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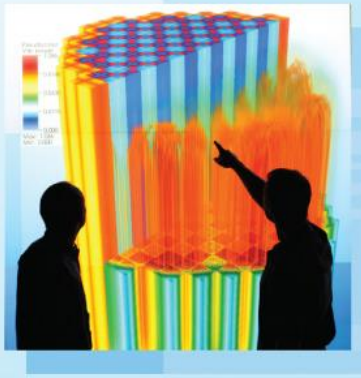

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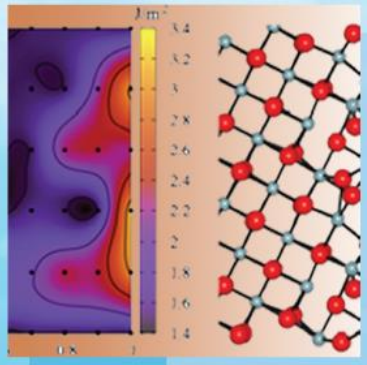

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L3:THM.CLS.P7.03 Bubble Condensation Heat Transfer in Subcooled Flow Boiling at PWR Conditions: a Critical Evaluation of Current Correlations

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Bubble Condensation Heat Transfer in Subcooled Flow Boiling at PWR Conditions: a Critical Evaluation of Current Correlations

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Abstract

Condensation of steam bubbles entrained by subcooled liquid flow plays an important role in determining the void fraction and average bubble size in the hot subchannels of Pressurized Water Reactor (PWR) fuel assemblies. Prediction of such quantities in multi-phase CFD codes requires the use of a closure relation that describes energy (heat) transfer from the vapor to liquid phase. In this study, seven correlations found in the literature are critically evaluated for their ability to predict the condensation heat transfer coefficient and bubble history in the PWR subchannels. It is found that no correlation is strictly valid within the range of the dimensionless numbers relevant to the PWR application. However, the use of the Warrier et al.'s and Kim-Park's correlations is recommended in the interim due primarily to their correct physical basis including the effects of turbulent flow, and also their relative ease of implementation in CFD codes. The development of a new correlation/model for heat transfer from condensing bubbles in PWR subchannels is also recommended, possibly through a combination of ad-hoc experiments and numerical simulations.

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1. Introduction

Boiling and condensation are important phenomena in many industrial applications including metallurgy, water desalination, power plants, refrigeration, just to mention a few. In nuclear systems, boiling occurs in all the fuel assemblies of the Boiling Water Reactor (BWR) and in the hot fuel assemblies of the Pressurized Water Reactor (PWR). Once entrained by the subcooled liquid flow, the bubbles generated in the PWR fuel assemblies also experience condensation. Evaporation and condensation differ by the direction of the moving liquid/vapor interface, and the behavior of thermal boundary layer in the region adjacent to interface. In evaporation, both the bubble interface and the thermal boundary layer expand, consequently, the ratio of the bubble radius to the thermal boundary layer thickness remains about constant. On the other hand, in condensation the bubble interface contracts and the thermal boundary layer expands, therefore the ratio of the thermal boundary layer thickness to the bubble radius continuously increases (Legendre, Borée, & Magnaudet, 1998). As such, a similarity analytical solution is not possible for condensation even for the simple situation of a single spherical bubble in a stationary subcooled liquid, let alone a realistic situation with non-spherical bubbles in a moving (possibly turbulent) fluid.

In PWRs the bubbles are generated by nucleate boiling at the heated wall (i.e. the outer surface of the fuel cladding). After nucleation, the bubble grows and then detaches from the heated wall because of a combination of drag, lift and buoyancy forces. Following detachment, energy from the surface is carried into the liquid by the motion of the steam bubbles, and later the condensation process takes place, driven by the temperature difference between the liquid phase (below saturation) and the vapor phase (at saturation)[1]. Condensation eventually leads to the collapse of the steam bubbles: the duration of the condensation process depends on the fluid properties, initial (departure) bubble diameter, temperature of the liquid, bubble/liquid slip, and the presence of turbulence in the flow. A schematic diagram of the important phenomena in subcooled flow boiling is shown in Figure 1.

In analyzing condensation heat transfer from a collapsing bubble, three thermal resistances in series can be identified: (1) the heat transfer within the steam bubble, which is usually negligible for bubbles that have detached from the wall and thus have no or little temperature gradient within the vapor phase, (2) the interfacial resistance due to the kinetic limit of condensation (i.e. vapor molecules crowding near the surface), which is also negligible (by orders of magnitude) at the condensation rates typical of PWR bubbles, and (3) convection heat transfer in the liquid, which is usually the dominant thermal resistance. The latter is expected to be strongly depended on the geometry of the bubble as well as the flow conditions surrounding the bubble. Note that because of the dynamic nature of condensation (the bubble continuously shrinks), a straight-out correlation or model for

[1] Interestingly, after detachment the bubbles may sometimes remain close to wall, thus effectively sliding along it (Basu, Warrier, & Dhir, 2005) and (Warrier & Dhir, Heat Transfer and Wall Heat Flux Partitioning During Subcooled Flow Nucleate Boiling—A Review, 2006). In these cases, both evaporation and condensation may be simultaneously present also after detachment.

convective heat transfer from a solid object (even one with the same instantaneous shape of the bubble) would not be an acceptable representation of the physical phenomena.

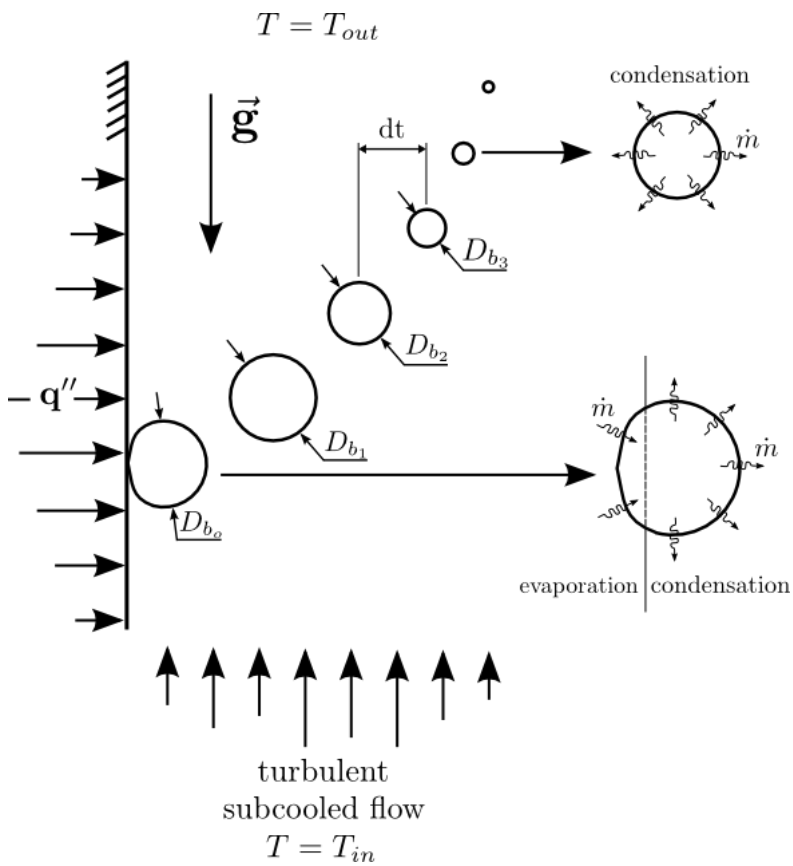


Figure 1. Schematic representation of bubble nucleation, growth, detachment and condensation in subcooled flow boiling, e.g. in the PWR hot subchannel. When the bubble is attached to the wall, evaporation and condensation take place simultaneously, at the base and head of the bubble respectively. After detachment, the condensation process leads to the eventual collapse of the steam bubble.

In multiphase CFD codes such as Hydra or STAR, which solve the phase-averaged conservation equations with a Eulerian approach, the bubble condensation process must be effectively represented by a closure relation that describes the energy (heat) transfer from the vapor to the liquid phase in the energy equations, and a corresponding mass transfer term in the mass equations. Sensitivity studies performed by the U-Michigan (Fidkowski, Asher, Drzewiecki, & Manera, 2011) for the Eulerian Multi-Phase (EMP) model in STAR-CD have indicated that important macroscopic parameters such as void fraction and pressure drop in a subcooled flow boiling channel are greatly sensitive to the diameter of the bubbles assumed in the model. Therefore, accurate prediction of the bubble size, which depends on the bubble departure diameter (initial condition) and the condensation rate, is key to the successful simulation of subcooled flow boiling.

The objective of this study is to evaluate several condensation heat transfer correlations found in the literature, to be used as closure relations in CFD codes for the prediction of PWR fuel assembly thermal-hydraulics. Since experimental data for steam bubble condensation at actual PWR conditions are not available, it is necessary to evaluate the similarities between the PWR and the existing databases and correlations through the use of dimensionless numbers.

Because of the high pressure and low surface tension of water at PWR conditions, the bubbles generated at the wall and then entrained by the subcooled liquid tend to be small, order of 100 μm and below. Therefore, in the analysis we shall assume an initial diameter at departure $D_{b0} = 100\ \mu\text{m}$. The fluid properties and operating conditions of the PWR hot channel are reported in Table 1. The relevant dimensionless numbers for the PWR bubbles are as follows:

$$\text{Reynolds: } Re_b \equiv \frac{\rho_f U_{rel} D_{b0}}{\mu_f} \approx 17$$

$$\text{Prandtl: } Pr_f \equiv \frac{c_{p,f}\mu_f}{k_f} \approx 1.4$$

$$\text{Jakob: } Ja \equiv \frac{\rho_f}{\rho_g}\frac{c_{p,f}(T_{sat}-T_{bulk})}{h_{fg}} < 2.0$$

$$\text{Bond: } Bo \equiv \frac{(\rho_f - \rho_g) g D_{b0}^{\ 2}}{\sigma} \approx 0.01$$

$$\text{Morton: } Mo \equiv \frac{g\mu_f^4(\rho_f - \rho_g)}{\rho_f^2 \sigma^3} \approx 3.4\times10^{-12}$$

$$\text{Weber: } We \equiv \frac{\rho_f U_{rel}^2 D_{b0}}{\sigma} \approx 0.005$$

where $c_{p,f}$ is the heat capacity of the liquid phase, h_{fg} is the latent heat, T_{bulk} and T_{sat} are the bulk liquid and saturation temperatures respectively; ρ_f and ρ_g are the liquid and vapor density, respectively, μ_f is the liquid viscosity, and k_f is the liquid thermal conductivity. For the Reynolds and Weber numbers, a slip velocity $U_{rel} = 0.02\ m/s$ was calculated by equating the buoyancy and drag forces on the bubble, and using the drag coefficient $c_d = 10.67/Re_b^{0.5}$ as found in (Ishii & Kataoka, 1972).

The value of the bubble Reynolds number suggests that the thermal boundary layer at the bubble surface remains laminar, although turbulent eddies exist in the bulk flow surrounding the bubble. The low values of the Bond and Weber numbers indicate that the shape of the bubble is not affected by either gravity or inertia forces, and thus it should be spherical under the effect of surface tension.

The structure of the report is as follows: the correlations are presented in Section 2, and downselected according to five selection criteria, including comparison to the experimental databases, in Section 3. The downselected correlations are applied to the bubbles in the PWR channel in Section 4. Conclusions and recommendations for future work are offered in Section 5.

Table 1. Operating conditions and fluid properties for PWR water.

Geometry	Rod bundle, D_e=11.8mm, vertical upflow	
Mass Flux [kg/m^2s]	~3700 (Re~5.9×10^5)	
Heat Flux [kW/m^2]	1000-1400	
Subcooling [°C]	10 – 30	
Property	*Sat. Liquid*	*Sat. Vapor*
ρ $[kg/m^3]$	595	101
μ $[\mu Pa \cdot s]$	73	23
c_p $[kJ/kg-K]$	9.1	13.7
k $[mW/m-K]$	448	123
σ $[mN/m]$	4.8	
h_{fg} $[kJ/kg]$	965	
T_{sat} $[K]$	617.8 (344.6°C)	
p $[MPa]$	15.5	

2. Literature review

Experimental data for bubble condensation in subcooled liquid flows are typically presented in terms of the condensation heat transfer coefficient, h_c, and the time-history of the bubble, $D_b(t)$. These two quantities are related by the instantaneous energy balance for the bubble:

$$h_{fg} A_s \rho_g d\left(\frac{D_b}{2}\right) = -h_c \Delta T A_s dt \tag{1}$$

where $A_s = \pi D_b^2$ is the area of the surface (assumed to be a sphere[2]), ΔT is the difference between the saturation temperature (temperature of the vapor) and the bulk liquid temperature, and t is time. Rearranging the equation above yields:

$$h_c = \frac{h_{fg}\rho_g}{2\Delta T}\left(-\frac{dD_b}{dt}\right) \tag{2}$$

This equation is actually used by experimentalists to estimate the heat transfer coefficient from the measured bubble history, which is typically acquired by high-speed videos. Vice versa, if the heat transfer coefficient is known from a correlation of the form:

$$Nu_c = \frac{h_c D_b}{k_f} = f(Re_b, Pr_f, Ja) \tag{3}$$

[2] If the bubble is not spherical, Eq. 1 is still valid but the bubble Sauter diameter has to be used instead of D_b.

then Eq. 2 becomes a first order ordinary differential equation in the only unknown D_b, which can be solved either analytically, if Eq. 3 is algebraically simple (see Appendix A), or numerically, e.g. with the Runge-Kutta method.

Table 2 lists the seven condensation heat transfer correlations analyzed in this study, their respective databases and reported range of applicability. They will be presented next and briefly discussed one at a time.

Table 2. Correlations commonly used for prediction of bubble condensation in subcooled flow boiling.

Reference	Dispersed phase	Continuous phase	Shape of dispersed phase	Correlation applicability	Comments
PWR hot channel	Steam bubbles	Water	Small, spherical	$0.9<Pr_f<1.4$, $Re_b\sim17$, $Ja<2$, $D_b\sim0.1$ mm	Representative operating conditions
Ranz and Marshall, 1952	Water droplets	Air	Spherical	$Re_b<200$, 0.6 mm$<D_b<$1.1 mm	Developed for evaporating droplets
Florschuetz and Chao, 1965	Steam/Ethyl Alcohol vapor bubbles	Water/Ethyl Alcohol	Spherical	$10<Ja<40$, 3 mm$<D_b<$9 mm	Stationary bubble (no slip) in stagnant liquid
Hughmark, 1967	Solid sphere	Water and many others	Spherical	$1<Re_b<10000$, $Pr_f<250$	Rigid spheres, no phase change
Chen and Mayinger, 1992	Propanol, ethanol, steam, R113 vapor bubbles	Propanol, ethanol, water, R113	Spherical and non-spherical	$Re_b<10000$, $2<Pr_f<15$, $Ja<80$	No turbulent flow
Zeitoun et al., 1995	Steam bubbles	Water	Spherical and non-spherical	$2500<Re_b<9000$, 2 mm$<D_b<$8 mm, $1.5<Pr_f<1.8$, $8<Ja<34$	Effect of multi-bubble mixing included, Turbulent flow
Warrier et al., 2002	Steam bubbles	Water	Spherical and non-spherical	$20<Re_b<700$, $12<Ja<100$, $Nu_c>2$, $1.8<Pr_f<2.9$	Turbulent flow
Kim and Park, 2011	Steam bubbles	Water	Non-spherical	$1.87<Pr_f<2.03$, $18<Ja<36$, 0.8 mm$<D_b<$6 mm, $700<Re_b<7500$	Turbulent flow

The pioneer experimental work of (Ranz and Marshall, 1952) on evaporation of spherical water droplets suspended in upward flow of dry air resulted in the development of a heat transfer correlation, which is still widely used in CFD codes:

$$Nu_c = 2 + 0.6Re_b^{1/2}Pr_f^{1/3} \tag{4}$$

The correlation is valid for $Re_b \leq 200$, and correctly reproduces the conduction limit ($Nu_c = 2$) for $Re_b \to 0$. Equation 4 is often taken as the starting point for more sophisticated correlations. The Ranz-Marshall correlation probably owes its popularity to its simplicity and easiness of implementation in codes. However, it was not developed for condensing bubbles. A modified version of the Ranz-Marshall correlation is often encountered in the literature (e.g., Warrier, Basu and Dhir, 2002):

$$Nu_c = 0.6Re_b^{1/2}Pr_f^{1/3} \tag{5}$$

The only advantage of Eq. 5 over Eq. 4 is that with the former a simple integration of Eq. 1 is possible to obtain the bubble diameter history analytically (see Appendix A).

Florschuetz and Chao (1965) obtained an analytical solution to describe a spherical bubble collapsing in a stagnant subcooled fluid when the rate of collapse is assumed to be dominated by heat transfer (vs. inertia). The variation of the condensation Nusselt number in terms of Jakob number and the dimensionless instantaneous bubble diameter $\beta \equiv \frac{D_b}{D_{b0}}$ is given by:

$$Nu_c = \frac{12}{\pi} Ja \frac{\beta^3}{(1-\beta^3)} \tag{6}$$

An investigation of heat transfer from rigid spheres (no phase change) was performed by Hughmark (1967), for a broad range of Reynolds and Prandtl numbers. The resulting equations are:

$$Nu_c = 2 + 0.6Re_b^{1/2}Pr_f^{1/3} \tag{8}$$

valid for $1 < Re_b < 450$ and $Pr_f < 250$, and

$$Nu_c = 2 + 0.27Re_b^{0.62}Pr_f^{1/3} \tag{9}$$

valid for $450 < Re_b < 10000$ and $Pr_f < 250$.

Chen and Mayinger (1992) studied condensation of vapor bubbles in slow flowing liquid ethanol, propanol, refrigerant R113 and water. They concluded that for low values of the Jakob number ($Ja < 80$) the condensation process is controlled by heat transfer in the liquid phase near the interface, while at higher values of the Jakob number ($Ja > 100$), liquid inertia limits the rate of bubble collapse. The data for the heat-transfer-dominated regime were correlated as follows:

$$Nu_{c0} = 0.185Re_{b0}^{0.7}Pr_f^{0.5} \tag{10}$$

where the Nusselt and Reynolds numbers are defined in terms of the initial bubble diameter. The range of applicability is $D_{b0} < 6$ mm, $2 < Pr_f < 15$, $Ja < 80$, and $Re_b < 10000$.

Zeitoun, Shoukri and Chatoorgoon (1995) studied steam bubble condensation in subcooled bubbly flow of water at near-atmospheric pressure in vertical conduits. They developed a correlation for the instantaneous Nusselt number as follows:

$$Nu_c = 2.04 Re_b^{0.61} Ja^{-0.308} \alpha_v^{0.328} \tag{11}$$

Note that α_v is the local value of the void fraction, which accounts for the mixing effect of multiple bubbles, and must be known from other means, i.e., a void fraction correlation/model or, in the case of a CFD calculation, solution of the conservation equations. Equation 11 is based on a database with the following ranges: $2\,mm < D_{b0} < 8\,mm$, $1.5 < Pr_f < 1.8$, $8 < Ja < 34$, $2500 < Re_b < 9000$, $0.01 < \alpha_v < 0.25$. Turbulence was present in the experiments with a test section Reynolds number ranging from 6,000 to 26,000. Unfortunately, Eq. 11 does not have an explicit dependence on the Prandtl number, which makes it difficult to extrapolate beyond its narrow database.

Warrier, Basu & Dhir (2002) developed a semi-empirical correlation for bubble condensation in subcooled flow boiling, based on their experimental data for steam bubbles in turbulent flow at atmospheric pressure. The model combines a Ranz-Marshall-type dependence on the bubble Reynolds number and the liquid Prandtl number, with a time-dependent term accounting for the thickening of the thermal boundary layer due to the condensation process:

$$Nu_c = 0.6 Re_b^{1/2} Pr_f^{1/3} \left(1 - 1.2 Ja^{9/10} Fo_0^{2/3}\right) \tag{12}$$

where $Fo_0 \equiv \frac{\alpha t}{{D_{b0}}^2}$ is the Fourier number, t is time after the start of bubble condensation, and $\alpha \equiv k_f / \rho_f C_{p,f}$ is the thermal diffusivity. According to the experimental database is based on, Eq. 12 is applicable in the following ranges: $20 < Re_b < 700$, $1.8 < Pr_f < 2.9$, $12 < Ja < 100$, and channel Reynolds number between 30,000 and 100,000.

Kim and Park (2011) investigated the interfacial heat transfer of large non-spherical condensing steam bubbles in subcooled turbulent flow of water at low pressure in vertical conduits. The data were correlated as follows:

$$Nu_c = 0.2575 Re_b^{0.7} Pr_f^{-0.4564} Ja^{-0.2043} \tag{13}$$

The range of applicability of the above equation is limited to $1.87 < Pr_f < 2.03$, $18 < Ja < 36$, 0.8 mm$< D_b <$6 mm, $700 < Re_b < 7500$, and channel Reynolds number between 4,000 and 5,000. Note that the negative exponent for the Prandtl number is contrary to physical expectation and probably an artifact of the very narrow range of Prandtl numbers explored in the study.

3. Correlation evaluation and down-selection

Here we evaluate the correlations discussed in Section 2 with respect to their ability to predict bubble condensation heat transfer in the PWR application. Ultimately, we wish to select one or more correlations that can be implemented in a multiphase CFD code such as Hydra or STAR. The selection criteria are as follows:

1) The correlation should be based on a database that includes condensing bubbles, not only rigid spheres or droplets
2) The correlation should be based on a database in which turbulent flow (not stagnant liquid or laminar flow) is present
3) The correlation should be reasonably accurate in reproducing the existing databases
4) The correlation applicability range, expressed in terms of the dimensionless numbers (Re_b, Pr_f, Ja), should overlap with the PWR range
5) The correlation should be simple to use and implement in a multiphase CFD code that solves the Eulerian phase-averaged conservation equations

A summary is shown in Table 3 and a brief discussion of each criterion follows.

Table 3. Comparison of correlations to selection criteria.

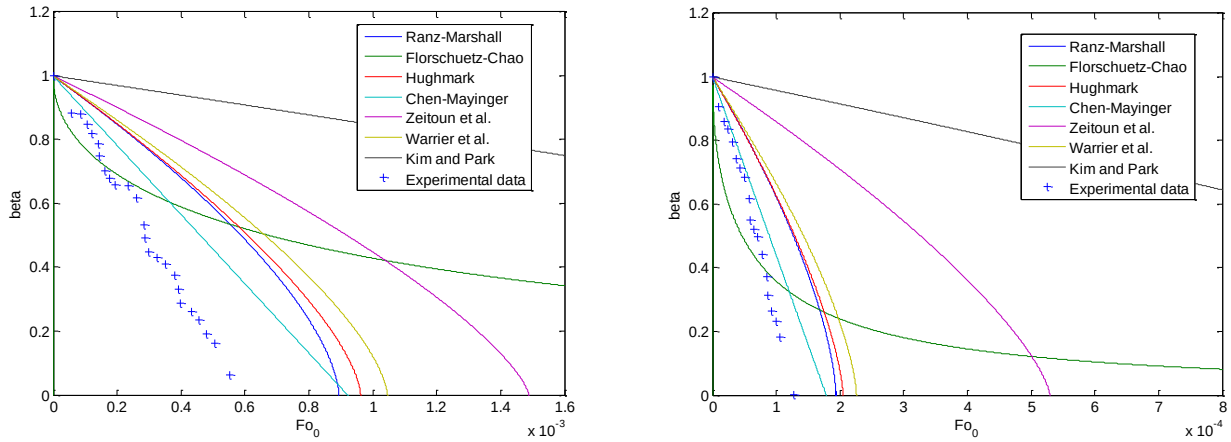
Reference	Criterion 1	Criterion 2	Criterion 3*	Criterion 4	Criterion 5
Ranz and Marshall, 1952	No	Yes	C-M: 81% K-P: 49% Z: 19%	No	Yes
Florschuetz and Chao, 1965	Yes	No	C-M: 56% K-P: 44% Z: 24%	No	Yes
Hughmark, 1967	No	No	C-M: 82% K-P: 54% Z: 27%	No	Yes
Chen and Mayinger, 1992	Yes	No	C-M: 51% K-P: 59% Z: 35%	No	Yes
Zeitoun et al., 1995	Yes	Yes	C-M: 115% K-P: 31% Z: 22%	No	Yes
Warrier et al., 1995	Yes	Yes	C-M: 89% K-P: 40% Z: 13%	No	No
Kim and Park, 2011	Yes	Yes	C-M: 144% K-P: 6% Z: 7%	No	Yes

* average error |exp. – calc.|/calc. for the databases of Chen-Mayenger (C-M), Kim-Park (K-P) and Zeitoun et al. (Z)

As explained in the introduction, bubble condensation is fundamentally different from droplet evaporation or single phase convection off a rigid sphere because of the establishment of a time-dependent thermal boundary layer due to the shrinking interface. Therefore, Criterion 1 disqualifies the Ranz-Marshall and Hughmark correlations, which were developed for evaporating droplets and rigid spheres, respectively.

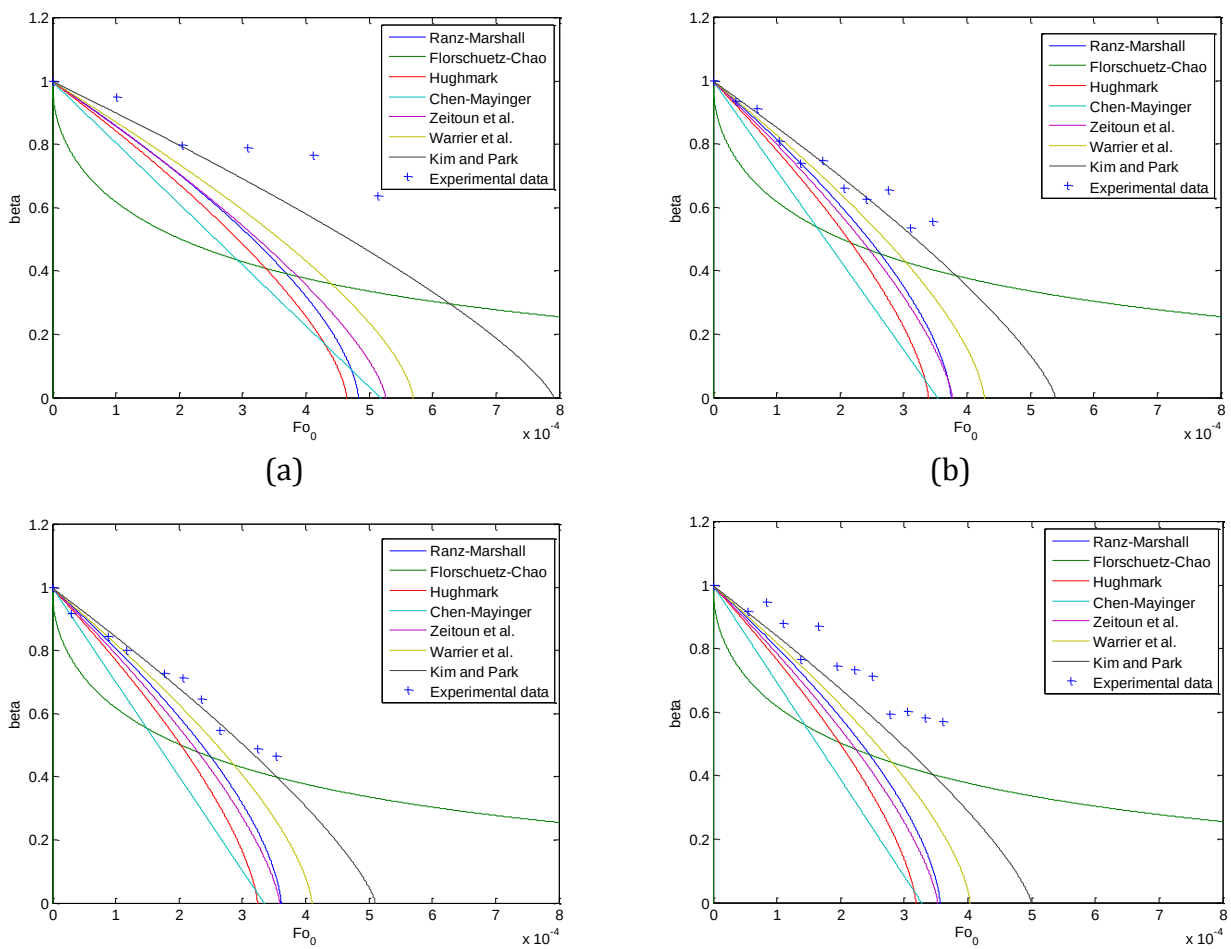
Criterion 2 actually refers to two separate physical phenomena: first, at sufficiently high *channel* Reynolds numbers (Re>2500) turbulent eddies are present in the bulk of the liquid approaching and surrounding the bubble; second, at sufficiently high *bubble* Reynolds numbers ($Re_b \sim 10^5$) the boundary layer around the bubble transitions from laminar to turbulent, which increases the heat transfer coefficient locally. Since the bubble Reynolds number in the PWR situation is low ($Re_b \approx 17$) but the channel Reynolds number is very high ($Re \sim 5.9\times10^5$), correlations that are derived from data without bulk turbulence should not be used for the PWR calculations. This disqualifies also the Chen-Mayenger and Florschuetz-Chao correlations.

Criterion 3 calls for reasonable accuracy in reproducing the available experimental databases. In the literature we found only three bubble condensation databases that provide sufficient information to allow a quantitative comparison to the correlations: the Chen-Mayenger's data, the Zeitoun et al.'s data and the Kim-Park's data. Figure 3 shows the dimensionless bubble diameter vs. the dimensionless time (Fourier number) for two bubbles in the Chen-Mayenger's database. All correlations tend to underestimate the condensation rate. Not surprisingly, the Chen-Mayenger correlation (which is derived from this database) displays the lowest deviations from the data. The Chen-Mayenger correlation also captures the approximately linear decay exhibited by the experimental data, which, from Eq. 2, suggests a constant heat transfer coefficient throughout the process. Note that a constant heat transfer coefficient implies an approximately constant thickness of the thermal boundary layer, hence an increase of the boundary layer thickness to bubble diameter ratio, consistent with the discussion in the Introduction. The correlations of Ranz-Marshall, Warrier et al. and Highmark are also reasonably close to the data. The Florschuetz-Chao correlation displays a positive concavity: this correlation does not include the effect of liquid motion around the bubble, thus the thermal boundary layer is allowed to grow un-physically large as the bubble diameter becomes smaller and smaller. Figure 3 shows again the bubble diameter history for six bubbles in the Zeitoun et al.'s database. Here all correlations are reasonably good, except the Florschuetz-Chao correlation, with the Kim-Park correlation being the most accurate. Figure 4 shows the bubble diameter history for one bubble in Kim-Park database. All correlations seem to overestimate the condensation rate, except for the Kim-Park correlation, which is rather accurate, not surprisingly since it was derived from this database. Finally, the bubble history error statistics for all correlations are reported in Table 3. We conclude that none of the correlations analyzed is accurate across the board. It should be kept in mind that the error statistics are biased by the use of Chen-Mayenger's, Zeitoun et al.'s and Kim-Park's databases, which tends to favor the respective correlations in the comparison.



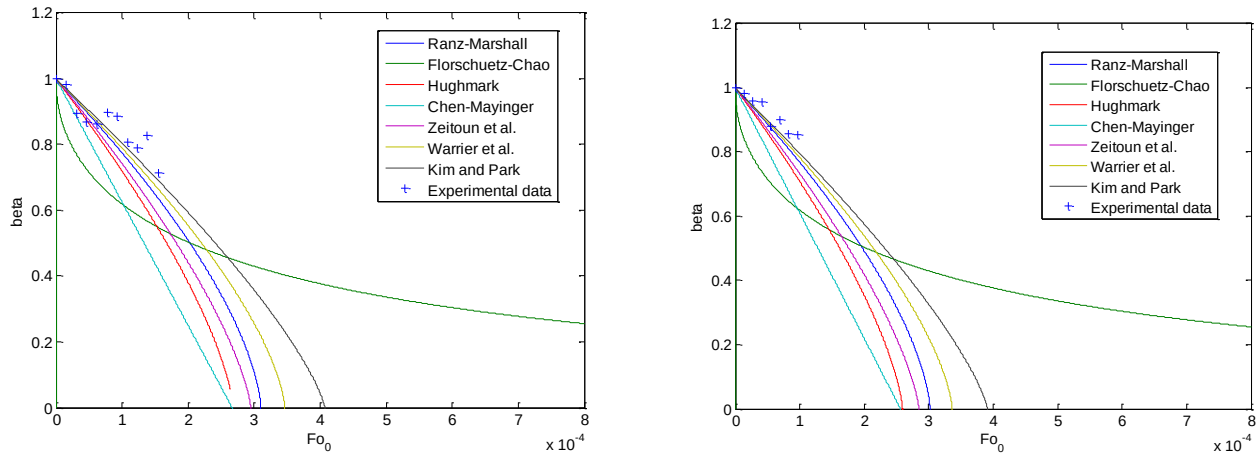
(a) (b)

Figure 2. Bubble diameter history (dimensionless diameter vs dimensionless time) from correlations and Chen and Mayinger's dataset. (a) $Ja = 11$, $Pr_f = 6.7$, $Re_{b0} = 750$, (b) $Ja = 42$, $Pr_f = 9.6$, $Re_{b0} = 893$ (figure best viewed in color)



(a) (b)

(c) (d)



(e) (f)

Figure 3. Bubble diameter history (dimensionless diameter vs dimensionless time) from correlations and Zeitoun et al.'s dataset; $Ja = 20, Pr_f = 1.5$and $\alpha_v = 0.06$ for all cases. (a) $Re_{b0} = 2100$, $D_{b0} = 1.81mm$ (b) $Re_{b0} = 3615$, $D_{b0} = 3.13mm$ (c) $Re_{b0} = 3916$, $D_{b0} = 3.39mm$ (d) $Re_{b0} = 4037$, $D_{b0} = 3.50mm$ (e) $Re_{b0} = 5408$, $D_{b0} = 4.69mm$ (f) $Re_{b0} = 5724$, $D_{b0} = 4.96mm$ (figure best viewed in color)

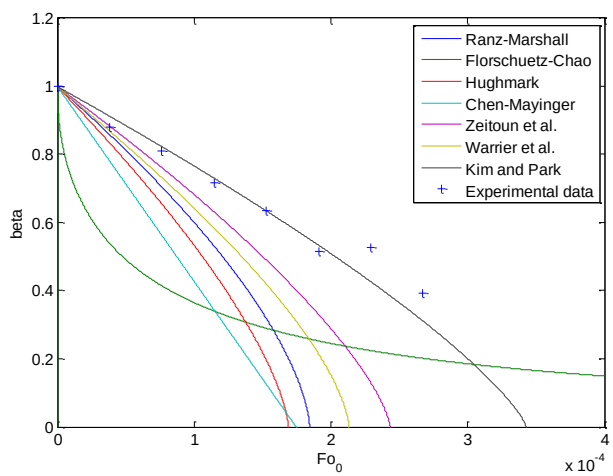


Figure 4. Bubble diameter history (dimensionless diameter vs dimensionless time) from correlations and Kim-Park's dataset. $Ja = 41, Pr_f = 1.7, Re_{b0} = 3254$ (figure best viewed in color)

Per Criterion 4, in order to extrapolate an empirical correlation beyond its database confidently, it is necessary to establish a similarity in terms of the dimensionless numbers (Re_b, Pr_f, Ja). Inspection of the dimensionless number ranges reported in Table 2 suggests that none of the correlations completely overlaps with the PWR situation, the correlations of Chen-Mayenger and Warrier et al. being the closest two.

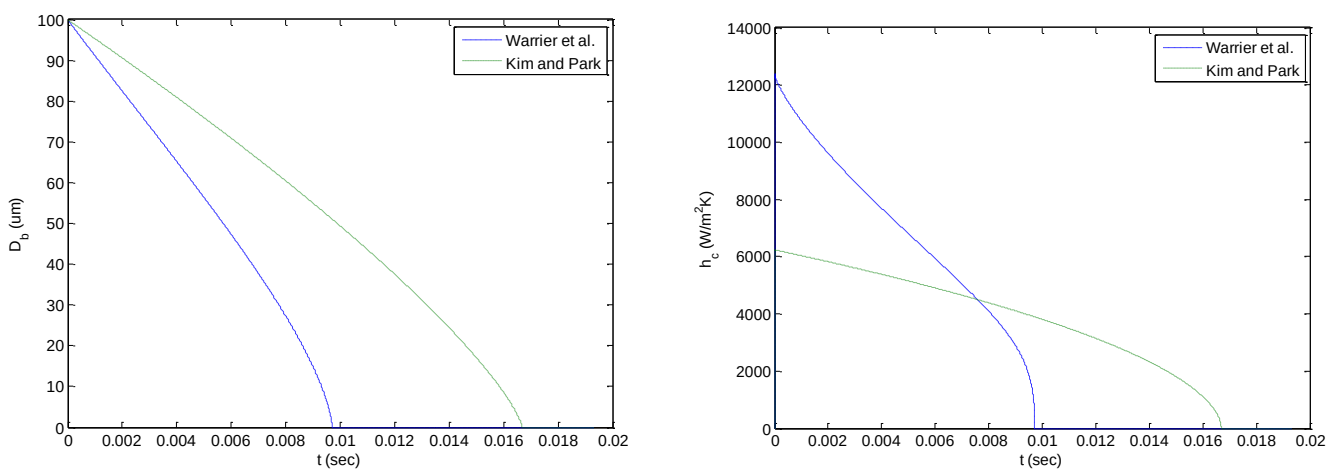
All the correlations considered here are algebraically simple (Criterion 5). Correlations that are time-independent are easier to implement in a multiphase CFD code that takes a

Eulerian approach in which individual bubbles are not resolved or followed as separate objects. Therefore, the correlation of Warrier et al. with an explicit dependence on time is not particularly convenient for implementation in such codes. However, this correlation can be recast in terms of initial bubble parameters, through a simple time integration (Appendix B).

In summary, none of the correlations considered in the present study satisfies all five postulated selection criteria. This highlights the need for further research to develop a bubble condensation correlation or model that is validated for PWR applications. However, pending the development of such new correlation/model, we recommend the use of the Warrier et al.'s and Kim and Park's correlations as interim predictive tools because they were developed specifically for condensing bubbles in subcooled turbulent flow, and unlike the Zeitoun et al.'s correlation, do not require prior knowledge of the local void fraction.

4. Application to PWR conditions

Here we use the Warrier et al.'s and Kim-Park's correlations, selected in Section 3, to estimate the order of magnitude of the heat transfer coefficient and the time to bubble collapse for the PWR bubbles. Figures 5a and 5b show the time evolution of the bubble diameter and the heat transfer coefficient for the PWR conditions, respectively. Note the large discrepancy among the predictions, which emphasizes on one hand the sensitivity of the calculated bubble diameter history to the assumed heat transfer coefficient, and on the other hand the uncertainty that can be expected in predicting the behavior of condensing bubbles at PWR conditions. The time to bubble collapse in the PWR application is order of 10 ms, and the heat transfer coefficient is order of 10 kW/m^{2}s.



(a) (b)

Figure 5. (a) Bubble diameter history and (b) condensation heat transfer coefficient for the PWR bubbles: $Ja = 2$, $Pr = 1.4$, $Re = 17$.

5. Conclusions and future work

In this study, we performed an analysis of seven empirical correlations found in the literature for prediction of the bubble condensation heat transfer coefficient in subcooled flow boiling. The current standard tool for prediction of bubble-to-liquid heat transfer is the Ranz-Marshall correlation, which actually was developed for heat transfer from spherical evaporating droplets, not condensing bubbles. Bubbles entrained by the coolant flow in a PWR channel are indeed near-spherical, but the liquid phase surrounding them is laden with turbulent eddies; therefore use of the Ranz-Marshall correlation is not physically appropriate. Similarly, none of the other correlations is rigorously applicable to the PWR situation either because of the inadequacy of their physical basis, or lack of appropriate validation in the range of dimensionless parameters relevant to the PWR. The correlations of Warrier et al. and Kim-Park are recommended as interim predictive tools.

Future work should include the following:

- Implement Warrier et al.'s and Kim-Park's correlations into Hydra. Since Hydra uses a Eulerian approach, we recommend to eliminate the explicit time dependence in the correlation of Warrier et al. by recasting it in terms of the initial parameters, as shown in Appendix B.
- Use Warrier et al.'s and Kim-Park's correlations correlation to conduct sensitivity studies of PWR channel-averaged flow parameters such as pressure drop and void fraction with respect to the bubble condensation heat transfer coefficient. This will motivate (or disprove) the need for a new, higher-fidelity, bubble condensation heat transfer correlation that is fully validated for the PWR bubbles.
- Generate a PWR-relevant database for the development of a new correlation applicable to the PWR bubbles. The database could be experimental, numerical or a combination of both:
    - Obvious challenges exist in conducting experimental measurements of bubble condensation heat transfer at the prototypical high pressure (>15 MPa) and temperature (>300°C) conditions of the PWR. Particularly difficult is the direct visualization of the small condensing bubbles (required to estimate the heat transfer rate) through viewing windows that would have to withstand such pressures and temperatures. However, through the use of alternative fluids (e.g., refrigerants), and careful control of the initial bubble size (via injection nozzles vs. boiling), the dimensionless numbers of the PWR situation (Re_b<20, Pr_f~1, Ja<2) can be reasonably approximated at pressures and temperatures that are more easily manageable in the lab.
    - The use of numerical simulations based on Interface Tracking Methods (ITM) such as Volume Of Fluid, Level-Set or Front Tracking, is promising because of the freedom a numerical approach affords in choosing the fluid properties, channel geometry and flow conditions. These methods can resolve the liquid/vapor interface and, combined with Direct Numerical Simulations (DNS) or Large Eddy Simulations (LES), can also capture the effects of turbulence. The idea is to run a set of simulations over a range of dimensionless numbers sufficiently broad to enable the extraction of trends, and thus the development of a simple (algebraic) bubble condensation heat transfer correlation, which would then be used in CFD codes such

as Hydra. However, ongoing work within CASL has shown that, at the present time, ITMs are not sufficiently mature for simulations of physical phenomena in which phase change plays a dominant role, such as boiling and condensation.

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Appendix A - Analytical expression for the time-history of the bubble diameter

If the condensation heat transfer correlation is algebraically simple, an analytical solution for the bubble diameter history $D_b(t)$ can be obtained readily. Let us assume the following functional form for the correlation:

$$Nu_c = \frac{h_c D_b}{k_f} = a_1 Re_b^{a_2} Pr_f^{a_3} Ja^{a_4} \tag{A.1}$$

where a_1, a_2, a_3 and a_4 are coefficients that depend on the correlation. (Note that not all correlations analyzed in this study fit the form of Eq. A.1.) Starting from the energy balance for the bubble (Eq. 1), using the definition of Re_b and rearranging the equation with respect to D_b yields:

$$D_b^{(1-a_2)}(-dD_b) = 2a_1 \left(\frac{\rho_f U_{rel}}{\mu_f}\right)^{a_2} Pr_f^{a_3} Ja^{1+a_4} \alpha \, dt \tag{A.2}$$

where $\alpha \equiv k_f/\rho_f C_{p,f}$ is the thermal diffusivity. Since the temperature range of interest in bubble condensation is typically small, the fluid properties can be assumed constant. Thus, the above equation can be easily integrated with respect to the bubble diameter and time:

$$\int_{D_{b,0}}^{D_b(t)} D_b^{(1-a_2)}(-dD_b) = 2a_1 \left(\frac{\rho_f U_{rel}}{\mu_f}\right)^{a_2} Pr_f^{a_3} Ja^{1+a_4} \alpha \int_{t=0}^{t} dt \tag{A.3}$$

which, after some algebra, becomes:

$$1 - \frac{D_b^{2-a_2}}{D_{bo}^{(2-a_2)}} = 2a_1(2-a_2) \left(\frac{\rho_f U_{rel}}{\mu_f}\right)^{a_2} Pr_f^{a_3} Ja^{1+a_4} \alpha t \frac{D_{bo}^{a_2}}{D_{bo}^2} \tag{A.4}$$

Introducing the definitions $\beta \equiv D_b/D_{bo}$, $Fo_0 \equiv \alpha t/D_{bo}^2$ and $Re_{bo} \equiv \rho_f U_{rel} D_{bo}/\mu_f$, the general analytical expression for the bubble history may be written as:

$$\beta = \left[1 - 2a_1(2-a_2) Re_{bo}^{a_2} Pr_f^{a_3} Ja^{1+a_4} Fo_0\right]^{\frac{1}{2-a_2}} \tag{A.5}$$

Appendix B – Elimination of time-dependence from the correlation of Warrier et al.

The explicit time-dependence of the Warrier et al.'s correlation is inconvenient for implementation in a Eulerian CFD code. It can be eliminated by integrating the condensation heat transfer coefficient over the lifetime of the bubble:

$$\bar{h}_c \equiv \frac{1}{\tau}\int_0^{\tau} h_c(t)dt \tag{B.1}$$

where τ is the time to bubble collapse. Using Eq. 2 (energy balance), the integral above becomes:

$$\bar{h}_c = \frac{1}{\tau}\int_{D_{b0}}^{0} \frac{h_{fg}\rho_g}{2\Delta T}(-dD_b) = \frac{h_{fg}\rho_g D_{b0}}{2\tau\Delta T} \tag{B.2}$$

which can be re-written in dimensionless form as follows:

$$\overline{Nu}_c \equiv \frac{\bar{h}_c D_{b0}}{k_f} = \frac{1}{2\,Ja\,Fo_\tau} \tag{B.3}$$

where $Fo_\tau \equiv \frac{\alpha\tau}{D_{b0}^2}$ is the dimensionless time to bubble collapse. Fo_τ can be found by substituting Eq. 12 into Eq. 2, integrating and setting $D_{b0} = 0$:

$$1 = 1.8\,Re_{b0}^{1/2} Pr_f^{1/3} Ja\,Fo_\tau\left(1 - 0.72 Ja^{9/10} Fo_\tau^{2/3}\right) \tag{B.4}$$

Once Fo_τ is found from Eq. B.4 (a non-linear algebraic equation), the heat transfer coefficient in Eq. B.3 becomes a function of only the initial diameter D_{b0}, fluid properties and other input parameters.