

The Implementation of an Activated Temperature Dependent Wall Boiling Model in an Eulerian-Eulerian Computational Fluid Dynamic Approach for Predicting the Wall Boiling Process

Ding, W.; Krepper, E.; Hampel, U.;

Originally published:

August 2018

Nuclear Technology 205(2018), 23-32

DOI: <https://doi.org/10.1080/00295450.2018.1496693>

Perma-Link to Publication Repository of HZDR:

<https://www.hzdr.de/publications/Publ-27872>

Release of the secondary publication
on the basis of the German Copyright Law § 38 Section 4.

1 **The Implementation of an Activated Temperature Dependent Wall Boiling**
2 **Model in an Eulerian-Eulerian Computational Fluid Dynamic Approach for**
3 **Predicting the Wall Boiling Process**

4
5 **Wei Ding ^{1,2}, Eckhard Krepper ², Uwe Hampel ^{1,2}**

6
7 ¹ Institute of Fluid Dynamics, Helmholtz-Zentrum Dresden-Rossendorf, Dresden, Germany

8 ²AREVA Endowed Chair of Imaging Techniques in Energy and Process Engineering, Technische
9 Universität Dresden, Germany
10 w.ding@hzdr.de

11
12
13 **ABSTRACT**

14 In this work, we report on a development of time averaged Eulerian multiphase approach applied in the
15 wall boiling process especially in the forced convective boiling process. Recently in order to get accurate
16 bubble dynamics and reduce the case dependency, a single bubble model for nucleate boiling based on the
17 known published models was developed. The model considers geometry change and dynamic contact and
18 inclination angles during the bubble growth. The model has a good agreement with experiments. However
19 the predicted bubble dynamics is wall superheat (cavity activation temperature) dependent. This single
20 bubble model requires an update of the current nucleation site activation and heat partitioning models in
21 time averaged Eulerian multiphase approaches. In this work, we will introduce this implementation in
22 detail. Further with help of the multiple size group (MUSIG) model and a breakup and coalescence
23 model, the time averaged Eulerian approach could simulate the bubble size distribution in a heated pipe.
24 With the necessary calibration of the nucleation site density the comparisons between the calculation
25 results and the Bartolomej's experiments demonstrate the success of the implementation and the accuracy
26 of this approach.

27 **KEYWORDS**

28 Wall boiling; Eulerian multi-phase approach; microlayer; cavity group activation; updated heat
29 partitioning

30 I. INTRODUCTION

31 Boiling and two phase flow involves mass, momentum and energy transfer at the liquid-vapor interface
32 and further involves heat conduction into solid walls. These complex phenomena bring much more
33 difficulties to understand, model and predict the boiling process with Computational Fluid Dynamics
34 (CFD). Currently the most widely used approach to model the boiling process is the Eulerian two fluid
35 framework of interpenetrating continua [1, 2]. In this approach, the equations of mass, momentum and
36 energy are taken for each phase separately and weighted by volume fraction which represents the local
37 ensemble averaged probability of occurrence of each phase. However in such a model, all the information
38 on and about the interface structure is lost due to the averaging process [3]. Consequently, models are
39 required to describe the interphase exchanges of the mass, momentum and energy. These models appear
40 as some terms of the balanced equations. For the case of wall boiling, a wall boiling model, which can
41 describe the heat transfer from heated wall to the bulk liquid, is strongly required. The heat partitioning
42 models, such as RPI (Rensselaer Polytechnic Institute) model developed by Kurul and Podowski [4] in
43 1990, have been widely adopted in CFD codes to date. The heat flux from the wall is there portioned into
44 contributions of liquid convection, quenching and evaporation. The quenching and evaporation terms are
45 calculated from several parameters, such as active nucleation site density, the bubble departure diameter
46 and bubble departure frequency. In this approach the proper consideration of the bubble dynamics such as
47 the bubble departure diameter and bubble departure frequency further the nucleation site density on the
48 heated wall is particularly important. Currently these important variables are predicted normally through
49 empirical correlations. For example, the bubble departure diameter is usually calculated from the
50 correlations of Tolubinsky and Kostanchuk [5], which give the bubble departure diameter as a function of
51 sub-cooling. Also for the bubble waiting time and bubble frequency, Tolubinsky and Kostanchuk
52 consider the constant ratio of waiting time and total time, with the waiting time being 80% of the bubble
53 detachment period. However the correlations were developed from pool boiling experiments under 1
54 atmospheric pressure. They are highly problem-specific and require careful consideration with respect to
55 their scope of application. In 2013, a CFD approach coupling the wall heat partitioning model (RPI) and

56 population models so called Multiple size group (MUSIG) and inhomogeneous Multiple size group
57 (iMUSIG) was introduced by Krepper et al. [2, 6, 7] which tracks bubbles with coalescence and breakup
58 and was recently extended to evaporation and condensation. In the paper, they assessed the necessary
59 recalibration of the empirical correlations for the specific experimental data.

60 Nevertheless currently the applied Eulerian CFD approach is still far away from being a predictive tool
61 due to the correlation based bubble dynamics. A critical review by Krepper et al. in 2013 [2] of the
62 employed correlations shows that some of the parameters are not suited for a broad usage for different
63 fluids or different pressure levels but have to be carefully recalibrated for the intended applications. In our
64 previous study [8] a single bubble model was developed to simulate and predict the bubble departure or
65 lift-off during pool or flow boiling which will be shortly introduced later. The model includes more
66 physics than the empirical correlations. The sub-model is rather case independent, which means there is
67 no need for recalibration under different conditions as mentioned above.

68 In this work, the well-developed single bubble model was implemented in the Eulerian CFD approach.
69 The new activation mechanism and heat flux partitioning were employed in order to enhance the
70 performance and improve the prediction accuracy. Further the CFD approaches are compared and
71 validated against different experimental cases.

72 73 **II. State of the Art of the Submodels**

74 As mentioned above, submodels are required to complete the missing information in the Eulerian-
75 Eulerian (EE) CFD approach. For wall boiling processes, as one of the most popular models, the RPI
76 model is often employed as a submodel to describe the bubble dynamics on the wall, cavity activation law
77 and the heat partitioning.

78 The bubble dynamics is commonly described by the bubble departure / lift-off diameter and bubble
79 generation frequency. It is quantified by two correlations in the RPI model in ANSYS CFX. One
80 correlation is derived from the investigations by Tolubinsky and Kostanchuk [5] for water at different
81 pressures and subcooling. The correlation is given as

82

$$83 \quad d_w = d_{ref} e^{\frac{T_{sat} - T_L}{\Delta T_{refd}}}, \quad (1)$$

84

85 where d_w is the bubble departure diameter, T_{sat} is saturation temperature and T_L is subcooling

86 temperature obtained by evaluating the non-dimensional temperature profile of Kader [9] at a fixed value

87 of y^+ . y^+ is defined as a dimensionless wall distance for a wall bounded flow $y^+ \equiv \frac{u_* y}{\nu}$. u_* is the friction

88 velocity at the nearest wall, y is the distance to the wall and ν is kinematic viscosity. d_{ref} and ΔT_{refd} are

89 parameters, which require adjustment for different cases [7]. From the assessment of Krepper, usually

90 ΔT_{refd} is set to 45 K while d_{ref} is case dependent. For example, in Krepper and Rzehak (2011) [7]

91 with reference to the DEBORA case, d_{ref} was set to $d_{ref} = 0.24$ mm and $d_{ref} = 0.35$ mm at pressures of

92 2.62 MPa and 1.46 MPa respectively.

93 The bubble frequency f in RPI model is given according to Cole (1960) [10] as a function of the

94 detachment size d_w as

95

$$96 \quad f = \sqrt{\frac{4g(\rho_L - \rho_G)}{3C_D d_w \rho_L}} \quad (2)$$

97

98 where g is gravity, ρ is density of liquid (L) and gas (G) and C_D is the drag coefficient. From Eq. 1 and 2,

99 we can conclude that the bubble dynamics is strongly dependent on the thermal properties of the fluid and

100 the bulk temperature. Base on the study of Tolubinsky and Kostanchuk [5], Kurul and Podowski [4] fixed

101 the ratio between bubble growth time and waiting time to a constant of $\frac{1}{4}$.

102 The bubble activation, that is the activated nucleation site density (N), is expressed by a correlation given

103 as

104

$$105 \quad N = N_{ref} \left(\frac{T_w - T_{sat}}{\Delta T_{refN}} \right)^p. \quad (3)$$

106

107 where constants $N_{ref} = 7.94e5 \text{ [m}^{-2}\text{]}$, $\Delta T_{refN}=10 \text{ [K]}$ and $P=1.805$ respectively. Again from the
108 assessment of Krepper, it is found that N_{ref} is also case dependent. For the other parameters the
109 previous values of ΔT_{refN} and p were found to yield satisfactory results in the overall model framework.
110 From Eq. 3, it is clear to see the activated nucleation site density is based on wall superheat ($T_W - T_{sat}$).
111 Accordingly, the feed heat flux Q_{tot} , applied to the heated wall can be considered as a sum of three
112 parts:

$$113 \quad Q_{tot} = Q_C + Q_Q + Q_E, \quad (4)$$

115 where Q_C , Q_Q and Q_E are the heat flux components due to single-phase convection, quenching, and
116 evaporation, respectively. The details of the RPI model can be found in the literature of Kurul and
117 Podowski [4].

119 **II.A New Bubble Model**

121 In this paper, we will shortly introduce a new wall boiling model [8], mainly focus on the novelty. Until
122 today it seems that the bubble dynamics models still require some empirical constants to account for
123 different thermal hydraulic conditions. To reduce the case dependency, a model without these constants
124 was developed and tested. The model has a low case dependency and a high accuracy to predict the
125 bubble dynamics, bubble departure and lift-off in pool or flow boiling. The model was built based on the
126 on previous studies, e.g. of Colombo and Fairweather [11], Raj et al. [16] and Mozzocco et al. [17]. In
127 2015, Colombo and Fairweather [11] developed a mechanistic model to simulate the bubble growth and
128 departure. In the model, they considered the contribution of the microlayer based on work of Cooper and
129 Lloyd [12], the superheated thermal liquid layer based on Plesse and Zwick [13] and the condensation
130 evaluated from Ranz and Marshall [14] to bubble growth. Further they applied the force balanced model
131 from Klausner et al [15] to determine the bubble departure. Based on the suggested contact angles from
132 Klausner et al. [15] and other empirically measured contact angles, the model seems had a good

133 agreement with data from different experiments. The bubble growth is described as an analytical solution
 134 as

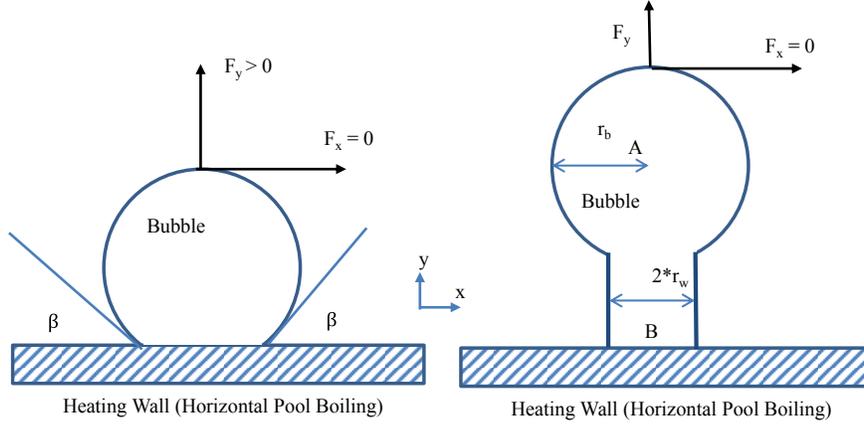
$$\frac{dr_b}{dt} = \frac{1}{C_2} Pr^{-0.5} Ja \left(\frac{k_l}{\rho_l C_{p,l}} \right)^{0.5} t^{-0.5} + \sqrt{\frac{3}{\pi}} k_l (T - T_{sat}) \left(\frac{k_l}{\rho_l C_{p,l}} \right)^{0.5} t^{-0.5} (1 - b) - \frac{k_l (2 + 0.6 Re^{0.5} Pr^{0.3}) (T_{sat} - T_L)}{2 r_b \rho_g h_{fg}} b. \quad (5)$$

135
 136 r_b is bubble radius, C_2 is microlayer constant evaluated as 1.78 by Cooper and Lloyd, k_l is liquid thermal
 137 conductivity, ρ_l is liquid density, $C_{p,l}$ is specific heat capacity, h_{fg} is latent heat, ρ_g is gas density, Ja is
 138 Jacob number, Pr is Prandt number, Re is Reynold number and b is the portion of the bubble surface in
 139 contact with the subcooled liquid.

140 However this model still required the empirical measured contact angle and base diameter to enhance the
 141 accuracy of prediction for different cases. In the new model which we developed [8], a dynamic contact
 142 angle method and a dynamic bubble geometry tracking method was applied to further improve the case
 143 dependency of the previous bubble model. These two models as the main novelties will be introduced in
 144 the next subsection.

145 **II.B Novelties of the Present Bubble Model**

146 As shown in Figure 1, after a fast expansion, the bubble's main body starts departing but as the
 147 evaporation of microlayer still produces enough vapor the main body remains connected to the wall. The
 148 base diameter of the bubble starts to shrink when the evaporation of microlayer is less than required to
 149 form a new bottleneck. Unlike in the conventional force analysis model the bubble departure or lift-off
 150 criterion is that the bottleneck breaks up or the base diameter shrinks to 0. The bottleneck breaks up is
 151 judged by the pressure difference between points A and B (Figure 1).



152

153 **Figure 1: Formation of a bottleneck after force unbalance and before bubble departure.**

154

$$\Delta p_{AB} = \frac{1}{2} \rho_g v_p^2 + \rho_g g h + \sigma \left(\frac{1}{r_w} + \frac{1}{r_\infty} - \frac{2}{r_b} \right). \quad (6)$$

155 where Δp_{AB} is the pressure difference between bubble main body and base, v_p is the bubble moving

156 velocity of mass center, r_w is the bubble base radius, $\frac{1}{r_w} + \frac{1}{r_\infty}$ is the curvature of the contact line at the

157 bubble base. when Δp_{AB} is larger than the total force in perpendicular direction acting on the base area,

158 that is $\frac{|F_{total,n}|}{A_{base}}$, the bottleneck will break up and the bubble will depart from the wall. From our tests, it is

159 found that when $r_\infty = r_w$, good agreements are got between models and experiments.

160 During the bubble growth, the dryout radius r_d increases when the sum of the negative forces which point

161 towards the wall (mainly surface tension force) is much higher than the one of the positive forces

162 preventing the bubble departure. This negative total force will drive the bubble to form a curvature and a

163 contact angle to reduce the surface tension force in the negative direction until the forces on the bubble

164 are balanced. The contact angle at which the force is again balanced is referred to as expected contact

165 angle (β_s). From the force calculation this expected contact angle can be derived as

$$\beta_s = \text{asin} \left(\frac{F_{growth,y} + F_{drag,y} + F_{cp,y} + F_{sl,y} + F_{b,y}}{F_{surf,y}} \right). \quad (7)$$

166 where $F_{growth,y}$, $F_{drag,y}$, $F_{cp,y}$, $F_{sl,y}$, $F_{b,y}$ and F_{surf} are growth force, drag force, contact pressure force,
 167 shear lift force, buoyancy in the wall perpendicular direction and total surface tension on the bubble
 168 respectively. The contact angle β can be calculated with the base radius and the bubble radius as

$$\beta(t) = \arcsin\left(\frac{r_w(t)}{r_b(t)}\right). \quad (8)$$

169 It decreases from an initial value $\beta(0) = \frac{\pi}{2}$ towards the expected value β_s in some finite time interval. So
 170 the contact angle becomes dynamically during the bubble growth.

171 In Klausner's work, the authors considered $d_w = 2 * r_w$ as a constant of 0.09 mm. Later Thorncroft [23]
 172 adopted $d_w = 2r_b \sin(\beta)$ in order to improve the modelling accuracy. A constant ratio with bubble
 173 diameter $d_w = \frac{2r_b}{15}$ was used by Yun et al. [22]. In this work we prefer to consider the relationship
 174 between the expansion rate of base radius \dot{r}_w and that of the bubble \dot{r}_b instead of absolute values r_w and r_b
 175 (as in Thorncroft et al. [23]) in order to account for a smooth growth of bubble. We express the expansion
 176 rate of r_w as

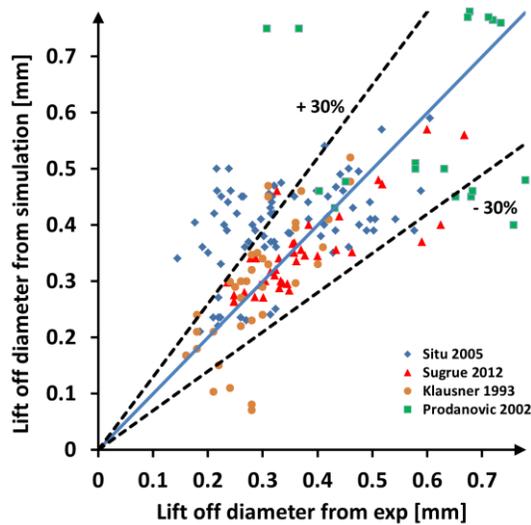
$$\dot{r}_w = \dot{r}_b \sin\left(\frac{\pi}{2} - \beta\right). \quad (9)$$

177 The total average error of 23% between the model and different experiments shows the reliability of the
 178 present model (See Figure 2). In particular, the comparison covers different mass load, heat flux,
 179 subcooling, pressure, orientation angle, pipe design and fluid material (See Table II).

180 **Table I: Experiments used for validation of the bubble dynamics**

	Duan [24]	Klausner et al. [15]	Situ et al. [25]	Sugrue [26]	Prodanovic [27]
Fluid	Water	R113	Water	Water	Water
Orientation	Horizontal	Horizontal	Vertical	0°,30°,45°,60°,90°,180°	Vertical
Channel	Plate	Rect.; D _h = 25 mm; no full filled	Ann.; D _h = 19.1 mm sampling points at different position	Rect.: D _h = 16.7 mm	Rect.: D _h = 9.3 mm
G/kg m ⁻² s ⁻¹	0	112-287	466-900	250-400	76.6 – 766
Q"/KW m ⁻²	28.7; 36	11-26	54-206	50,100	200 - 1000
ΔT _{sub} /°C	0.5;1	saturated	2-20	10,20	10, 20 , 30
p/bar	1.01	1.5	1.01	1.01;2.02;5.05	1.05; 2
Uncertainties from Measurement	±0.07 mm	±0.03 mm	±0.016	±0.113 mm	

181
 182



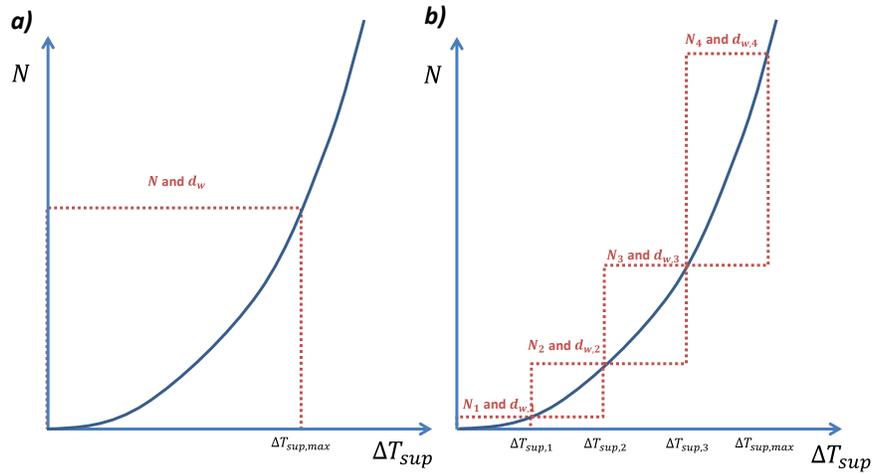
183
 184 **Figure 2: Comparison of the bubble lift off diameter between experiments and simulation in flow**
 185 **boiling under different conditions.**

186 From the sensitivity analysis, the model can accurately reproduce the dependency of bubble departure and
 187 lift-off diameter on different impact parameters such as mass load, heat flux, subcooling temperature,
 188 pressure and orientation angle. The model confirmed the conclusions of previous works, such as that an
 189 increase of inflow velocity leads to smaller departure/lift-off diameter, higher pressure leads to smaller
 190 departure/lift-off diameter and so on. The model is even helpful to consider the contrary conclusions, e.g.
 191 that higher heat flux leads to larger departure/ lift-off diameter in Situ and Sugrue’s case [25, 26] and
 192 higher heat flux leads to smaller lift-off diameter in the Prodanovic’s case [27]. It was found that the
 193 increase or decrease of the lift-off diameter is strongly condition-dependent. The model is also helpful to
 194 characterize the impacts of different parameters quantitatively. Differs from the introduced RPI model,
 195 the bubble departure diameter and frequency in the new developed bubble model is a function of wall
 196 superheat.

197
 198 **II.C. Cavity Group Activation Model**

199 The new single bubble model has an acceptable accuracy for both pool boiling and flow boiling under
 200 different conditions, which is preferential for CFD codes. The difference between the subcooled

201 dependent bubble dynamics in RPI model and the wall superheat dependent one in new single bubble
 202 model troubles the implementation of the single bubble model into the EE CFD approach.
 203 In order to consider the wall superheat dependency of the bubble dynamics in the new single bubble
 204 model, the way to implement the bubble dynamics must be updated. We simply classify the activated
 205 nucleation sites into different groups with different wall superheat. For each activated group, bubbles
 206 have the same bubble dynamics for both departure diameter and frequency with known boundary
 207 conditions, such as flow velocity and bulk temperature (See Figure 3).
 208



209
 210 **Figure 3: The Nucleation site density (N) and bubble dynamics in the conventional RPI model (a)**
 211 **and in the group activation model (b).**

212 The nucleation site density N_1 is still following Eq. 3. N_2 , N_3 and N_4 are calculated with Eq. 3, which can
 213 be written as

$$214 \quad N_i = N_{ref} \left(\frac{\Delta T_{sup,i}}{\Delta T_{refN}} \right)^p - N_{ref} \left(\frac{\Delta T_{sup,i-1}}{\Delta T_{refN}} \right)^p \quad (10)$$

215 where N_i is the nucleation site density at group i and $\Delta T_{sup,i}$ is the activation superheat of group i . In this
 216 way, the bubble dynamics impacted by wall superheat will be implemented into the CFD code as the
 217 condition to calculate the heat fluxes.

218 II.D. Updated Heat Partitioning Model

219 As is introduced, the heat partitioning model is employed in the conventional RPI model shown in Eq. 4.
220 However if the group activation model is applied, the heat partitioning can be simplified. If we consider the
221 boiling as a stable process in the nucleation boiling region, it means that in the bubble influenced area
222 (evaporative area) the time averaged heat flux due to the evaporation and quenching is always equal to the
223 feed heat flux. In the other words, instead of the heat balance between Q_{tot} calculated by Eq. 4 and the
224 input heat flux on the wall Q_{feed} , the heat balance between Q_{tot} and Q_c becomes dominant to the heat
225 conservation in the CFD calculation. Due to the steady state of boiling in the bubble influenced area, it
226 means that the average wall superheat of the evaporative area is on average constant in each activation
227 group respectively. The wall superheat in the area of single phase convective heat transfer should be the
228 maximum wall superheat $\Delta T_{sup,max}$. This maximum value further determines the evaporative area fraction
229 or the void fraction of the bubble on the wall and in the bulk with other conditions such as flow profile
230 and bulk temperature.

231 III. VALIDATION 232

233 In order to develop reliable models for calculation of the thermohydraulic characteristics of the steam
234 generating channels with subcooled boiling, Bartolomej et al. (1982) [28] did experimental investigations
235 on the volumetric vapour content in vertical channels with uniform heat release over length. The
236 experimental Cr18Ni10Ti steel channel is of 12 mm internal diameter and 2 mm wall thickness. The
237 experiments covered different pressure, mass flux, heat flux density and inlet water temperature. The
238 main investigated parameter was volumetric steam content which was measure by γ -radiation from a Tu-
239 170 source. Some experiments are selected to be compared with the CFD calculations which covers mass
240 load $405 \sim 2024 \text{ kgm}^{-2}\text{s}^{-1}$, pressure $7 \sim 15 \text{ MPa}$, heat flux $790 \sim 1130 \text{ KWm}^{-2}$ and inlet liquid temperature
241 $421 \sim 598 \text{ K}$ (See Table III).

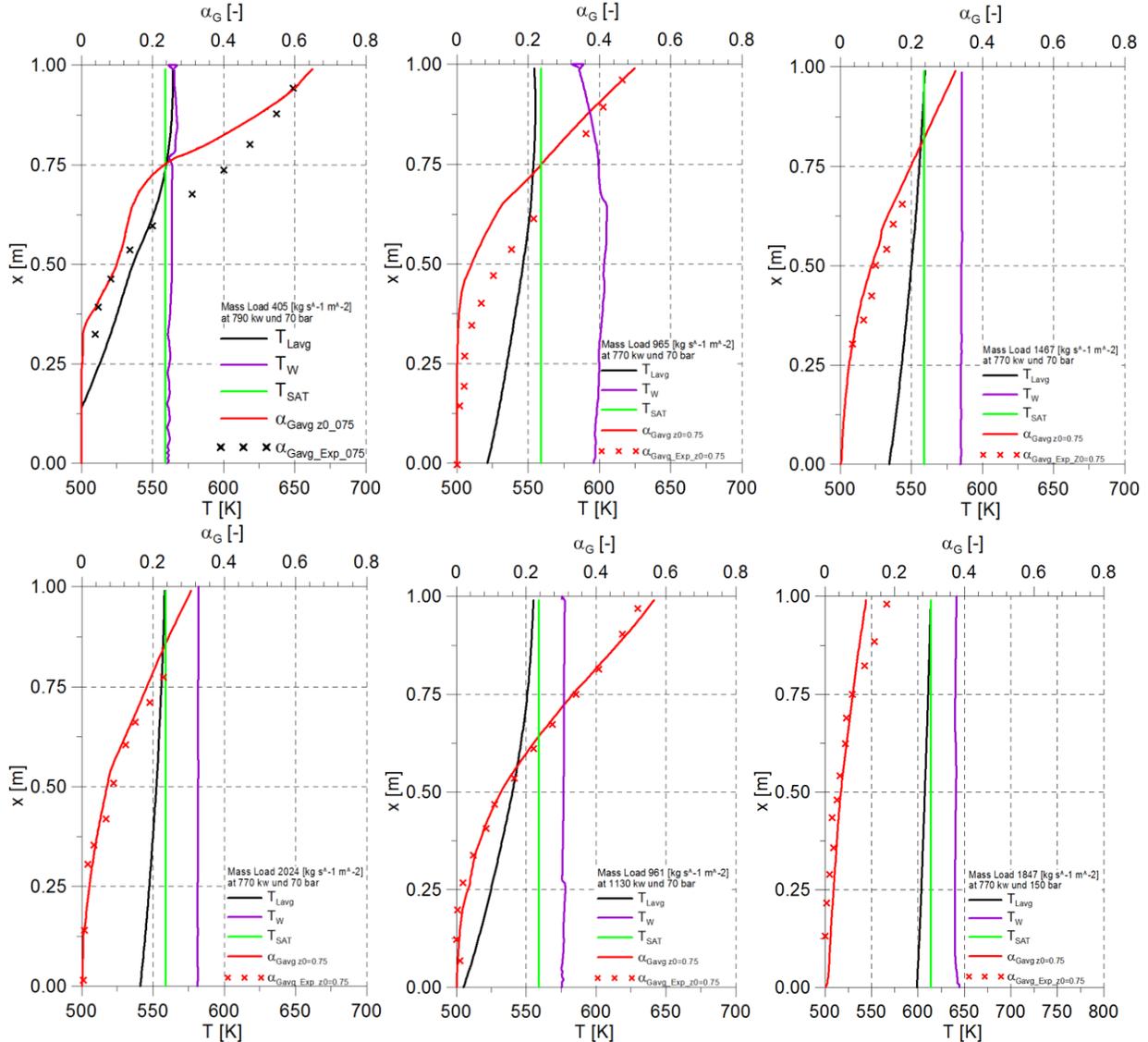
242 The simulation is carried out on the ANSYS CFX 14.5. All the model setups are referenced with respect
 243 to the Bartolomej case validation in the work of Krepper in 2007 [29]. The gas phase is considered as a
 244 mono dispersed bubble phase with bubble size between 0.05 mm to 2 mm with a subcooling dependent
 245 blending function defined in ANSYS CFX. Due to limitation of ANSYS CFX, the bubble departing from
 246 the wall into bulk is still with an averaged mono size group, which will be further improved in the new
 247 version of ANSYS CFX.

248 **Table II Selected test cases of Bartolomej [28] under different conditions**

	Pressure [MPa]	Mass flow rate [kg m ⁻² s ⁻¹]	Wall heat flux [kW m ⁻²]	Inlet temp. [K]	Test no.
BART1	7	405	790	421	P7G0.405Q790
BART 2	7	965	790	493	P7G0.965Q790
BART 3	7	1467	790	519	P7G1.467Q790
BART 4	7	2024	790	520	P7G2.024Q790
BART 5	7	961	1130	466	P7G0.961Q1130
BART 6	15	1847	770	598	P15G1.847Q770

249 The test number was derived basing on the test parameters in the following way: P stands for pressure in
 250 0.1 MPa, G for mass flow rate in 1000 kg m⁻²s⁻¹, Q for wall heat flux in kWm⁻² and T for the subcooling
 251 in K.
 252

253 With help of the single bubble model d_{ref} is not needed to be calibrated again. However, because the
 254 nucleation site density is strongly dependent on the wall surface finishing method, which still lacks a clear
 255 description, it is still necessary to do a calibration. Here we found for the Bartlomej experiments, that N_{ref}
 256 is equal to 7.5×10^7 .



257

258

259

Figure 4: Comparison of simulation and experiments for cases of Bartolomej [28] given in Table II.

260

261

262

263

264

IV. CONCLUSIONS

265

266

267

Of cause this good agreement between experiments and simulation in the validation (See Figure 4) is only a preliminary result for the new implemented models. More information such as the bubble population distribution in the pipe and the wall temperature is still missing. The further validation will be done with the DOBERA cases [2, 30, 31] in which the details of bubble size and wall superheat were captured.

EE CFD approaches were widely applied in the simulation of the boiling process. However due to the employment of too many correlations, the approach becomes very specific which requires carefully recalibration such as for nucleation site density N_{ref} and departure diameter d_{ref} . In order to reduce the case

268 dependency, a new single bubble model was developed. To implement this model requires the adaption of
269 the approach with new activation and heat partitioning sub models. In this paper, the cavity group
270 activation model and updated heat partitioning model were introduced. With these two models, the single
271 bubble model can be successfully implemented in the EE CFD approach. A comparison between the
272 experiments of Bartlomej and model shows good agreement in the void fraction with only one time
273 calibration of nucleation site density. The good agreement shows the applicability of the single bubble
274 model and the new developed implement submodels under different flow conditions, e.g. subcooling, feed
275 heat flux, pressure and mass load. In the near future, with help of bubble population balanced model
276 (inhomogeneous MUSIG [6, 32] and other submodels [2]) the approach will be extended to comparison
277 with DOBERA cases which captured the bubble size distribution and wall superheat.

278 V. ACKNOWLEDGMENTS

279 This work is funded by the German Federal Ministry of Economic Affairs and Energy (BMWi) under
280 grant number 1501473C on the basis of a decision by the German Bundestag.

281 VI. REFERENCES

- 282 1. G.H. Yeoh, J.Y. Tu, Computational techniques for multiphase flows — basics and applications.
283 *Elsevier Science and Technology*, Butterworth-Heinemann (2012).
- 284 2. E. Krepper, R. Rzehak, C. Lifante, T. Frank, CFD for subcooled flow boiling: coupling wall boiling
285 and population balance models, *Nucl. Eng. Des.* **255** 330–346 (2013).
- 286 3. A. Prosperetti, G. Tryggvason, Computational methods for multiphase flow, Cambridge University
287 Press, New York (2007).
- 288 4. N. Kurul, M.Z. Podowski, Multidimensional effects in forced convection subcooled boiling, in:
289 *Proceedings of the 9th International Heat Transfer Conference*, Jerusalem (1990).
- 290 5. V.I. Tolubinsky, D. M. Kostanchuk, Vapor bubbles growth rate and heat transfer intensity at
291 subcooled water boiling, in: *Proceedings of the 4th International Heat Transfer Conference*, Paris
292 (1970).

- 293 6. E. Krepper, D. Lucas, T. Frank, H.-M. Prasser, P. Zwart, The inhomogeneous MUSIG model for the
294 simulation of polydispersed flows. *Nucl. Eng. Des.* **238**, 1690-1702 (2008).
- 295 7. E. Krepper, M. Beyer, D. Lucas, M. Schmidtke, A population balance approach considering heat and
296 mass transfer – Experiments and CFD simulations. *Nucl. Eng. Des.* **241**, 2889-2897 (2011).
- 297 8. W. Ding, E. Krepper, U. Hampel. Evaluation of the microlayer contribution to bubble growth in
298 horizontal pool boiling with a mechanistic model that considers dynamic contact angle and base
299 expansion. *Int. J. Heat and Fluid flow* 72, pp 274-287 (2018).
- 300 9. B.A. Kader. Temperature and concentration profiles in fully turbulent boundary layers, *Int. J. Heat*
301 *Mass Transfer* **24**, pp. 1541-1544 (1981)
- 302 10. R. Cole, A photographic study of pool boiling in the region of the critical heat flux. *AIChE J.* **6**. 533–
303 542 (1960).
- 304 11. M. Colombo, M. Fairweather, Prediction of bubble departure in forced convection boiling: A
305 mechanistic model, *Int. J. Heat Mass Transfer* 85 (2015) 135–146.
- 306 12. M.G. Cooper, A.J.P. Lloyd, The microlayer in nucleate pool boiling, *Int. J. Heat Mass Transfer* **12**
307 895–913 (1969).
- 308 13. M.S. Plesset, S.A. Zwick, The growth of vapour bubbles in superheated liquids, *J. Appl. Phys.* 25
309 (1954) 493–500.
- 310 14. W.E. Ranz, W.R. Marshall, Evaporation from drops, *Chem. Eng. Prog.* 48 (1952) 141–146.
- 311 15. J.F. Klausner, R. Mei, D.M. Bernhard, L.Z. Zheng, Vapor bubble departure in forced convection
312 boiling, *Int. J. Heat Mass Transfer* 36 (1993) 651–662.
- 313 16. S. Raj, M. Pathak, M. K. Khan, An analytical model for predicting growth rate and departure
314 diameter of a bubble in subcooled flow boiling, *Int. J. Heat Mass Transfer* 109 (2017) 470-481.
- 315 17. T. Mozzocco, W. Ambrosini, R. Kommajosyula, E. Baglietto, A reassessed model for mechanistic
316 prediction of bubble departure and lift off diameter, *Int. J. Heat Mass Transfer* 117 (2018), 119-124
- 317 18. B. B. Mikic, W. M. Rohsenow, P. Griffith, On bubble growth rates, *Int. J. Heat Mass Transfer* 13,
318 657–666 (1970).

- 319 19. Y. Utaka, Y. Kashiwabara, M. Ozaki, Microlayer structure in nucleate boiling of water and ethanol at
320 atmospheric pressure, *Int. J. Heat and Mass Transfer* **57** 222 – 230 (2013).
- 321 20. D. Chen, L.M. Pan, S. Ren, Prediction of bubble detachment diameter in flow boiling based on force
322 analysis, *Nuclear Engineering and Design* **243** 263–271 (2012).
- 323 21. N. Zuber, The dynamics of vapor bubbles in nonuniform temperature fields, *Int. J. Heat Mass*
324 *Transfer* **2** (1961) 83–98
- 325 22. B. J. Yun, A. Splawski, S. Lo, , C. Song, Prediction of a subcooled boiling flow with advanced two-
326 phase flow models, *Nuclear Engineering and Design*, **253** (2012) 351-359.
- 327 23. G.E. Thorncroft,, J.F.Klausner, R. Mei, Bubble forces and detachment models. *Multiphase Science*
328 *and Technology* **13**, (2001) 35–76.
- 329 24. X. Duan, B. Phillips, T. McKrell, and J. Buongiorno. “Synchronized high-speed Video, infrared
330 thermometry, and particle image velocimetry data for validation of interface tracking simulations of
331 nucleate boiling phenomena.” *Experimental Heat Transfer* **26**, no. 2 3 169-197 (2013):
- 332 25. R. Situ, T. Hibiki, M. Ishii, M. Mori, Bubble lift-off size in forced convective subcooled boiling flow,
333 *Int. J. Heat Mass Transfer* **48** 5536–5548 (2005).
- 334 26. R.M. Sugrue, J. Buongiorno, A modified force-balance model for predicting bubble departure
335 diameter in subcooled flow boiling, in: *Proceedings of the 15th International Topical Meeting on*
336 *Nuclear Reactor Thermal-Hydraulics*, Pisa, (2013)
- 337 27. V. Prodanovic, D. Fraser, M. Salcudean, Bubble behaviour in subcooled flow boiling of water at low
338 pressures and low flow rates, *Int. J. Multiphase Flow* **28** 1–19 (2002).
- 339 28. G.G. Bartolomej, V.M. Chanturiya. Experimental study of true void fraction when boiling subcooled
340 water in vertical tubes, *Thermal Engineering* Vol. **14**, pp. 123-128, *translated from Teploenergetika*
341 Vol. **14**, 2, pp. 80-83 (1967).
- 342 29. E. Krepper, B. Koncar, Y. Egorov. CFD modelling of subcooled boiling-Concept, validation and
343 application to fuel assembly design, *Nuclear Engineering and Design* Vol. **237**,716-731 (2007)

- 344 30. E. Manon. Contribution à l'analyse et à la modélisation locale des écoulements bouillants sous-saturés
345 dans les conditions des Réacteurs à Eau sous Pression, PhD thesis, Ecole Centrale Paris, Nov. 2000
- 346 31. J. Garnier, E. Manon, G. Cubizolles. Local measurements on flow boiling of refrigerant 12 in a
347 vertical tube, *Multiphase Science and Technology*, **13**, pp. 1-111 (2001).
- 348 32. T. Frank, P. Zwart, E. Krepper, H.-M. Prasser, D. Lucas, Validation of CFD models for mono- and
349 polydisperse air–water two-phase flows in pipes, *Nuclear Engineering and Design*, **238**, 647-659
350 (2008).