time in this experiment was only 500 s, the reasons for this deviation were difficult to assess.

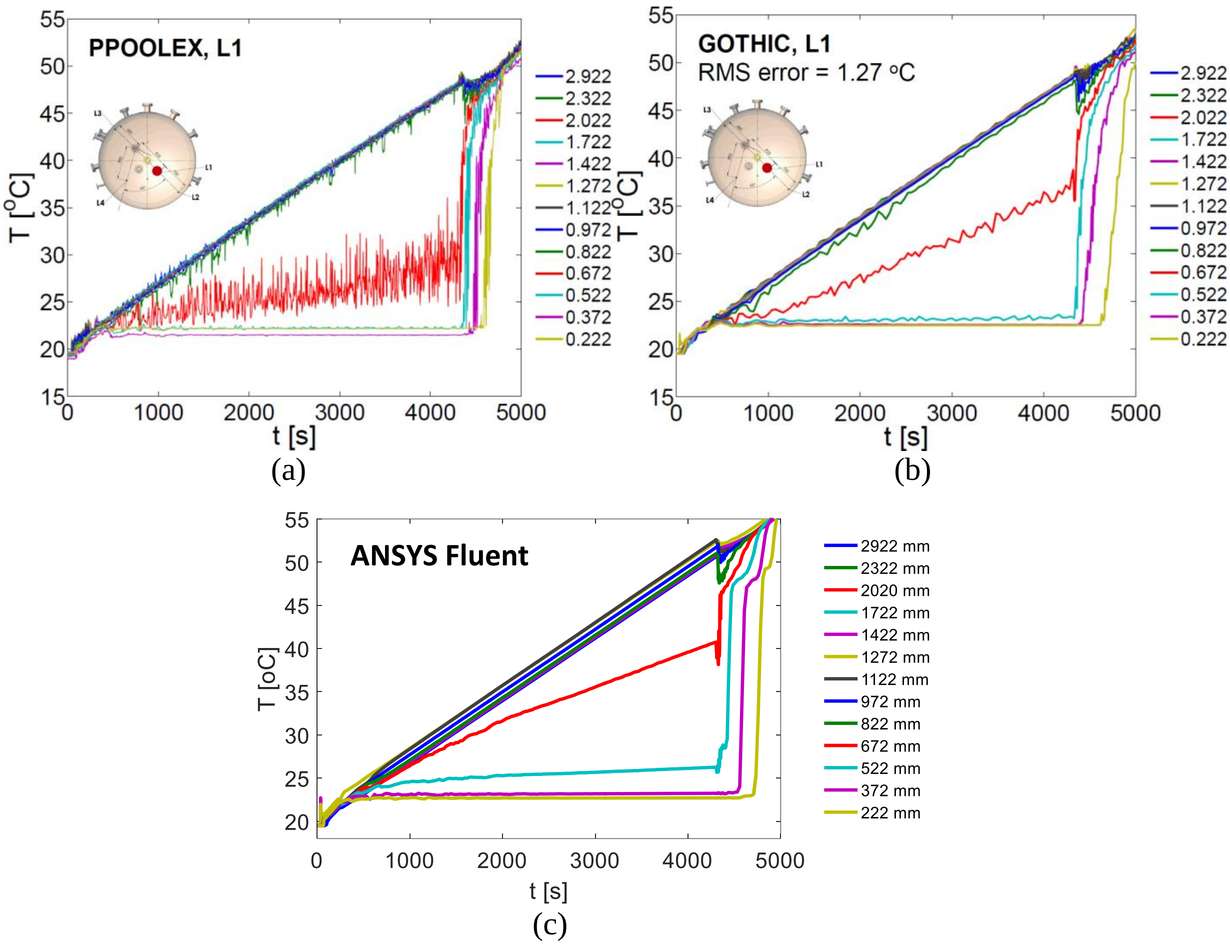
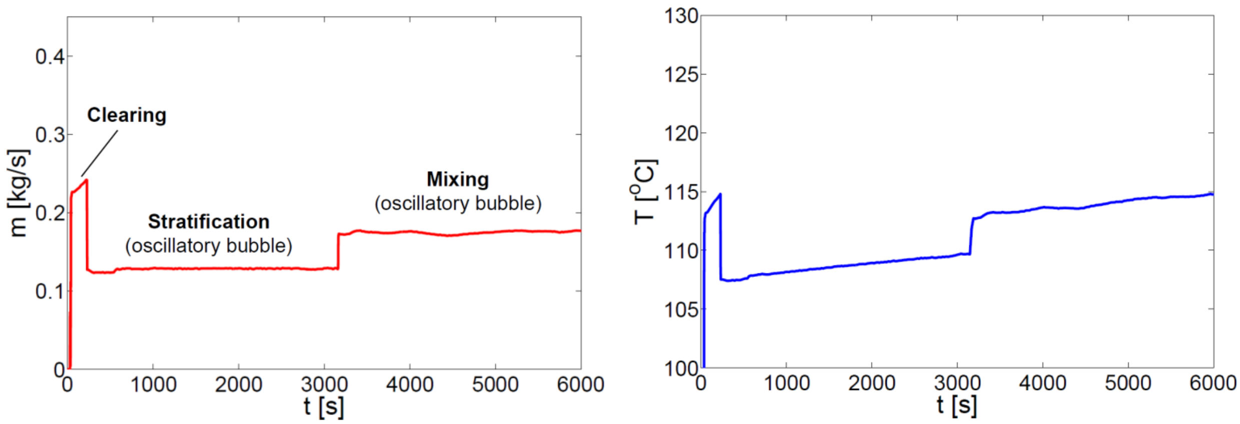


Figure 8: Validation of the EHS/EMS models for spargers against the first 5000 s of the PPOOLEX-SPA T3 experiment. Pool temperature at the TC locations of the L3 train obtained in (a) PPOOLEX experiment, (b) GOTHIC, and (c) ANSYS Fluent 16.2 simulation.

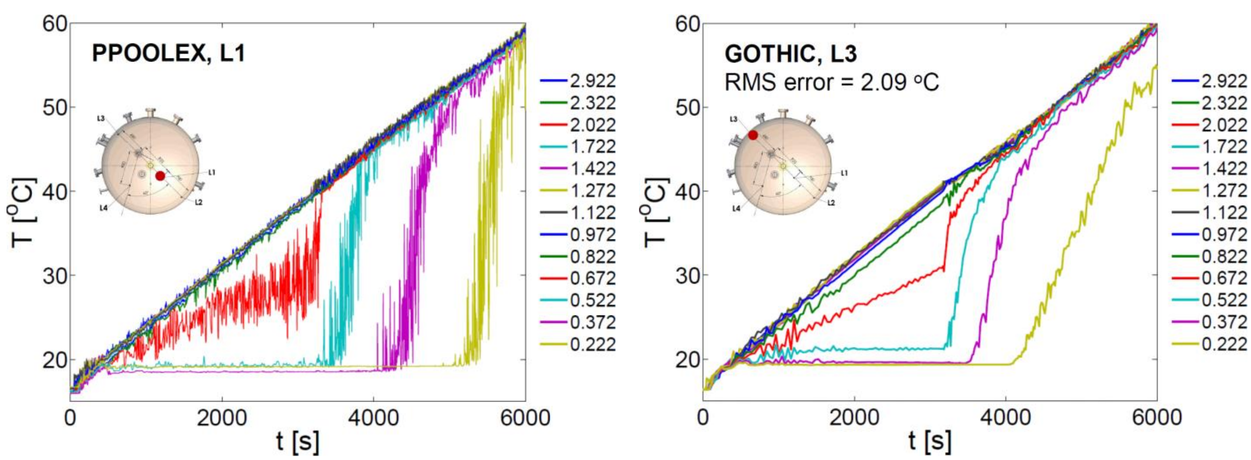
2.3.4. T4 experiment

Details of the validation results of the EHS/EMS models against the T3 experiment can be found in (Gallego-Marcos et al., 2015). The mass flow and temperature of the steam injected into the pool during the first stratification and mixing phases of the T4 experiment is presented in Figure 9. In both phases, the steam condensation regime was the oscillatory bubble. The main feature of this experiment is the long mixing phase, which lasted about 3000 s. Such long phase is very useful for the validation since it highlights deviations between the simulation and the experimental results.



(a) (b)

Figure 9: PPOOLEX-SPA T4 experiment (Laine et al., 2015), (a) steam mass flow, (b) average temperature of the 3 TCs located inside the sparger pipe at the injection holes level.



(a) (b)

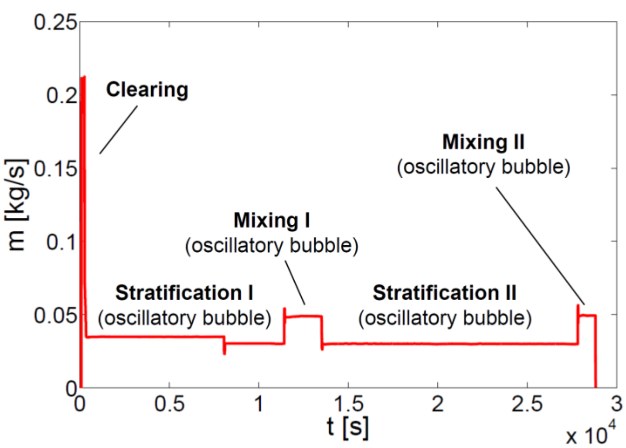
Figure 10: Validation of the EHS/EMS models for spargers against the first 6000 s of the PPOOLEX-SPA T4 experiment. Pool temperature at the TC locations of the L3 train obtained in (a) PPOOLEX experiment, and (b) GOTHIC simulation.

Figure 10 presents the pool temperatures obtained in the experiment and in the simulation. The stratification phase was very well predicted using the same condensation regime coefficient C as in the T3 experiment. In the mixing phase, the experiment shows that the stratified layer was eroded at a constant rate, maintain a sharp temperature gradient at the interface (Figure 10a). In the simulation, the stratified layer was initially eroded at a similar rate as in the experiment. However, as the transient continued, the temperature gradient at the interface began to be smeared, and the erosion velocity began to be reduced. This could be due to the Cartesian mesh used in GOTHIC, especially for the ellipsoidal shape of the bottom cap of the PPOOLEX vessel. Further analysis using a body fitted mesh should be done to clarify this uncertainty.

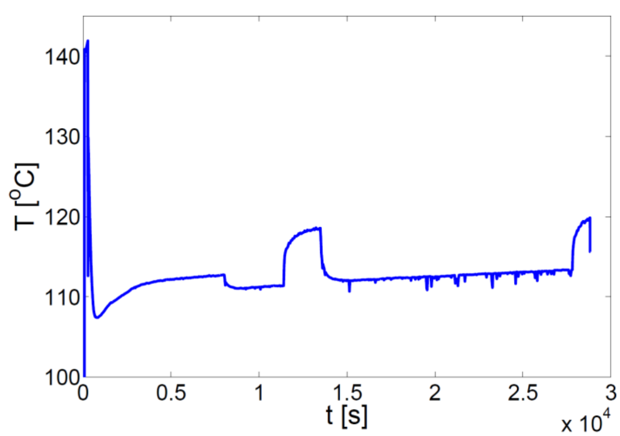
2.3.5. T7 experiment

The T7 experiment was designed to analyze the separate effect of the Load Reduction Ring (LRR). All of the injection holes at the sparger head were blocked, only the LRR holes were left open. With this configuration, the flow pattern at a certain distance after the injection can be considered to be axisymmetric around the sparger axis. The advantage of this flow pattern is that it allows us to perform 2D axisymmetric simulations, which are much less computationally expensive than the 3D simulation presented in the previous sections. Since the jets from the LRR were all oriented downwards towards the bottom of the pool, it was assumed that the off-centered location of the sparger within the pool would not induce major 3D effects.

The mass flow and temperature of the steam injected into the pool during the first stratification and mixing phases of the T7 experiment is presented in Figure 11. The steam condensation regimes covered were all of oscillatory bubble. Using a desktop computer with i7-4770 processor, 3.4 GHz, and 16 GB RAM, the 15000 s of the T7 experiment were simulated in about 1 day.



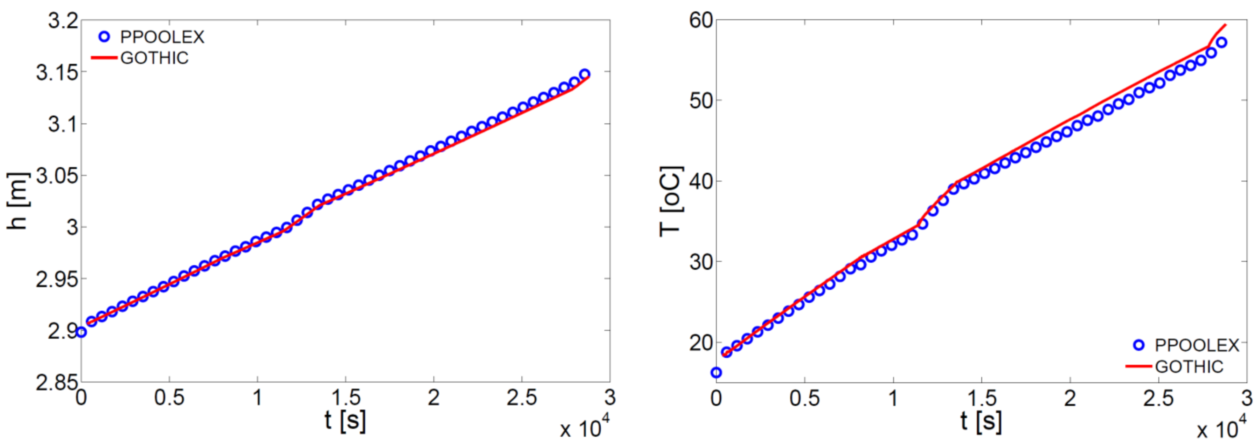
(a)



(b)

Figure 11: PPOOLEX-SPA T7 experiment (Puustinen et al., 2016), (a) steam mass flow, (b) average temperature of the 3 TCs located inside the sparger pipe at the injection holes level.

The average pool temperature in PPOOLEX and in GOTHIC was computed as a spatially weighted average of all of the TCs located in the L1, L2, L3, and L4 trains. This value can be a good estimation of the pool conditions; however, it should be noted that it can vary depending on the flow field since it is only computed from specific locations of the pool. We can observe in Figure 12 that the liquid level and average pool temperature obtained in the simulation gave a good fit to the experimental data, meaning that the mass and energy injections obtained with equations (13), (14), and (15) respectively were computed correctly. The slight over-prediction of the pool temperature during the second stratification phase suggests a slight under-estimation of the heat transfer coefficient through the vessel walls. It was also observed that the mass flow measured by the flow meter had an error of about 9 %. This error was estimated based on the over-prediction of the measured liquid level when using the flow rate given by the flow meter. Thus, the simulations presented in Figure 12 were run with a 9 % lower mass flow rate than the one measured in the experiment.



(a) (b)

Figure 12: Validation of the EHS/EMS models for spargers against the PPOOLEX-SPA T7 experiment. (a) Pool liquid level, (b) pool temperature, obtained as an average of all of the TCs located in the L1, L2, L3, and L4 trains.

Figure 13 presents the pool temperatures obtained in the experiment and in the simulation. The first stratification and mixing phases were well predicted using similar values of the condensation regime coefficient C as in the T1, T3, and T4 experiments. However, in the second stratification phase, we can see in Figure 13a that the experiment showed a slow erosion of the stratified layer. This slow erosion was not captured in the simulation. Thus, further investigation on the effective momentum generated at pool temperature of 40-60 ^{o}C is needed. Similar to the T1 experiment, fast mixing was observed in the T7 experiment. We can observe in Figure 14 that the sudden mixing between the upper hot part of the pool and the lower cold bottom was well predicted.

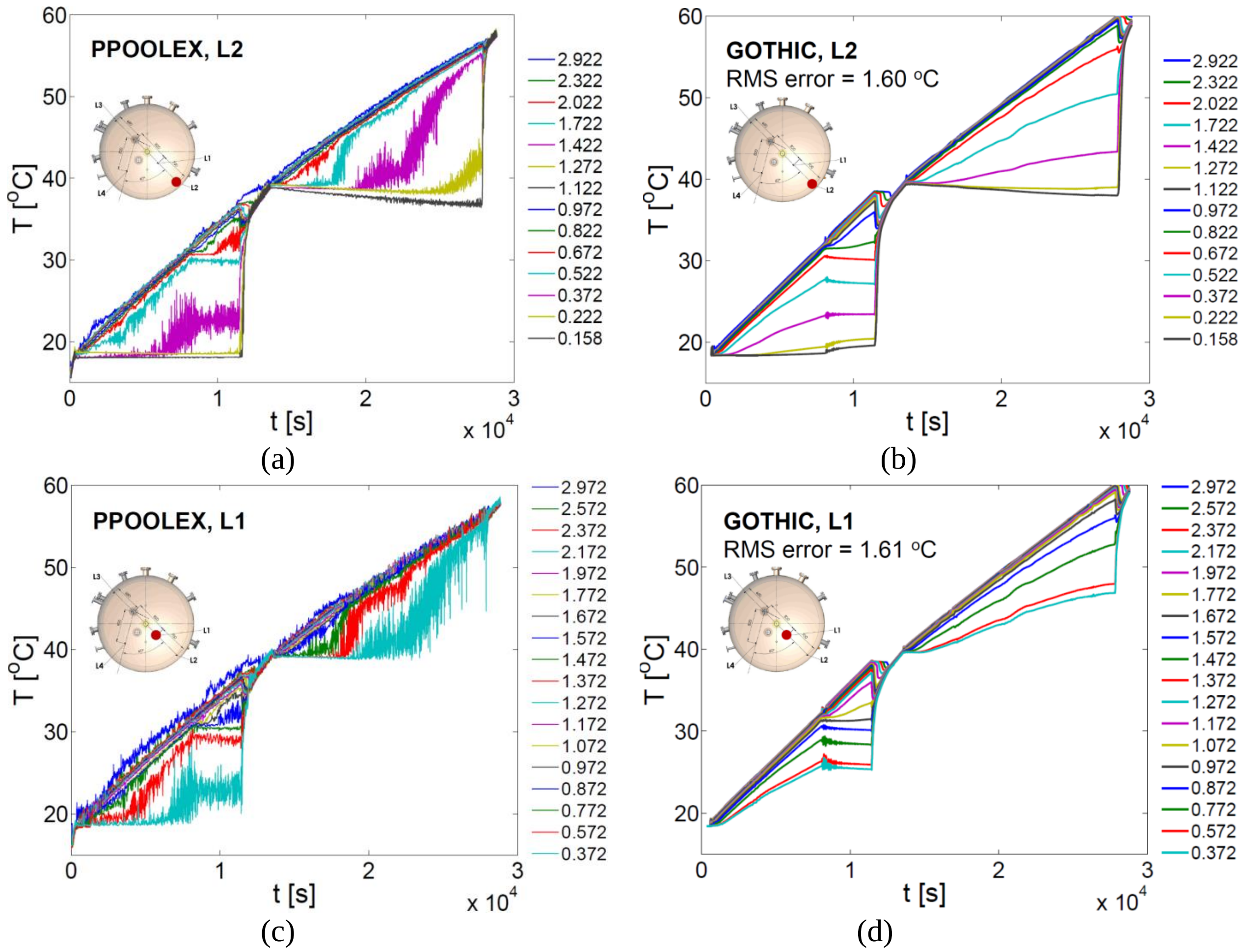


Figure 13: Validation of the EHS/EMS models for spargers against the PPOOLEX-SPA T7 experiment. Pool temperature at the TC locations (a) PPOOLEX measurements, L2 train, (b) GOTHIC results, L2 train, (c) PPOOLEX measurements, L1 train, (d) GOTHIC results, L1 train.

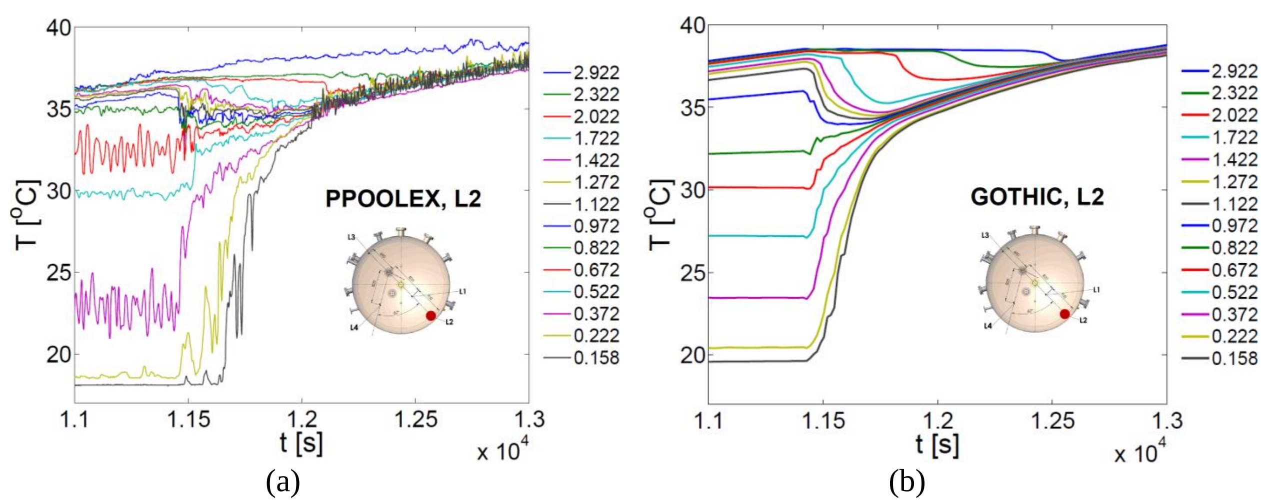


Figure 14: Validation of the EHS/EMS models for spargers against the PPOOLEX-SPA T7 experiment. Pool temperature at the TC locations (a) PPOOLEX measurements, L1 train, detail of the mixing phase, (b) GOTHIC results, L1 train, detail of the mixing phase

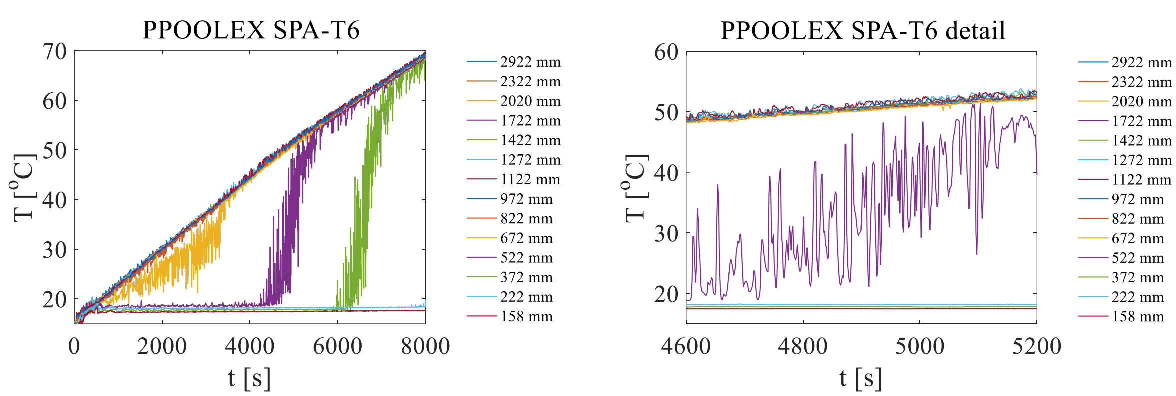
2.4. Scaling of the erosion of a thermally stratified layer

The sparger experiments performed in the PPOOLEX (Laine et al., 2015) and PANDA (Kapulla et al., 2015) facilities showed that, during a steam injection at low momentum, the stratified layer was eroded very slowly at the surface. An example could be the first mixing phase of the PPOOLEX T6 experiment, Figure 15, where we can see that it took about 1 hour to erode 130 mm of the stratified layer. In this section, we will analyse the mechanisms which could lead to such slow erosion of the layer, and propose an effective model to simulate this behaviour using a coarse mesh.

Fernando et al. (1997) and McGrath et al. (1997) analysed theoretically and experimentally the erosion mechanisms of a stable stratified layer in shear-free flows (zero mean flow, non-zero turbulence). They demonstrated that the erosion mechanism of a stratified layer can be obtained as a function of a single non-dimensional number, the Richardson number equation (12), which is the ratio between buoyant and inertial forces. In the equation, Δb is the density jump across the thermocline; L_H the length scale of the turbulent eddies above the thermocline; and u_H the horizontal root mean square (rms) velocity at the same location. At Richardson numbers between $35 \lesssim Ri \lesssim 90$, they concluded that the erosion mechanism is dominated by the intermittent break-up of waves developing at the interface, between the high and low density fluids, induced by the turbulent eddies. The interaction between these waves leads to a resonant growth where the amplitude increases and the frequency decreases. When a certain threshold of amplitude and frequency are reached, the waves become unstable and break up, inducing local mixing. For this erosion regime, it was determined in (Fernando et al., 1997) that the erosion velocity u_E (the displacement of the interface in the vertical direction as a function of time) can be computed as a function of the Richardson number using equation (13).

$$Ri = \frac{\Delta b L_H}{{u_H}^2} \tag{12}$$

$$\frac{u_E}{u_H} = 4.5 Ri^{-5/3} \tag{13}$$



(a) (b)

Figure 15: Evolution of the pool temperatures measured along a vertical line of TCs during the PPOOLEX T6 experiment with spargers. (a) Full transient, (b) detail.

The features of the erosion mechanism described in the previous paragraph were found to be similar to the pool behaviour during the PPOOLEX and PANDA experiments with spargers. We can see in Figure 15 that during the mixing phase, low frequency of about 0.05 Hz oscillations developed at the interface (Gallego-Marcos et al., 2016c). These oscillations could be source of the slow wave-breaking erosion described in the previous paragraph. Next section will be dedicated to the quantification of such similarity.

2.4.1. Richardson scaling of the PPOOLEX and PANDA experiments

The relation between the erosion velocity and the Richardson number shown in equation (13) was compared to the erosion velocities measured during the PPOOLEX and PANDA experiments, and the estimated Richardson numbers during such transients. Details can be found in (Gallego-Marcos et al., 2016c). An over-view of the main steps taken is presented below.

To estimate the Richardson number above the stratified layer, the buoyancy jump across the thermocline, Δb, was calculated using equation (14). The densities of the hot and cold layers were derived from the temperatures measured by the TCs, whose spatial resolution in the vertical direction was about 150 mm. The integral length scale of turbulence above the thermocline, L_H, was reported in (De Silva et al., 1992) to be directly proportional to the distance between the turbulent source (sparger outlet in our case) and the thermocline z as shown in equation (15). Thus, the same equation was used in our estimation of L_H.

$$\Delta b = g\frac{\rho_c - \rho_h}{\rho_h} \tag{14}$$

$$L_H = 0.1z \tag{15}$$

The horizontal rms velocity, u_H, was the variable subject to more uncertainty. In the experiments found in the literature, where turbulence was induced with an oscillatory grid, this value was either measured or estimated with equation (16). In the equation, S is the amplitude of the strokes, M the size of the grid, and f the oscillation frequency of the grid. It was then assumed that, similarly to equation (16), u_H is also inversely proportional to z, and equal to u_{H0} at the spargers injection level. To calculate u_{H0}, it was assumed that the steam jets condense over a short length, inducing a liquid jet expanding with an angle of 12 degrees and with an average turbulent intensity of 20 %. More details of the assumptions can be found in (Gallego-Marcos et al., 2016c).

$$u_H\ (\text{grid}) = 0.22(S^3M)^{\frac{1}{2}}fz^{-1} \tag{16}$$

$$u_H = \frac{u_{H0}}{1+z} \tag{17}$$

The erosion velocity was calculated using equation equation (18), where Δz is the vertical distance between two TCs, and Δt the time that the thermocline took to pass through these two TCs. The thermocline was assumed to be at the level of the TC when the temperature measured by the TC was equal to the average of the hot and cold layers.

$$u_e = \frac{\Delta z}{\Delta t} \tag{18}$$

Using equations (14), (15), (17), and (18), the Richardson number and erosion velocities estimated from the PPOOLEX and PANDA experiments with spargers were compared to the analytical expression in equation (13). The results are presented in Figure 16. We can see that the experimental data and analytical expression are well correlated. Different assumptions on how to calculate u_H were observed to shift the experimental points from the analytical curve (Gallego-Marcos et al., 2016c). However, in all of these cases, the trend was conserved similar to equation (13). This confirmed that equation (13) has to potential to be used to calculate the erosion velocity of a stratified layer.

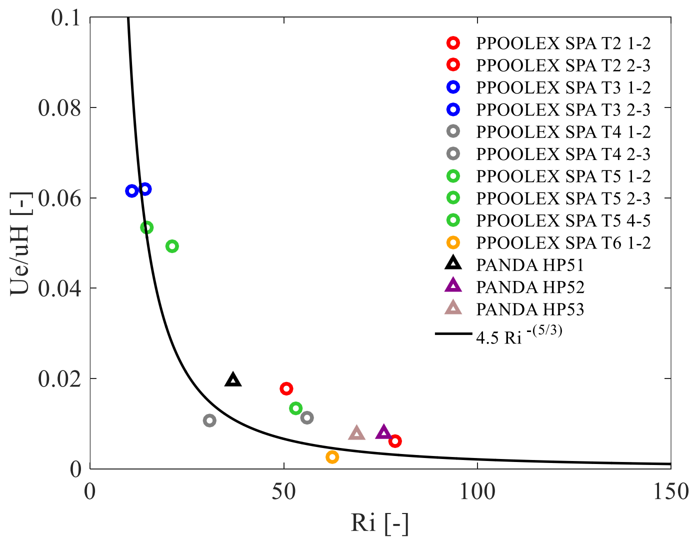


Figure 16: Erosion velocity of a stable thermally stratified layer as a function of the Richardson number. Comparison between the experimental data obtained in the PPOOLEX and PANDA experiments with spargers and the analytical expression.

2.4.2. Application of Richardson scaling to a coarse mesh model

We have shown in the previous section that the erosion velocity can be computed as a function of the Richardson number using equation (13). This can be applied to a coarse mesh simulation of the pool where, instead of resolving the eddy splashing and wave breaking phenomena, the erosion velocity is directly imposed in the simulation. A similar approach was presented by GOTHIC developers in (Ozdemir et al., 2015), where a 1D model of a pool was artificially mixed using a pump connecting the mixed and stratified layers. The mass flow through the pump was controlled with several analytical expressions. We will use a similar approach as in (Ozdemir et al., 2015), but using equation (19) to control the volumetric flow rate through the pump Q. In the equation, u_E is the erosion velocity, A the cross section of the pool, and Ri the Richardson number.

$$Q = u_e A = \left(u_H 4.5 Ri^{-5/3}\right) A \tag{19}$$

A 2D model of the PPOOLEX pool was implemented in GOTHIC to simulate two of the PPOOLEX experiments with sparger, Figure 18. The erosion velocities measured in the experiment were imposed in the simulation using a pump connecting the last cell at the bottom of the pool to another cell located close to the pool surface. More details of the implementation can be found in (Gallego-Marcos et al., 2016c).

The results of the model are presented in Figure 17. Each simulation was completed in about 90 s using 1 core in an i7 desktop computer. We can see that the model was able to reproduce very well the gradual erosion of the stratified layer while maintaining the sharp temperature gradient across the thermocline. Further development and validation of this approach will enable accurate and computationally efficient simulations for prediction of the pool behaviour.

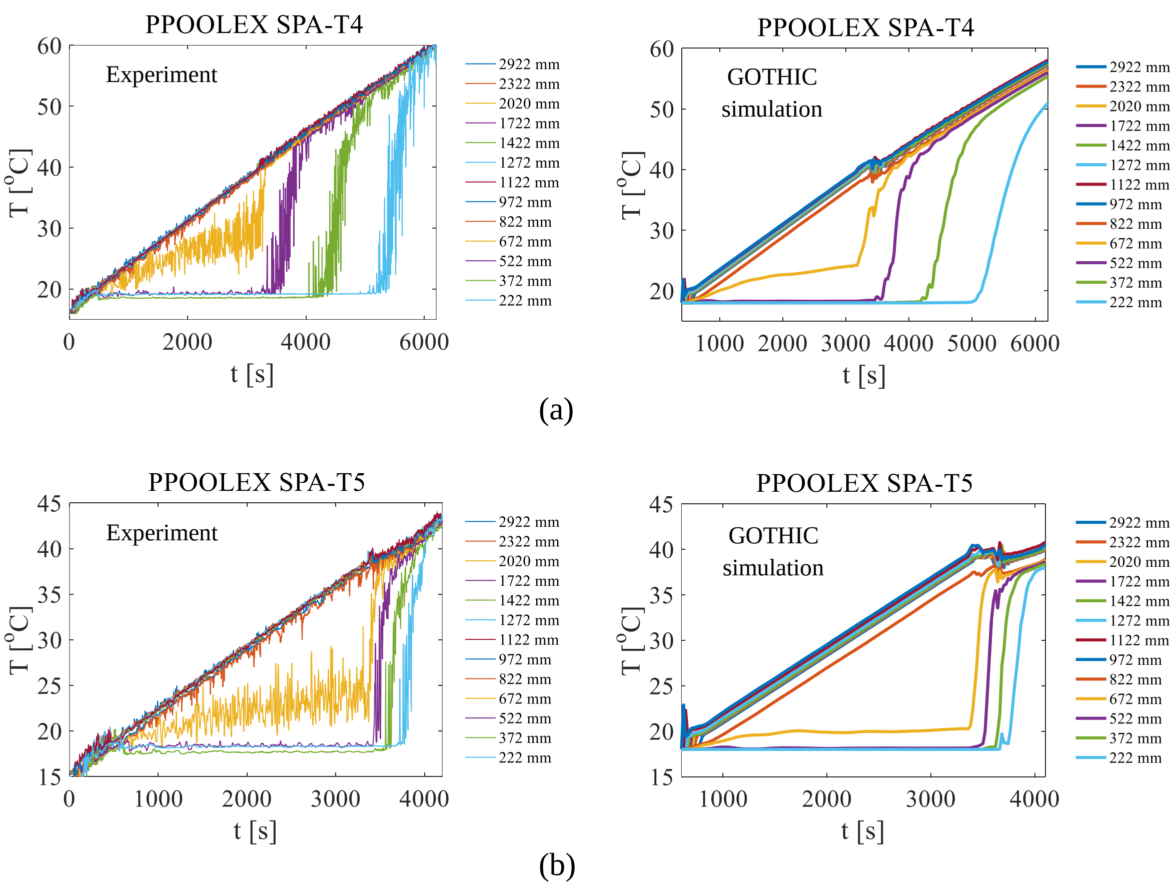


Figure 17: Experimental results and GOTHIC simulation of the PPOOLEX (a) SPA-T4 and (b) SPA-T5 experiments with spargers.

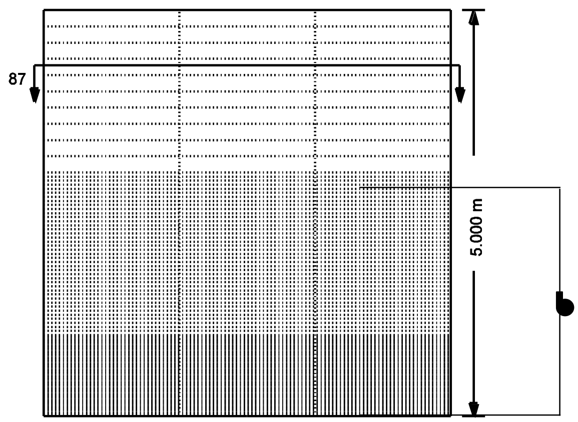


Figure 18: GOTHIC model used for the application of Richardson scaling to the PPOOLEX experiments with sparger.

3. Mixing nozzles

In a BWR, mixing nozzles inject water at high momentum into the wetwell pool to break any thermal stratification that might develop during an accident. This could occur, for example, in a SBO where power supply is suddenly recovered. In this case, thermal stratification induced by the steam injection through spargers could be broken by activating the mixing nozzles, leading to a decrease in the pool surface temperature, and a subsequent decrease in the containment pressure. In this section, we present the scaling, pre-test, and experimental campaign done with mixing nozzles in the PPOOLEX facility to investigate the effect of different injection parameters in the mixing efficiency.

The mixing nozzles are part of the Residual Heat Removal (RHR) system, which drains water from the wetwell pool and returns it cooled to the wetwell through strainers and nozzles. In a prototypic Nordic BWR, the strainers are long perforated plates or cylinders with a total injection hole are of about 1 m^2 per train. With such large area, the momentum of the water injected through them is small and they are not expected to be able to mix the pool. Since nozzles inject large amount of water through much smaller orifices, the momentum is much larger than in the strainers, and thus, they will be the dominant mixing mechanism during the RHR functioning. Prototypical nozzle designs in Nordic BWRs are presented in Table 2. We can see that there are several nozzles in the wetwell. However, only one of them injects a substantial amount of momentum which can induce mixing. For this reason, the PPOOLEX experiments with mixing nozzle were scaled to induce a similar behaviour as Nozzle 2.

Table 2**: Liquid injection conditions of the mixing nozzles in a prototypic Nordic BWR.**

Mixing nozzles in a BWR	Liquid flow rate	Diameter of the nozzle	Reynolds number at exit [a]	Momentum of the injected liquid [a]
Nozzle 1 (×2)	10 kg/s	0.033 m	4.8e5	117 kg·m/s^2
Nozzle 2 (×1)	170 kg/s	0.12 m	2.2e6	2542 kg·m/s^2

[a] Assuming liquid injection at 30 ºC: μ = 8e-4 kg/(ms), ρ = 1000 kg/m^3

3.1. Scaling of the nozzle experiments

Similar to the scaling of the sparger, the goal of the scaling was to preserve prototypical ranges of injection conditions and pool regimes occurring during a liquid injection through the mixing nozzle from Table 2. Since the spatial and temporal scales of all the processes occurring at full scale cannot be preserved simultaneously in a reduced-scale facility such as PPOOLEX, we will emphasize that it will not be possible to extrapolate the experimental results obtained with the scaled design to predict what would happen in full scale. The experimental results will be mainly used for code validation. Then, only through codes which have been validated for the regimes and conditions of the plant, it will be possible predict the full scale plant behavior.

In our scaling methodology, the design parameters were divided into similar groups as in the sparger: macro-scale (water pool) and micro-scale (injection holes). A detailed description of the goals at each scale and design parameters needed to achieve these goals is given below:

Macro-scale (water pool): The goal is to study different regimes of pool mixing by the momentum injected through the nozzle. To induce a similar thermal behaviour in the pools, we should preserve ranges of mass, momentum, and energy time scales, and spatial similarity between the PPOOLEX and BWR pools. To achieve this goal, the design parameters needed to be determined are the (i) pool depth, (ii) location of the nozzle, (iii) orientation of the nozzle, (iv) liquid mass flow through the nozzle, and (v) total injection hole area. The selection of the design parameters is given below.

(i) The pool depth was set to 3 m, the same value as the one used in the sparger experiments. This depth gave a good spatial similarity between the water volume around a *single* sparger in a BWR, and the PPOOLEX pool. However, since there is only *one* mixing nozzle in a BWR (Nozzle 2 in Table 2), its area of influence is the whole pool. The prototypic height to diameter ratio of a BWR pool is about 0.3; whereas in PPOOLEX, with the chosen 3 m pool depth, it is 1.25. Therefore, the pool behavior induced by the nozzle in PPOOLEX is expected to be more affected by confinement effects, such as interaction with the walls, than in the BWR pool.

(ii) The nozzle was located in the center of the pool and submerged 0.5 m below the surface. Prototypical submergences of the mixing nozzles in a BWR are about 15 % of the wetwell pool depth. In our case, the 0.5 m submergence in the 3 m pool leads to a similar ratio of 16 %. In a BWR, the nozzles are usually located close to the wall since the RHR piping is arranged around the wetwell walls. However, we decided to locate the nozzle in the center of the pool to allow a more efficient validation of the models.

(iii) The nozzle was designed to allow both horizontal and vertical downwards injections. In a BWR, Nozzle 2 is near the wall, oriented horizontally and with an azimuthal angle of about 45º which would induce a rotating flow pattern in the pool. Due to the already high spatial distortions between the PPOOLEX and BWR pools, we decided to maintain the nozzle in the center of the pool, injecting horizontally and vertically, without inducing the rotating flow pattern in the pool. The vertical injection, despite not found in the BWRs, would allow a more efficient validation using 2D axisymmetric models.

(iv, v) Given the aforementioned pool dimensions, the order of magnitude of the mass, momentum, and energy time scales were preserved by setting a total injection hole area of 64 mm^2 and a liquid mass flow of 1 kg/s. The mass time scale, equation (20), was defined as the ratio of mass injected into the pool to mass in the pool. The momentum time scale, equation (22), was defined as the momentum rate injected through the nozzle to the potential energy needed to mix the pool. The energy time scale, equation (21), was defined as the ratio of energy rate injected into the pool to the energy of the pool.

$$\omega_m = \frac{\dot{m}_{nzl}}{m_L} \tag{20}$$

$$\omega_p = \frac{\dot{m}_{nzl} v_{nzl}}{m_L \sqrt{gH}} \tag{21}$$

$$\omega_e = \frac{\dot{m}_{nzl} h_{nzl}}{m_L h_L} \tag{22}$$

In the equations, m, $\dot{m}$, h, and v are the mass, mass flow rate, enthalpy, and velocity of the fluid; sub-indexes nzl and L the nozzle and pool respectively. H is the total height of the pool and g the acceleration due to gravity. The results are presented in Table 3. We can see that the time scales are in the same order of magnitude, suggesting that similar thermal behaviour of the BWR and PPOOLEX pools can be expected. However, this is something which will need to be verified in section 3.2 with the pre-test simulations since it is also influenced by the confinement of the PPOOLEX vessel and the flow field.

Table 3: Energy and momentum time scales during a liquid injection through the mixing nozzles

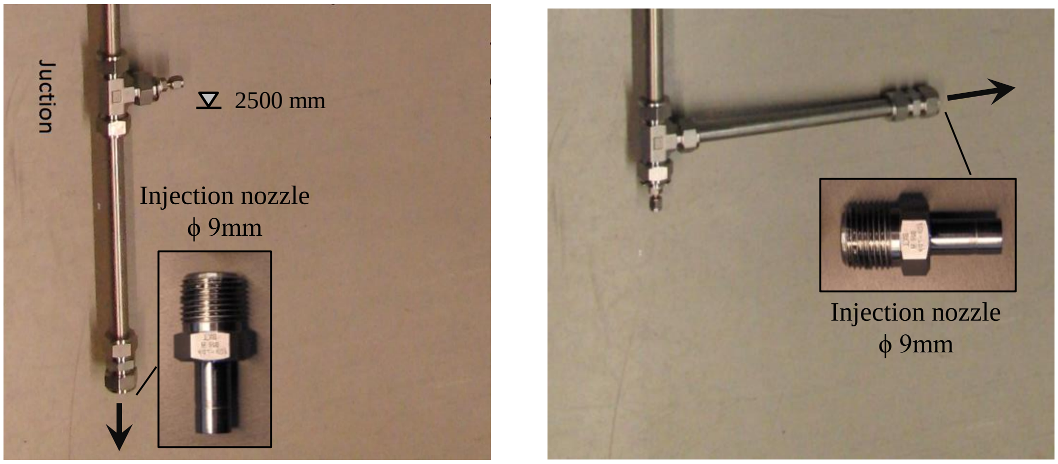
	Mass time scale ω_m [1/s]	Momentum time scale ω_p [1/s]	Energy time scale ω_e [1/s]
BWR[a]	$8.5 \cdot 10^{-5}$	$1.7 \cdot 10^{-4}$	$8.5 \cdot 10^{-5}$
PPOOLEX	$7.9 \cdot 10^{-5}$	$2.3 \cdot 10^{-4}$	$7.9 \cdot 10^{-5}$

[a] Using Nozzle 2 design presented in Table 2 and assuming a wetwell pool of 2000 m^3 and 6 m height.

Micro-scale (injection nozzle): The goal is to confirm that the injection is in turbulent regime, similar to plant case. To achieve this goal, the design parameters needed to be determined are the (i) Reynolds number at injection point. The selection of the design parameters is given below.

(i) The total injection hole area of 64 mm^2 determined in the macro-scale section leads to a nozzle of 9 mm inner diameter. With these dimensions, and using the 1 kg/s flow rate also determined in the macro-scale section, the Reynolds number at the nozzle exit is 1.6e5, which corresponds to a turbulent regime, similar to the one in the BWR presented in Table 2.

The final design of the experiment and nozzle can be observed in Figure 19. Vertical and horizontal injections were achieved by placing a junction in the main pipe. After the junction, a straight pipe of about 200 mm (~200 times the pipe diameter) was used to minimize and flow rotations or inclinations by the junction.



(a) (b)

Figure 19: Mixing nozzles for (a) vertical downwards and (b) horizontal injection PPOOLEX experiments. Images courtesy of operators at PPOOLEX facility, LUT, Finland.

3.2. Pre-test of the nozzle experiments

Pre-test simulations were run using GOTHIC 8.1 (QA) to verify that the scaled nozzle design can induce mixing of the pool. Thermal stratification was first created using sparger, where the EHS/EMS models for spargers presented in 0 were used. After a 20-25 ^oC temperature difference was reached between the top and bottom of the pool, the nozzle was activated to induce mixing of the pool.

Due to the axisymmetric flow created by the vertical injection, the simulations were run using a 2D axisymmetric model of the pool, Figure 20. The cell sizes were about 50 mm in the vertical direction and 15 mm in the radial direction. According to the mesh sensitivities done in (Gallego-Marcos et al., 2015), these values are expected to be fine enough to capture the sharp temperature profiles during the stratification phase created by the sparger, and the jet expansion during the nozzle injection.

The simulations were run using the standard k-Epsilon turbulence model. To avoid unphysical mixing induced by the pool surface, a surface wave damping factor of 60 was used. In the run control parameters, a second order bounded upwind discretization scheme was used in space and a semi-implicit discretization in time. The pressure equation was solved with the conjugate gradient method until a 1e-7 residual was reached after 4 outer implicit loops with 1000 internal iterations each. The minimum time step was set to 1e-7 s and the maximum to 0.08 s

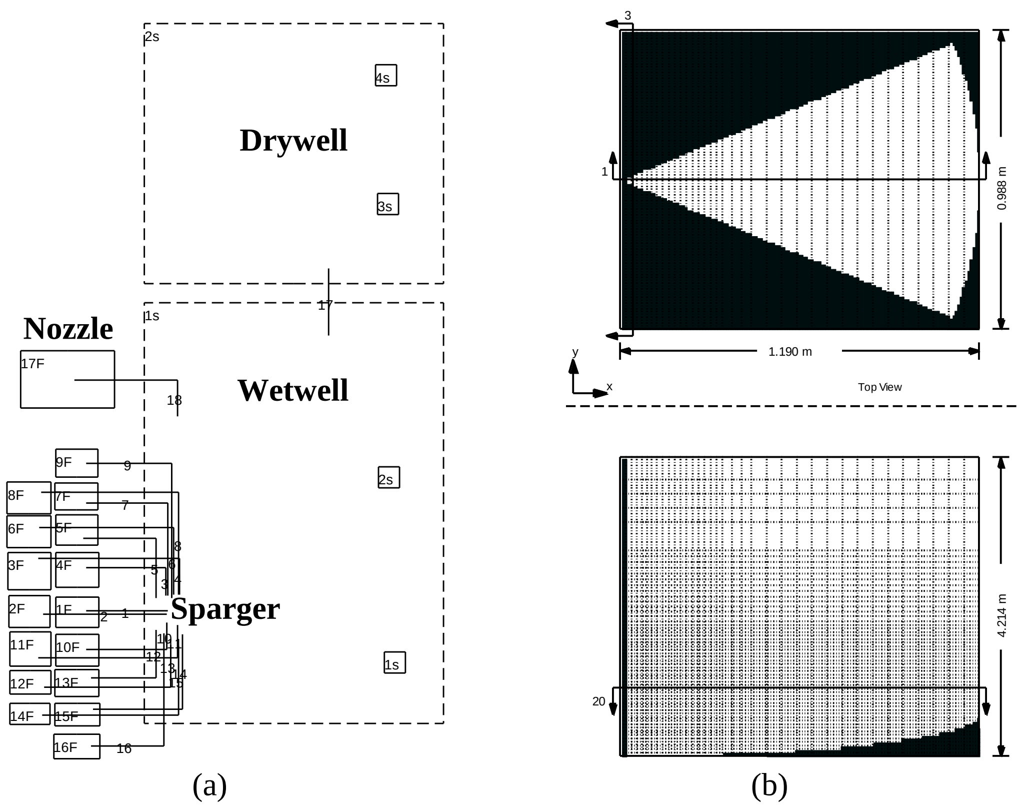
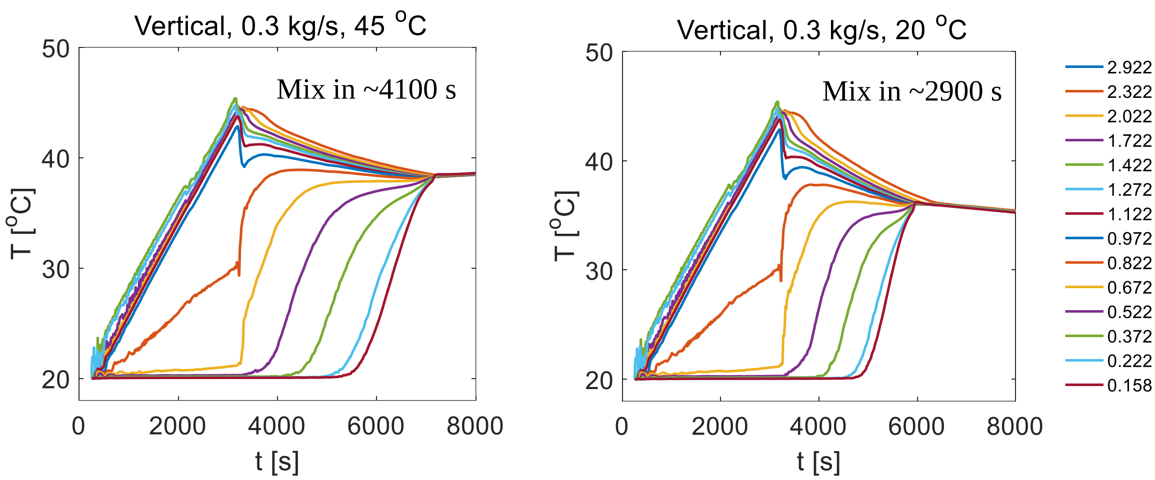


Figure 20: GOTHIC model used during the pre-test nozzle simulations. (a) Control volumes (b) wetwell pool mesh.

The results of the vertical injection are presented in Figure 21 and Figure 23a. It was observed that the 1 kg/s injection determined in the scaling induced a complete mixing of the pool in about 100 s, which is a short transient difficult to use for code validation. Therefore, the flow through the nozzle was reduced to 0.3 kg/s. This flow rate was still able to induce mixing of the pool, but in a much longer time of about 3000 s. The injection temperature through the nozzle was observed to be very influential in the mixing time. We can see in Figure 21a that when the flow was injected at 45oC, same temperature as the pool surface, it took about 2000 s more to mix the pool than in the 20oC injection, Figure 21b. This is due to the absence of buoyancy forces which would naturally drive down the cold flow injected by the nozzle.



(a) (b)

Figure 21: Pre-test simulations of the PPOOLEX experiments with nozzle. Vertical downwards injection of 0.3 kg/s at (a) 45 oC and (b) 20 oC.

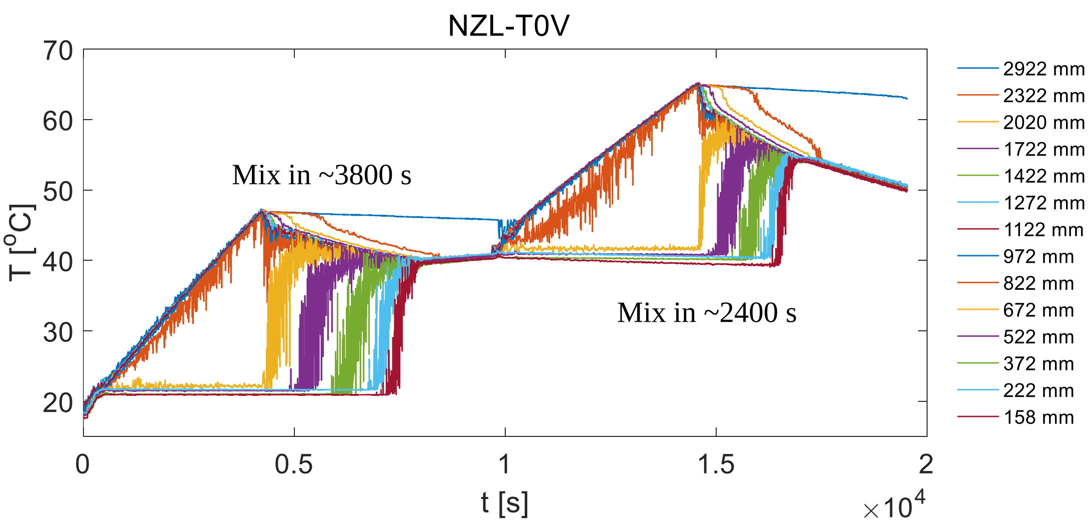


Figure 22: PPOOLEX NZL-T0 experiment. Vertical downwards injection of 0.3 kg/s at 45 oC, mixing phase 1, and 20 oC, mixing phase 2.

Pre-test simulations of the horizontal injection were also carried out. Due to the 3D flow structure induced by the horizontal injection, the simulations were run using a 3D model of the pool. The cell sizes in the vertical direction were maintained at 50 mm, and increased to 120 mm in the horizontal direction. A finer mesh, similar to the one used in 2D, would have been better to capture the jet expansion of the nozzle. However, due to the computational restrictions, such fine mesh could not be afforded.

We can see in Figure 23 that the horizontal injection was much less efficient at mixing the pool than the vertical injection. This is due to the jet impingement on the vessel walls, which reduces the amount of momentum directed downwards, towards the stratified layer. In the vertical case, all of the momentum is directed towards the stratified layer, inducing a much faster mixing.

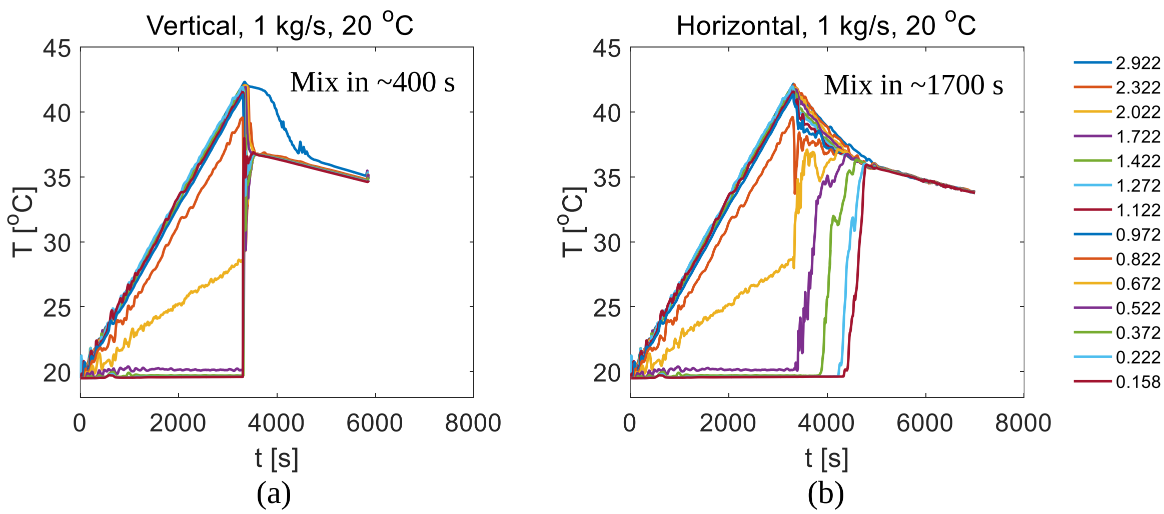


Figure 23: Pre-test simulations of the PPOOLEX experiments with nozzle. (a) Vertical downwards and (b) horizontal injection of 1 kg/s at 20 oC.

The conclusion form the pre-test simulations is that, with the scaled design proposed in section 3.1, the stratified layer can be mixed. The horizontal injection, the one found in the BWRs, was able to induce mixing using the 1 kg/s flow rate determined in the macro-scaling section. The vertical injection, used to allow a more efficient validation, was more efficient in mixing the pool, and the flow rate had to be reduced to 0.3 kg/s in order to have a reasonably long mixing phase.

3.3. PPOOLEX tests with nozzles

Three experiments were performed in the PPOOLEX facility using the scaled nozzle design presented in section 3.1. The goal was to analyze the separate effects of (i) injection temperature, (ii) injection mass flow rate, (iii) temperature difference in the pool, and (iv) orientation of the nozzle. This was achieved through the test-matrix presented in Table 4.

All of the tests began injecting steam at low momentum through the sparger to create a thermally stratified layer. When a certain temperature difference ΔT was reached between the top and bottom of the pool, the nozzle was activated to induce mixing. To analyze the separate effect of the nozzle, the steam injection through the sparger was stopped during the mixing phase. After the first mixing phase, another the stratification-mixing phases were repeated.

The results of the T0V test are presented in Figure 22. This test was designed to study the effect of a different injection temperature through the nozzle. We can see that the mixing phase 1, where water at 45 ^{o}C was injected through the nozzle, was about 1.5 times slower than the mixing phase 2, where the temperature was decreased to 20 ^{o}C. The mixing times were very similar to the ones predicted in the pre-test simulations, Figure 21. We can also see that the erosion of the stratified layer was very slow. It took about 1 hour to erode 500 mm of the stratified layer.

Table 4: Test matrix used in the PPOOLEX experiments with nozzle.

NZL series	Nozzle orientation	Stratification phase 1	Mixing phase 1	Stratification phase 2	Mixing phase 2
T0V	Vertical downwards	ΔT = 20 ^{o}C [a]	0.3 kg/s [b] 45 ^{o}C [b]	ΔT = 20 ^{o}C	0.3 kg/s 20 ^{o}C
T1V	Vertical downwards	ΔT = 20 ^{o}C	0.5 kg/s 45 ^{o}C	ΔT = 40 ^{o}C	0.3 kg/s 20 ^{o}C
T1H	Horizontal	ΔT = 20 ^{o}C	1.0 kg/s 20 ^{o}C	ΔT = 20 ^{o}C	0.3 kg/s 20 ^{o}C

[a] Temperature difference between cold stratified layer and the hot region above it
[b] Flow rate and temperature of the liquid injected through the nozzle

We can see in Figure 22 that, during the mixing phases, the jet induced by the mixing nozzle was not able to penetrate into the stratified layer. The stepwise temperature increase of the TC measurements located at the bottom of the pool indicate that the stratified layer was slowly eroded at the interface. Moreover, the TCs located at the interface showed low frequency and high amplitude oscillations during this erosion. This is the same behavior as the one observed in the PPOOLEX sparger tests, Figure 15. A Fourier analysis of the temperature measurements located at the interface revealed that there is a leading frequency of about 0.07 Hz, Figure 24. These oscillations are not turbulent since turbulence should have a higher frequency. They were observed to be very similar to the natural oscillation frequencies of the pool, Table 5. Therefore, it was concluded that the pool was excited to this frequency by the action of turbulence. The Brunt–Väisälä frequency, which is the frequency at which a fluid parcel in a stable stratified fluid moves when it is displaced from its stable position, was estimated to be an order of magnitude higher. This is above the acquisition frequency of the TCs. Therefore, it cannot be concluded if this oscillation was also present during the experiment.

Equations (23) and (24) were used to calculate the natural oscillation frequency. It was assumed that the system behaves like a cold pool of depth H with a thermocline separating it from a hot pool above it. With this assumption, H is the stratified layer thickness, R the radius of the tank, k_n the n[th] root of the derivative of the first order Bessel function (k_1 = 1.84, k_2 = 5.33, k_3 = 8.53), and g' the reduced gravity, computed as a function the cold $\rho(T_c)$ and hot $\rho(T_h)$ densities across the thermocline. For the TCs located inside the ellipsoidal cap of the vessel, an equivalent cylinder of radius R with the same volume as ellipsoidal cap below the analyzed TC was used. In the Brunt–Väisälä frequency, equation (25), the density derivative was approximated to a linear density gradient along a thermocline of thickness z_{tc}, which, based on Figure 25, should have a value of about f z_{tc} = 0.1 m. This value derived from the fact that, when the oscillation in a TC reaches its maximum, the TC below does not show any oscillation, thus, z_{tc} < 0.15 m. On the other hand, after the maximum has passed, simultaneous oscillations are observed in the upper and lower TCs, indicating that z_{tc} > 0.075 m. This gives the average value of 0.1 m.

$$f_n = \frac{1}{2\pi}\sqrt{g'\frac{k_n}{R}\tanh\left(H\frac{k_n}{R}\right)} \tag{23}$$

$$g' = g\frac{\rho(T_c) - \rho(T_h)}{\rho(T_c)} \tag{24}$$

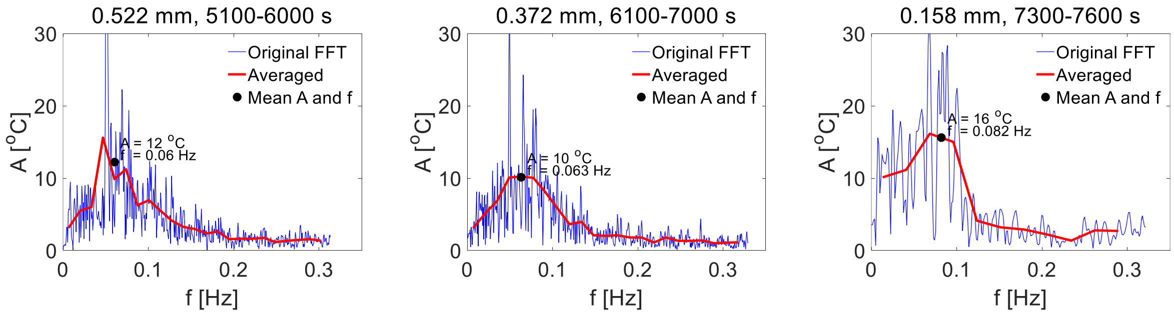
$$N = \sqrt{-\frac{g}{\rho}\frac{\partial\rho}{\partial z}} \approx \sqrt{\frac{g'}{z_{tc}}} \tag{25}$$

Table 5: Comparison between the frequencies observed at the thermocline in the PPOOLEX NZL-T0 experiment, the natural frequencies of the pool, and the Brunt–Väisälä frequencies.

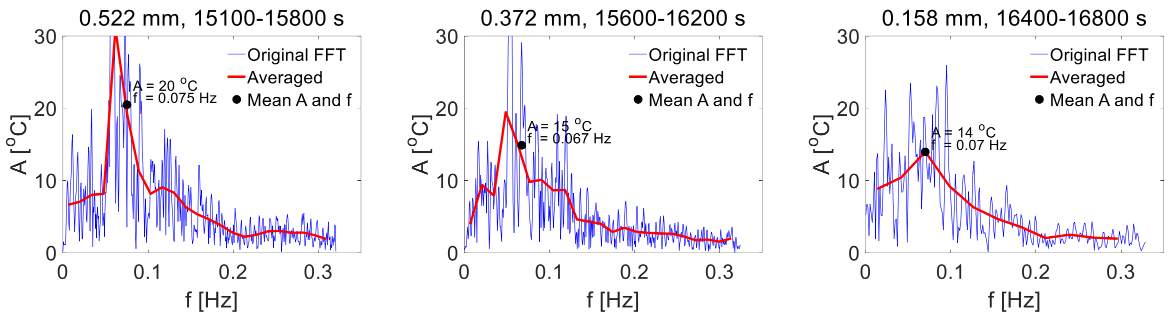
TC location	PPOOLEX NZL-T0V f [Hz]	Natural oscillations f [Hz]	Brunt–Väisälä f [Hz]
0.522 mm	~ **0.067**	ΔT = 40-22 °C, g' = 0.054 m/s^2 R = 0.935 m f_1 = **0.045**, f_2 = **0.078** f_3 = **0.098**	g' = 0. 054 m/s^2 z_{tc} = 0.1 m f = **0.73**
0.158 mm	~ **0.076**	ΔT = 38-21 °C, g' = 0.049 m/s^2 R = 0.583 m f_1 = **0.043**, f_2 = **0.072** f_3 = **0.092**	g' = 0. 049 m/s^2 z_{tc} = 0.1 m f = **0.70**

Fernando et al. (1997) and McGrath et al. (1997) demonstrated that, when the momentum forces are small in comparison with buoyancy (large Richardson numbers), the erosion of a stable stratified layer is dominated by the breakup of interfacial waves. This corresponds well to the slow erosion and 0.07 Hz oscillations observed in the PPOOLEX experiments with nozzle. Therefore, the erosion mechanism during these experiments could have been the breakup of the 0.07 Hz oscillations.

It is remarkable how the pre-test simulations provided quite accurate prediction of the results despite the cell size of 15 mm, which is certainly not enough to resolve wave-breaking events. Further analysis needs to be done to clarify the erosion mechanism of the stratified layer.



(a)



(b)

Figure 24: Fast Fourier Transform of the TC measurements from the POOLEX NZL-T0V experiment located at the thermocline during the (a) first and (b) second mixing phases.

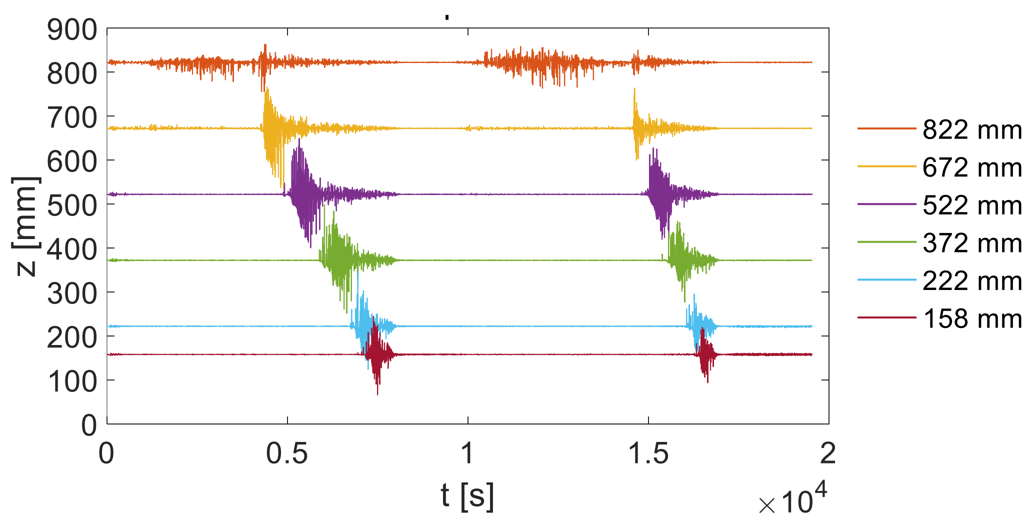
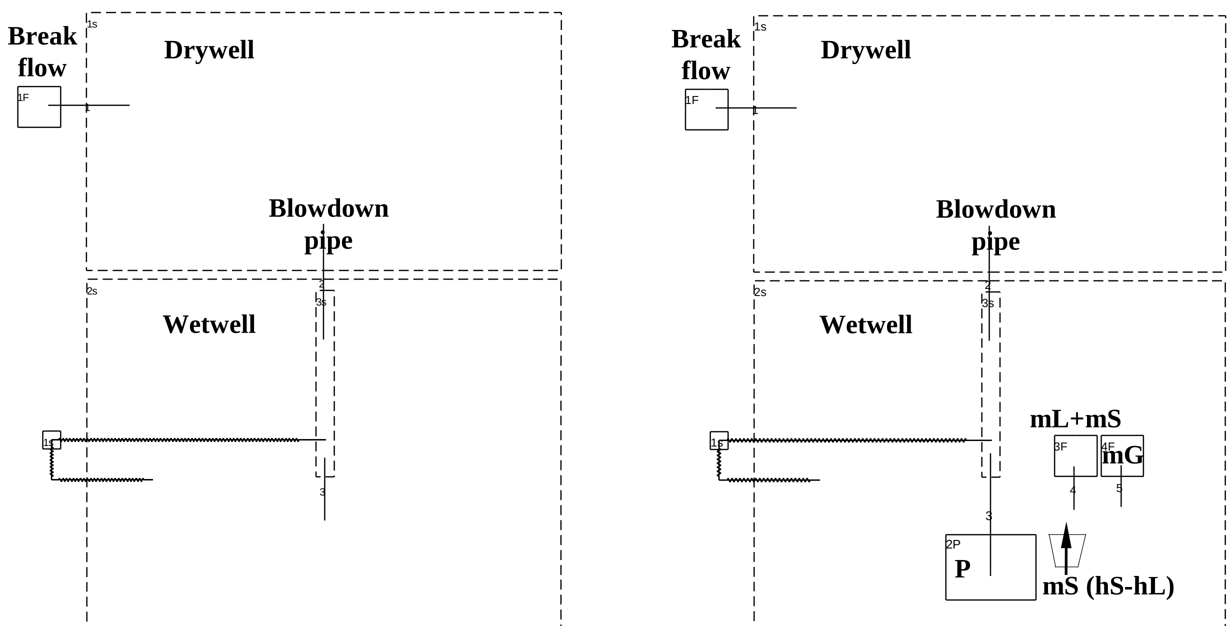


Figure 25: Estimation of the amplitude of the oscillation at the thermocline observed in the POOLEX NZL-T0V experiment.

4. Containment model in GOTHIC

The EHS/EMS models for spargers, blowdown pipes, and mixing nozzles presented in this work and in (Li et al., 2014a, 2014b; Gallego-Marcos et al., 2015, 2016a, 2016b) have been developed and validated against experimental data from the PPOOLEX and PANDA facilities. In this section, we present an over-view on how to implement the EHS/EMS models in an integrated containment simulation, including drywell and wetwell, using GOTHIC. All details can be found in (Gallego-Marcos et al., 2016d). This allows an accurate and computationally efficient manner to model the behavior of containment during an accident.

To use the EHS/EMS models in a full containment analysis, we need to (i) identify the condensation regime based on the pool temperature and steam flow injected into the pool, and (ii) impose the effective condensate velocity based on such condensation regime. In GOTHIC, the mass flow injected into the pool can be obtained by placing a control variable in the flow path at the blowdown pipe outlet. However, allowing the blowdown pipe to inject steam directly into the wetwell prevents us from imposing the effective condensate velocity (steam has already been injected into the pool). This issue was solved by decoupling the blowdown pipe outlet from the wetwell pool, Figure 26b. Decoupling means that the outlet is connected to a pressure boundary condition '**P**' instead of to the wetwell. Control variables were then used to set the pressure and temperature of this boundary condition, equal to the pressure and temperature of the pool at the level of the blowdown pipe outlet. With this approach, the pressure difference between the drywell and wetwell is preserved, and the mass flow going through the blowdown pipe is the same as in a direct steam injection.



(a) (b)

Figure 26: (a) Standard direct steam injection and (b) EHS/EMS model of a containment proposed in this paper. Drywell: 3800 m3 of air. Wetwell: 3800 m3 containing a water pool of 7.3 m depth a gas space. Blowdown pipe submergence in the wetwell pool is 5.3 m.

To make sure that mass and energy are conserved in the system, the liquid '**mL**', steam '**mS**', and gas '**mG**' flow rates which were injected into the pressure boundary condition have to be re-injected into the pool through flow boundary conditions. Since we do not intend to resolve direct contact condensation, the steam flow was injected as condensed liquid. The velocity of this condensate liquid is then determined based on the EHS/EMS models. To conserve the energy, the latent heat removed during the artificial condensation of the steam was imposed in the pool using a heater at the blowdown pipe outlet.

4.1. Time averaging of the numerical oscillations

In GOTHIC, when steam is injected into a pool, large amplitude numerical oscillations appear at the blowdown pipe outlet. The numerical origin can be identified by the fact that a small change in the problem setup, such as including several cells in the domain, leads to a completely different pattern of the oscillations. To minimize the effect of the numerical oscillations, the oscillations were time-averaged before injecting the flow into the pool. The time average was applied to the flow at the blowdown pipe outlet, connected to the pressure boundary condition '**P**', and the result was then used in the boundary conditions '**mL+mS**' and '**mG**'.

The moving average was implemented in a DLL and calculated during run time. Moving averages calculate an average over a certain time (Δt_{av}) and then move forward to compute another average after a certain time increment (Δt_{inc}) has passed. A sketch of the process is presented in Figure 27. Details of the implementation can be found in (Gallego-Marcos et al., 2016d). A short description of the steps taken during the averaging are presented below.

1. Beginning of the simulation. The mass flow averages during each Δt_{inc} are calculated using the instantaneous mass flow $\dot{m}_\iota$ and time step size dt_i. Once a $\overline{\dot{m}_{\iota nc_k}}$ is obtained, it is added to the previous one and given as a forcing function to the boundary condition in GOTHIC.
2. When the simulation time is higher than Δt_{av}, the time average $\overline{\dot{m}_{av_1}}$ is calculated, given as a forcing function to the boundary condition in GOTHIC, and maintained at that value until the next $\overline{\dot{m}_{av_2}}$ is calculated.
3. The next incremental average is calculated.
4. The next $\overline{\dot{m}_{av_2}}$ is calculated using the new incremental average from Sept 3, and removing the oldest incremental average.
5. Steps 3 and 4 are repeated for the rest of the simulation to obtain all of the Δt_{av_k}.

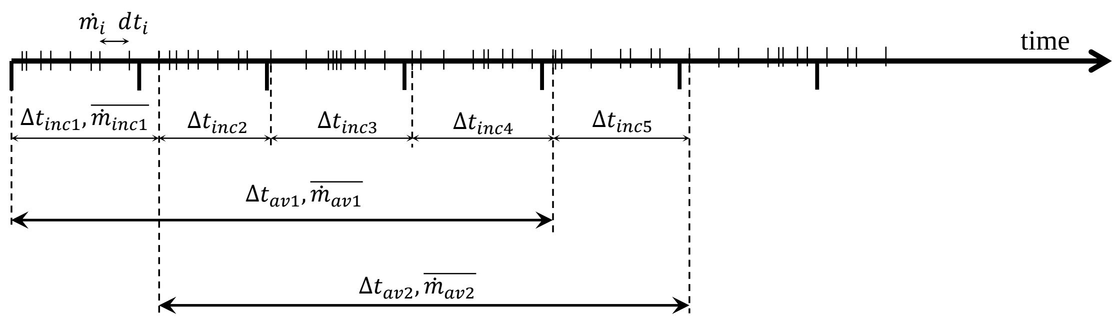


Figure 27: Moving average implemented in a Dynamically Linked Library (DLL) in GOTHIC to time average the numerical oscillations at the blowdown pipe outlet during a steam injection.

The results of a moving average with Δt_{av} = 6 s and Δt_{inc} = 1 s done during a test simulation of the containment from Figure 26b are shown in Figure 28a. We can see that the spikes of the numerical oscillations of the vapor flow at the blowdown pipe outlet were removed, and a stable mean flow was obtained. However, we can also see that the oscillatory behavior of the oscillations was maintained. Therefore, the moving average was modified so that Δt_{inc} could be a variable parameter that would increase or decrease depending on the amplitude of the oscillations, Figure 28b.

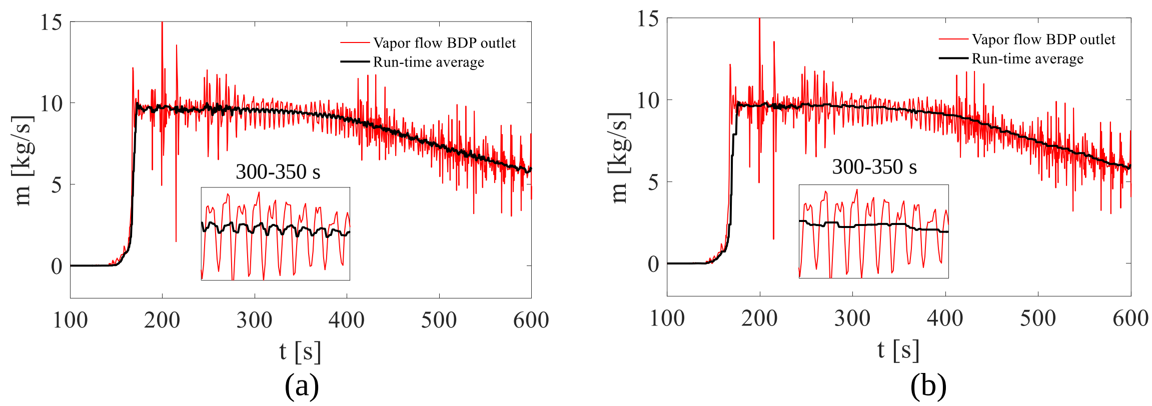


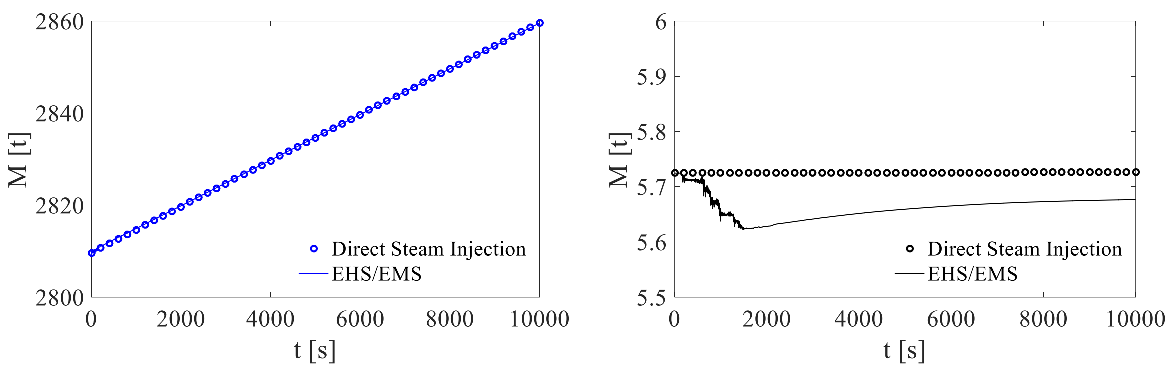
Figure 28: Moving average of the liquid and vapor oscillations at the blowdown pipe outlet using (a) $\boldsymbol{\Delta t_{av}}$ = 6 s and $\boldsymbol{\Delta t_{inc}}$ = 1 and (b) $\boldsymbol{\Delta t_{av}}$ = 6 s and a variable $\boldsymbol{\Delta t_{inc}}$ according to the wavelength of the oscillations.

4.2. Comparison between EHS/EMS model and a direct steam injection

A comparison between a standard direct steam injection simulation (blowdown pipe outlet directly connected to the wetwell), and the EHS/EMS containment model presented in this section, including the time averaging of the numerical oscillations, was performed and presented in (Gallego-Marcos et al., 2016d). For both simulations, the boundary condition was a constant 5 kg/s break flow injecting superheated steam into the containments from Figure 26. The drywell and wetwell were meshed with 3D and 2D meshes respectively. The cell size in the vertical direction in the wetwell was 100 mm.

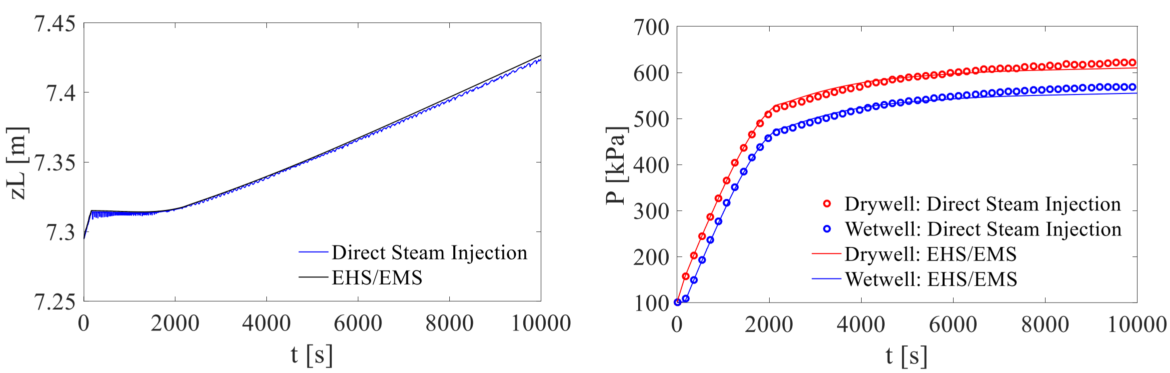
The total water and non-condensable gas masses in the containment are presented in Figure 29. The water inventory was conserved in the EHS/EMS simulation. The deviation in the total gas mass, which should be constant since the break injects pure steam, was due to an inaccurate estimation of the gas flow going through the flow path. GOTHIC does not provide a control variable to obtain the gas flow through a flow path, only the steam + gas flow rate is given. Thus, the gas flow was computed based on the mass gas fraction at the cell connected to the flow path.

The liquid level in the wetwell pool and pressures in the containment are presented in Figure 30. The oscillations of the liquid level during the direct steam injection simulation are due to the numerical oscillations of the flow at the blowdown pipe outlet, which drained and injected water into the pool cyclically. In the EHS/EMS model, the time averaging of the oscillations avoided this behavior. We can also see that the pressures in the containment were very similar in both simulations. The small deviations are due to the differences in the gas masses in the containment and the amount of condensed steam



(a) (b)

Figure 29: Total (a) water and (b) gas masses in the containment during the direct steam injection and EHS/EMS simulations.



(a) (b)

Figure 30: Comparison between the (a) wetwell pool liquid level and (b) pressures in the containment during the direct steam injection and EHS/EMS simulations.

The flows at the blowdown pipe outlet during the direct steam injection are presented in Figure 31. We can see that the results were buried in numerical oscillations. The liquid flow was constantly oscillating with amplitudes about 100 times higher than its mean flow. The oscillations in the vapour seem to be smaller. However, we should recall that the density of the gas and steam are about 1000 times smaller than the liquid, meaning that a small oscillation in their flow displaces a considerably big amount of liquid in the pool.

The results of the EHS/EMS simulation are presented in Figure 32. Some numerical oscillations were still present due to the instabilities of the steam condensation inside the blowdown pipe. However, we can see that they were much lower than in the direct steam injection solution. This is due to the stabilizing effect of connecting the blowdown pipe outlet to the pressure boundary condition '**P**' in Figure 26b, whose pressure was based on the static head at the injection level. The run-time averaging of the numerical oscillations, presented in Figure 33, minimized further the effect of the oscillations. The periodic oscillations of the liquid and gas were well averaged to a stable mean flow. However, during a part of the transient, the gas flow was observed to oscillate first above the mean and then below it, as it is shown in the detail at Figure 33. This is different from the oscillations around the mean observed in the liquid and in Figure 28. Since this effect was not taking into account in the time averaging model, it led to a step up/down time averaging which followed the pattern of the oscillations. Further calibration of the values of Δt_{av} and Δt_{inc} should be done to remove this effect.

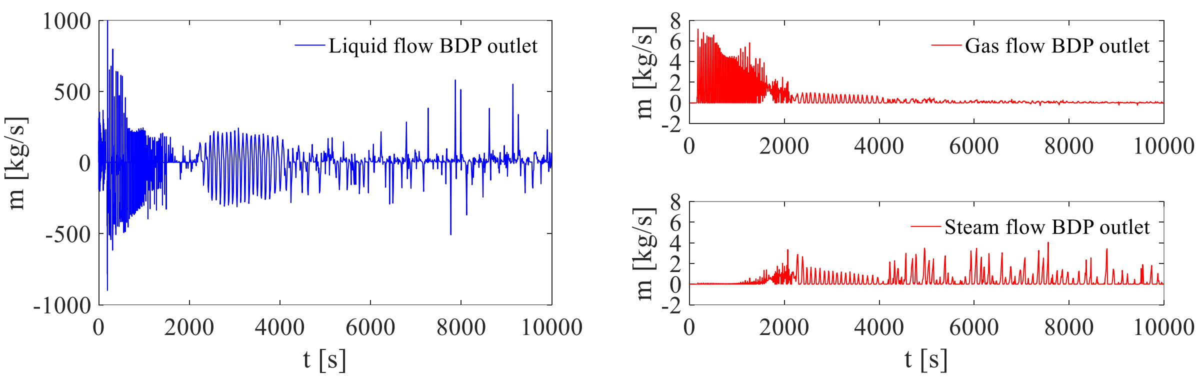


Figure 31: Numerical oscillations at the blowdown pipe outlet during the direct steam injection simulation.

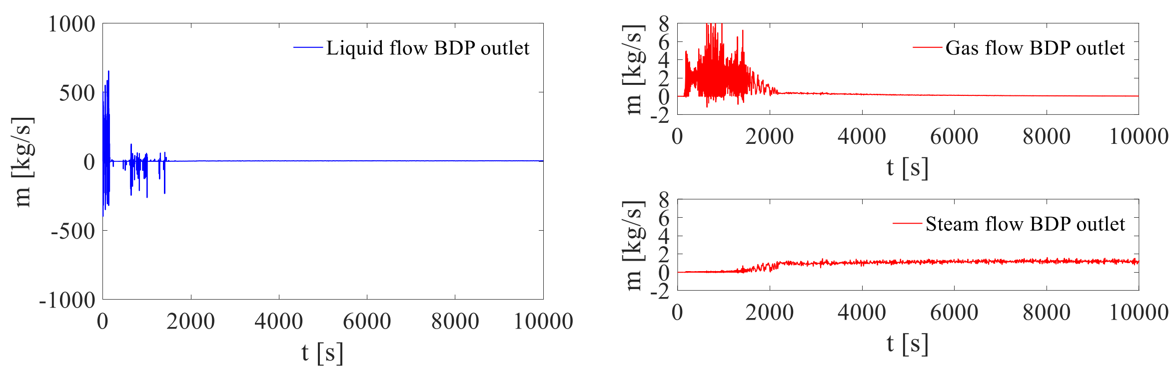


Figure 32: Numerical oscillations at the blowdown pipe outlet during the EHS/EMS simulation.

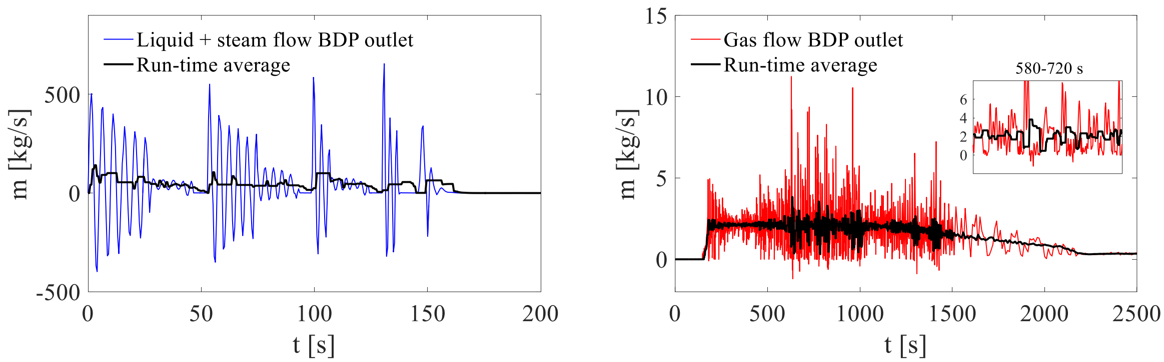


Figure 33: Run-time average of the oscillations from Figure 32 performed during the EHS/EMS simulation.

The pool temperatures during the transient are presented in Figure 34. In the direct steam injection, the numerical oscillations from Figure 31 caused a complete artificial mixing of the pool. On the other hand, the sable flow rates used in the EHS/EMS simulation allowed the development of a non-uniform temperature distribution. In this case, the low steam flow rates and high submergence of the blowdown pipe led to a small thermal stratification development. However, in a real LOCA scenario, thermal stratification could have been much more intense and induce significant effects in the containment which would not be predicted with an artificially mixed pool.

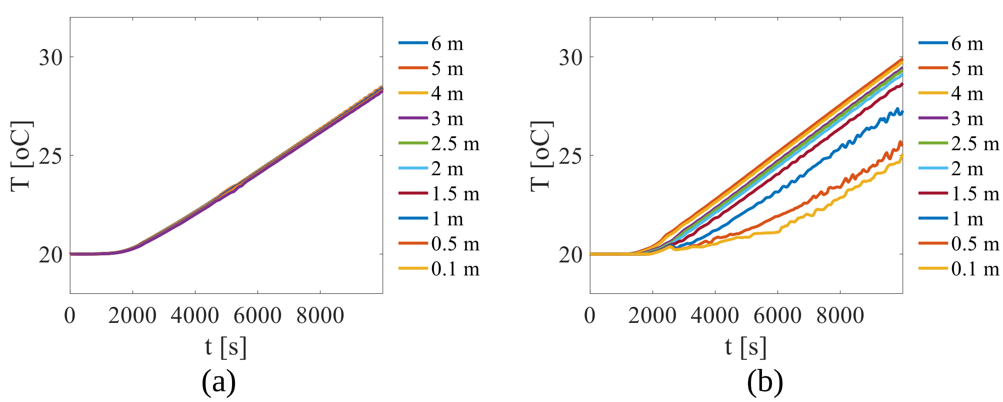


Figure 34: Wetwell pool temperatures obtained with the (a) direct steam injection and (b) EHS/EMS simulations.

5. Conclusions

The development of thermal stratification in the pressure suppression pool of BWRs and PWRs is a safety issue since it can (i) affect the operation of the spray and Emergency Core Cooling System (ECCS), and (ii) lead to higher containment pressures than in completely mixed conditions. The main systems responsible for inducing thermal stratification or mixing of the pool are the spargers, mixing nozzles, blowdown pipes, and sprays. In this work, we have presented the development and validation of Effective Heat Source and Effective Momentum Source (EHS/EMS) models for spargers, the scaling, pre-test, and experimental results of the nozzle experiments, and the implementation of the EHS/EMS models in a full containment model using GOTHIC.

In the spargers, the momentum transfer from the steam to the mean flow was observed to vary with the condensation regime. This behavior was included in the EHS/EMS models with a condensation regime coefficient. The results obtained with the implementation of the EHS/EMS in GOTHIC 8.1 (QA) showed a good comparison to the PPOOLEX experiments. Implementation of the EHS/EMS models in ANSYS Fluent 16.2 using a radial mesh gave similar results than in GOTHIC.

The scaling of the PPOOLEX experiments with nozzles was done to preserve prototypical ranges of injection conditions and pool regimes occurring during a liquid injection through nozzles. Pre-test simulations were done to confirm the mixing capability of the mixing nozzles, and to propose a test matrix. In the experiments, the effects of different injection flow rates, temperatures, pool temperatures, and orientation of the nozzles was analyzed. The experimental results were observed to be very similar to the pre-test predictions.

The implementation of the EHS/EMS models in the containment model using GOTHIC 8.1 (QA) was done to control the heat and momentum injected into the pool, and to minimize the effect of the numerical oscillations at the blowdown pipe outlet by time-averaging them. The results were observed to provide a more realistic pool behavior than the standard direct steam injection approach.

Further development and validation of the EHS/EMS models will be done against available experimental data to confirm the current hypothesis and further improve the prediction capability.

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Disclaimer

References

1. Abarbanel, H.D., Holm, D.D., Marsden, J.E., & Ratiu, T., 1984. Richardson Number Criterion for the Nonlinear Stability of Three-Dimensional Stratified Flow. Physical Review Letters. 52: 2352-2355.

2. Chan, C.K. & Lee, C.K.B., 1982. A regime map for direct contact condensation. International Journal Multiphase Flow. 8: 11-20.

3. D'Auria, F., & Galassi, G.M., 2010. Scaling of nuclear reactor system thermal-hydraulics. Nuclear Engineering and Design. 240: 3267-3293.

4. De Silva, I.P.D., & Fernando, H.J.S., 1992. Some aspects of mixing in a stratified turbulent patch. Journal of Fluid Mechanics. 240: 601-625.

5. Fernando, H.J.S., & Hunt, J.C.R., 1997. Turbulence, waves and mixing at shear-free density interfaces. Part 1. A theoretical model. Journal of Fluid Mechanics. 347: 197-234.

6. Gallego-Marcos, I., Filich, L., Villanueva, W., & Kudinov, P., 2015. Modelling of the Effects of Steam Injection through Spargers on Pool Thermal Stratification and Mixing. Research report NKS-347.

7. Gallego-Marcos, I., Villanueva, W., Kapulla, R., Paranjape, S., Paladino, D., & Kudinov, P., 2016a. Modeling of thermal stratification and mixing induced by steam injection through spargers into a large water pool. OECD/NEA & IAEA Workshop CFD4NRS-6, Cambridge, MA, September 13-15, 2016.

8. Gallego-Marcos, I., Villanueva, W., Kapulla, R., Paranjape, S., Paladino, D., & Kudinov, P., 2016b. Scaling and CFD Modelling of the Pool Experiments with Spargers Performed in the PANDA Facility. NUTHOS-11: The 11th International Topical Meeting on Nuclear Reactor Thermal Hydraulics, Operation and Safety, Gyeongju, Korea, October 9-13, 2016.

9. Gallego-Marcos, I., Villanueva, W., & Kudinov, P., 2016c. Scaling of the Erosion of a Thermally Stratified Layer in a Large Water Pool during a Steam Injection Through Spargers. NUTHOS-11: The 11th International Topical Meeting on Nuclear Reactor Thermal Hydraulics, Operation and Safety, Gyeongju, Korea, October 9-13, 2016. N11P0525.

10. Gallego-Marcos, I., Villanueva, W., & Kudinov, P., 2016d. Modeling of Thermal Stratification and Mixing in a Pressure Suppression Pool Using GOTHIC. NUTHOS-11:

The 11th International Topical Meeting on Nuclear Reactor Thermal Hydraulics, Operation and Safety, Gyeongju, Korea, October 9-13, 2016. N11P0524.

11. Gamble, R.E., et al., 2001. Pressure suppression pool mixing in passive advanced BWR plants. Nuclear Engineering and Design. 204: 321-336.

12. Howard, L.N., 1961. Note on a paper of John W. Miles. Journal Fluid Mechanics. 10: 509-512.

13. Kang, H.S., & Song, C.H., 2008. CFD analysis for thermal mixing in a subcooled water tank under a high steam mass flux discharge condition. Nuclear Engineering and Design. 238: 492-501.

14. Kang, H.S., & Song, C.H., 2010. CFD analysis of a turbulent jet behavior induced by a steam jet discharge through a single hole in a subcooled water tank. Nuclear Engineering and Design. 240: 2160-2168.

15. Kapulla, R., Mignot, G., Paranjape, S., Paladino, D., Fehlmann, M., & Suter, S., 2015. OECD/NEA HYMERES project: HP5 Test Results. 6th Meeting of the Programme Review Group and Management Board of the HYMERES Project, PSI Villigen, Switzerland, November 17-19, 2015

16. Laine, J., Puustinen, M., & Räsänen, A., 2015. PPOOLEX Experiments with a Sparger. Research report NKS-344.

17. Li, H., Villanueva, W., & Kudinov, P., 2014a. Approach and development of effective models for simulation of thermal stratification and mixing induced by steam injection into a large pool of water. Science and Technology of Nuclear Installations. 2014.

18. Li, H., Villanueva, W., Puustinen, M., Laine, J., & Kudinov, P., 2014b. Validation of Effective Models for Simulation of Thermal Stratification and Mixing Induced by Steam Injection into a Large Pool of Water. Science and Technology of Nuclear Installations. 2014.

19. Li, X., Zhang, M., Du, Z., & Fu, X., 2014c. Scaling analysis of coolant spraying process in automatic depressurized system. Annals of Nuclear Energy. 72: 350-357.

20. Malavasi, S., Messaa, G., Fratino, U., & Pagano, A., 2012. On the pressure losses through perforated plates. Flow Measurement and Instrumentation. 28: 57–66.

21. Miles, J.W., 1961. On the stability of heterogeneous shear flows. Journal Fluid Mechanics. 10: 496-508.

22. Moon, Y.T., Lee, H.D., & Park, G.C., 2009. CFD simulation of a steam jet-induced thermal mixing into a subcooled water pool. Nuclear Engineering and Design. 239: 2849-2863.

23. McGrath, J.L., Fernando, H.J.S., & Hunt, J.C.R., 1997. Turbulence, waves and mixing at shear-free density interfaces. Part 2. Laboratory experiments, Journal of Fluid Mechanics. 347: 235-261.

24. Ozdemir, O.E., & George, T.L., 2015. BWR MARK I Pressure Suppression Pool Mixing and Stratification Analysis Using GOTHIC Lumped Parameter Modeling Methodology. Annals of Nuclear Energy. 85: 532–543.

25. Pan, L.M., Tan, Z.W., Chen, D.Q., & Xue, L.C., 2012. Numerical investigation of vapor bubble condensation characteristics of subcooled flow boiling in vertical rectangular channel. Nuclear Engineering and Design. 248: 126– 136.

26. Pershagen, B., 1996. Light Water Reactor Safety. Pergamon Press, 2nd edition.

27. Peterson, P.F., 1994. Scaling and analysis of mixing in large stratified volumes. International Journal Heat Mass Transfer. 37: 97-106.

28. Puustinen, M., Laine, J., Räsänen, A., 2016. Additional Sparger Tests in PPOOLEX with Reduced Number of Injection Holes. Research report NKS-364.

29. Sonin, A.A., 1981. Scaling laws for small-scale modeling of steam relief into water pools. Nuclear Engineering and Design. 65: 17-21.

30. Tang, J., Yan, C., & Sun, L., 2015. A study visualizing the collapse of vapor bubbles in a subcooled pool. International Journal of Heat and Mass Transfer. 88: 597–608.

31. Yuan, F., Chong, D., Zhao, Q., Chen, W., Yan, J., 2016. Pressure oscillation of submerged steam condensation in condensation oscillation regime. International Journal of Heat and Mass Transfer. 98: 193-203.

32. Zilitinkevich, S.S., et al., 2008. Turbulence energetics in stably stratified geophysical flows: Strong and weak mixing regimes. Quarterly Journal of the Royal Meteorological Society. 134: 793-799.

33. Zuber, N., Wilson, G.E., & Ishii, M., 1998. An integrated structure and scaling methodology for severe accident technical issue resolution: Development of methodology. Nuclear Engineering and Design. 186: 1-21.

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Author(s)	Ignacio Gallego-Marcos, Walter Villanueva, Pavel Kudinov
Affiliation(s)	Division of Nuclear Power Safety, Royal Institute of Technology (KTH), Stockholm, Sweden
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Abstract
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In a Boiling Water Reactor, steam released from primary coolant system is condensed in the pressure suppression pool. Thermal stratification in the pool affects pressure suppression capacity of the pool. Heat and momentum sources generated by the steam condensation define pool behavior. Direct Contact Condensation (DCC) of steam present a challenge for contemporary modeling tools. In previous work, the Effective Heat Source (EHS) and Effective Momentum Source (EMS) models were proposed to simulate development of thermal stratification or mixing induced by steam injection into a large pool of water. These models are computationally efficient and sufficiently accurate in resolving the effect of DCC phenomena on the large scale pool circulation.

In this work, we present the validation of the EHS/EMS models for spargers and mixing nozzles. Validation results with EHS/EMS implemented in GOTHIC and ANSYS Fluent show a good agreement in comparison to the PPOOLEX experiments. The scaling of the PPOOLEX experiments with mixing nozzles was done to preserve prototypical ranges of injection conditions and pool regimes. The experimental results are similar to the pre-test analysis data.

An implementation of the EHS/EMS models for analysis of steam injection into a containment pool was developed. The results of analysis provide a realistic pool behavior. Modeling of direct steam injection showed that without EHS/EMS models the results are severely affected by numerical instabilities.

Key words: Thermal Stratification, Mixing, Pressure Suppression Pool, Spargers, Mixing Nozzles, Containment, Thermal Hydraulic, GOTHIC, BWR

Available on request from the NKS Secretariat, P.O.Box 49, DK-4000 Roskilde, Denmark.
Phone (+45) 4677 4041, e-mail nks@nks.org, www.nks.org