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Improvement of Interfacial Area Prediction on Condensing Steam-water Flow Using Bubble Collapse Model

HERRY Tanguy[1], RAVERDY Bruno[1], MIMOUNI Stéphane[2], VINCENT Stéphane[3]

[1] Université Paris-Saclay, CEA, Service de Thermo-hydraulique et de Mécanique des Fluides
91191 Gif sur Yvette, France
tanguy.herry@cea.fr; bruno.raverdy@cea.fr

[2] Electricité de France (EDF)
stephane.mimouni@edf.fr

[3] Université Gustave Eiffel
stephane.vincent@univ-eiffel.fr

Abstract - Computational Fluid Dynamics (CFD) simulations are performed in this work on an experiment where polydisperse steam bubbles are condensed in sub-cooled water. The saturated steam bubbles are injected in sub-cooled water inside a large vertical pipe and the steam volume fraction, velocity, bubble size distribution and liquid temperature are measured as radial profile at different heights. Six test cases with various pressure, liquid sub-cooling and diameter of the gas injection orifices are simulated. The simulations are largely improved by the introduction of a bubble collapse model in the Interfacial Area Transport Equation (IATE) of Neptune_CFD code. This model allows to consider the phenomena of polydisperse bubbles condensation despite the monodisperse model used in the one-group IATE and gives equivalent results as MUltiple-SIze Group (MUSIG) model with a reduced computational cost.

Keywords: CFD modeling, Condensation, Two-phase flow, IATE, Bubble collapse, Polydisperse

1 INTRODUCTION

The condensation phenomena can be encountered in day-to-day life as well as in multiple industrial applications. For nuclear reactor in particular, wall condensation is extensively studied in the containment vessel and bubble condensation plays also a key role in case of sub-cooled boiling or bubbles entrainment caused by Emergency Core Cooling (ECC) injection. In order to study these flows, the Eulerian Two-Fluid Model (TFM) is well adapted. The Neptune_CFD code which uses this model is therefore suitable to simulate condensing flows. Nevertheless, several models are needed in order to perform consistent simulations. Especially, the prediction of interfacial area is critical because many significant models as for the drag force and even for the interfacial heat and mass transfer are dependent of the interfacial area prediction. Two different models are usually used by CFD codes, on one hand, an IATE is resolved and on the other hand, the MUSIG model is applied. The first one considers only one group of bubbles and the interactions between liquid and bubbles and also between bubbles themselves are represented by models inside the IATE, such as coalescence and break-up models, or nucleation and condensation models for non-isothermal flow. The second one considers multiple groups of bubble size, usually dozen of groups [1]. In this model, there are as many mass conservation equations there are groups. Therefore, this second model allows to easier consider the polydisperse effect of the flow than the first one, but ats higher computational cost, due to the resolution of numerous mass equations for the gas phase. The aim of this work is to benefit of the reduced computational cost of the first model while keeping information about the polydispere effects, at least concerning the polydisperse effect on the bubble condensation. In order to do this, we decided to implement the condensation sink term proposed by Park et al. [2] linked to the bubble collapse of some small bubbles due to condensation inside the IATE of Neptune_CFD. In parallel

of the interfacial area prediction, the condensation model used to predict the Nusselt number and so, the interfacial heat and mass transfer is crucial in order to well predict the void fraction. In order to find the most accurate condensation model, some simulations are previously performed on this experiment with experimental interfacial area imposed inside the simulations in order to avoid the uncertainty linked to the interfacial area prediction. These simulations show, in accordance with Liao et al. [1, 3], that the widespread Ranz-Marshall correlation clearly under-estimates the condensation rate. Those simulations show that Chen-Mayinger correlation [4] gives way better prediction of the void fraction. Therefore, Chen-Mayinger correlation is chosen to predict the Nusselt number in our simulations.

2 EXPERIMENTAL FACILITY

TOPFLOW experiment is described in detail by Lucas et al. [5, 6, 7]. The test section is a large vertical pipe with an inner diameter of 195.3mm and a length of about 8m. Steam bubbles are injected by orifices of 1mm and 4mm diameter equally distributed around the pipe, which assures a rotation-symmetric gas injection. Six test cases with different pressure, initial sub-cooling and orifice diameters are investigated in this work, the detail is given in Table 1. For all those tests cases, the liquid and gas superficial velocity are respectively 1.017m/s and 0.219m/s. Measurements of radial profile of gas volume fraction, gas velocity, bubble size distribution and liquid temperature are acquired at different heights with a wire-mesh sensor and a lance of thermocouples. The height position of each level relative to the steam injection, for each orifice diameter, is given in Table 2. Liao et al. [1], simulate these test cases with MUSIG model, claim that some vortices exist below Level A/B and disappear before reaching Level A/B. It is why they use Level A or Level B as inlet conditions in their simulations. Following the same approach, Level A/B are used as inlet conditions in this work.

Case	P [bar]	ΔT_{in} [K]	$D_{orifice}$ [mm]
1	10	3.9	1.0
2	10	5.0	1.0
3	20	3.7	1.0
4	20	6.0	1.0
5	20	6.0	4.0
6	40	5.0	1.0

Table 1: Selected test cases

$D_{orifice} = 1.0mm$		$D_{orifice} = 4.0mm$	
Level	Height [m]	Level	Height [m]
A (Inlet)	0.221	B(Inlet)	0.278
C	0.335	E	0.551
F	0.608	H	1.495
I	1.552	K	2.538
L	2.595	N	4.474
O	4.531		

Table 2: Heights relative to steam injection position

3 NEPTUNE_CFD MODELS

Neptune_CFD code is developed in the NEPTUNE multiscale thermal-hydraulic platform, which is financially supported by EDF (Electricité De France), CEA (Commissariat à l'Energie Atomique), IRSN (Institut de Radioprotection et de Sûreté Nucléaire) and Framatome. Neptune_CFD is a 3D multifield CFD code using Eulerian approach [8]. The solver is based on a pressure correction method simulating multi-component multiphase flows by solving the three balance equations for each phase.

The turbulence of the liquid phase is modeled using the $R_{ij} - \varepsilon$ *EBRSM* model [9]. The closure laws of interfacial momentum transfers used in the bubbly flow model are defined as follows: the Ishii model [10] was used for drag force, Zuber model [11] for added-mass force, Tomiyama SMD model [12] for lift force and Generalized Turbulent Dispersion model [13] for turbulent dispersion force.

3.1 Mass and heat transfer model

If the mechanical terms are neglected in comparison to the thermal terms in the averaged form of the energy jump condition, the energy jump condition reduces to:

$$\Gamma_l = \frac{\Pi'_{li} + \Pi'_{gi}}{h_{fg}} = \frac{\Pi'_{li}}{h_{fg}} = \frac{a_i h_l (T_{sat} - T_l)}{h_{fg}}. \quad (1)$$

where h_{fg} represents the latent heat. For saturated steam, Π'_{gi} is neglected.

The heat transfer coefficient h_l can be calculated by various correlations. Ranz-Marshall correlation [14] is used by most of CFD codes. As mentioned previously, simulations with imposed experimental diameter show that Ranz-Marshall correlation largely underestimates the condensation rate on TOPFLOW experiment. However, Chen-Mayinger correlation [4] provide accurate results. This correlation is:

$$h_l = \frac{\lambda_k}{d_{32}} \left(0.185 Re_b^{0.7} Pr_l^{0.5}\right), \quad (2)$$

with $d_{32} = \frac{6\alpha_g}{a_i}$ is the sauter diameter, directly linked with the interfacial area by the void fraction. Re_b and Pr_l are respectively the bubble Reynolds number and the liquid Prandtl number. It is noteworthy that the range of validity of this correlation is ($400 < Re_b < 10^4$), which is consistent with experimental data.

3.2 IATE

Ishii et al. [15, 16] derive an interfacial area transport equation from a statistical model of a fluid particle number transport equation. The general form of their IATE is given by:

$$\frac{\partial a_i}{\partial t} + \nabla(a_i v_i) \approx \frac{2}{3}\left(\frac{a_i}{\alpha_g}\right)\left(\frac{\partial \alpha_g}{\partial t} + \nabla(\alpha_g u_g)\right) + \frac{1}{3\psi}\left(\frac{\alpha}{a_i}\right)^2 \sum_j R_j + \pi D_{ph}^2 R_{ph} \quad (3)$$

$$= \frac{2}{3}\frac{a_i}{\alpha_g \rho_g}\left[\Gamma_{g,i} - \alpha\frac{d\rho_g}{dt}\right] + \frac{1}{3\psi}\left(\frac{\alpha}{a_i}\right)^2 \sum_j R_j + \pi D_{ph}^2 R_{ph} \quad (4)$$

where v_i, ψ, D_{ph}, R_j, R_{ph} are respectively the interfacial velocity, a factor depending on the shape of the bubbles, the critical bubble size, the changing rate of interfacial area due to bubble breakup or coalescence and the changing rate of interfacial area due to a phase change. The interfacial velocity is assumed to be equal to the gas velocity in Neptune_CFD code.

The source and sink terms in the right hand side of equation (4) can be divided into two categories. The first category corresponds to the terms in brackets of the right hand side of equation (4) and represents the change in bubble volume at a fixed bubble number density. The first term represents the volume expansion due to evaporation and volume contraction due to condensation through a bubble interface and the second one represents the changes in pressure due to compressibility.

The second category corresponds to the interfacial area change due to change in number density. Change comes from two mechanisms: interaction between bubbles such as bubble break-up and coalescence, which are taken into account in the second term of right hand side; the second mechanism is the phase change such as wall nucleation and bubble collapse through condensation, which are represented in the last term. In Neptune_CFD, those source terms for bubbles break-up, coalescence and nucleation ($\pi D_{nuc}^2 R_{nuc}$) are modeled following the moment-density approach of Ruyer and Seiler [17, 18]. This approach consists of assuming a quadratic form for the bubble diameter distribution, and then solving equations on the moments defining this distribution.

In the current form of the Neptune_CFD IATE, the changing rate of interfacial area due to phase change is exclusively represented by the nucleation. The variation of interfacial area by a number density change due to an entire bubble collapse resulting from condensation is not currently modeled. However, as highlighted by Morel et al. [19], if bubbles with different size condensate, the smaller ones condensate and collapse more rapidly, leaving the bigger ones which may results in an increase of the averaged bubble size, and the bubble diameter is directly linked to the interfacial area. Park et al. [2] propose a model for this bubble collapse phenomena in one-dimensional IATE, with the assumption that all bubbles have the same diameter, equal to sauter diameter. We propose in this work to adapt this model to the

assumption of quadratic shape of the bubble diameter distribution proposed by Ruyer et al. [17] and to implement it in this local 3D framework.

Following the approach of Park et al. [2], for a condensing flow without nucleation, the equation (4) can be written:

$$\frac{\partial a_i}{\partial t} + \nabla(a_i v_g) = \phi_{PC} + \phi_{PV} + \phi_{BB} + \phi_{BC} + \phi_{CO}, \tag{5}$$

with ϕ_{PC} and ϕ_{PV} source and sink terms of an expansion or shrinkage due to a phase change and a pressure change, corresponding to terms in brackets in equation (4). ϕ_{BB} and ϕ_{BC} correspond to bubble break-up and coalescence, and ϕ_{CO} means the sink term due to bubble condensation.

3.3 Additional sink term in IATE for bubble collapse phenomena

The model proposed by Park et al. [2] is based on the consideration that the condensing region for a sub-cooled condition can be divided into two regions: the heat transfer-controlled region and the inertia-controlled region. In their view, in the first region, the Nusselt number approach is appropriate and in the second one, the bubbles are collapsed by the inertia of the surrounding liquid during a short period of time. The part of the condensation related to the first region can be characterized by the sink term ϕ_{PC} while the part related to the second region can be characterized by the last term ϕ_{CO}. The boundary between both region is determined using the time history of a collapsing single bubble in a sub-cooled liquid, using the Rayleigh solution [20] as well as Zwick and Plesset one [21].The boundary is found when there is a rapid change in the non-dimensional bubble diameter $\beta = D/D_{32}$, with D_{32} the sauter diameter. Park et al. assumed that the non-dimensional bubble diameter is 0.4 on the edge of the region. As a consequence, the boundary diameter can be defined as $D_b = 0.4D_{32}$.

The modeling of the term ϕ_{PC} is already satisfactory in Neptune_CFD code and the interfacial area sink term due to a condensation in the inertia-controlled region can be calculated as follows:

$$\phi_{CO} = \pi D_b^2 R_{ph} = -\frac{\pi D_b^2 n_b}{t_c}, \tag{6}$$

with n_b the bubble number density and t_c the residence time in the heat-transfer controlled region expressed as:

$$t_c = \frac{D_{32}^2 - D_b^2}{4} \frac{\rho_g h_{fg}}{Nu \lambda_f \Delta T_{sub}}. \tag{7}$$

Following the assumption of quadratic shape of the bubble diameter distribution, the bubble number density can be estimated as a function of the interfacial area a_i and void fraction α_g [22]:

$$n_b = \frac{1}{24.3\pi} \frac{a_i^3}{\alpha_g^2}. \tag{8}$$

Therefore, equation (6) is expressed with only known variables. The term Φ_{CO} was implemented in Neptune_CFD code and the prediction of the sauter diameter with and without this term will be compared in section 4.

3.4 Mesh and boundary conditions

Because of the axisymmetrical nature of the experimental facility and the flow, the simulations are carried out in an angular sector (4°) of the section of the pipe. Meshes are generated as three dimensional ones, with only one cell in the orthoradial direction. The results are thus calculated in the r,z plane, with 25 cells in r direction and 625 cells in z direction. Four different types of boundary conditions were applied in the simulation: inlet, outlet, wall and symmetry. The inlet profile of steam volume fraction, velocity, sauter diameter and liquid temperature were defined according to experimental data. The liquid velocity profile is not measured experimentally, so it is postulated to have an identical profile as the measured gas velocity, while preserving the inlet liquid flowrate. The solid wall was considered

adiabatic and smooth, the outlet pressure is defined from the inlet measured pressure minus the loss pressure associated with the water column.

The experimental profiles [7] show that for all the test cases studied in this work, only two phenomena are predominant on the change of interfacial area: condensation and coalescence. Coalescence and condensation coexist between the inlet and the elevation z=0.6m with a predominance of coalescence. At elevation above 0.6m, it seems that only condensation exists and have an impact on the interfacial area. In order to evaluate this condensation phenomena, in this work, the experimental sauter diameter is imposed in the simulations below 0.6m, where there is a coexistence of multiple phenomena, and to let the IATE model calculates the sauter diameter above 0.6m. Since it was observed that no coalescence and break-up exist above 0.6m, the source terms linked to coalescence and break-up were set to zero in these simulations. For case 5, no coalescence at all was measured, and so for this test case, the experimental diameter was not imposed at all.

4 CROSS-SECTION AVERAGED SAUTER MEAN BUBBLE DIAMETER AND GAS VOLUME FRACTION

The simulation results performed in this study, with and without the new model presented in section 3.3 as well as simulation results conducted by Liao et al. [1] with MUSIG model were compared with experimental measurements. It is noteworthy that Liao et al. define the Nusselt number by a different correlation, Tomiyama [23] correlation. The modeling of bubble collapse phenomena is immediate in their approach, when the bubbles that belong to group with smallest bubble size condensate, they automatically vanish. Unlike what is done in this work, they predict the bubble diameter everywhere in the pipe, including below 0.6m, and using models for coalescence and break-up. First of all, figure 1 shows that simulations results with IATE but without sink term for bubble collapse phenomena (blue line), are not consistent. Bubble diameter reaches zero very rapidly for all cases, which is not the case experimentally. This is due to the one-group model with IATE and the fact that all bubbles shrink due to condensation but does not disappear. As a consequence, the predicted bubble sauter diameter is way underestimated.

The introduction of a sink term which characterizes the effect of bubble collapse on the interfacial area greatly improves the simulation results as one can see on the green line. This term counteracts the effect of shrinkage due to condensation. In fact, the shrinkage due to condensation is still taken into account, alike the previous simulations, which has an effect of decreasing the sauter diameter, and the new term takes into account the collapse of small bubbles, which has an effect of increasing the sauter diameter.

Those results are at least as good as those obtained by Liao et al. [1] with MUSIG model, which is much more time consuming, due to the resolution of mass balance equations for all the bubble size groups. The comparison of wall clock times in this work with both models was not possible, but Habiyaremye et al. [24] show that on adiabatic test series of TOPFLOW experiments, simulations with IATE are 6/7 times faster than with Fixed Pivot Technique approach, where bubble size distribution is discretized into multiple size classes, in same way that MUSIG model. Those results are very encouraging since it proves that the polydisperse effects, at least in term of bubble condensation, can be captured by a one-group IATE model, with the introduction of this new term.

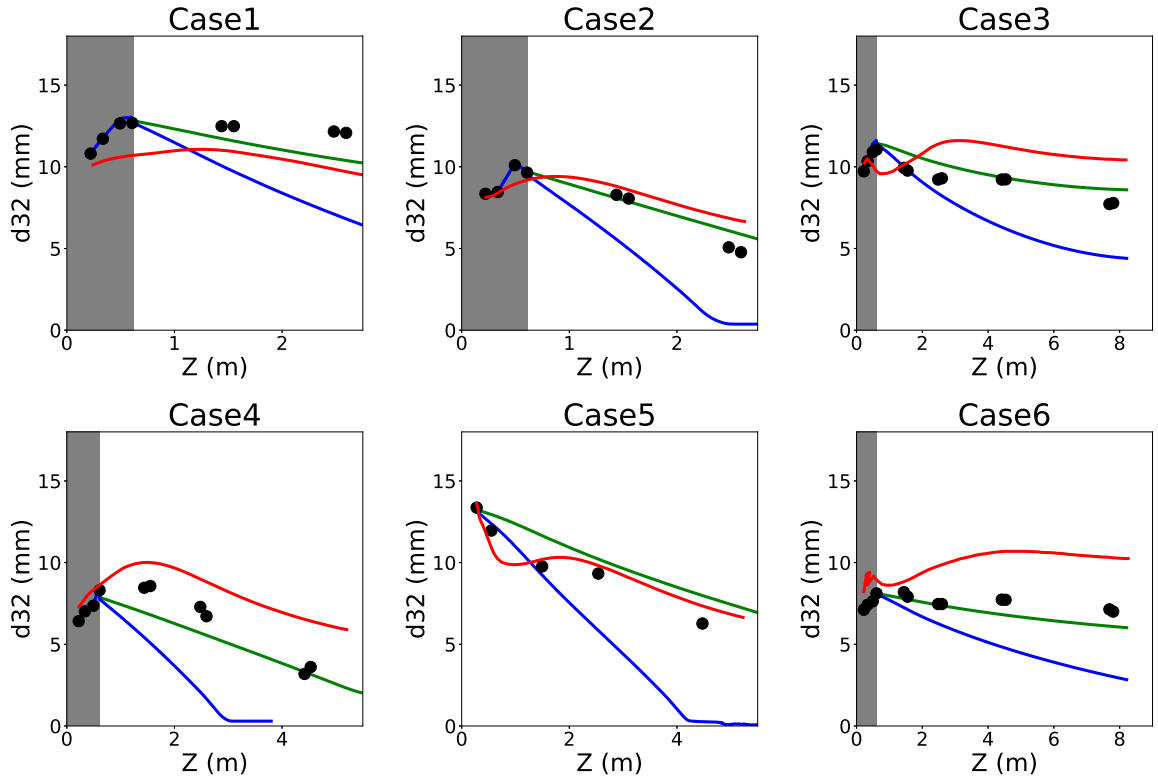

Figure 1: Evolution of cross-section averaged Sauter mean bubble diameter in the axial direction (symbol: experiment; blue line: Results without new sink term in IATE (old model); green line: Results with new term in IATE; red line: Results with MUSIG approach [1]).

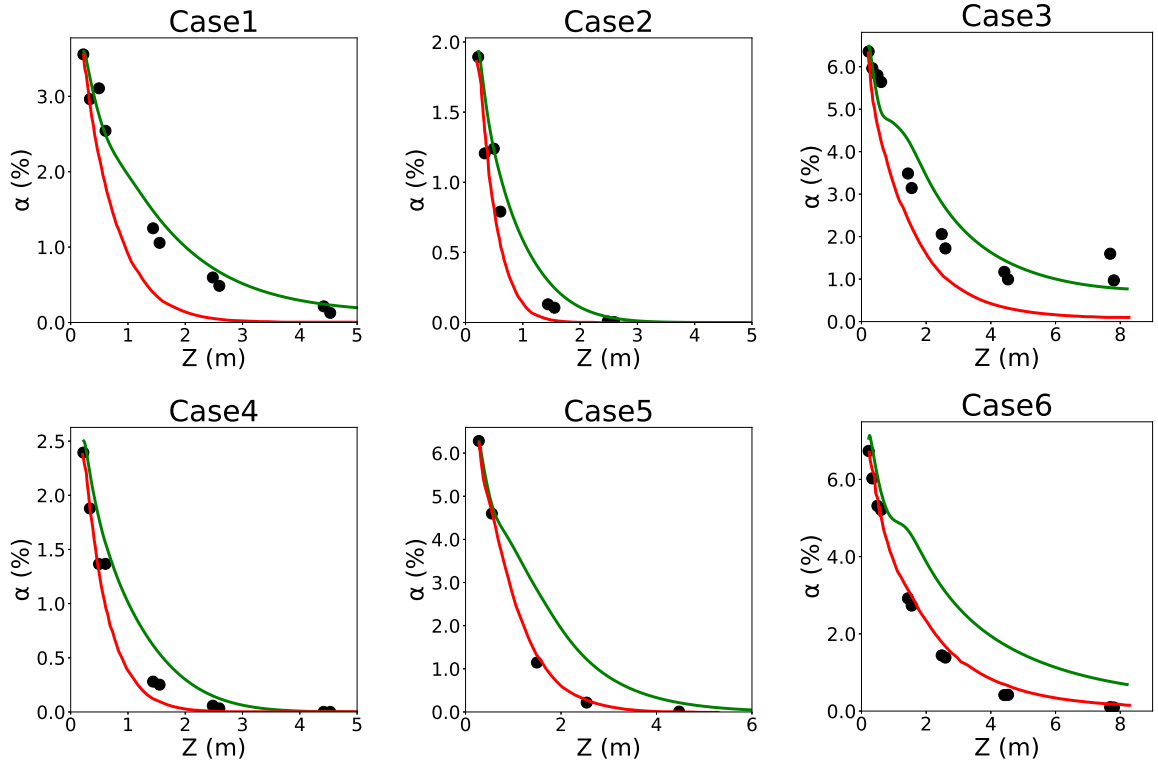

Figure 2: Evolution of cross-section averaged void fraction in the axial direction (symbol: experiment; green line: Results with IATE including new term; red line: Results with MUSIG [1]).

The evolution of cross-sectional averaged gas volume fraction is shown in figure 2 for the six test cases. The green line was obtained in this work with IATE and new sink term, the red one is still the simulation results obtained with MUSIG model by Liao et al. For both models, the axial evolution of averaged void fraction is well captured. There is a slight overestimation of the void fraction in test cases 5 and 6 with the simulations performed in this study but overall, the results are relatively satisfactory with both models.

5 CONCLUSION

A new sink term corresponding to the effect of bubble collapse phenomena on interfacial area evolution was implemented in the IATE of Neptune_CFD. The benefit of this new term was investigated on TOPFLOW experiments, which consist of condensation of steam bubbles in sub-cooled water flowing through a large vertical pipe. Sauter diameter prediction was largely improved by the introduction of this new term, to such an extent that the predictions were as good as those obtained by MUSIG model, which is much more time consuming. This paves the way to the possibility of modeling polydisperse bubbly flow with only a one-group IATE, by modeling some of the effects of polydispersion. The prediction of axial averaged gas volume fraction was also quite good with IATE model, of similar magnitude of those obtained with MUSIG model.

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