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Modelling of the Effects of Steam Injection through Spargers on Pool Thermal Stratification and Mixing

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Abstract

In a Boiling Water Reactor, steam is discharged into the pressure suppression pool through spargers to protect the primary circuit from overpressurization. If thermal stratification develops, the pressure suppression capability is reduced. Mixing or stratification of the pool is determined by the interplay between heat and momentum sources generated by the steam condensation. Different momentum can be generated in different condensation regimes, depending on steam mass flux, pool temperature and sparger design. Simulation of Direct Contact Condensation (DCC) is a challenge for contemporary modeling tools, especially for prototypic long-term transients.
In previous work, the Effective Heat Source (EHS) and Effective Momentum Source (EMS) models were proposed to simulate thermal stratification and mixing during a steam injection into a large pool of water. These models are (i) computationally efficient, since the small scale phenomena of DCC is not resolved, and (ii) sufficiently accurate, since the integral effects of these phenomena on the large scale pool circulation are taken into account. EHS/EMS models have been developed and validated for blowdown pipes using experimental data from the PPOOLEX facility at LUT.
The goal of this work is to develop and validate EHS/EMS models for spargers. The models are implemented in the containment code GOTHIC. To obtain data for validation, a set of experiments are proposed in the PPOOLEX facility using a scaling methodology to ensure that the ranges of important parameters and regimes from the plant scale are addressed in the experiment. Pre-test analysis was carried out in order to (i) confirm the scaling methodology, (ii) provide suggestions for the instrumentation, (iii) get insights about detailed thermal-hydraulic behavior of the pool, and (iv) provide detailed instructions for the test procedures. A preliminary validation against the experiments shows overall good predictive capabilities of the EHS/EMS models. However, it was observed that accurate prediction of the effective momentum for the unstable steam condensation regimes requires further development of the model closures.

Key words

Thermal Stratification, Mixing, Pressure Suppression Pool, Spargers, Containment, Thermal Hydraulic, GOTHIC, Light Water Reactor

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Final Report from the NKS-R ENPOOL activity (Contract: NKS_R_2011_90)

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Executive Summary

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In previous work, the Effective Heat Source (EHS) and Effective Momentum Source (EMS) models were proposed to simulate thermal stratification and mixing during a steam injection into a large pool of water. These models are (i) computationally efficient, since the small scale phenomena of DCC is not resolved, and (ii) sufficiently accurate, since the integral effects of these phenomena on the large scale pool circulation are taken into account. EHS/EMS models have been developed and validated for blowdown pipes using experimental data from the PPOOLEX facility at LUT.

The goal of this work is to develop and validate EHS/EMS models for spargers. The models are implemented in the containment code GOTHIC. To obtain data for validation, a set of experiments are proposed in the PPOOLEX facility using a scaling methodology to ensure that the ranges of important parameters and regimes from the plant scale are addressed in the experiment. Pre-test analysis was carried out in order to (i) confirm the scaling methodology, (ii) provide suggestions for the instrumentation, (iii) get insights about detailed thermal-hydraulic behavior of the pool, and (iv) provide detailed instructions for the test procedures. A preliminary validation against the experiments shows overall good predictive capabilities of the EHS/EMS models. However, it was observed that accurate prediction of the effective momentum for the unstable steam condensation regimes requires further development of the model closures. Using the developed closures, we were able to reproduce the pool temperature field with an average error less than 3^{o}C during a 6000 s transient.

Keywords: Thermal Stratification, Mixing, Pressure Suppression Pool, Sparger, Containment, Thermal Hydraulic, GOTHIC, Light Water Reactor

1. Introduction

The pressure suppression pool of a BWR is designed to limit the containment pressure by condensing steam during abnormal situations. During a Loss of Coolant Accident (LOCA), the steam released in the drywell is injected into the pool through blowdown pipes of about 600 mm diameter [1]. During a Station Black-Out (SBO), over-pressurization of the primary circuit is avoided by opening the Safety Relief Valves (SRV), which discharge steam from the main steam lines into the pool through spargers. Spargers are pipes of about 150 mm diameter with multiple injection holes of about 10 mm diameter each. During any of these steam blowdowns, the interplay between the buoyancy and the effective momentum generated by the different steam condensation regimes can lead to either mixing or thermal stratification of the pool. If the thermal stratification develops, the water volume in which the latent heat of the steam is distributed is reduced; leading to a higher pool surface than if would have been mixed. The risk associated with a high pool surface temperature is that it increases steam pressure in the wetwell gas space, which induces an over-all higher pressure in the containment.

The safety related importance of the pool thermal behaviour shows that there is a need to understand and be able to predict this phenomena for a given steam condensation regime. To do this in an efficient manner, Li and co-workers [2] 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 behaviour, 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 analysing the long-term transients of a BWR. EHS/EMS models have already been developed and validated for blowdown pipes for the condensation regimes of chugging and condensation inside the pipe [2], [3]. In this work, we extend the EHS/EMS models to the condensation regimes appearing in spargers.

Specific research done in spargers focused in the In-containment Refuelling Water Storage Tank (IRWST) of the new advanced light water reactors APR1400 and AP1000. For the spargers in the IRWST, the stable condensation regimes appearing at high steam mass fluxes ranging between 250-1000 kg/(m^{2}s) have been studied by [4], [5], and [6] in terms of shapes of the jet, penetration lengths, velocity profiles, and temperature fields. The pool thermal behaviour induced by these spargers under the stable condensation regimes has also been analysed experimentally by [7], [8], and [9]. In these works, the experimental data was also used for validation of models and CFD codes such as CFX and FLUENT. Due to the limitations of current CFD codes in predicting the sudden condensation of a steam jet, a similar approach as the one used in the EHS/EMS models was adopted: computation of the direct contact condensation was avoided by using the so called steam condensation region model. In the simulations done by [7], [8], and [9] the total transient times simulated are 10 s, 30 s, and 1000 s respectively. In general, the validations show good agreement with the experimental data.

We can see from the previous paragraph that there has been a lot of research in stable jets appearing at high steam mass fluxes. However, for a BWR, these high steam mass fluxes are only expected to appear during a small time frame after the SRVs, connected to the spargers, are activated (see Table 1 in section 2.2). After the initial depressurization, the steam mass flow injected into the pool decreases due to the reduction of the core decay heat, moving the condensation regime from the stable condensation region to the oscillatory bubble and chugging regimes appearing between 0-200 kg/(m^2s) [10]. Due to the lower steam mass flux in comparison with the stable jets, it is actually these regimes the ones which are most likely to induce thermal stratification in the pool. However, to the author's knowledge, no research has yet been done to assess what is the effective momentum which they transfer to the pool.

The goal of this work is to develop and validate EHS/EMS models which can be used to simulate in a reasonable computational time the pool thermal behaviour during a steam injection through spargers. The focus is in the unstable condensation regimes appearing at low steam mass fluxes. To generate a set of experimental data which can be used for the validation of these EHS/EMS models, several tests are proposed in the PPOOLEX (Pressurized POOL EXperiments) facility in Lappeenranta University of Technology [11]. To achieve this goal, our first task is to derive a scaling methodology which will ensure that the experimental design preserves the ranges of important parameters and regimes which would appear in full scale BWR. The second task is to perform pre-test simulations to confirm that, with the scaled design, the pool regimes of thermal stratification and mixing can be reproduced. Once these two steps are finalized, a preliminary validation of the developed EHS/EMS models for sparger against two of the experiments is shown. Validation of the developed models with the rest of the experimental data will be presented in further publications.

2. Scaling of the PPOOLEX tests with sparger

Computational tools are frequently used to predict the behaviour of nuclear power plants during a transient. Due to the prohibitive costs of performing full-scale plant experiments, the experimental data needed for the validation of the computational tools is mainly obtained in reduced-scale facilities. For the experimental data to be of any use, the facilities have to be designed to reflect the regimes and conditions of importance appearing in full-scale. This can be achieved through an appropriate scaling.

The general conclusion of the scaling approaches found in the literature is that, in a reduced-scale facility, it is not possible to preserve simultaneously exact similitude between all the processes occurring at full scale. To avoid arbitrariness in selecting which process should be preserved, Zuber [12] developed a Hierarchical Two-Tiered Scaling (H2TS) methodology where scaling groups are first obtained through the analysis of the conservation equations and then ranked by importance through their common variable: the time scale. To consider all possible processes, the conservation equations need to be derived for any geometrical configuration of the phases involved in the different sub-systems in which our reference scaling system can be decomposed. This methodology is applied by Peterson [13] to analyse the thermal behaviour of a water pool during jets and plumes injection. Assuming thermally stratified pool conditions, he derives a set of dimensionless numbers which can be used to predict the injection conditions that would cause transition to mixing. In these dimensionless numbers, the total height of the pool, fluid properties, diameter of the injection hole, and velocity of the injected water appear as the main parameters needed to be considered in the design of a scaled-down facility. However, no hierarchy of these scaling parameters is provided. Specific scaling analysis of the pressure relief system of a BWR was done by Li and co-workers [14] and Sonin [15]. Following the H2TS methodology proposed by Zuber [12], Li and co-workers [14] decompose the full scale domain into three sub-systems: pool, sparger piping, and injection holes; and derives a complete set of conservation equations for the phases appearing in each. From these equations, the parameters needed to be preserved are identified to be similar to the ones proposed by Peterson [13] however, they emphasized that at the injection hole level, it is not only the dimensionless number that needs to be preserved, but also the parameters which appear on it: same diameter, same mass flux, and same thermo-physical properties of the fluid. Using the Buckingham π theorem, Sonin [15] derives a set 12 dimensionless numbers which lead to similar scaling groups as the ones predicted by Peterson [13] and Li and co-workers [14].

Work done by D'Auria & Galassi [16] reviews most of the scaling approaches used in the nuclear reactor thermal-hydraulics. Given the great number of approaches, they propose a general “roadmap to scaling” to be used in the design of an experiment. Its goal is to produce data for code validation and to assess the capabilities of the code to predict the full-scale plant behaviour. The roadmap begins by identifying the nuclear reactor type and transient to be scaled; then, the processes involved in such transient are divided into the different levels where they appear: the macro, meso, and micro scales. For the meso and micro scales, the scaling groups can be determined by the analysis of the conservation equations. For the macro scale, D'Auria & Galassi state that minimum distortions with respect to the prototype can be achieved if the experiment is designed to be full-length, full-pressure, and time-preserving. However, they also recognize that this might not be possible in some cases due to the cost of building such facility. In such case, the resulting distortions of spatial and temporal scales should be addressed. An example of a non-preserving length and time scaling design is presented by Ishii and co-workers in [17] for the PUMA facility, which has been used to analyse different Loss of Coolant Accidents transients in a BWR.

2.1. Scaling methodology

The goal of our scaling is to design an experiment which can reproduce prototypical ranges of steam injection conditions and pool regimes occurring during a BWR transient of steam discharge through spargers. The experiments were designed in the PPOOLEX facility in LUT [11],which comprises a 6 m height vessel of 2.4 m diameter with a floor at 4.5 m separating the drywell from the wetwell, and a steam generator of 1MW capacity. 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.

The BWR scenario which was taken as a basis for the scaling was a SBO where 8 Safety Relief Valves (SRV) are opened to discharge steam into the suppression pool. It was assumed that the valves remained open once they were activated. The importance of this scenario lies on the Fukushima Daiichi accident at Unit 3, where it has been suggested that the steam injection into the wetwell due to activation of the SRVs and the RCIC system exhaust induced a thermal stratification development in the pool which accelerated the pressure increase in the containment [18]. The transient time during which the pressure increase was observed in Unit 3 was about 1 day; thus, the SBO scenario used for scaling will also consider steam injection conditions appearing at the late stages of the accident, when the decay heat from the core has decreased and the steam flow is lower.

Due to the safety importance of thermal behaviour of the pressure suppression pool, our experiment was not only designed to preserve the scaling parameters proposed by Peterson [13], Li and co-workers [14], and Sonin [15], but also to reproduce the pool regimes of thermal stratification and mixing which can develop in the considered BWR transient. These two goals were achieved through a two-step process in which the scaling methodology was first applied to obtain a preliminary design of the experiment, and then, pre-test simulations were run to check if the pool regimes of thermal stratification and mixing could be reproduced with such design.

In our scaling methodology, the scaling groups proposed by Peterson [13], Li and co-workers [14], and Sonin [15] were divided into the scales where they appear: macro-scale (water pool), meso-scale (sparger pipe), 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 reproduce the pool regimes of thermal stratification and mixing which would appear in the pool of the considered BWR transient. To induce a similar thermal behaviour in the pools, we should preserve ranges of time scales of energy and momentum changes in the pool, and spatial similarity between the PPOOLEX pool and the water volume surrounding a single sparger in a BWR. To achieve this goal, the design parameters needed to be determined are the (i) pool depth, (ii) sparger submergence depth, (iii) sparger location within the tank, (iv) total steam mass flow, and (v) total injection hole area.

- **Meso-scale (sparger pipe)**: The goal is to preserve the ranges of condensation regimes inside the sparger pipe, which control how the heat and momentum sources are distributed within the pool. To achieve this goal, the design parameters needed to be determined are the (i) sparger pipe diameter and thickness, and the (ii) location and dimensions of the LRR.
- **Micro-scale (injection holes)**: The goal is to preserve the ranges of micro scale phenomena and prototypic dimensions of the injection holes. Doing this will ensure that the same steam jet which would appear in a BWR sparger can be reproduced in the PPOOLEX facility. Thus, if the model developed for the steam jet is validated with the experimental data from the facility, it will be possible to claim that it would work equally well for the BWR. To achieve this goal, the design parameters needed to be determined are the (i) steam mass flux (ii) injection hole diameter and geometry, (iii) pitch to diameter ratios between adjacent injection holes, and (iv) steam injection conditions.

2.2. Scaling results

The range of steam injection conditions obtained in a GOTHIC simulation of a BWR transient in which 8 safety relief valves are activated and left open is presented in Table 1. According to the condensation regime map from Chan & Lee [10], the steam mass fluxes at the injection holes from Table 1 show that stable jets are only expected to appear during the first 500 s, while the rest of the transient is dominated by the condensation regimes of oscillatory bubble and chugging. Thus, the PPOOLEX experiments were designed to study the low steam mass flux condensation region, which appears to be the dominant condensation regime during the BWR transient.

Table 1: Steam injection conditions during a BWR transient where 8 safety relief valves are activated and maintained open.

Time after SRVs activation	Steam pressure at the sparger inlet	Steam mass flow through all spargers	Steam mass flux through sparger pipe [a]	Steam mass flux through injection holes [b]
300 s	400 kPa	140 kg/s	250 kg/(m^{2}s)	430 kg/(m^{2}s)
500 s	240 kPa	66 kg/s	115 kg/(m^{2}s)	200 kg/(m^{2}s)
10000 s	190 kPa	20 kg/s	35 kg/(m^{2}s)	60 kg/(m^{2}s)

[a] Assuming a total of 32 spargers, each with a pipe diameter of 150 mm

[b] Assuming a total of 32 spargers, each with an injection hole area of 10100 mm^2

The following points present the design parameter used in the experiments and provide an explanation of why we chose them.

Macro-scale (pool): (i) The pool depth was set to 3 m. As the PPOOLEX tank diameter is 2.4 m, the ratio between the height of the pool and its diameter became 1.25. In a prototypic BWR, if we consider the water volume surrounding a single sparger, the ratio between its height and diameter ranges between 1.8 and 3. We can see that the spatial ratios in PPOOLEX and BWR are in the same order of magnitude. However, their difference shows that the water pool in the PPOOLEX facility is broader than the volume surrounding a single sparger in a BWR pool. This could have been improved by raising the liquid level higher than 3 m; however, since the total height of the vessel in PPOOLEX is 4.5 m, this would have limited the liquid level increase during the transients and given a very small volume of the gas space. **(ii)** The sparger submergence depth was set to 1.8 m. It has been observed in [19] that the sparger submergence is usually on the range of 70 % of the total pool's height. In order to preserve a similar ratio of active and inactive volumes of the pool during the stratification phase, the submergence fraction was set to a similar value of 60 %. **(iii)** The sparger was located 420 mm off-centered from the pool's axis in order to have a good angle for the PIV cameras. This off-center location increases the difficulty of the validation process since will induce asymmetric flows which can be difficult to measure. However, it can also be regarded as a benefit since in a BWR pool, the spargers are also located close to the walls. **(iv, v)** Given the aforementioned pool dimensions, the order of magnitude of the energy and momentum time scales was preserved by setting a total injection hole area of 2010 mm^2, and a steam mass flow between 0.12-0.4 kg/s at 230 kPa. The energy and momentum time scales were calculated using equations (1) and (2) respectively.

$$\omega_E = \frac{\dot{m}_S h_S}{m_L h_L} \tag{1}$$

$$\omega_M = \frac{\dot{m}_S v_S}{m_L v_L} \tag{2}$$

In the equations, $\dot{m}$, h, and v are the mass flow rate, enthalpy, and velocity of the fluid; sub-indexes S and L the steam injected and the liquid pool; and ω_E, ω_M the specific frequencies (time scales) of energy and momentum respectively. The resulting values are presented in Table 2. 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 are expected in terms of stratification and mixing; however, this is something which will need to be verified in section 3 with the pre-test simulations since it is also influenced by the confinement of our PPOOLEX vessel and the resulting flow field. The difference between the time scales only indicates that the time needed to observe temperature and momentum changes in the pool will be different by a certain factor than in the BWR.

Meso-scale (sparger pipe): (i) The sparger pipe was designed with a 68 mm inner diameter and a 4 mm thickness. Given the same steam injection conditions, the main parameters affecting the condensation regime in a submerged pipe are the steam mass flux and the pool temperature [10]. Using the maximum steam flow which can be generated in the PPOOLEX facility of 0.43 kg/s, the steam mass flux through the proposed sparger is 118 kg/(m^{2}s), similar to the one observed in

Table 1 for 500 s after the SRVs activation. Since the pool temperature can also be preserved in the experiment, this 68 mm diameter shows that it would be possible to preserve the condensation regimes inside the sparger occurring 500 s after SRVs activation. Another parameter which can influence the steam condensation inside the sparger is the submergence depth. The submergence of our sparger was set to 1.8 m, whereas in a BWR it can vary between 4 and 7 m. For high steam mass fluxes the condensation inside the sparger pipe is negligible, and a difference in the submergences just leads to a different steam temperature at the outlet. It is only low steam mass flux regimes of complete condensation inside the pipe and chugging where differences between our facility and the BWR would be observed. Thus, the transition to these regimes in our PPOOLEX sparger is expected to happen at higher steam mass fluxes than in a BWR. **(ii)** The LRR was located 700 mm above the sparger end, with a diameter of 110 mm, and a height of 34 mm. Prototypical designs of BWR spargers show that the distance from the LRR to the sparger end is located between 30 to 50 % of the sparger submergence depth. In order to reproduce a similar flow field, our LRR was located at a ratio of 40 %. The interaction between the jets from the LRR and the jets from the sparger head will be different since they will be closer to each other.

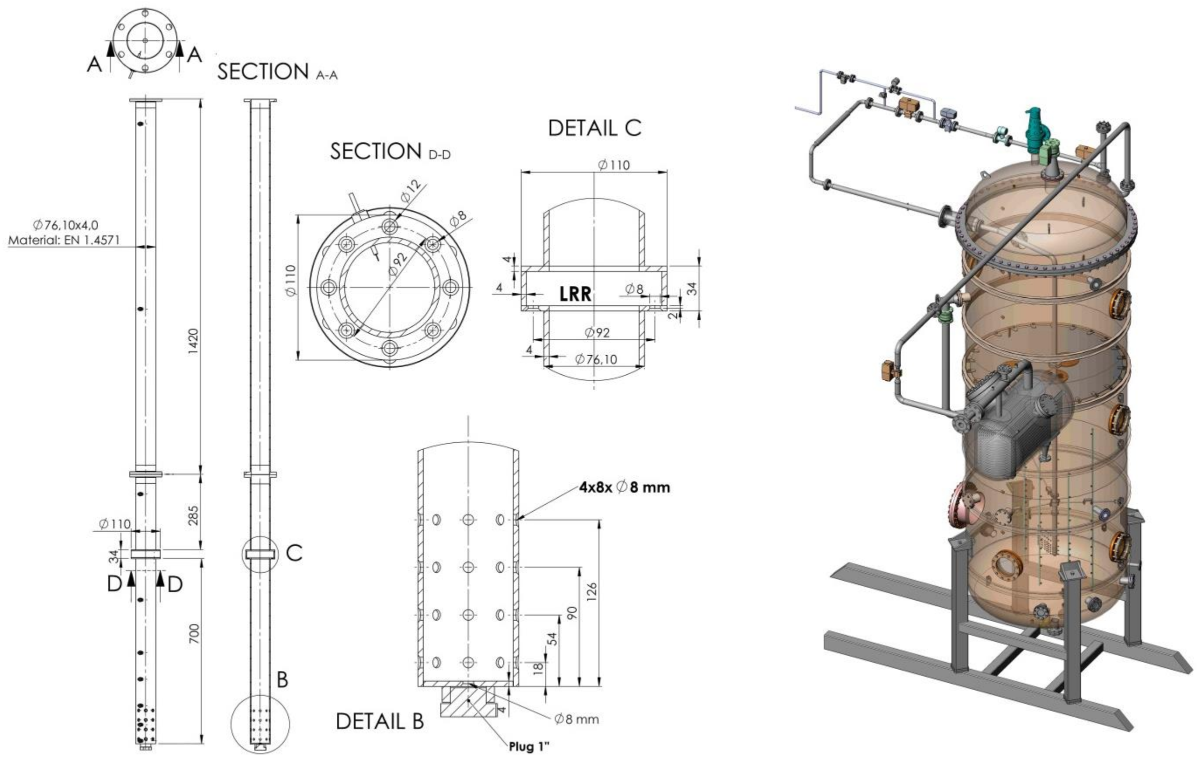
Table 2: Energy and momentum time scales during an BWR transient where 8 safety relief valves are activated and maintained open.

	Energy time scale ω_E [1/s]		Momentum time scale ω_M [v_L/s]	
	500 s after SRV	10000 s after SRV	500 s after SRV	10000 s after SRV
BWR[a]	$7.1 \cdot 10^{-4}$	$2.0 \cdot 10^{-4}$	$3.5 \cdot 10^{-3}$	$3.4 \cdot 10^{-4}$
PPOOLEX	$9.5 \cdot 10^{-4}$	$2.8 \cdot 10^{-4}$	$4.5 \cdot 10^{-3}$	$4.1 \cdot 10^{-4}$

[a] BWR transient presented in Table 1

Micro-scale (injection holes): (i) The total injection hole area of 2010 mm^2 determined in the macro-scale section was used. As the maximum steam mass flow available in PPOOLEX is about 0.43 kg/s, the range of steam mas fluxes which can be covered with the proposed total hole area is 0-200 kg/(m^{2}s), which is in the same range as the stem mass fluxes appearing 500 s after SRV activation (Table 1). This injection hole area was distributed between the LRR and the sparger head in a 20 to 80 % fraction respectively. Prototypic sparger designs found in the literature have all shown to keep this ratio of 20-80 % between the LRR and the sparger head [9]. **(ii)** The injection holes were designed with 8 mm diameter and a chamfer of 12 mm at the outer side of the hole. In a prototypic BWR sparger, the diameter of the injection holes is about 10 mm. Due to our reduced injection hole area, we had to reduce this diameter in order to have a sufficiently high number of holes which could provide a similar arrangement as in the BWR sparger. The chamfer at the injection holes has also been observed in prototypic sparger designs. **(iii)** In the LRR, 8 holes were arranged in a single ring. In the sparger head, 32 holes were arranged in 4 rings with 8 holes each. Given the sparger pipe diameter of 68 mm and the hole diameter of 8 mm, the pitch to diameter in the horizontal direction is 3.3, comparable to the pitch to diameters of about 3.6 found in the BWR spargers. Setting a separation between the rings of injection holes of 36 mm gives a vertical pitch to diameter of 4.5, again similar to the 4.5 pitch to diameter found in the BWR sparger. All of these design parameters for the injection holes aim to reproduce a similar steam jet at the injection hole and similar interaction between neighboring jets.

The final design of the experiment and the sparger can be observed in Figure 1. The next step is to confirm that with such design, the pool regimes of thermal stratification and mixing can be developed.



(a) (b)

Figure 1: Design of the experimental setup obtained with the scaling. Drawings courtesy of operators at PPOOLEX facility, LUT, Finland [11]. (a) Sparger design used in the PPOOLEX-SPA tests. (b) General-view of the PPOOLEX vessel and steam generator**.**

3. Pre-test simulations of the PPOOLEX test with sparger

The sparger and pool design presented in Figure 1 are scaled-down models which can be used to reproduce prototypical ranges of the phenomena appearing at full-scale conditions. However, this is not the only goal of the experiment; it is also of major importance that the experimental data can be used efficiently for code validation. In the sparger from Figure 1, the effective momentum transferred to the pool depends on processes such as the condensation of a single jet, the interaction between neighboring jets, and the flow distribution between the LRR and the sparger head. Given a limited set of instrumentation, if all of these processes appear in the same test, it can be difficult to assess how much did each one contribute in the effective momentum. To address each process individually, this test series was designed to study the separate effect of the sparger head jets by blocking the LRR holes. Doing this breaks the similarity with the BWR sparger behaviour, but it increases the confidence of the validated models since a good agreement with experimental data would mean that, given a known steam mass flow through the injection holes, the steam jet and steam jet interaction were modeled adequately. Once our model is validated for the sparger head jets, the complexity of the next test series will proceed to include the effect of the LRR.

3.1. EHS/EMS models for spargers

Current CFD codes cannot resolve adequately the direct contact condensation phenomena appearing during a steam blowdown into a water pool. Moreover, the low time steps and fine mesh resolutions needed to resolve it make it unfeasible to analyse the long-term transients of a BWR. For these reasons, the computation of the direct contact condensation appearing at the sparger injection holes was avoided in this work. Instead, the idea of the Effective Heat Source (EHS) and Effective Momentum Source (EMS) models presented in Li and co-workers [2] was adopted. The idea behind these models is that the global pool behaviour during a steam injection can be predicted if we provide the effective (time-averaged) heat momentum transferred from the steam condensation to the large scale flow circulation. EHS/EMS models have already been developed and validated for the chugging regime appearing in blowdown pipes [3]; in this work, we extend the EHS/EMS models to spargers.

For a sparger with blocked LRR holes, the effective heat and momentum transferred from the steam jets to the liquid was estimated using the steam condensation region approach in [20], [7], and [9]. This approach resolves the conservation equations of mass, momentum, and energy for the control volume where the steam jet is expected to condense completely, and provides the condensate and entrainment boundary conditions as single-phase liquid. The condensation length of a steam jet can vary between 1-10 times the injection hole diameter, and depends mainly on the steam mass flux, hole geometry, and pool sub-cooling. This behaviour cannot be easily taken into account in a CFD simulation since it would require that the control volume where the steam jet equations are solved changes during the transient. To address this issue, a series CFD simulations using different condensation lengths was performed in [9], and it was concluded that the influence of the condensation length on the global pool behaviour is little as long as a reasonable value is selected. Therefore, for the range of steam mass fluxes of 0-200 $kg/(m^2s)$

where our scaled sparger design is expected to work, the condensation length was taken to be a constant value of 1.5 times the injection hole diameter. It was also assumed that the steam jet does not expand in such short distance, leading to a condensate area equal to the injection hole area. Having defined the condensation region, equations (3), (4), and (5) were used to compute the effective momentum (6). Due to the lack of available experimental data relative steam injection through spargers, the dependency of the effective momentum with the steam condensation regime could not be estimated in the pre-test analysis. Thus, the set of equations presented are not expected to provide an accurate effective momentum, but just a reasonable estimate which can be used to assess if the pool regimes of thermal stratification and mixing can be reproduced with the experimental design obtained in the scaling section. The dependency of the effective momentum with the condensation regime will be the focus of the post-test analysis (section 5).

$$m_S + m_E = m_C \tag{3}$$
$$m_S u_S = m_C u_C \tag{4}$$
$$m_S h_S + m_E h_E = m_C h_C \tag{5}$$

$$M_{eff} = m_C u_C \tag{6}$$

In the equations, m, u, and h are the mass flow, velocity, and enthalpy of the fluid; sub-indexes S, E, and C the phases of steam, entrainment, and condensate liquid; and M_{eff} the effective momentum rate. Since this model was used to simulate sub-sonic steam injections, no modifications to the equations were needed to account for chocked flow conditions. The major assumptions behind this model are:

- The steam jet condenses completely within a cylindrical control volume of 1.5 times the injection hole diameter length.
- The velocity at the injection holes is homogeneous.
- The entrained water flows perpendicularly to the direction of the jet.
- The pressure along the jet axis is constant.
- Friction and gravity forces are negligible in comparison with the inertia forces of the jet.

3.2. Implementation of the EHS/EMS models in GOTHIC

The thermal hydraulic code of GOTHIC was chosen as the platform to implement the EHS/EMS models for spargers presented in section 3.1. This code balances computational efficiency and accuracy combining the 3D Reynolds-Averaged Navier-Stokes Equations (RANS) with a set of correlations for boundary layers and heat transfer which enable it to run in a much coarser mesh. GOTHIC has already been proven to provide satisfactory results in many applications for nuclear power plant related transients [21]. In our pre-test simulations, we used GOTHIC version 8.0 (QA).

GOTHIC uses the Cartesian grid meshing system instead of the boundary fitted approach of most of the CFD codes. It allows local refinement of the mesh by using nested volumes linked by 3D connectors. During a steam injection into a water pool, local refinement is mainly needed in the steam injection region (high velocity gradients), and in the vertical direction of the pool (high temperature gradients). In the pre-test simulations, the sparger jets region was meshed with hexahedral cells of 20 mm; the cell size in the pool was increased to about 150 mm in the x-y directions and to 100 mm in the vertical z direction; and the transition region between the small cells of the jet and the ones of the pool was meshed with hexahedral cells of about 50 mm. Due to the smaller velocities and temperature gradients expected in the gas, the wetwell gas space was meshed with much coarser mesh of about 500 mm size. The total number of cells was 13464.

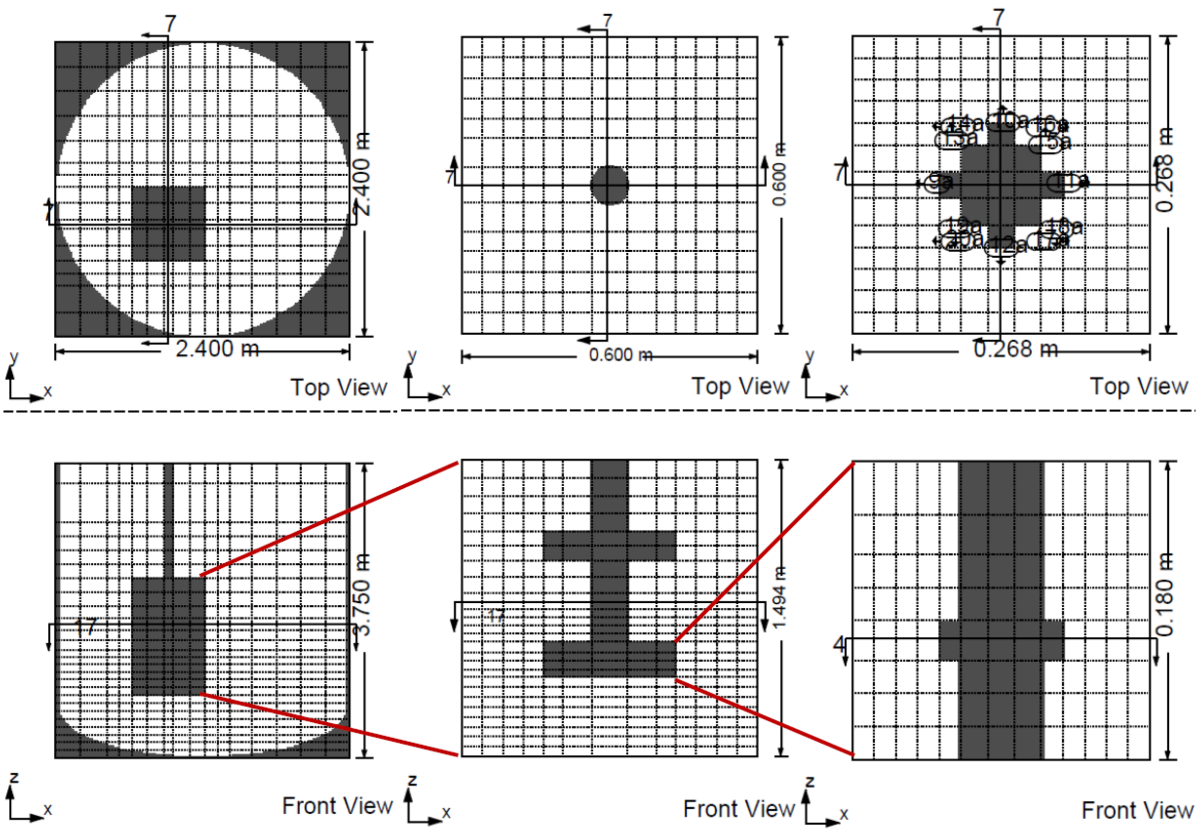


Figure 2: Mesh used in the pre-test simulations. Smallest and biggest cell sizes are 20 mm and 500 mm respectively.

The EHS/EMS models for spargers were implemented in GOTHIC using boundary conditions which provided the single-phase liquid condensate and entrainment flows. The solution of equations (3), (4), and (5) was computed every time step using external functions implemented in 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 [7], [9]. It was assumed that a pitch to diameter ratio of 4.5 was high enough to assume negligible jet interaction, and that the steam injection conditions of pressure and temperature were the same for all the injection holes. Figure 2 presents the flow path distribution used to model the radial distribution of the steam jets, and the mesh used in each one of the nested volumes. In the jet volume, porosity factors of 0 were given to the cells where the steam condensation would have taken place.

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.

3.3. Pre-test simulation results

The pool temperatures obtained in the pre-test simulations of a sparger with blocked LRR holes are presented in Figure 6. The results confirm that, using the range of steam mass flow available in the PPOOLEX facility (~0.43 kg/s max), the pool regimes of thermal stratification and mixing are achievable with the sparger and experiment design proposed in the scaling section (Figure 1). Transition to mixing is expected to happen at steam flow rates between 0.18-0.2 kg/s. In the simulations, a steam flow rate of 0.06 kg/s was initially injected to develop stratification; once a temperature difference between the top and bottom of the pool of about 10 ^{o}C was reached, the mass flow was increased to different values to see which one caused transition to mixing. The steam injection conditions were taken as saturated at 230 kPa.

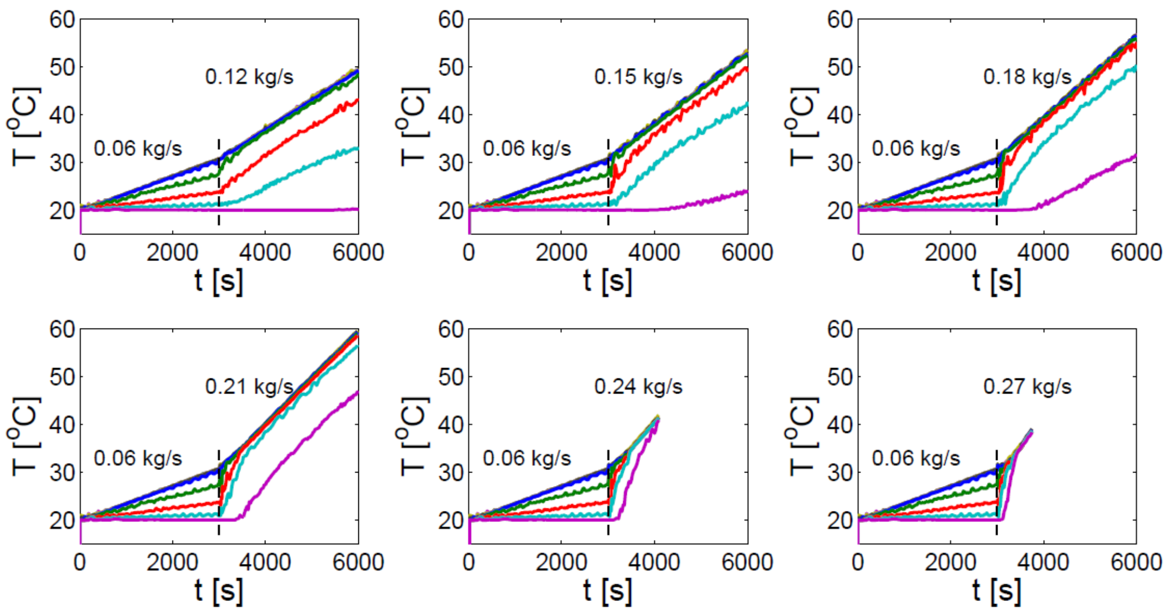
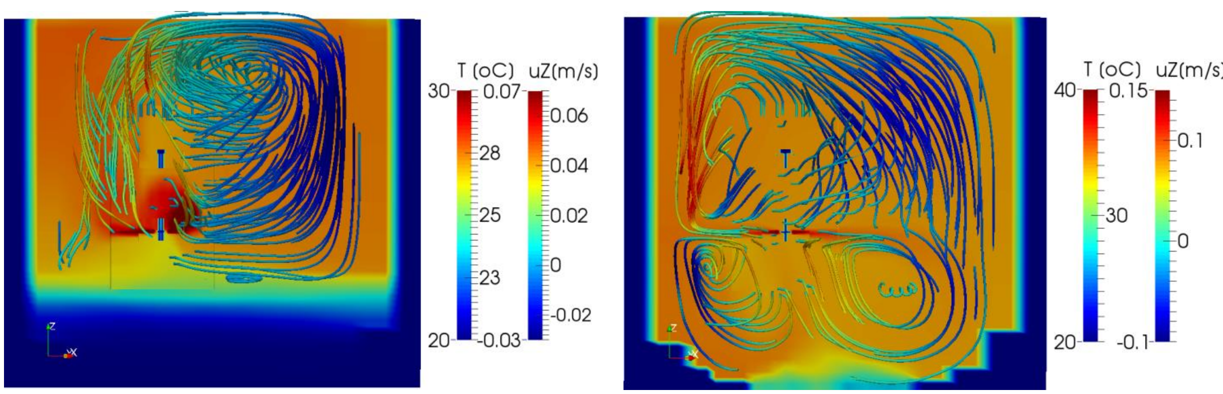


Figure 3: GOTHIC results of the pre-test analysis of the sparger with blocked LRR holes. Temperature along a vertical line located in the middle of the pool.

Snapshots of the temperature and velocity fields appearing during some of these simulations can be observed in Figure 4. At low steam mass flows, momentum was created mostly by buoyancy, which drove the flow upwards before it interacted with the vessel walls. Due to the asymmetry of the sparger location, an asymmetric and rotational 3D flow structure was created. Since no momentum was directed towards the bottom of the pool, the water volume below the sparger remained stratified, and a thermocline-type profile developed: thermally mixed region above the sparger head and a sharp temperature gradient below it. At higher steam mass flow rates, contribution of the jet inertia to the momentum gradually increased and the jets began to interact with the wall. As a result, part of the momentum of the jets was reflected downwards and the stratified layer below the sparger began to be mixed with the rest of the pool.



(a) (b)

Figure 4: GOTHIC results of the pre-test analysis of the sparger with blocked LRR holes. Snapshot of the temperature field and stream lines. (a) Simulation with 0.06 kg/s, snapshot at t = 2000 s (b) Simulation with 0.27 kg/s, snapshot at t = 3500 s

4. PPOOLEX tests with spargers

The design of the PPOOLEX experiments with sparger was based on the scaling analysis presented in section 2. In brief, the pool height of the 2.4 m diameter tank was set to 3 m, and a sparger of 66 mm diameter and a total injection hole area of 2010 mm^2 was submerged 1.8 m into the pool and located 420 mm off-centered (Figure 1). The instrumentation used during the tests was decided according to the temperature and velocity fields observed in the pre-test simulations presented in section 3. A general view of the instrumentation is presented in Figure 5 [11], where the brown dots in the vertical green lines and in the circled section "A" represent the location of the TCs. In the pre-test simulations, the water volume below the sparger was observed to be the region with higher temperature gradients. Thus, vertical trains of thermocouples (TCs) of 2 Hz were arranged with a 200-300 mm separation above the sparger head, and refined with a 100-200 mm separation below it. Since the sparger pipe was located 420 mm off-centered in the vessel, four vertical trains of TCs were arranged into different locations to capture the asymmetries in the flow field. A grid of 6×7 TCs of 20 Hz was located in front of the injection holes to analyze the temperature at the condensation region, the jet interaction patterns, and the frequencies of the oscillatory bubbles. TC measurements were also located inside the sparger pipe to analyse the temperature drop through its length and to determine the steam conditions right at the injection holes. The steam mass flow through the sparger was measured with flow meters. The liquid level increase during the transient was measured with level-meters. Temperature measurements of the lab were also done to assess the heat transfer through the vessel walls, which were not isolated.

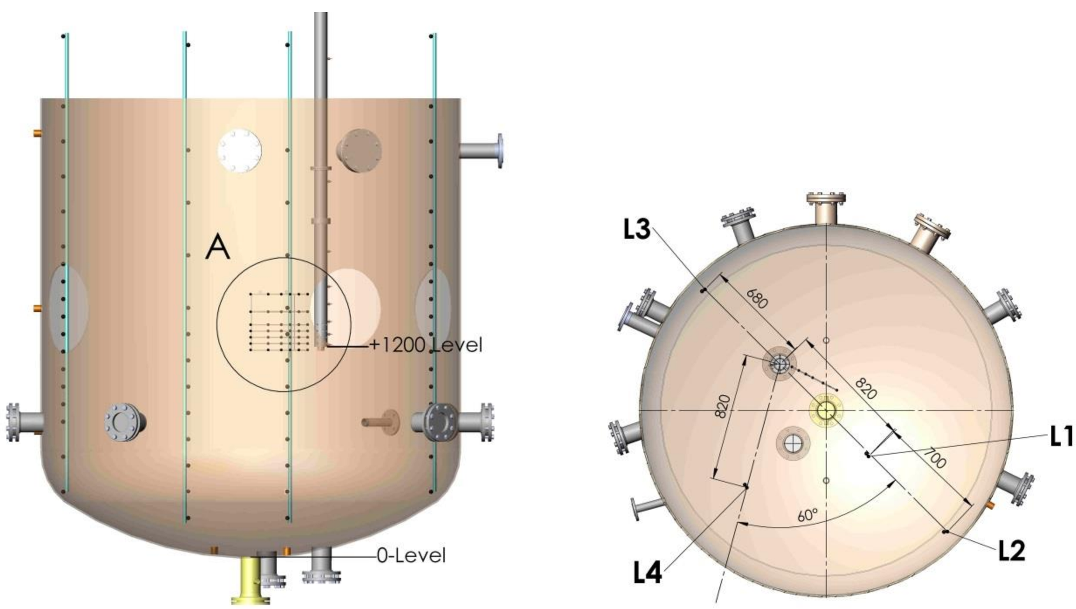


Figure 5: Over-view of the instrumentation used during the PPOOLEX-SPA tests.
Drawings courtesy of operators at PPOOLEX facility, LUT, Finland [11].

4.1. Test matrix

The test matrix was designed to cover the steam condensation regimes appearing at low steam mass fluxes of 0-200 kg/(m^2s), which are the ones of importance during the considered BWR transient (see Table 1). Due to the limitation in the number of tests, each test was designed to maximize the amount of information that we could gain from it by combining stratification and mixing phases until a pool temperature of about 95 ^{o}C was reached. The time needed to mix a stratified layer is a very useful parameter since it indicates the magnitude of the effective momentum transferred from the steam jets to the liquid pool.

The condensation regime of the steam jets can be predicted using condensation regime maps. In the literature, regime maps for blowdown pipes were developed by Aya & Nariai [22], where the drywell volume acts as a buffer for the amplitude and frequency of the condensation oscillations; single hole spargers by Chan & Lee [10], where the effect of the drywell disappears; and multi hole spargers by Song and co-workers [23], where interaction between steam jets is taken into account. Focusing on the regime maps developed for spargers, and assuming that the pitch to diameter ratios of our PPOOLEX sparger are big enough to allow the steam jets to condense without interacting with each other, the regime map from Chan & Lee [10] was used as a basis to predict the steam jet condensation regime appearing at our sparger head holes. The regime map from Song and co-workers [23] was not used as basis due to its incompleteness.

Figure 6 presents the regions of the condensation regime map covered in the sparger tests performed in the PPOOLEX-SPA series [11]. We can see that the focus was on the condensation regime of oscillatory bubble. Only one exploratory test PPOOLEX-SPA T2 was conducted in the chugging region. This regime was not analysed in detail due to the unavailability of more fast TCs which could be placed inside the sparger pipe to determine the amplitude and frequency of the oscillations needed to compute the effective momentum injected into the pool [3]. The PPOOLEX-SPA T1 test was a done with a single ring of holes in the sparger head (LRR and 3 rings in the sparger head were blocked). This was done to reach the high steam mass fluxes where stable condensation is expected, and to analyze the interaction between neighboring jets.

In the PPOOLEX-SPA tests, the boundary between thermal stratification and mixing was observed to be between steam mass fluxes of 93-108 kg/(m^2s): 0.15-0.175 kg/s of steam injected at 150 kPa. Given a thermally stratified pool of about 20 ^{o}C, the time needed to induce complete mixing of the pool using these steam injection conditions was 10000-3000 s respectively. In the pre-test simulations from section 3, the boundary between stratification and mixing was estimated to be between 111-130 kg/(m^2s): 0.18-0.21 kg/(m^2s) of steam injected at 230 kPa. With the large amount of uncertainties that we had in the pre-test, its results can be considered as a good estimation. Complete mixing of the pool was also observed when steam mass fluxes lower than 40-70 kg/(m^2s) were injected into a sufficiently cold pool due to the development of the chugging regime. The frequency and amplitude of the chugging oscillations was measured to be in the order of 1.5-2 Hz and 0.1-0.35 m respectively. The boundary between chugging and oscillatory bubble agreed relatively well with the condensation regime maps from Chan & Lee [10] and Song and co-workers [23] (Figure 6). The main discrepancy was observed to appear at high pool temperatures, where the condensation efficiency of the water decreases and the bubble collapse due to sudden condensation can disappear. In our experiments, no chugging was observed when the pool temperature was higher than 65 °C, whereas in Chan & Lee [10] this transition temperature was estimated to be about 80 °C.

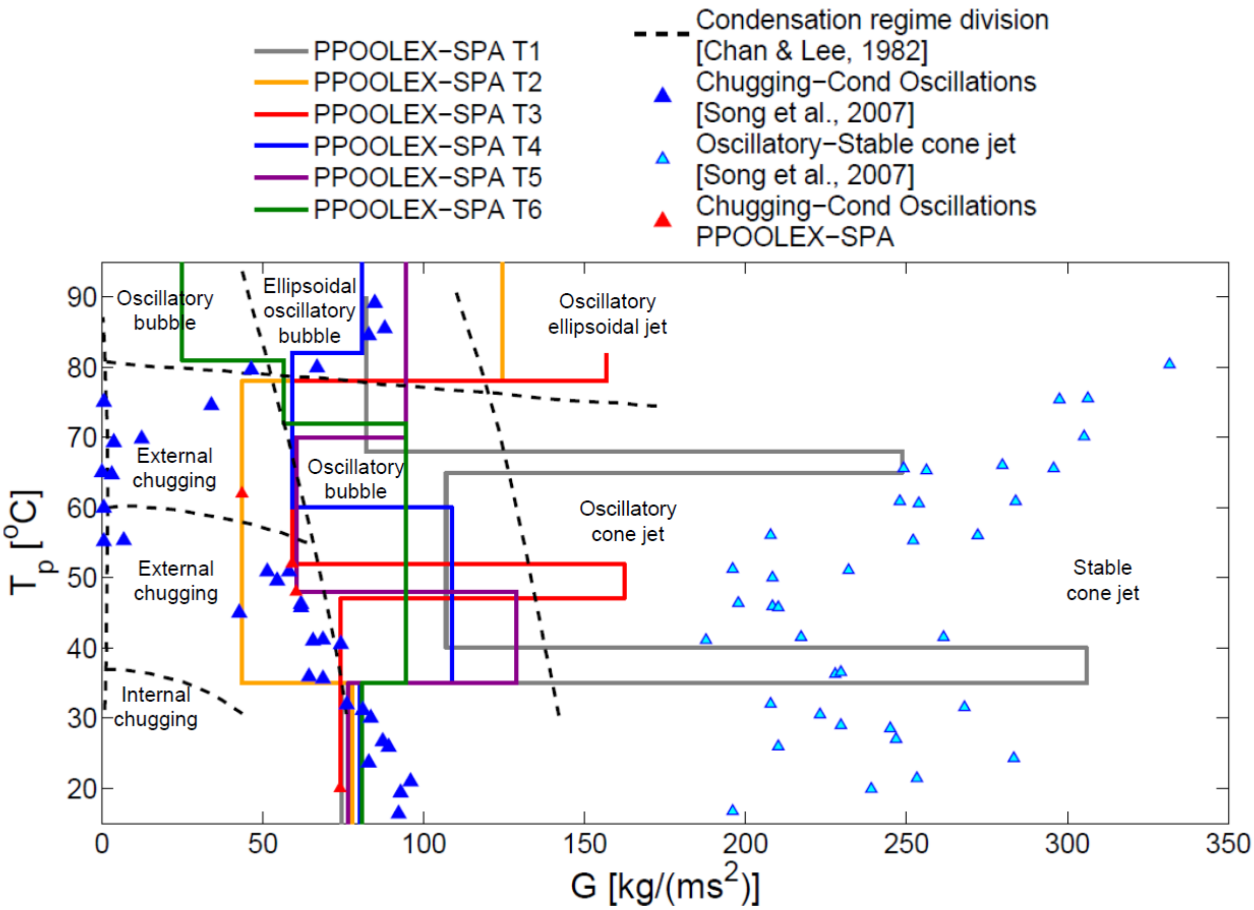


Figure 6: Steam condensation regimes covered in the PPOOLEX-SPA tests with spargers [11].

5. Validation of the EHS/EMS models for spargers

In the beginning of the report it was stated the goal is to develop and validate EHS/EMS models for spargers. Through the scaling and pre-test presented in sections 2 and 3, we now have a set of experimental data relevant to the behaviour of the BWR sparger and pool regimes which can be used for the validation. This section presents the first step towards the validation of the EHS/EMS models using the experimental data from the PPOOLEX-SPA T3 and T4 experiments (Figure 6).

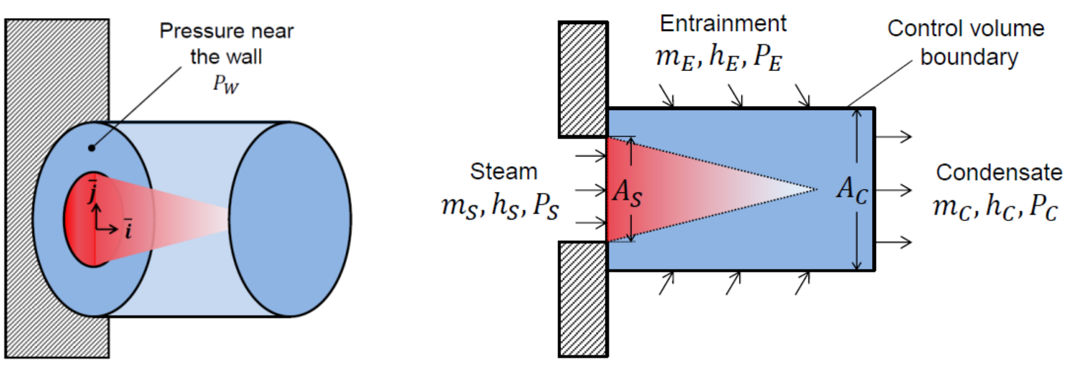
5.1. Improvement of the closures for effective momentum

During the validation process, several modifications were done to the EHS/EMS models presented in section 3.1 for the pre-test analysis. It was observed that equations (3), (4), and (5) under-estimated the effective momentum during the mixing phases of the T3 and T4 experiments, and over-estimated the momentum during the stratification phases.

Considering the control volume shown in Figure 7, it is clear that several factors have been neglected in equations (3), (4), and (5). Specifically, the pressure difference along the jet axis, possible effect of the unsteady steam-liquid interface, and the entrainment.

In order to include the effect of the pressure forces at the control volume surface we make following assumptions. At the injection hole, the steam pressure is assumed to be homogeneous with a value of P_S. In the rest of the surfaces of the control volume occupied with liquid, it is assumed that the pressure will be homogeneous and equal to the hydro-static pressure of the pool at the injection holes level P_C. The effect of the entrainment and oscillatory interface are lumped into an extra term M_{CR} (Momentum rate due to the effect of Condensation Regime).

$$\rho_S u_S^2 A_S + P_S A_S = \rho_C u_C^2 A_C + P_C A_S + M_{CR} \qquad (7)$$



(a) (b)

Figure 7: Schematic of the control volume used for the equations of the EHS/ESM models for spargers, (a) 3D view, (b) 2D view.

The value of M_{CR} will be determined in the model calibration process. If the effect is strongly governed by the condensation regimes, then M_{CR} is expected to depend on the steam mass flux and on the pool temperature.

The equations of the EHS/EMS model for sparger for mass, momentum, and energy are presented in equations (8), (9), and (10) respectively. A solution of these equations was obtained every time step. The steam injection conditions (sub-index S) were taken from the experiment. The saturation pressure P_S was obtained from the TC measurements located inside the sparger pipe at the level of the injection holes in combination with the Bernoulli equation (11). Inside the sparger pipe, steam travels with a certain velocity u_0 and pressure P_0, but when it is pushed through a smaller injection hole area, this velocity increases to u_S and reduces the saturation pressure to P_S. Compressibility effects were taken into account in the Bernoulli equation by defining a different density for the sparger pipe (ρ_0) than for the injection holes (ρ_S). Due to the proximity of the TC measurements to the injection holes, gravitational effects were not taken into account in the Bernoulli equation.

$$m_S + m_E = m_C \tag{8}$$

$$m_S u_S + P_S A_S = m_C u_C + P_C A_S + M_{CR} \tag{9}$$

$$m_S h_S + m_E h_E = m_C h_C \tag{10}$$

$$P_S = P_0 + \frac{1}{2}(\rho_0 (u_0)^2 - \rho_S (u_S)^2) \tag{11}$$

5.2. Sensitivity studies

All of the simulations done in the sensitivity studies analysed the first stratification and mixing phases of the PPOOLEX-SPA T4 experiment (Figure 19). It should be noted that during these sensitivity studies, the effective momentum of the mixing phase was still not clear due to the uncertainty in the condensation regime term M_{CR} from equation (9), and to the fact that the thermal response of the pool changed in every simulation due to different discretization errors. For this reason, direct comparison between the experiment and the GOTHIC results is not presented in this section.

5.2.1. Mesh

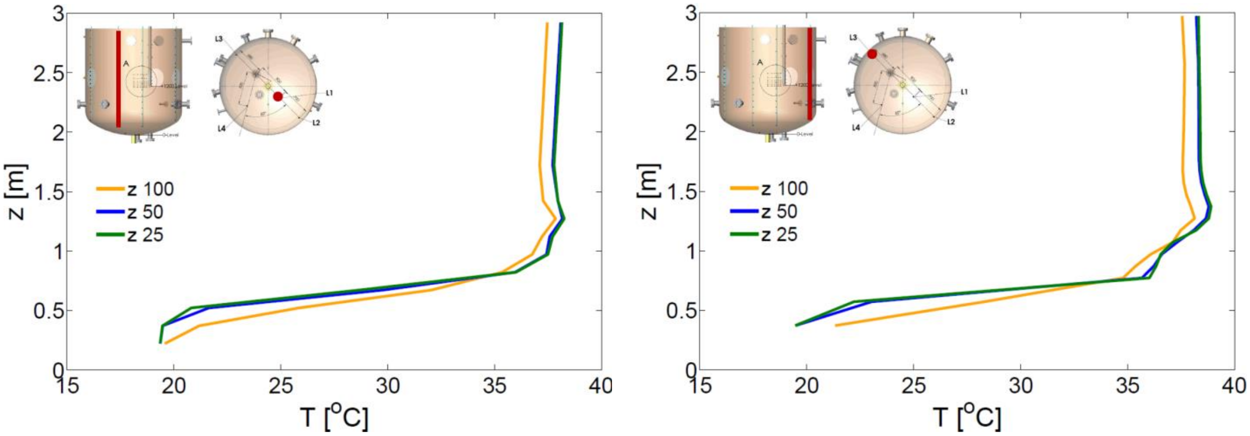
The cell sizes used during the mesh sensitivity study are presented in Table 3. We can see that in each mesh, only one parameter was changed at a time in order to analyse the effect of the cell size in a specific region of the pool. All of the simulations from the table were run with the standard k-Epsilon turbulence model and a second order spatial discretization scheme.

Table 3: Cell sizes used in the mesh sensitivity study.

<table>
<tr><th rowspan="2">Model identifier</th><th colspan="2">Cell size in vertical
z direction [mm]</th><th colspan="2">Cell size in horizontal
x and y directions [mm]</th></tr>
<tr><th>Above sparger outlet</th><th>Below sparger outlet</th><th>Region where sparger is close to vessel walls</th><th>Region far from sparger</th></tr>
<tr><td>z 100</td><td rowspan="3">90</td><td>100</td><td rowspan="3">150</td><td rowspan="3">150</td></tr>
<tr><td>z 50</td><td>50</td></tr>
<tr><td>z 25</td><td>25</td></tr>
<tr><td>xy 130 130</td><td rowspan="4">90</td><td rowspan="4">50</td><td>130</td><td>130</td></tr>
<tr><td>xy 75 130</td><td>75</td><td>130</td></tr>
<tr><td>xy 75 75</td><td>75</td><td>75</td></tr>
<tr><td>xy 50 130</td><td>50</td><td>130</td></tr>
</table>

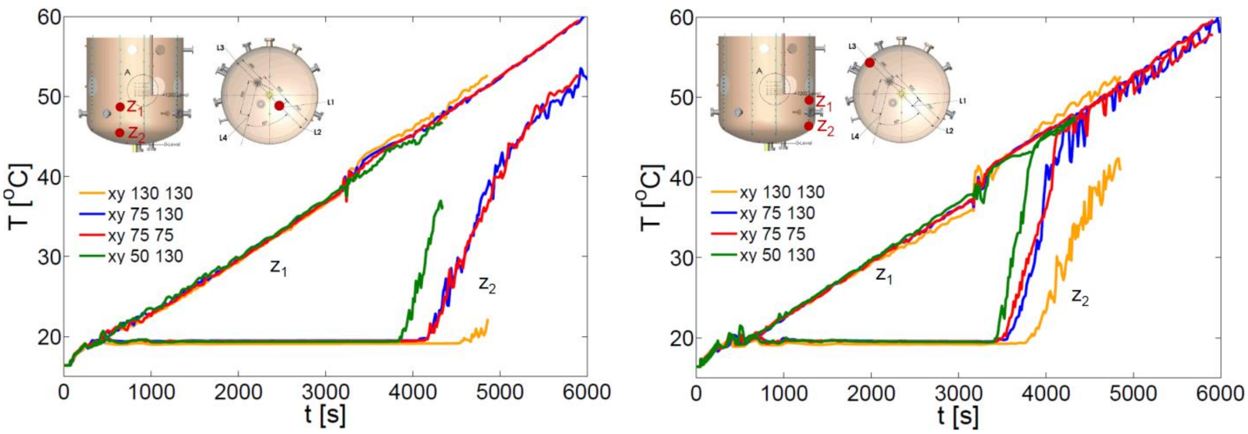
We can see in Figure 8 that in the vertical z direction, a cell size of 50 mm was enough to capture the sharp temperature gradients occurring below the sparger injection holes, located at z = 1.2 m. In the horizontal *x* and *y* directions, it was observed that a cell size of 50 mm was needed in the region where the sparger is close to the walls in order to capture the flow structure generated by the impingement of the jets (Figure 9). A coarser cell size in this region under-estimated the inertia of the downwards recirculation generated by the impingement, causing the bottom of the pool to remain cold since it could not be eroded and mixed with the rest of the pool. This behaviour can be observed in the results from the *130x130mm* mesh size in Figure 9. Far from the sparger, since the velocity of the jets had already decayed to a low value, a cell size of about 130 mm was enough to capture the flow structure. We can see in Figure 9 that a refinement to 75 mm in this region (mesh *75x75mm*) did not cause any noticeable change in the temperature trend.

In conclusion, the sensitivity study suggested that the cell sizes from mesh *50x130mm* (Table 3) give converged results. The total number of cells of this mesh was 47166, much finer than the one with 13464 used in the pre-test simulations, leading to a big increase in the computational time. A 2D model of the vessel could have reduced the computational time; but due to the asymmetric location of the sparger within the pool (Figure 5), it was decided to continue with the 3D model in order to resolve the global flow structure. The effect of an even finer mesh resolution *x* and *y* directions in the region where the sparger is close to the vessel walls should be further investigated; however, the computational cost of such mesh will be much higher.



(a) (b)

Figure 8: Sensitivity study of the cell size in the vertical *z* direction. Pool temperature profile obtained with GOTHIC in the simulation the T4 experiment: t = 2800 s, stratification phase. (a) L1 train of TCs, (b) L3 train of TCs.



(a) (b)

Figure 9: Sensitivity study of the cell size in the horizontal *x* and *y* directions. Pool temperatures obtained with GOTHIC in the simulation of the T4 experiment. (a) L1 train, TCs located at z_1 = 672 mm and z_2 = 222 mm, (b) L3 train, TCs located at z_1 = 972 mm and z_2 = 372 mm.

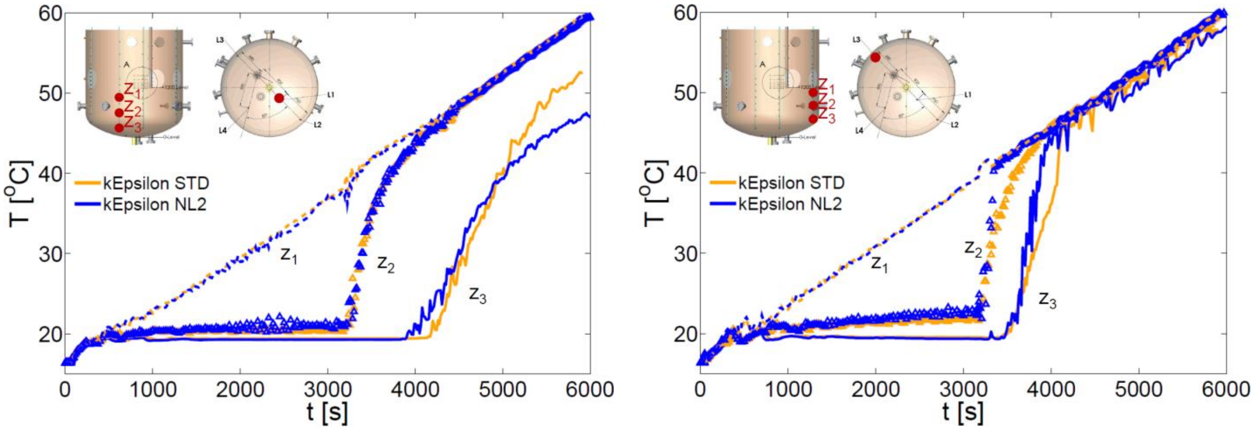
Regarding the pool surface, the pre-test simulations showed that when the liquid level of the pool crossed one cell, unphysical temperature and pressure changes in the whole pool were obtained in GOTHIC. In the pre-test model, this issue was avoided by setting a 500 mm high cell at the pool surface which would contain the rising liquid level during the whole transient. Due to this big cell size, the pool surface temperature was under-estimated by about 8 °C in comparison with the experiment. Thus, in the model used during the validation, the rising liquid level was tracked by setting a finer mesh size of 100 mm, which allowed a proper prediction of the pool surface temperature. The issue of the unphysical temperature and pressure changes when the liquid level crossed a cell was observed to be solved when the surface wave damping factor was reduced from 100 to 10. The surface wave damping factor of 100 used in the pre-test simulations over-restricted the motion of the pool surface. A sensitivity study with factors of 1, 3, 10, 30, and 100 showed that 10 gave the best results in terms of allowing the pool surface to move and dissipate momentum by forming waves while not imposing severe restrictions in the time step by resolving the smaller-scale waves.

5.2.2. Turbulence model

The available turbulence models in GOTHIC are the Mixing-Length algebraic model, and different forms of the k-Epsilon two-equation model such as the standard (STD), Re-Normalized Group (RNG), and Non-Linear Second order (NL2) Reynolds-Stress models. The Mixing-Length model was not considered in the sensitivity study due to its limitations and dependency on the user-defined mixing-length. Thus, only the k-Epsilon models were analyzed. All of the simulations were run with the *xy 75 130* mesh (see section 5.2.1) and a second order spatial discretization scheme.

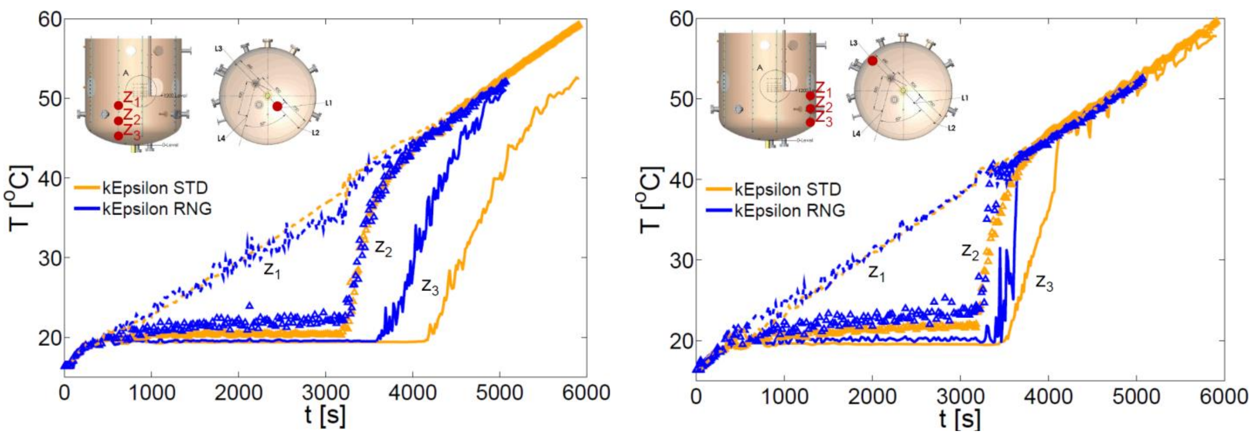
We can see in Figure 10 that during the stratification and mixing phases, the NL2 and STD model gave very similar results. The only difference was observed at the TC located at the bottom of the pool (z_3), where the NL2 model predicted that it would not mix with the rest of the pool. In the T4 experiment, this TC mixed with the rest of the pool (Figure 19). Since the NL2 model is more computationally expensive than the STD and it did not predict mixing of the bottom TC, the latter was preferred for further simulations.

The RNG model showed similar results as the STD model during the stratification phase (Figure 11). On the other hand, the mixing time was much shorter with the RNG model. The main difference between the RNG and STD models is that the RNG includes an extra term in the epsilon equation which reduces the turbulent diffusion in regions of high strain rates [25]. For the cases of jets, this term induces a lower spread; and thus, a higher velocity than the STD. This would explain the faster mixing time. We can also see in Figure 11 that the pool temperatures oscillated more in the RNG than in the STD model. These oscillations are probably due to numerical issues; however, their origin is still not clear. To analyse these oscillations, further simulations with the RNG model using the *xy 75 130* mesh (see section 5.2.1) and different surface wave damping factors were run. In all of the cases, the oscillations were still observed and the mixing times were also faster than predicted with the STD model. Due to these temperature oscillations the STD model was preferred over the RNG for further simulations. However, we will see in section 5.4.2 that the mixing pattern predicted with the STD model did not reproduce well some of the TC measurement from the experiment, suggesting that the RNG model might be more convenient.



(a) (b)

Figure 10: Sensitivity study of the k-Epsilon STD and NL2 turbulence models.
Pool temperatures obtained with GOTHIC in the simulation of the T4 experiment. (a) L1 train, TCs located at z_1 = 672 mm, z_2 = 552 mm, and z_3 = 222 mm, (b) L3 train, TCs located at z_1 = 972 mm, z_2 = 572 mm, and z_3 = 372 mm.



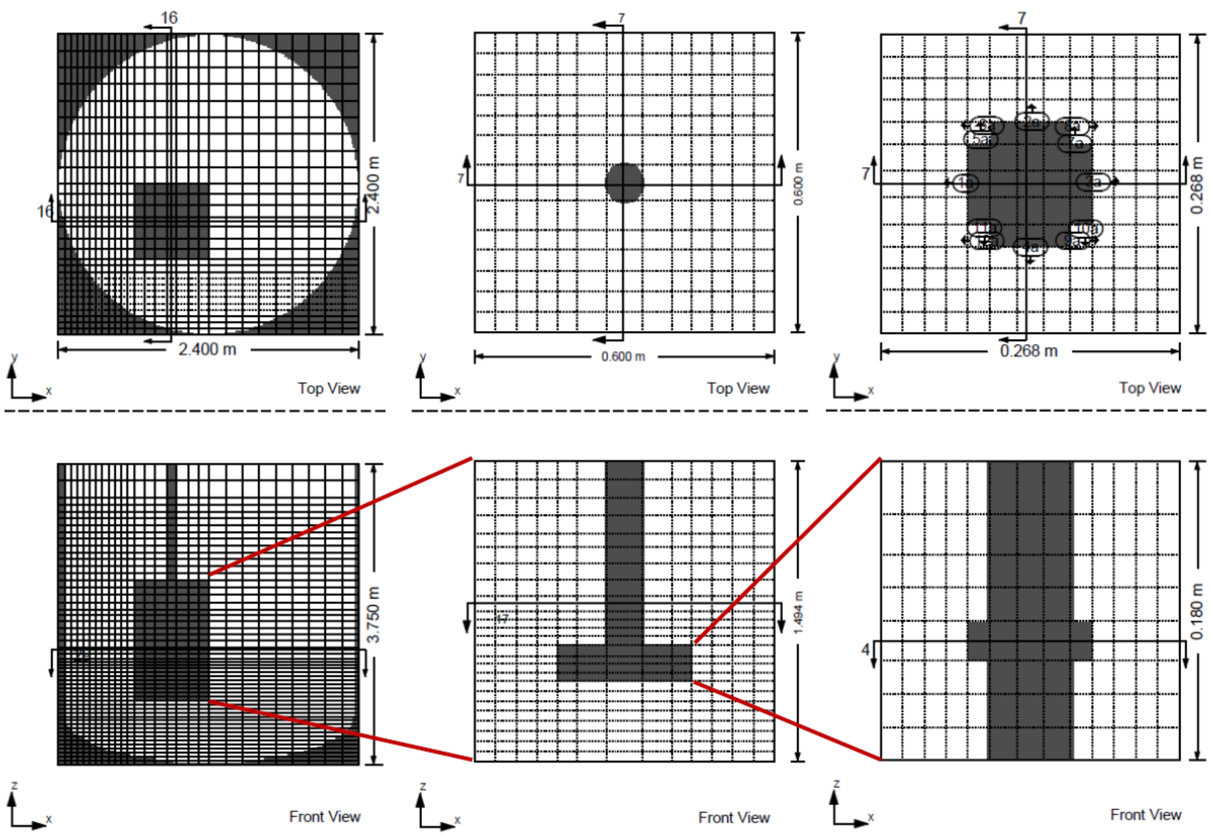
(a) (b)

Figure 11: Sensitivity study of the k-Epsilon STD and RNG turbulence models.
Pool temperatures obtained with GOTHIC in the simulation of the T4 experiment. (a) L1 train, TCs located at z_1 = 672 mm, z_2 = 552 mm, and z_3 = 222 mm, (b) L3 train, TCs located at z_1 = 972 mm, z_2 = 572 mm, and z_3 = 372 mm.

5.3. Implementation of the improved EHS/EMS models in GOTHIC

The implementation in GOTHIC of the improved EHS/EMS models from section 5.1 was similar to the one presented in section 3.2 in terms of number of volumes, arrangement of the flow paths, and boundary conditions providing the single-phase liquid flow. However, after doing the sensitivity studies from section 5.2, some modifications were done in the mesh and control parameters of the simulation. This section gives an over-view of the features of the improved GOTHIC model used in the validation.

The mesh is presented in Figure 12, which corresponds to mesh *xy 50 130* from Table 3. The total number of cells is 47166. Three nested volumes are used in order to increase the mesh resolution in regions where higher velocity and temperature gradients are expected. In Figure 12c we can see the flow paths which inject the condensate liquid at the mass flow, velocity, and temperature computed from equations (8), (9), and (10). The condensate liquid flow was injected homogeneously along the 8 radial directions.



(a) (b) (c)

Figure 12: Mesh used during the validation of the EHS/EMS models for spargers. (a) Wetwell pool and gas space, (b) region near the sparger head, (c) sparger head.

The PPOOLEX vessel was not insulated during the tests. Thus, heat transfer through the vessel walls was taken into account in the simulations. In the side of the vessel walls in contact with the liquid, the built-in Diffusion Layer Model (DLM) was used. On the side in contact with the lab atmosphere, the heat flux was computed using the lab temperatures measured during the experiment and a constant heat transfer coefficient of 3 kW/(m^2s). In the experiments, the drywell was connected to the wetwell gas space through 3 rubber valves to avoid over-pressurization of the vessel. Therefore, the model used for the validation included the drywell and a flow path with a high friction coefficient to simulate the rubber valves.

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.

Since a new GOTHIC version was released within the time that the PPOOLEX tests were performed, the models were upgraded to the GOTHIC version 8.1.

5.4. Validation against PPOOLEX experiments

In the validation, the goal is to verify that the mass, momentum, and energy injected into the pool were able to reproduce the liquid level, pool temperature field, and average pool temperature measured in the experiment respectively. The fit of the pool temperature field (the parameter of safety importance for the plant) to the experimental data, was quantified with the average Root Mean Square Error (RMSE), which is defined by equation (12). The RMSE was computed for each data point and then averaged for the whole transient and for all of the TCs located in the L1, L2, L3, and L4 trains.

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}\left(T_{PPOOLEX,i} - T_{GOTHIC,i}\right)^2}{N}} \tag{12}$$

Table 4 presents the empirical condensation regime term M_{CR} from equation (9) used during the simulations. These values are specific to our sparger, they can vary depending on the number of holes and the injection hole diameter. Therefore, to make the model general to any sparger, we computed the fraction of the momentum which was not transferred to the condensate liquid due to the unstable condensation. Given the momentum equation (9), this fraction is defined with equation (13). Since M_{CR} is expected to be higher than zero for an unstable condensation and zero for stable condensation, the coefficient C will have a value between 0 and 1 for unstable condensation and 1 for stable jets. For a given steam condensation regime, this coefficient C is expected to be the same regardless of the number of holes or diameter of the sparger. The C coefficients are presented in Table 4.

Table 4: Empirical condensation regime closures used in the simulations of the PPOOLEX SPA-T3 and T4 experiments.

Experiment		Steam mass flux [kg/(m^{2}s)]	Condensation regime term M_{CR} [kg·m/s^2]	Condensation regime coefficient C [-]
T3	Clearing	138	55	0.30
	Stratification	74	18	0.16
	Mixing	162	64	0.37
T4	Clearing	146	53	0.31
	Stratification	80	19	0.18
	Mixing	110	39	0.29

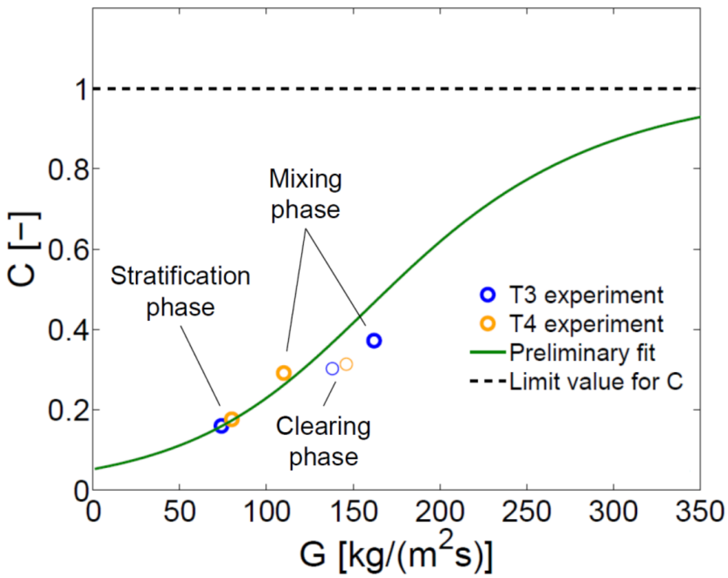


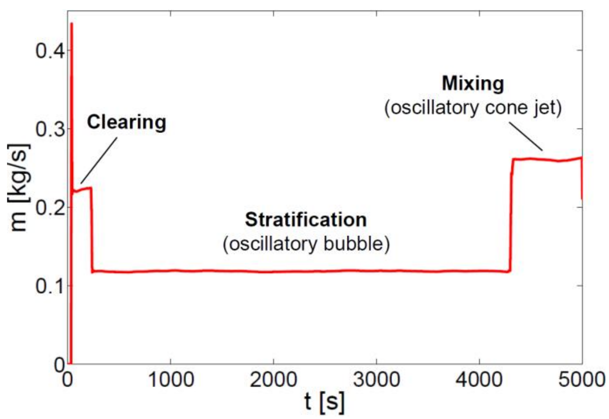
Figure 13: Empirical condensation regime coefficient used in the simulations of the PPOOLEX SPA-T3 and T4 experiments as a function of the steam mass flux through the injection holes.

If we plot them as a function of the steam mass flux, we can see in Figure 13 that there is pattern: At low steam mass fluxes the jet is very unstable and the fraction of momentum transferred to the liquid is very low; as we increase the steam mass flux, the jet becomes more stable and the fraction of momentum transferred to the liquid increases. It is expected that at even higher steam mass fluxes of about 300 kg/(m^{2}s), this coefficient will tend to 1 since the jet is already stable. This is in accordance with the momentum equation used by [7] and [9] for spargers.

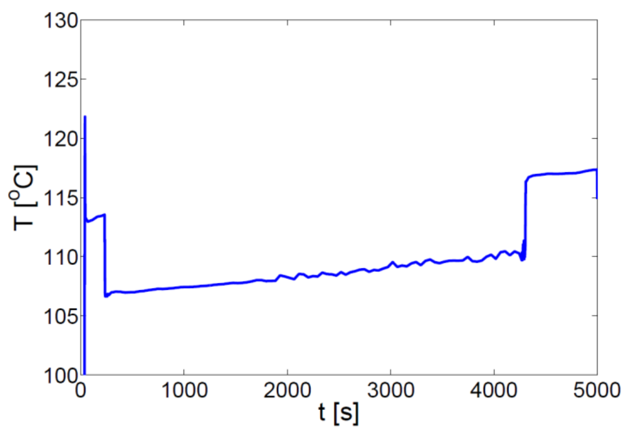
$$C = \frac{m_C u_C}{m_C u_C + M_{CR}} \tag{13}$$

5.4.1. T3 experiment

The mass flow and temperature of the steam injected into the pool during the first stratification and mixing phases of the T3 experiment is presented in Figure 14. The steam condensation regimes covered were the oscillatory bubble and oscillatory cone jet. The main feature of this experiment is the high steam mass flow used during the mixing phase, which leads to a condensation regime which is close to the stable cone jet. Using a desktop computer with i7-4770 processor, 3.4 GHz, and 16 GB RAM, the first 5000 s of the T3 experiment were simulated in about 6 days.



(a)



(b)

Figure 14: PPOOLEX-SPA T3 experiment [11], (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 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 15 that the liquid level and average pool temperature obtained in the simulation gave an excellent fit to the experimental data, meaning that the mass and energy injections obtained with equations (8), (9), and (10) respectively, and the heat transfer through the vessel walls were computed accurately.

Figure 16 presents the pool temperatures obtained in the experiment and in the simulation. The clearing, thermal stratification, and mixing phases were very well predicted by GOTHIC. The average RMS error during the 5000 s transient for all the TCs in the L1, L2, L3, and L4 trains was computed to be 1.2 ^{o}C. The only major deviation with the experimental data was observed in the lowest TC at L3 train (Figure 16b, 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.

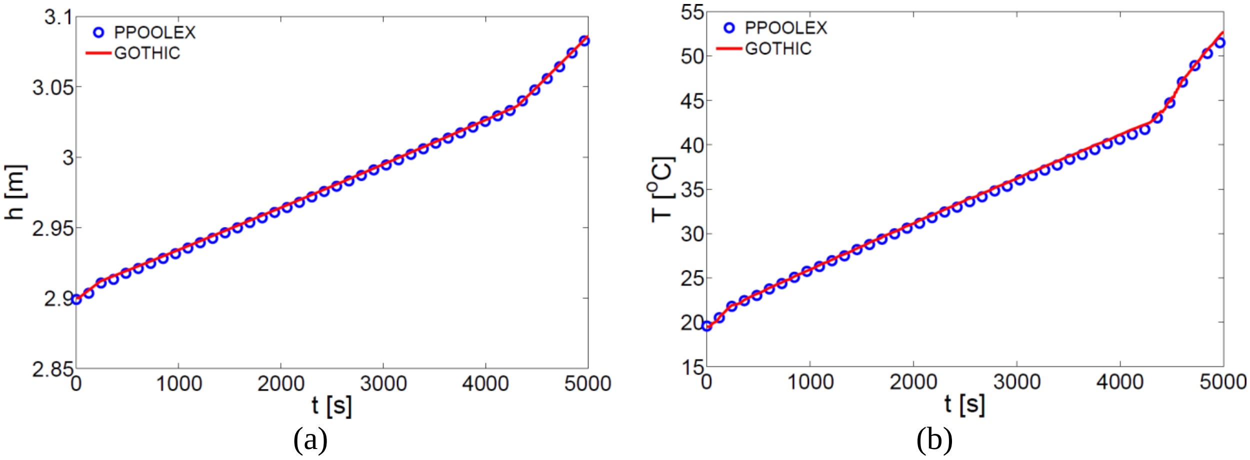


Figure 15: Validation of the EHS/EMS models for spargers against the first 5000 s of the PPOOLEX-SPA T3 experiment. (a) Pool liquid level, (b) pool temperature, obtained as an average of all of the TCs located in the L1, L2, L3, and L4 trains.

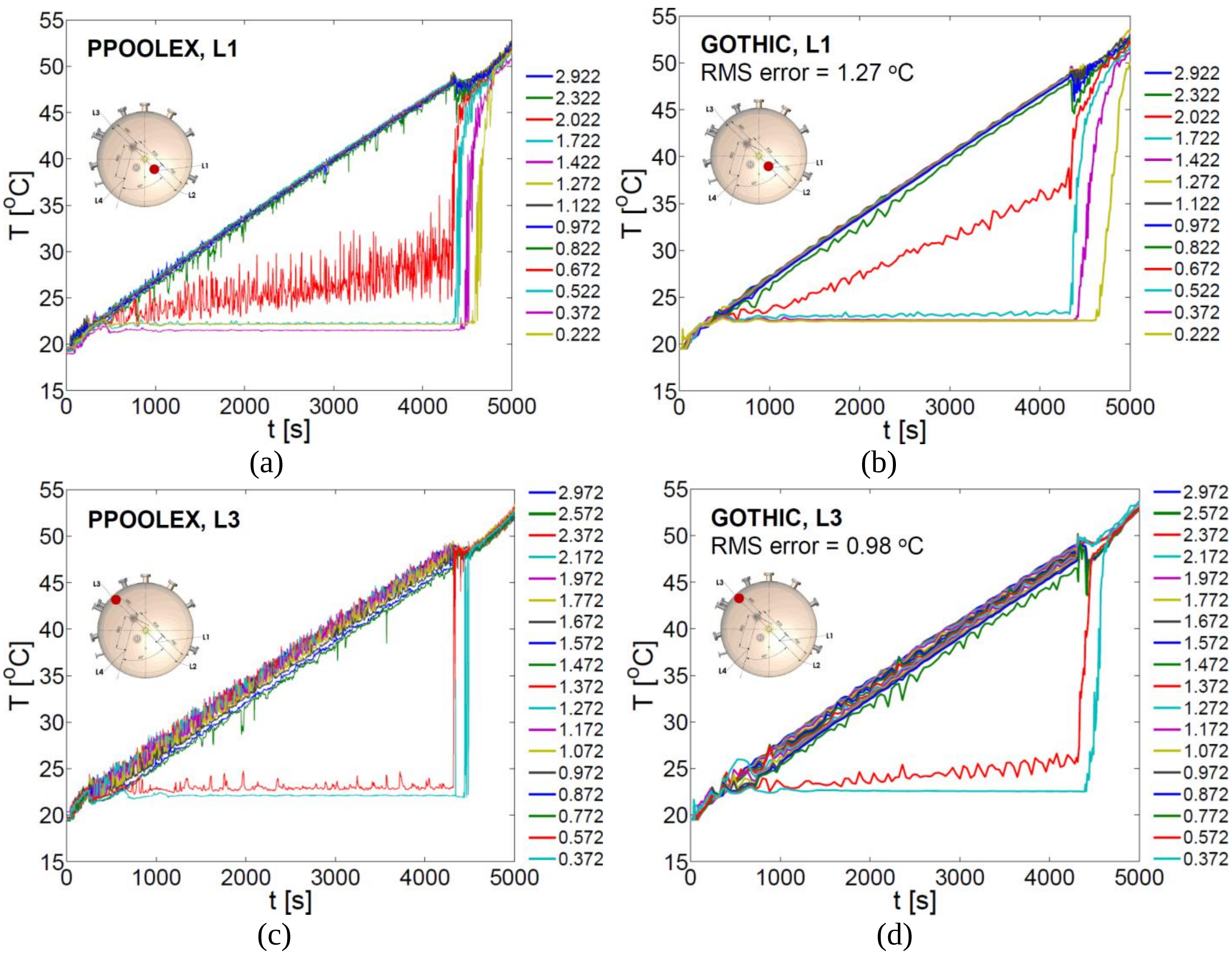
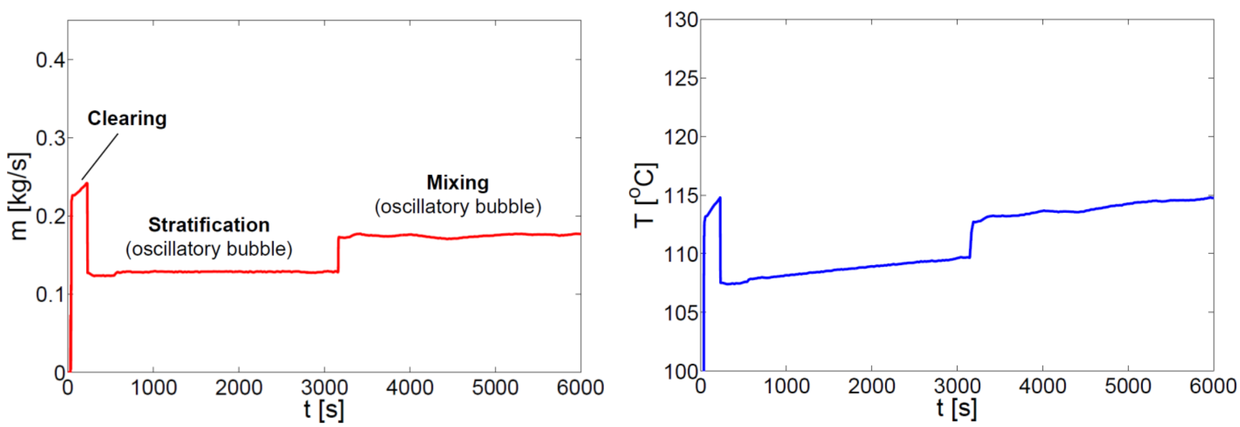


Figure 16: Validation of the EHS/EMS models for spargers against the first 5000 s of the PPOOLEX-SPA T3 experiment. Pool temperature at the TC locations (a) PPOOLEX measurements, L3 train, (b) GOTHIC results, L3 train, (c) PPOOLEX measurements, L1 train, (d) GOTHIC results, L1 train.

5.4.2. T4 experiment

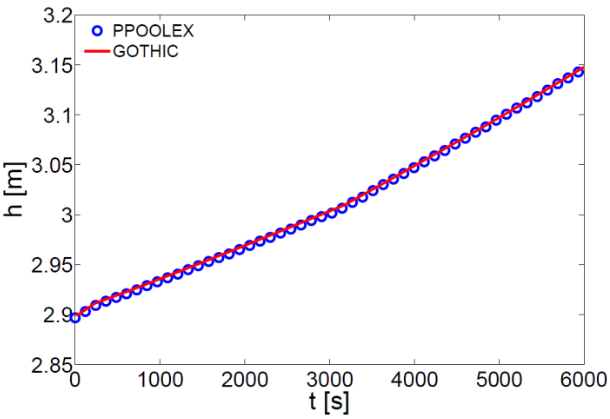
The mass flow and temperature of the steam injected into the pool during the first stratification and mixing phases of the T4 experiment is presented in Figure 17. In both phases, the steam condensation regime was the oscillatory bubble. The main feature of this experiment is the long mixing phase, which lasted about 3000 s. Such long phase will be very useful for the validation since it will highlight the deviations between the code and the experimental results. Using a desktop computer with i7-4770 processor, 3.4 GHz, and 16 GB RAM, the first 6000 s of the T4 experiment were simulated in about 6 days.



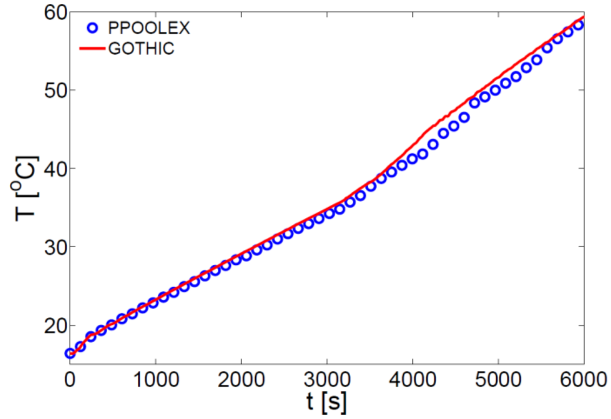
(a) (b)

Figure 17: PPOOLEX-SPA T4 experiment [11], (a) steam mass flow, (b) average temperature of the 3 TCs located inside the sparger pipe at the injection holes level.

We can observe in Figure 18 that the liquid level obtained in the simulation gave an excellent fit to the experimental data. The average pool temperature was also well predicted. However, during the stratification phase, the temperature increase in the simulation was slightly faster than in the experiment, leading to an over-estimation of about 1 °C at the end of the phase. This could be due to an under-estimation of the heat transfer coefficient through the vessel walls. In the mixing phase, the simulation also shows a different trend than the experimental data; however, at the end, both of them converge to the same value. This is probably due to the issue discussed in section 5.4.1 of computing the average pool temperature from the TC measurements located in limited pool locations, which can give different results depending on the flow field.



(a)



(b)

Figure 18: Validation of the EHS/EMS models for spargers against the first 6000 s of the PPOOLEX-SPA T4 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 19 presents the pool temperatures obtained in the experiment and in the simulation. The stratification phase was very well predicted. Only the sharp temperature gradient between the hot upper layer and cold lower layer was slightly under-predicted (Figure 19b, TCs at z = 522 and 822 mm). This deviation could be due to numerical diffusion errors caused by a 50 mm cell size in the vertical direction. However, the mesh sensitivity study from section 5.2.1 showed that cells of 50 and 25 mm gave identical results. In the mixing phase, the experiment shows that the cold stratified layer was eroded at a constant rate (Figure 19a); whereas the simulation predicted an initially faster erosion which then slowed down during the phase. We can observe this in Figure 19b, where the bottom TC located at z = 222 mm began to increase its temperature about 1000 s earlier than in the experiment but then it did not mix with the rest of the pool. This behaviour suggests that the downward recirculation caused by the jets impingement on the vessel walls was not well captured in the simulation. Possible reasons could be the effect of coarse mesh resolution, inadequate turbulence model, etc., further investigation is necessary.

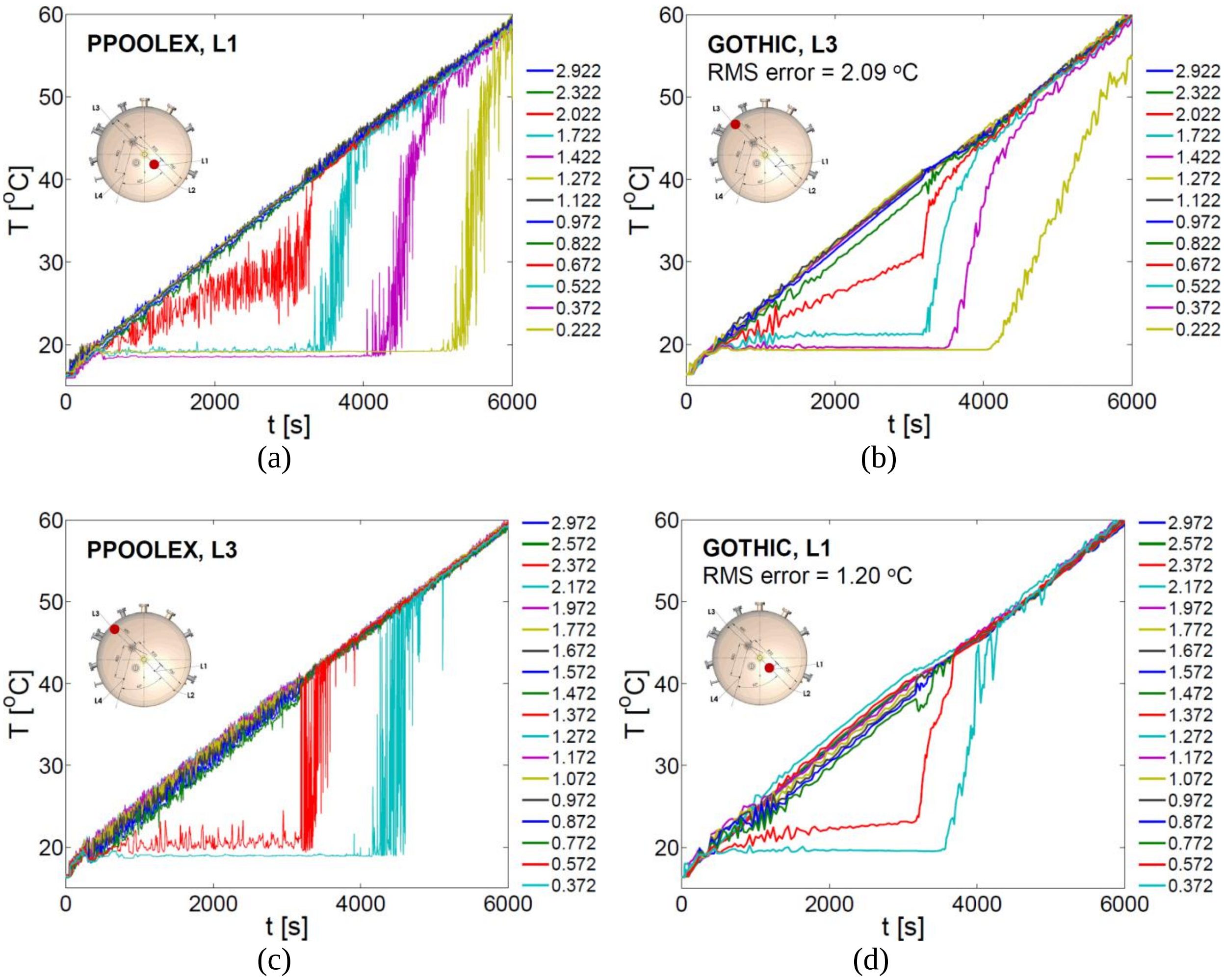


Figure 19: Validation of the EHS/EMS models for spargers against the first 6000 s of the PPOOLEX-SPA T4 experiment. Pool temperature at the TC locations (a) PPOOLEX measurements, L3 train, (b) GOTHIC results, L3 train, (c) PPOOLEX measurements, L1 train, (d) GOTHIC results, L1 train.

6. Conclusions

In a BWR, the development of thermal stratification in the pressure suppression pool during a steam blowdown event accelerates the pressure increase in the containment. This is particularly important for a SBO, where the unavailability of the safety cooling systems using AC power leaves the pool and the sparger injection lines as the main system which can limit the containment pressure by condensing steam. Stratification is likely to develop at the late stages of the SBO, when the decay heat from the core is reduced and the steam flow injected through the spargers is low.

This work has proposed a computationally efficient model which can be used to predict the effective momentum transferred from the sparger condensation regimes appearing at low steam mass fluxes to the pool.

A set of experiments with a reduced scale model of the BWR sparger and pool have been performed to provide data for validation of this model. The design of the experiments was obtained through a scaling methodology which ensured that the ranges of important parameters and pool regimes which would appear in full scale were preserved.

In the validation of the experiments, it has been observed that in the oscillatory bubble regime, the fraction of momentum transferred from the steam to the pool is smaller than in case of stable cone jet. An empirical coefficient has been proposed to model this behavior.

A preliminary validation of the proposed model and its implementation in the thermal-hydraulic code of GOTHIC has shown a very good agreement against the first stratification and mixing phases of the PPOOLEX-SPA T3 and T4 experiments. The average root mean square error of the pool temperature during a 6000 s transient was computed to be lower than 3 ^{o}C. Validation of the model against the rest of the experiments will be presented in further publications to confirm the validity of the assumptions used and to improve the prediction capabilities.

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Disclaimer

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Abstract
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In a Boiling Water Reactor, steam is discharged into the pressure suppression pool through spargers to protect the primary circuit from over-pressurization. If thermal stratification develops, the pressure suppression capability is reduced. Mixing or stratification of the pool is determined by the interplay between heat and momentum sources generated by the steam condensation. Different momentum can be generated in different condensation regimes, depending on steam mass flux, pool temperature and sparger design. Simulation of Direct Contact Condensation (DCC) is a challenge for contemporary modeling tools, especially for prototypic long-term transients.

In previous work, the Effective Heat Source (EHS) and Effective Momentum Source (EMS) models were proposed to simulate thermal stratification and mixing during a steam injection into a large pool of water. These models are (i) computationally efficient, since the small scale phenomena of DCC is not resolved, and (ii) sufficiently accurate, since the integral effects of these phenomena on the large scale pool circulation are taken into account. EHS/EMS models have been developed and validated for blowdown pipes using experimental data from the PPOOLEX facility at LUT.

The goal of this work is to develop and validate EHS/EMS models for spargers. The models are implemented in the containment code GOTHIC. To obtain data for validation, a set of experiments are proposed in the PPOOLEX facility using a scaling methodology to ensure that the ranges of important parameters and regimes from the plant scale are addressed in the experiment. Pre-test analysis was carried out in order to (i) confirm the scaling methodology, (ii) provide suggestions for the instrumentation, (iii) get insights about detailed thermal-hydraulic behavior of the pool, and (iv) provide detailed instructions for the test procedures. A preliminary validation against the experiments shows overall good predictive capabilities of the EHS/EMS models. However, it was observed that accurate prediction of the effective momentum for the unstable steam condensation regimes requires further development of the model closures.

Key words: Thermal Stratification, Mixing, Pressure Suppression Pool, Spargers, Containment, Thermal Hydraulic, GOTHIC, Light Water Reactor

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