Numerical analysis of the bubble detachment diameter in nucleate boiling

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Abstract. The present paper presents a tri-dimensional CFD (Computational Fluid Dynamics) model to investigate the fluid flow around bubbles attached to heated walls. Transient solutions of the governing field equations in a domain containing the bubbles and the surrounding liquid have been obtained. The nucleation, growing and detachment processes have been analyzed. Concerning the software, the open source OpenFOAM has been used. Special attention has been given to the bubble detachment diameter. Two mechanisms have been considered as physically related to the detachment: surface tension and buoyancy. As expected, it has been verified that the bubble detachment diameter depends on the contact angle, operating pressure and properties of the fluid. Several fluids have been considered (water, R134a, ammonia and R123), as well as several operating pressures (between 0.1 and 10 bar) and contact angles (between 10 and 80º). It has been concluded that the detachment diameter depends strongly on the contact angle and fluid properties and slightly on the pressure. A correlation for the bubble detachment diameter has been developed based on the obtained numerical results. Data from this expression compare reasonably well with those from other correlations from the literature.

1. Introduction
Nucleate boiling is one of the most efficient modes of heat transfer. It takes place in many high-flux engineering applications, such as nuclear, refrigeration, chemical processing, etc. Ever since the first investigations on nucleate boiling appeared, about the thirties of last century, one of the research objectives has been to characterize the bubble detachment diameter. This is function of the forces actuating on a bubble, i.e., inertia, drag, buoyancy and surface tension. Surface tension holds the bubble to the wall, while inertia, drag and buoyancy pull it from the wall. When the bubble grows large enough, the detachment forces dominate and the bubble departures from the heating surface.

The first researcher who formulated a correlation for the bubble detachment diameter was Fritz [1]. Neglecting inertia and drag forces, he proposed an expression based on a balance between buoyancy and surface tension. Cole and Shulmann [2] obtained experimental data on toluene at 48 mmHg, acetone at 222 and 461 mmHg, carbon tetrachloride at 138 mmHg, n-pentane at 524 and 760 mmHg, methanol at five pressures ranging from 134 to 540 mmHg and water at five pressures ranging from 50 to 360 mmHg. From these data, Cole and Shulmann proposed an expression which takes into account the pressure and forces of surface tension and buoyancy. Cole [3] studied acetone, carbon tetrachloride, methanol, n pentane, water, nitrogen and carbon tetrachloride at pressures ranging from 50 to 760 mmHg. He proposed a correlation based on the Jakob number (which represents a relation between the sensible and latent heat) and forces of surface tension and buoyancy. Cole and Rohsenow [4] proposed a similar expression for the bubble detachment diameter. Kutateladze and Gogonin [5]
studied data of water, ethyl alcohol, nitrogen, methyl alcohol, n-pentane, benzene and refrigerant R12. They proposed an expression which involves the forces of inertia and surface tension, the Jakob number and the viscosity of the liquid and vapor. Jensen and Memmel [6, apud Ribatski] proposed a similar expression.

In recent years, advancements in computer hardware have made CFD more efficient in modeling bubble growth and detachment. One can refer to publications by Dhir and co-workers [7-11] and Stephan and co-workers [12-14]. Other numerical studies about bubbles growth are those by Miller et al. [15], Bazdidi-Tehrami and Zaman [16], Luo et al. [17], Tanguy et al. [18] and Gibou et al. [19].

In the present paper, a new correlation for the bubble detachment diameter is proposed based on data obtained from a boiling model numerically solved. The proposed correlation is compared with other from the literature. Present correlation results are closer to those from the Jensen and Memmel [6] correlation, though being mostly higher than those from the other correlations. Though most of the correlations from the literature are contact angle independent, the comparison has been made for a range of contact angles of 10º around an average of 54º.

2. Mathematical model

2.1. Problem definition

The purpose of the present paper is to present a numerically developed bubble detachment correlation based on data resulting from a bubble growth mathematical model. This model considers a vapour nucleus seated on a heated wall and immersed in a pool of liquid. The following are a set of basic assumptions made in the model development:
- Incompressible and laminar flow.
- Constant properties (except surface tension).
- Vapor phase at saturation temperature.
- Constant wall temperature.
- Boussinesq approximation.

2.2. Governing equations

The computational domain has been divided into micro and macro-regions, as shown in Fig. 1 (a). The macro-region includes the heated wall, the pool of liquid and the bubble. On the other hand, the micro-region is modeled as a highly superheated thin layer of liquid located under the bubble which extends over a region close to the three phase contact point. In spite of its small size, evaporation in the micro-region is intense and is responsible for a fair amount of heat removal from the wall [11-15].

![Figure 1](image-url)  
**Figure 1.** (a) Computational domain: the micro and the macro-region; (b) Schematic representation of the micro-region along with physical parameters
2.2.1. Micro-region

The micro-region involves a layer of liquid of very small thickness, as illustrated in Fig. 1 (b). As a result, it is modeled separately of the macro-region, which is of much larger extent. The micro-region model is based on the following effects/assumptions:

(i) Curvature and evaporation are considered at the liquid-vapor interface.
(ii) Momentum equation is based on the lubrication theory.
(iii) Solid-liquid attraction effects are included in the Laplace type of equation which expresses the relation between the vapor and liquid pressures at the interface.
(iv) Thermal convection is deemed negligible, not so with thermal conduction effects in the thin liquid layer.

Figure 1 (b) displays a schematic representation of the micro-region including the main physical parameters. The model is reduced to a set of four ordinary differential equations in terms of radial coordinate and involving the superheated liquid thickness, liquid-vapor interface temperature and rate of mass transfer at the interface. The boundary conditions at the micro-region are the following.

\[ \delta = \delta_0, \quad \frac{\partial \delta}{\partial r} = 0, \quad q = 0 \quad \text{at} \quad r = R_0 \]  

\[ tg(\phi) = \frac{\gamma|_{\delta=\delta_0} - \gamma|_{\delta=R_1}}{R_1 - R_0} \]  

where \( \delta \) is the thickness of the micro-layer, \( \delta_0 \) the thickness at the beginning of the microlayer, \( R_0 \) and \( R_1 \) the radiuses over which the micro-layer extends over the heated surface, \( q \) the heat transferred and \( \phi \) the contact angle.

Details of the micro-region model can be found in Stephan and Busse [20], Stephan and Hammer [21] and Lamas [22].

The set of differential equations has been solved by a fourth order Runge Kutta procedure. The resulting parameters allow the determination of the rate of heat transfer at the wall in the micro-region, which is given by the following expression:

\[ \dot{Q}_{micro} = \int_{R_0}^{R_1} 2\pi r k(\frac{T_w - T_{int}}{\delta}) \, dr \]  

where \( T_w \) is the wall temperature and \( T_{int} \) the interface temperature. The superheated liquid from the micro-region evaporation rate can then be determined by the following equation:

\[ \dot{V}_{micro} = \frac{\dot{Q}_{micro}}{\rho h_b} \]  

The evaporation rate is an input parameter from the micro-region into the macro-region.

2.2.2. Macro-region

The macro-region governing equations are the three field equations: conservation of mass, momentum and energy. The liquid-vapor interface has been modeled by the so called “level set” method, developed by Osher and Sethian [23]. The method consists on assigning a scalar parameter, \( \phi \), to the distance from the interface. The interface is then characterized by a value of \( \phi \) equal to zero. The advection of \( \phi \) is given by the following equation:
$$\frac{\partial \phi}{\partial t} + u_{\text{int}} |\nabla \phi| = 0 \quad (5)$$

where $u_{\text{int}}$ is the interface velocity, obtained from the continuity at the interface:

$$\vec{m} = k \nabla T = \rho \left( u_{\text{int}} - u \right) \rightarrow u_{\text{int}} = u + \frac{1}{\rho} \frac{k_\iota \nabla T}{h_i} \quad (6)$$

where $\rho$ and $u$ are the density and the velocity at the interface of either the liquid or the vapor phase.

More details about the level set procedure applied in the present work can be found elsewhere [7,8,9,10,11,24].

2.3. Numerical procedure

The problem has been solved by the open code OpenFOAM (Open Field Operation and Manipulation), based on the finite volume procedure. The mesh consists of 3,200,000 hexahedral elements, refined in the zone close to the wall. The pressure-velocity coupling has been treated using the PISO (Pressure Implicit Splitting of Operators) procedure. The equations have been discretized by the QUICK interpolation and the temporal treatment has been solved by an implicit method (i.e., which involves the derivatives of the next time level) has been used. The main advantage of the implicit approach is that the stability can be maintained over much large values of the time step. Hence, considerable fewer time steps are needed, what reduces the computer time. The solution has been checked for refinements sensibility on both the mesh size and the time step. In addition, several tests have been performed in order to determine the adequate extent of the numerical domain in such a way to eliminate any potential effect of the outer boundaries (theoretically at infinity) on the flow close to the bubble. The maximum velocity has been the variable to characterize the sensibility of the problem to variations of the time step, size mesh and dimensions of the domain. The computation time of each simulation has been 26 hours using 8 Intel Core i-7 processors running on a 64-bits Linux operating system.

3. Results

From the numerical point of view, the bubble leaves the heating surface from the instant when it does not touch it any longer. This instant has been determined by following closely the growing of the bubble from the numerical solution. At the detachment, the bubble shape is not spherical, what requires the determination of an equivalent spherical diameter, which is the one corresponding to a sphere of volume equal to that of the detaching bubble. The actual detaching volume is determined from the numerically obtained bubble shape.

Detachment diameters have been obtained through an extensive numerical investigation for different conditions such as pressure, contact angle and four fluids: R718 (water), R717 (ammonia), R134a and R123. Numerical results have been evaluated by experimental ones obtained by Mukherjee [11] for water at atmospheric pressure. Details of this validation process can be found elsewhere [22, 24].

3.1. Effects of contact angle and pressure on the detachment diameter

The bubble detachment diameter has been investigated since the early trials to model nucleate boiling in the thirties. The simple model by Fritz [1] obeys a common sense treatment of bubble detachment, that is, two basic effects are responsible for it: the surface tension which tends to retain the bubble attached to the wall and the buoyancy that tends to remove it, other effects such as drag being neglected. Most of bubble detachment experimental investigations have focused on very restricted operational conditions and a single fluid (or a gas/liquid combination). The present numerical
investigation has allowed determining detachment diameters for a wide range of operational conditions and different fluids. In the results reported herein, the effect over the detachment diameter of two important physical parameters has been investigated: the pressure and the contact angle.

Figure 2 (a) displays the plot of the bubble detachment diameters against the saturation pressure of different boiling fluids assuming a constant contact angle of 54°. It can be noted that the diameter diminishes with pressure, a result that is confirmed by visual observation of boiling liquids. This result could be explained by a simple physical argument related to the surface tension, which diminishes with the saturation pressure. Thus, since a reduced surface tension diminishes the retaining force over the bubble, the observed trend in Fig. 2 (a) is physically consistent. It can also be noted in Fig. 2 (a) that the detachment diameter of water bubbles are the highest whereas those of refrigerant R123 is the smallest. This trend is also related to the surface tension effect which is higher in water than in R-123. In addition it is also observed that, though both refrigerants R-134a and R-123 do have close surface tension values at normal atmospheric saturation pressure, of the order of 0.015 N/m, the detachment diameter of R134a bubbles is higher than that of refrigerant R-123. This trend is related to buoyancy effects which are higher in R-123, since the liquid-vapor density difference for refrigerant R123 is slightly higher than that of refrigerant R-134a, 1,444 kg/m$^3$ as compared to 1,357 kg/m$^3$, at atmospheric pressure, for example.

![Figure 2](attachment:image.png)

**Figure 2.** Variation of the detachment diameter with (a) pressure for a contact angle of 54°; and (b) contact angle for a normal atmospheric pressure.

The effect of the contact angle over the detachment diameter is illustrated in the plot of Fig. 2 (b). It can be noted that the bubble detachment diameter increases with the contact angle. This is physically consistent since the contact angle is closely related to surface tension. However, it must be emphasized that this dependency is affected by the liquid-surface couple, as should be expected. Thus, the plot of Fig. 2 (b) is purely theoretical, but it has been considered as a mean to correlate the detachment diameter with other physical parameters, among them the contact angle. The development of a correlation will be treated in the next section. Arguments similar to those of pressure effects can be used to explain the observed fluid effect in the plot of Fig. 2 (b).

### 3.2. Bubble detachment diameter correlation

The procedure for the determination of the bubble detachment diameter has been summarized in previous sections along with some results related to the effect of the pressure and contact angle. An extensive data bank of detachment diameters has been gathered during the present numerical simulation of boiling. These data could be correlated in terms of dimensionless parameters that govern the mechanism of bubble detachment. The following dimensionless groups have been obtained by applying the Buckingham’s $\pi$ theorem:
\[ \pi_1 = \theta \]  (7)
\[ \pi_2 = \frac{d^2 g (\rho_l - \rho_v)}{\sigma} \]  (8)
\[ \pi_3 = \frac{\rho_c \Delta T}{\rho h_v} \]  (9)
\[ \pi_4 = \frac{\rho}{\rho_v} \]  (10)

\( \pi_1 \) is the contact angle. \( \pi_2 \) is the Bond number, which represents the ratio of gravitational force to surface tension force. \( \pi_3 \) is the Jakob number, which represents the ratio between sensible and latent heat. \( \pi_4 \) is the density ratio.

All the detachment diameter data points available from the numerical investigation have been fitted in terms of the dimensionless parameters according to the following expression:

\[ \pi_2 = 0.0027 \pi_1^{0.148} \pi_4^{-0.024} e^{0.027 \theta} \]  (9)

**Figure 3.** (a) Correlation \( \pi_2 \) against numerical data for pressure in the range between 1 and 10 bar, contact angles between 10 and 80º and 5ºC of wall temperature superheating; (b) variation of the detachment diameter with pressure according to proposed correlation and others from the literature for water and 54º contact angle.

The numerical dimensionless diameter is plotted against the fitted one in Fig. 3 (a) to illustrate the significance of the correlation. The absolute average deviation of correlation data with respect to the numerical data is of the order of 15.9%, a reasonable result given the wide range of physical conditions related to the data points. It is interesting to note in Fig. 3 (a) that water and ammonia data are closer to each other whereas the same trend is observed with data corresponding to refrigerants R134a and R123. These trends are probably related to surface tension effects which are closer for each pair water and ammonia and R134a and R123. It must be noted at this point that the results plotted in Fig. 3 (a) are for a wall superheating of 5ºC. The wall superheating has been considered in the proposed correlation, Eq. (9), through the Jakob number. However, more numerical data, including different values of wall superheating, must be gathered in order to adequately correlate its effects over the detachment diameter. It must be noted that most of the literature correlations do include the wall superheating effect through the Jakob number, though not considering contact angle effects. A comparison of the proposed correlation with others from the literature is shown in Fig. 3 (b), where the bubble detachment diameter is plotted against the pressure for water and a contact angle of 54º. A significant dispersion can be noted among the different correlations, with the proposed correlation being the one with higher values of the detachment diameter for most of the pressure range. Since the
correlations used for comparison do not include the contact angle, the results of the present correlation have been presented in a range of 20º, with an average of 54º. The Jensen and Memmel [6] seems to be the correlation that compares closely with the proposed one, though, as mentioned before, does not include contact angle effects.

4. Conclusions
An investigation involving the bubble detachment diameter has been developed, a summary of it is reported herein, based on a boiling model numerically solved. Data for fluids such as water, R134a, ammonia, and R123 under different operational conditions have been gathered. It has been concluded that the detachment diameter depends strongly on such physical parameters as the contact angle and pressure besides other fluid properties. Based on the obtained numerical results, a correlation for the bubble detachment diameter has been proposed which correlates the following dimensionless parameters: contact angle, the bubble diameter ratio, the Jakob number, and the density ratio. The comparison of the present correlations with others from the literature, contact angle independent, has shown that the proposed correlation diameter is mostly higher than that of the literature ones though closer to the one by Jensen and Memmel [6].

5. References
[1] Fritz W 1935 Maximum volume of vapour bubbles Physic Zeitschr 36 379-384.
[2] Cole R and Shulman H L 1966 Bubble departure diameters at subatmospheric pressures Chemical Engineering Progress 62 6-16.
[3] Cole R 1967 Bubble frequencies and departure volumes at subatmospheric pressures AIChE Journal 13 779-783.
[4] Cole R and Rohsenow W 1969 Correlations of bubble departure diameters for boiling of saturated liquids Chemical Engineering Progress 65 211-213.
[5] Kutateladze S S and Gogonin I 1979 Growth rate and detachment diameter of a vapor bubble in free convection boiling of a saturated liquid High Temperature 17 667-671.
[6] Jensen M and Memmel G J 1986 Evaluation of bubble departure diameter correlations Proceedings of the 8th International Heat Transfer Conference.
[7] Son G, Dhir V K and Ramanujapu N 1999 Dynamics and heat transfer associated with a single bubble during nucleate boiling on a horizontal surface Journal of Heat Transfer 121 623-631.
[8] Son G. and Dhir V K 1998 Numerical analysis of film boiling near critical pressure with level set method Journal of Heat Transfer 120 183-192.
[9] Abarajith H S and Dhir V K 2002 Effect of contact angle on the dynamics of a single bubble during pool boiling using numerical simulations Proceedings of IMECE2002 ASME International Mechanical Engineering Congress & Exposition, New Orleans.
[10] Son G, Ramanujapu N and Dhir V K 2002 Numerical simulation of bubble merger process on a single nucleation site during pool nucleate boiling Journal of Heat Transfer 124 51-62.
[11] Mukherjee A 2004 Numerical and experimental study of lateral merger of vapor bubbles formed on a horizontal surface during nucleate pool boiling. Ph. D. Thesis, University of California, EEUU.
[12] Kunkelmann C and Stephan P 2009 CFD simulation of boiling flows using the volume-of-fluid method within OpenFOAM. Numerical Heat Transfer, Part A: Applications 56 631-646.
[13] Kunkelmann C and Stephan P 2010 Modification and extension of a standard volume-of fluid solver for simulating boiling heat transfer Proceedings of V European Conference on Computational Fluid Dynamics, ECOMAS CFD 2010.
[14] Shu B, Dammel F and Stephan P 2011 Implementation of the level set method into OpenFOAM for capturing the free interface in incompressible fluid flows. Proceedings of 5th Open Source CFD International Conference.
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