PROPOSAL OF A POOL SCRUBBING MODELLING FOR ASTEC: BUBBLE HYDRODYNAMIC AND THERMALHYDRAULIC ASPECTS

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ABSTRACT

After the Fukushima Daiichi accident of March 2011, one of the main concerns of the nuclear industry has been the research works for improving atmospheric radioactive release mitigation systems. Pool scrubbing is one of the technologies used in reactors to mitigate radioactive release during a reactor severe accident. It is based on the injection and transfer of gases containing fission products in aerosol and gaseous forms through a water pool. During the residence of the bubbles through the water pool, fission products may be transferred to the bubble surface thanks to deposition mechanisms for aerosols, mass transfers and chemical reactions for gaseous species. Fission products are then partially retained in the water.

At IRSN, work is in progress in order to improve the pool scrubbing modelling in the ASTEC code. The first step of this work has been dedicated to a literature review on bubble hydrodynamics and on thermalhydraulics in the water pool in order to specify updated models. These models allow to describe the formation of a bubble at the gas sparger outlet in the water pool for different sparger configurations and to describe the bubble plume behavior with the determination of the bubble plume velocity and the void fraction. The bubble temperature evolution in the water pool has also been modelled by taking into account heat transfers and phase change phenomena with the presence or not of non-condensable gases in the bubbles. Main features of these models are presented in this paper.

KEYWORDS
Pool scrubbing, hydrodynamic, thermalhydraulic, bubble, modelling

1 INTRODUCTION

Pool scrubbing refers to a set of physical and chemical processes which lead to the retention of fission products (FP), in the aerosol and gaseous forms, carried by a gas through a pool of water. The injection of the carrier gas through the pool leads to the formation of bubbles and, during their rise along the pool, FP can reach the bubble surface due to different aerosol deposition mechanisms such as Brownian diffusion, inertial impaction and due to mass transfers for gaseous species. For these latter, chemical reactions can then occur at the bubble interface. The net resulting effect of all these phenomena is a partial retention of FP in the water. The retention efficiency of a water pool is generally expressed in terms of decontamination factor (DF) which is the ratio of the FP mass flow rate entering the pool, $\dot{m}_{in}$, and the FP mass flow rate leaving the pool, $\dot{m}_{out}$, as follows:

$$DF=\frac{\dot{m}_{in}}{\dot{m}_{out}} \tag{1}$$

Pool scrubbing is a filtration process which can be used for the mitigation of radioactive release during a severe accident (SA) on nuclear power plant (NPP). Dedicated systems based on pool scrubbing are notably:

- Pressure suppression pool (PSP) of the boiling water reactors (BWR). These pools are designed to mitigate over-pressurization of the drywell space in case of events like a large break in the reactor coolant system. Non-condensable gases and steam, containing FP in a SA, are discharged into PSP by quenchers (multi-hole spargers), downcomers (vertical pipes with large diameter (for example, about 60 cm) and a downward injection) or large horizontal vents [1],
- Filtered containment venting systems (FCVS) which are widely implemented on NPP [2]. These are generally tanks of several meters high, filled with water and the carrier gas containing FP is injected through the water by multi-hole spargers.

After the risk and safety assessments ('stress tests') carried out on all EU NPP which followed the Fukushima Daiichi accident, the interest of improving the NPP filtration efficiency has been renewed. In this context, the PASSAM European project (2013-2016) was focused on mitigation systems in case of SA, and more specifically, on existing source term mitigation devices based on pool scrubbing and solid filters with the goal to reduce potential radioactive atmospheric releases to the environment [3]. This project was mainly based on experimental studies. More recently, the IPRESCA project launched in January 2018 in the NUGENIA frame, aims at integrating international research activities related to pool scrubbing by providing support in:

- Experimental research to improve the current knowledge and database,
- Analytical research to facilitate systematic validation and model enhancement of the existing pool scrubbing models/codes.

The IPRESCA project overall goal is to achieve new/improved models or stand-alone pool scrubbing codes which can be implemented in system codes such as ASTEC [4]. The ongoing work carried out at IRSN on pool scrubbing modelling is completely in accordance with the IPRESCA objectives. More precisely, this work aims at implementing an improved lumped-parameter modelling in the ASTEC code in order to predict the DF needed by ASTEC/SOPHAEROS module for evaluating the transport and the chemistry of FP in SA in light water reactors [5]. Currently, the SPARC code is integrated in ASTEC for determining the DF [6]. SPARC was mostly developed in the early 1990 and was validated and adjusted on several experiments dedicated to pool scrubbing. Nevertheless, the global validation of SPARC by comparing its predictions and the experimental results, for the DF, is judged unsatisfactory [7]. Moreover, the SPARC code structure is not easily upgradable and, due to the complex pool scrubbing phenomenology, it is also necessary to have a more flexible code allowing the implementation of the recent results on the subject. The pool scrubbing modelling under development at IRSN aims at substituting the SPARC code in ASTEC. This work is planned to be performed in several steps:

- **The first step** is devoted to the modelling of bubble hydrodynamics and thermalhydraulics, focusing on the description of relevant phenomena for FCVS and PSP of BWR. A bibliography review has been carried out in order to determine parameters such as the size, the velocity, the temperature of the bubbles and the void fraction of the water pool. This review has considered models already implemented in the pool scrubbing codes such as SPARC and BUSCA [8] and models from the literature elaborated in hydrodynamic field,
- **The second step** is devoted to the identification of the relevant aerosol deposition mechanisms into the bubble and to the implementation of the corresponding modelling. For this latter point, it is planned to extend the models implemented in ASTEC/SOPHAEROS module,

- **The third step** is devoted to the modelling of volatile iodine species retention mechanisms. The modelling will be based on the work which has been recently carried out at IRSN for describing the mass transfers and the chemical reactions at the bubble interface with the water for the species such as I_2, CH_3I, HOI.

In this paper, the modelling work carried out for the first step is reported. Firstly, the expressions of the DF are presented in order to identify the variables linked with the bubble hydrodynamics and the thermalhydraulics. The second part of this paper aims at giving an overview of the proposed bubble hydrodynamic and thermalhydraulic modelling. Main features of the models are then presented in the last part of the paper.

2 DECONTAMINATION FACTOR DETERMINATION

DF is evaluated from the knowledge of FP masses entering and leaving the water pool following equation (1).

If FP are in gaseous form in the bubbles, mass balance equations formulated for each gaseous species (I_2, CH_3I, etc.) give the evolution of the species masses during the residence time of the bubbles along the water pool. In these equations, mass transfers in the gas phase and in the liquid phase can be considered and evaluated from correlations expressed as function of the dimensionless numbers such as the Reynolds Number, the Schmidt Number and the Sherwood Number. Moreover, mass transfer coefficients in both phases are linked with the partition coefficient. At the bubble interface, chemicals reactions such as I_2 and CH_3I hydrolysis, HOI disproportionation can happen.
This representation of the gaseous species behavior in the bubbles, involving mass transfers and chemical reactions, depends on parameters of bubble hydrodynamics and thermalhydraulics. These parameters are notably the size, the velocity and the temperature of the bubbles and the void fraction of the water pool.

If the FP are in the aerosol form in the bubbles, DF can be expressed as function of aerosol deposition velocities. Indeed, it is usual to assume that the aerosol deposition mechanisms do not evolve significantly with the time and can be described each separately by a deposition velocity, the total aerosol deposition velocity being the sum of the deposition velocity for each deposition mechanism [9]. On the basis of these assumptions, the evolution of the aerosol mass in the gas phase, m, is given by:

$$\frac{dm}{dt}=-m(t)\sum_{j=1}^{n}\beta_j \qquad (2)$$

with β_j, the mass depletion rate due to the j-th deposition mechanism, n, the number of deposition mechanism. By integrating over the residence time, Δt, it follows:

$$m(t+\Delta t)=m(t)\cdot \exp(-\sum_{j=1}^{n}\beta_j\Delta t) \qquad (3)$$

By replacing equation (3) in equation (1), DF is then expressed by:

$$DF=\exp(\sum_{j=1}^{n}\beta_j\Delta t) \qquad (4)$$

β_j is defined by the following ratio:

$$\beta_j=\frac{v_j S_{gas}}{V_{gas}} \qquad (5)$$

v_j is the aerosol deposition velocity at the bubble surface for the j-th deposition mechanism considered. Different deposition mechanisms are involved in the trapping of aerosols at the bubble interface with the water. It can be mentioned, for example, the mechanism of aerosol sedimentation, Brownian diffusion, inertial impaction. When a thermal imbalance exists between the mixture of steam and non-condensable gases in the bubbles and the water pool, mechanisms such as thermophoresis and diffusiophoresis take place. The expression of v_j depends thus on the mechanism considered. It has to be noted that the contribution of a mechanism to the aerosol deposition at the bubble surface depends on the part of the water pool considered, entrance zone, bulk of the pool, etc. For example, inertial impaction is predominant for a jet of gas at the entrance of the water pool. S_{gas} and V_{gas} are the surface and the volume of the bubbles.
v_j, S_{gas}, V_{gas} and Δt, involved in the DF determination with equation (4), depend on the bubble hydrodynamics and thermalhydraulics. They are linked with the size, the velocity and the temperature of the bubbles and the void fraction of the water pool.

The bubble hydrodynamic behavior in a water pool, resulting of a gas injection, has been characterized as decomposing mainly into three zones [7]:

- **The injection zone** where the carrier gas is injected through the pool by a sparger. Depending on different parameters, notably the injected gas velocity, two types of regime can take place; the bubbly regime with the formation of a big bubble or the jet regime,
- **The transition zone**, just above the injection zone, takes place when the bubbly regime prevails in the injection zone. It is a zone for which the bubble is detached from the sparger orifice and it begins to rise in the pool. Due to the instabilities at the bubble surface, it distorts, breaks up and splits to form a swarm of smaller bubbles. This is the beginning of the bubble rise zone,
- **The bubble rise zone** is the part of the pool where a bubble swarm is formed. Different flow regimes can take place, notably the bubbly regime and the churn-turbulent regime. The bubbly regime is characterized mainly by discrete small bubbles in an almost continuous liquid. They can be spherical, ellipsoidal or cap-shaped. The churn-turbulent regime is more agitated and unsteady leading to bubble coalescence and break-up. The bubble shape is also irregular and distorted. At the water pool surface, the bubble rupture takes place causing production of many micro-droplets. Some of them are entrained by the gas flow transporting aerosol and gaseous FP and the others fall back in the water pool due to their size by gravity.

The size, the velocity, the temperature of the bubbles and the void fraction of the water pool have to be expressed in each previous zone as function of the flow topology. DF are evaluated accordingly in each zone; the global DF of the water pool being the product of DF in each zone.

In the section below, an overview of the chosen modelling for expressing in each zone the size, the velocity, the temperature of the bubbles and the void fraction of the water pool is presented.

3 OVERVIEW OF THE MODELLING AND ASSUMPTIONS

3.1 Water Pool Representation

Based on the description of the bubble hydrodynamic behavior made in the section 2, the water pool has been splitted in three zones (Figure 1).

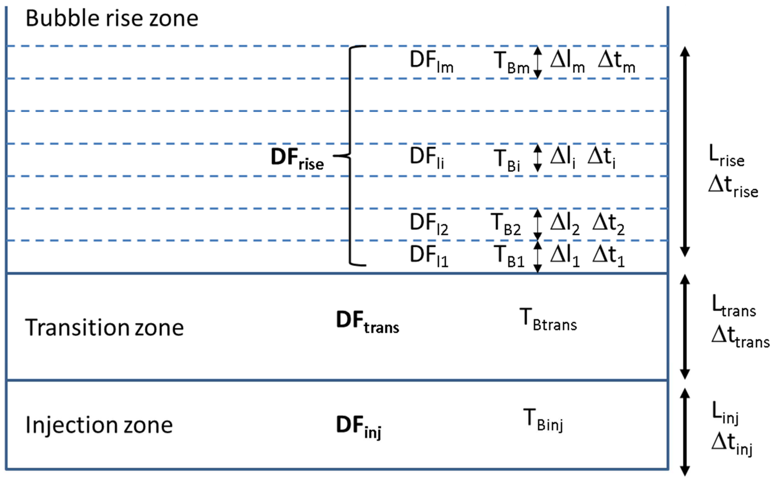

Figure 1 Zones and meshes of the water pool considered for DF evaluation

Concerning the bubble rise zone, it has been observed in several experiments ([3], [10]) that the size, the velocity of the bubbles and the water pool void fraction evolve with the pool height. In order to be consistent with these observations, it has been chosen to mesh the bubble rise zone in the axial direction. Figure 1 depicts the bubble rise zone meshing. DF_{li}, Δl_i and Δt_i are the DF, the length and the residence time for the i-th mesh; the overall DF_{rise} being the product of DF_{li}.

In the pool scrubbing applications, the injected gas temperature is typically between 373 °K-573 °K [7] and is different from the water pool temperature (which can evolve from ambient temperature until the boiling temperature). The injected gas composition is generally a mixture of steam and non-condensable gases (often air). Since steam is almost always present in the injected gas composition, phenomena such as condensation/evaporation take place at the bubble interface with the water. The temperature of the bubbles and the steam mass in the bubbles evolve during the bubble residence time along the water pool. Steam mass balance equation and enthalpy equation are then considered for evaluating the steam mass and the temperature evolution. The size, the velocity of the bubbles and the water pool void fraction are a part of the terms of these conservation equations. Consequently, the steam mass balance equation and the enthalpy equation are formulated in each zone of the water pool and, for the bubble rise zone, in each mesh.

3.2 Assumptions In Each Water Pool Zones

3.2.1 Injection Zone

In this zone, the residence time, Δt_{inj}, the final size of the bubble (diameter, surface and volume) formed at the sparger orifices, the steam mass and the temperature of the bubble have to be evaluated.

As it has been explained in the section 2, two types of regime can take place in the injection zone: the bubbly regime and the jet regime. For the first version of the pool scrubbing modelling in ASTEC, only the bubbly regime is modelled with appropriated models determining the final size of the bubble formed at the sparger orifices (see Section 4). For the jet regime, instead of that, values for DF in such conditions will be considered in ASTEC. Notably, experimental works performed in the PASSAM project allowed to obtain DF values for a jet configuration in the injection zone [3]. Improvement of the jet regime representation will be made in a future version of the modelling, notably depending on the IPRESCA outcomes.

Concerning the residence time, it is formulated as follows:

$$\Delta t_{inj} = \frac{L_{inj} S_{gas}}{\dot{V}_{inj}} \qquad (6)$$

$\dot{V}_{inj}$ is the injected gas volume flow rate and L_{inj} is the injection zone length. This latter parameter is evaluated by adding the bubble final size and the neck which links the bubble base to the orifice until its detachment. These two parameters are determined by dedicated models presented in Section 4.
It has to be noted that, for the jet regime, L_{inj} has to be evaluated too. It is not needed for evaluating the residence time, because the DF is not calculated and is imposed by an experimental value, but it is needed for deducing the axial coordinate corresponding to the beginning of the bubble rise zone.
In [11], a model is proposed for the jet penetration length corresponding to L_{inj}.

3.2.2 Transition Zone

In this zone, the residence time, Δt_{trans}, the size (diameter, surface and volume) and the velocity of the bubble, the steam mass and the temperature of the bubble have to be evaluated. A semi-empirical description is used for this zone.

Concerning the residence time, it is formulated as follows:

$$\Delta t_{trans} = \frac{L_{trans}}{v_T} \qquad (7)$$

v_T is the bubble velocity called also bubble terminal velocity and L_{trans} is the transition zone length. This latter parameter is evaluated from available experimental observations made in the experiments dedicated to the study of bubble hydrodynamics or from correlations used in the SPARC or/and the BUSCA codes.
This length with the bubble terminal velocity determine the residence time in this zone (equation (7)). The model for the bubble terminal velocity is presented in Section 4. Concerning the diameter of the bubble needed for the evaluation of the bubble terminal velocity, it is planned to establish a relation between the bubble diameter in the injection zone and the size of the bubble at the beginning of the swarm in the bubble rise zone in order to obtain an estimation of this diameter. Concerning the thermal aspects, the same equations and models as considered in the bubble rise zone are used in the transition zone for evaluating the bubble steam mass and temperature (see Section 4).

3.2.3 Bubble Rise Zone

For each mesh of this zone, the residence time, Δt_i, the bubble terminal velocity, the bubble swarm velocity, the void fraction, the bubble surface and volume, the bubble steam mass and temperature have to be evaluated.

The size of the bubbles in each mesh of this zone is imposed and is represented by a log-normal distribution with a geometrical standard deviation and a geometrical bubble diameter. This representation has been chosen on the basis of experimental observations made in experiments dedicated to the pool scrubbing [3][10].

Concerning the residence time in each mesh, it is evaluated as follows:

$$\Delta t_i = \frac{\Delta l_i}{v_{gas,i}} \quad (8)$$

$v_{gas,i}$ is the bubble swarm velocity in the i-th mesh evaluated with the models presented in Section 4 whereas Δl_i is calculated for each mesh of the bubble rise zone from the first axial one until the last one corresponding to the pool surface by considering the ratio of the mesh volume and the mesh surface. The mesh surface is evaluated from the pool geometry. The mesh volume is equal to the sum of the bubble volume ($V_{gas,i}$) and the water volume ($V_{liq,i}$) in the mesh. The following expression links the mesh void fraction (α_i), $V_{gas,i}$ and $V_{liq,i}$ as follows:

$$V_{gas,i} = \frac{\alpha_i}{1-\alpha_i} V_{liq,i} \quad (9)$$

$V_{liq,i}$ is obtained by dividing the water volume of the bubble rise zone by the number of mesh in this zone. It has to be pointed out that the water pool volume is evaluated by the ASTEC/SOPHAEROS module (for a stand-alone calculation) or by the ASTEC/CPA module (for a coupled calculation). α_i is determined by the bubble plume models presented in Section 4.

Concerning the situations for which the heat transfers and phase change phenomena take place at the bubble interface with the water, it has to be pointed out that the temperature of the bubbles is evaluated in each mesh of the zone only if the bubbly regime prevails in the injection zone. As previously explained, for the jet regime, the temperature in the injection zone is not evaluated since no model for the jet hydrodynamics has been specified. Since the bubble temperature in the injection zone is needed for the initial boundary condition of the first mesh of the bubble rise zone, it is not possible to evaluate correctly the bubble temperature in the bubble rise zone. In this case, DF is not calculated by the models, instead available experimental values for the DF are considered for the entire water pool.

4 MAIN FEATURES OF THE MODELS

4.1 Bubble Hydrodynamics In The Injection Zone

4.1.1 Criteria For Determining The Regime Type

Three criteria have been selected in the literature for evaluating the transition point between the bubbly regime and the jet regime; **Gaddis** [12], **Zhao** [13], **Sundar** [14]. They have all been established from physical considerations involving a sparger with a single orifice. They are expressed with dimensionless numbers such as the gas Weber number and the Kutateladze number.

For example, the criteria of **Zhao** described the formation of an instability at the bubble surface. The author considers that if the bubble surface is smooth; a bubble forms and if the bubble surface becomes unstable with the appearance of ripples; a jet forms. For modelling this instability, two characteristic times are evaluated; the instability propagation time and the instability growth time by using the Rayleigh-Taylor and the Kelvin-Helmholtz instability. The transition is given by the equality of these characteristic times as follows:

$$We_{gas\ trans} = 10.5 \left(\frac{\rho_{liq}}{\rho_{gas}} \right)^{0.5} \quad (10)$$

$We_{gas\ trans}$ is the gas Weber dimensionless number at the transition between the two regimes. If the gas Weber dimensionless number is greater than $We_{gas\ trans}$, it indicates that the jet regime prevails.

4.1.2 Bubble Final Size Evaluation For The Bubbly Regime

For evaluating the final size of the bubble formed when the bubbly regime prevails, two situations have been distinguished; spargers with one-single orifice and multi-orifice. The former one is encountered in the experiments dedicated to the pool scrubbing and in the PSP of BWR with the downcomers and the large horizontal vents, the latter one being encountered in FCVS and in the PSP with the quenchers. Four models have been found in the literature for modelling these two situations.

- The model of **Kumar** [15] for evaluating the final volume and diameter of a bubble formed at one-single inclined orifice with an angle ϕ between the horizontal and the inclined orifice,
- The model of **Tsuge** [16] for evaluating the bubble final size formed at one-single downward orifice,
- The model of **Gaddis** [12] for evaluating the final volume and diameter of a bubble formed at one-single vertically-oriented orifice,
- The model of **Loimer** [17] for evaluating the bubble size at a multi-orifice sparger. It has been established from experimental and theoretical considerations obtained with sieve plates and inviscid liquids.

The first three models chosen for one-single orifice sparger are based on a two-step description for the bubble formation and used the basic force balance approach for evaluating its final size [18]. The two-step models describe the bubble formation as a sequential process with an expansion step, firstly, and a detachment step, secondly. During the expansion step, the bubble expands while its base remains attached to the tip of the orifice. When the lifting forces just exceed the restraining forces, the bubble base moves away from the tip of the orifice. In the same time, the bubble continues to grow and stays in contact with the orifice through a neck of negligible volume compared to the bubble volume. This is the detachment step which ends when the neck breaks.

For example, in the **Gaddis** model, the author expresses the force balance applied to the bubble considered as being spherical at the end of the detachment step. The restraining forces considered are the buoyancy force and the force due to the injected gas momentum and the lifting forces are the surface tension force, the drag force and the inertia force. The expression of these forces lead to the following equation for the bubble final diameter, d_B:

$$d_B^3 = \frac{6D_{inj}\sigma}{\left(\rho_{liq}-\rho_{gas}\right)g}\left(1-\frac{We_{gas}}{4}\right)+\frac{1}{d_B}\frac{81\mu_{liq}\dot{V}_{inj}}{\pi\left(\rho_{liq}-\rho_{gas}\right)g}+\frac{1}{d_B^2}\frac{\rho_{liq}\dot{V}_{inj}^2}{\left(\rho_{liq}-\rho_{gas}\right)g}\left(\frac{135}{4\pi^2}+\frac{27\rho_{gas}}{\pi^2\rho_{liq}}\right) \tag{11}$$

We_{gas} is the gas Weber dimensionless number, σ is the surface tension and μ_{liq} is the liquid dynamic viscosity.

4.2 Bubble Hydrodynamics In The Bubble Rise Zone

4.2.1 Bubble Plume Velocity And Void Fraction

In the bubble rise zone, to evaluate the bubble plume velocity and the void fraction at each mesh of the zone, two situations have been distinguished depending on the confinement as follows.

In the first situation, the bubble flow takes place in confined space. It can be the case for a bubble plume in FCVS. FCVS are generally tanks in which the carrier gas is injected by several injectors with multi-orifice [19][20]. For this type of configuration, it can be considered that the orifices of each injector create a bubble plume and these bubble plumes will overlay each other in the bubble rise zone. The resulting bubble plume is expected to develop over the entire cross-section of the tank. The bubble flow characteristics and the void fraction are then determined from the drift-flux models established for large diameter pipes.

This model allows to derive the one-dimensional drift-flux equation as follows:

$$\left\langle\left\langle v_g \right\rangle\right\rangle = \frac{\left\langle J_{gas} \right\rangle}{\left\langle \alpha \right\rangle} = C_o \left\langle J \right\rangle + V_{gj} \tag{12}$$

where $\langle \ \rangle$ represents area-averaged quantities defined by $\langle F \rangle = \frac{1}{A}\int_A F dA$, $\left\langle\left\langle v_g \right\rangle\right\rangle$ represents the void-fraction-weighted mean value of the gas velocity and is also equal to the bubble plume velocity over the pool cross-section, v_{gas}. J_{gas} is the superficial gas velocity, J is the total volumetric flux given by $J = J_{gas} + J_{liq}$, J_{liq} is the liquid superficial velocity which is zero for a stagnant water pool, C_o is the distribution parameter and V_{gj} is equal to the following ratio $\left\langle \alpha v_{gj} \right\rangle / \left\langle \alpha \right\rangle$ and is the void-fraction-weighted mean drift-flux. In order to evaluate $\left\langle\left\langle v_g \right\rangle\right\rangle$ and α from equation (12), correlations are needed for determining C_o and V_{gj}. In [21], **Schlegel** has proposed a comprehensive set of correlations, established for large diameter pipes, as function of the regime type in the bubble swarm for evaluating C_o and V_{gj}. For distinguishing the type of the regime in the bubble swarm and, thus, for applying the appropriated correlations, criteria specified in [21] and [22] are used.

In the second situation, the bubble flows take place in non-confined or weakly confined space which is generally the case for a bubble plume in the PSP of the BWR [20]. The size of the bubble plume formed by each quencher, downcomer or horizontal vent is considered to be relatively small compared to the size of the PSP so that the plume remains weakly confined. An integral approach is then used to determine the horizontal expansion of the plume, the bubble flow characteristics and the void fraction [10].

This model describes the gross behavior of a bubble plume generated by the release of air in a stagnant water pool of uniform density. The bubble plume consists of a bubble core and a surrounding entrained water flow with upward movement. Due to the entrainment from the bulk, the bubble plume expands while it is rising [23][24].
The modelling is based on the assumption of the flow self-similarity for which radial velocity profiles have similar forms at different pool heights and it is based on the entrainment hypothesis for which the volume of surrounding liquid that is entrained into the plume is proportional to both the local centerline velocity and the plume circumference. The void fraction, the gas and the water velocities are commonly described by Gaussian or top-hat profiles. These functions are specified to satisfy appropriated boundary conditions and the conservation equations of mass and momentum in integral form. The equation resolution gives the plume width, the gas and the water velocities and the void fraction as a function of the elevation above the gas injection. Moreover, the integral model involved empirical parameters in the conservation equations and, consequently, closures have to be formulated in order to resolve the equation system. **Kubasch** has applied the integral model for describing the bubble plumes studied in the framework of experiments performed in a water pool of 1m in diameter and 3 m for the height, with an injected air flow rate by a single orifice at the bottom of the pool [10]. Measurements were performed for obtaining data on void fraction, gas and water velocities radial profiles. From the application of the integral model to each experiment, **Kubasch** derived values for the empirical parameters of the models.

4.2.2 Bubble Geometrical Aspects

In the bubble rise zone, the size of the bubbles is given by a log-normal distribution with the following probability density function in each mesh of this zone:

$$f\left(d_B\right)=\frac{1}{d_B\sqrt{2\pi}\ln\left(\sigma_g\right)}\exp\left(-\frac{\ln^2\left(\frac{d_B}{d_{gm}}\right)}{2\ln^2\left(\sigma_g\right)}\right) \tag{13}$$

d_B can refer to the bubble equivalent diameter or to the bubble major axis depending on the type of measurements carried out in the experiments.
σ_g and d_{gm} are the parameters of the log-normal probability density function, respectively the geometrical standard deviation and the geometrical bubble diameter. In general, experimental data that characterize the distribution are expressed in terms of mean diameter and standard deviation. The following expression links the mean diameter, d_m, to the geometrical bubble diameter:

$$d_{gm}=d_m\exp\left(-\frac{\ln^2\left(\sigma_g\right)}{2}\right) \tag{14}$$

A log-normal probability density function can be defined in each horizontal mesh of the bubble rise zone (see paragraph 3.1) with specific mean diameter and standard deviation. These both latter parameters can be derived from bubble size measurements in the context of experimental works.

In order to evaluate the surface of the bubbles, their shape has to be known. The work carried out by **Besagni** [25][26] aimed at, notably, estimating the aspect ratio and the shape of a bubble rising in a bubble swarm, on the basis of his experimental results obtained in a large air/water bubble column by using image analysis. This work is used for determining the shape of the bubbles in the bubble rise zone. The bubble surface, S_{gas}, is then deduced from geometrical considerations.

4.2.3 Bubble Terminal Velocity

The chosen correlation is the one of **Rodrigue** established by using dimensional analysis [27][28]. This correlation is a single equation based on a velocity and a flow number, valid for uncontamined Newtonian viscous fluid which is quiescent and unbounded. Due to the large range of fluid physical properties considered for the validation of the correlation, this latter is defined whatever the bubble regime (laminar, turbulent) and whatever the bubble shape (spherical, distorted, spherical cap). The following expressions were derived for expressing v_T:

$$F=g\left(\frac{\rho_{liq}^5 d_B^8}{\sigma\mu_{liq}^4}\right)^{1/3} \qquad V=\frac{F}{12}\left[\frac{\left(1+1.31\,10^{-5}\ Mo^{11/20}F^{73/33}\right)^{21/176}}{\left(1+0.02\,F^{10/11}\right)^{10/11}}\right] \qquad v_T=V\left(\frac{\rho_{liq}^2 d_B^2}{\sigma\mu_{liq}}\right)^{-1/3} \tag{15}$$

F and V are the velocity and the flow numbers.

4.3 Thermohydraulics

In the three zones (injection, transition, bubble rise) of the water pool, steam mass balance equation and bubble enthalpy equation are considered and solved for getting the steam mass evolution in the bubbles and the temperature evolution of the bubble along the water pool. These equations are formulated depending on the bubble gas composition that is to say if only steam is present or if a mixture of steam and non-condensable gases such as air is present. For example, for this latter situation, the following system of equation is considered:

$$\frac{dm_{steam}}{dt} = S_{gas}\, h_m\, M_{steam} C_{gas} Ln\left(\frac{1\text{-}X_B}{1\text{-}X_{B,i}}\right)$$
$$\frac{dH_{gas}}{dt} = S_{gas}\, h_{conv}\left(T_{pool}\text{-}T_B\right) + h_{steam}\frac{dm_{steam}}{dt} \tag{16}$$

m_{steam} is the steam mass in the bubbles. The model of convection/diffusion (also called the Stefan flow) is used for determining the steam mass evolution, dm_{steam}/dt [29] [30]. The ratio $\frac{1\text{-}X_B}{1\text{-}X_{B,i}}$ is the Spalding Number which characterizes the extent of the mass transfer; X_B is the steam molar fraction in the bubble and $X_{B,I}$ is the steam molar fraction at the bubble interface with the water. S_{gas} is the bubble surface in the zone considered. h_m is the mass transfer coefficient due to the Stefan flow, linked with the Sherwood dimensionless number. The correlation of Ranz and Marshall is used for expressing this last parameter [31].

H_{gas} is the bubble enthalpy. This evolution is due to two contributions; the convective heat transfer in the bubble toward the bubble interface with the water (first term of the equation) and the evaporation/condensation processes at the bubble interface with the water (second term of the equation). h_{conv} is the convective heat transfer coefficient due to the stefan flow, linked with the Nusselt dimensionless number. The correlation of Ranz and Marshall is also used for expressing this last parameter [31]. T_{pool} is the water pool temperature and T_B is the bubble temperature.

It has to be noted that the bubble hydrodynamic parameters which are involved in the determination of parameters of equations (13) such as the mass transfer coefficient, the convective heat transfer coefficient are those evaluated in the considered zone.

5 CONCLUSION

The work on-going at IRSN in the pool scrubbing field aims at implementing an improved pool scrubbing modelling in the integral ASTEC code. The first step of this work, presented in this paper, has been devoted to the bubble hydrodynamic and thermalhydraulic modelling. Models for describing the bubble characteristics such as the size, the velocity, the temperature and the void fraction in the different parts of the water pool have been selected. It is the result of a bibliography review including works performed in the hydrodynamic field and models used in the current pool scrubbing codes. For the first version of this pool scrubbing modelling, work has been focused on the description of the phenomena in PSP of BWR and in FCVS. In the injection zone of the water pool, the bubbly regime has been modelled and different models have been chosen in order to evaluate the bubble final size formed at sparger orifices depending on the sparger configuration (upward and downward injectors, inclined or not, one-single orifice and multi-orifice).

In order to complete this first step, work is now on-going for the implementation in ASTEC of the specified models and their subsequent validation. In this objective, experiments in the literature dedicated to the bubble hydrodynamic and thermalhydraulic studies for pool scrubbing have been identified with notably the work carried out in the Lace-Espana program [32] and more recently with the PASSAM project [3] and the THAI program [33][34]. The comparison between the experimental data and the outputs of the models such as the bubble final size in the injection zone, the bubble size and velocity in the transition zone, the bubble velocity in the swarm and the void fraction for the bubble rise zone, the lengths of the injection zone and the bubble rise zone will allow to assess the capability of the chosen models for evaluating these variables.

In the future, improvements for the modelling of bubble hydrodynamics and thermalhydraulics are expected. These improvements can notably result from the validation work mentioned in the previous paragraph. Moreover, a model for the jet regime instead of DF experimental values would allow getting a more predictive description of the injection zone in such situation. The representation of the transition zone has also to be improved since it is mainly based on empirical considerations. In the context of IPRESCA project, a work package is dedicated to the modelling of bubble hydrodynamics and thermalhydraulics and it is expected to consider and to improve some weaknesses identified in the models of the pool scrubbing codes. Outcomes of this project should be used to enhance the pool scrubbing modelling in ASTEC.

NOMENCLATURE

S_{gas}: bubble surface (m^2)
V_{gas}: bubble volume (m^3)
Δt: residence time (s)
$\dot{V}_{inj}$: injected gas volume flow rate (m^3/s)
v_T: bubble terminal velocity (m/s)
v_{gas}: bubble plume velocity (m/s)
H_{gas}: bubble enthalpy (J)
r_B, d_B : bubble radius and diameter (m)
m_{steam} : steam mass (kg)
h_{steam}: steam specific enthalpy (J/kg)
M_{steam}: steam molar mass (kg/mol)
X_B: steam molar fraction in the bubble (-)
$X_{B,I}$: steam molar fraction at the bubble interface of the bubble and the water (-)
D_{iff}: steam/non-condensable gas mixture diffusion coefficient (m^2/s)
h_{conv}: convective heat transfer coefficient in the bubble ($W/m^2/K$)
T_B: bubble temperature (°K)
T_{pool}: water pool temperature (°K)
h_m: mass transfer coefficient in the bubble (m/s)
C_{gas}: molar concentration of the steam/air mixture in the bubble (mol/m^3)
U_B: bubble velocity (m/s)
D_{inj}: diameter of the sparger orifice (m)
α: void fraction (-)
ρ_{liq}: liquid density (kg/m^3)
ρ_{gas}: gas density (kg/m^3)
σ: surface tension (N/m)
μ_{liq}: liquid dynamic viscosity (Pa.s)
μ_{gas}: gas dynamic viscosity (Pa.s)
λ_{gas}: gas heat conductivity (w/m.K)
We_{gas} : gas Weber dimensionless number ($\rho_{gas} V_{inj}^2 D_{inj} / \sigma$) (-)
Nu_{gas} : Nusselt dimensionless number $\left(h_{conv} d_B / \lambda_{gas} \right)$ (-)
Sc_{gas}: Schmidt dimensionless number $\left(\mu_{gas} / \rho_{gas} D_{iff} \right)$ (-)
Sh_{gas} : Sherwood dimensionless number $\left(h_m d_B / D_{iff} \right)$ (-)

Mo: Morton dimensionless number $\left(g\mu_{liq}/\rho_{liq}\sigma^3\right)$ (-)

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