ON THE USE OF ANALYTICAL MODELLING FOR DESIGN IMPROVEMENT OF RIFLED TUBES

Cees van der Geld

ABSTRACT

Usually design recommendations for evaporators are based on experiments. However, the value of the added mass coefficients of objects in vorticity flows is the same as those in inviscid flow. This gives the possibility to apply analytical modelling to the hydrodynamics of bubbles in evaporator tubes, and to draw conclusions with regard to tube design. It is shown that a swirl should be created in vertical tubes with up-flow, since hydrodynamic lift forces drive bubbles, once detached from the wall, back towards the wall. So-called rifled tubes create this swirl, and the geometry of rifled tubes is therefore studied in some detail. A combination of CFD modelling and analytical modelling is applied, the latter using a Lagrangian approach. The full added mass tensor for both growing, truncated spheres on a plane wall and for deforming, detached spheres in the vicinity of such a wall is presented as a function of the governing geometrical parameter. Explicit expressions for the hydrodynamic forces are given, in particular for the contributions to the inertia lift force normal to the wall. This force hampers bubble migration. Design recommendations for rifled tubes are given.

Keywords: bubble detachment, rifled tube, tube design, added mass, hydrodynamic forces, potential flow

NOMENCLATURE

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Unit</th>
<th>Description</th>
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<td>b</td>
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<td>F</td>
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<td>C</td>
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<td>$[J]$</td>
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<td>r</td>
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<td>radius (of bubble foot)</td>
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<td>radius (of truncated sphere)</td>
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Subscripts and Superscripts

L, b, w liquid, bubble, wall
CM centre of mass
foot bubble foot
ω vorticity-related

1. INTRODUCTION

When the escape of volumes of a lighter phase from a heated wall is the most important phenomenon for safe or optimal operation of a steam generator, the performance of a heat exchanger tube is largely determined by such quantities as the bubble size at detachment. Other parameters are given below. In sub-critical conditions, high heat fluxes correspond to boiling, whereas in supercritical flows high heat fluxes create turbulent patches that contain a relatively hot, lighter phase. Since conventionally fired electric power plants in part-load usually operate at sub-critical conditions, the present study focuses at boiling. This study is about prediction tools that may assist in improving the design of rifled tubes (Figure 1).

The advantage of a rifled evaporator tube is the presence of mechanisms that move bubbles, formed at the inner wall, towards the centre. An additional body force, induced by the swirling motion created by fluid flowing along helically shaped ribs (Fig. 1),

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and the Coriolis force are created to this effect. However, existing correlations for bubble detachment do not take these forces into account. In addition, the swirling motion induces a non-axial velocity component parallel to the wall, effectively increasing shear at places near the ribs. Would this velocity component promote bubble detachment and would it promote bubble escape from the wall after detachment? So the question arises how to account for the effect of swirl on bubble detachment and migration in simulations of two-phase flow in the complex 3D-geometry of a rifled tube. The present paper addresses this question (section 2).

The main parameter that makes the difference between boiling in rifled and straight tubes with identical heating conditions (exchange area, heat flux, mass flow rate coolant) is expected to be the bubble detachment diameter, because other parameters, such as

- nucleation site density
- bubble growth time for given detachment size
- waiting time between consecutive bubbles at a nucleation site,

are merely dependent on the velocity profile via the heating conditions [1,2]. In order to predict the bubble detachment diameter, the forces exerted on the bubble should be known at all times during its growth. Previous modelling attempts usually suffered from a lack of knowledge of hydrodynamic lift and inertia forces, which gave rise to fit parameters that had a large experimental uncertainty [3-6]. At present, analytical solutions exist that pave the way towards analytical prediction of detachment radii [7-9]. This analysis is based on Lagrangian modelling of the forces on the bubble. Main features are presented in section 2, where the effect that the bubble approach velocity component parallel to the wall has on both detachment and escape from the wall is highlighted. Also the effects of drag and of vorticity in the flow will be discussed.

Even with a homogeneous heating at the outside, the single-phase heat flux at the inside of a rifled evaporator tube is inhomogeneous. The rifles act as fins that promote heat transfer and cause inhomogeneous wall temperatures. Thus, the occurrence of helically shaped rifles has two main consequences, apart from the increase in heat exchanging area for given outside diameter [10]:

- swirl in the two-phase mixture is created that affects redistribution of heat in the flow, and
- the heat transfer coefficient from the wall to the mixture is locally augmented.

Since these mechanisms obviously affect boiling, optimisation of the geometry of a rifled evaporator tube is only possible if the helical structures are fully modelled. In view of the complexity of the geometry this necessitates the application of CFD. Vice-versa, local heating conditions are affected by boiling, which in principle would necessitate the accounting for a two-way coupling between the dispersed phase (vapour) and the fluid. It has been investigated what nowadays the possibilities are with straightforward extensions of commercially available CFD packages [11]. Results of this are reported in section 3, where design recommendations for the geometry of rifled tubes will be given taking full advantage of the modelling results of section 2.

## 2. PREDICTION OF BUBBLE DETACHMENT AND MIGRATION

### 2.1. Vorticity considerations

Two effects of rotational flow in a pipe, swirl, on single bubble detachment are:

- An additional pressure gradient perpendicular to the tube wall is induced, and
- A nonzero azimuthal mean flow component parallel to the wall is introduced.

![Figure 2. Schematic of the way the flow that approaches a bubble in the shape of a truncated sphere is split up in a uniform part plus a simple shear part.](image-url)
force that must be estimated from an expression for isolated bubbles like:

\[ F_\omega = V_b \rho_0 C_\omega \nabla \times \nabla \times \nabla \times V_b \] (1)

Here \( C_\omega \) is a Reynolds-dependent coefficient with a value that for bubbles in the vicinity of a wall is expected to be close to 0.5 [4]. Bubble volume is \( V_b \) and \( \rho \) denotes mass density. Both the approach velocity, \( V_b \), and the curl of \( V_b \), the vorticity \( \omega \) that occurs in the above expression, are in the present study estimated from single phase computations performed with CFD packages. The action of the vorticity lift force is negative in the sense that it drives a fully detached, spherical bubble towards the wall in upward, vertical flow. However, another important force component is the inertia lift force due to the homogeneous flow component that approaches a bubble that is growing at a wall (Fig. 2). This contribution is modelled in section 2.2, and must be added to the force of Eq. (1), as will be discussed shortly.

The vorticity fluctuations introduced by turbulence are an order of magnitude less than the above simple shear component, and can be shown to have a negligible force contribution in boiling applications.

Existing correlations for the drag force coefficient are for flow situations when a fully developed wake downstream of the bubble is present. A typical boiling bubble, on the contrary, grows in 3 ms from a radius of zero to one of 0.5 mm. The wake is practically non-existent in this case and the vorticity generated at the bubble boundary is confined to a thin layer at the surface. Bubble growth is rapid, and known to be controlled by heat transfer from the thermal boundary layer and by inertia forces [1,2]. Surely in low-viscous fluids such as water, drag plays no role of importance [7]. Homogeneous flow over a bubble that is growing by boiling at a solid boundary is therefore a typical example of inviscid flow. It is modelled in section 2.2 as a potential flow with the aid of an Euler-Lagrange-Kirchhoff approach. The inertia forces to be considered are due to deformation of the bubble, due to motion of its centre-point and due to the uniform approaching flow component. The bubble size in high-pressure boiling is relatively small, so deformation is merely isotropic expansion. The bubble shape is therefore assumed to be that of a truncated sphere with radius \( R \) and distance \( h \) of the centre to the wall.

Much work was expended in the decoupling of the basic force terms governing the motion of the centre point of a bubble. Howe [12] showed that when a body with a constant volume moves in a viscous, rotational flow at rest at infinity, the added mass force can be separated from the force due to vorticity. The added mass coefficients of bubbles computed for inviscid flow retain their value in flows with vorticity. This is an important result for which much other evidence exists, both numerical and analytical [14]. It would be beyond the scope of the present paper to discuss derivations in detail. The main conclusion, however, is that the added (or virtual) mass coefficients computed in section 2.2 are generally applicable, and that the resulting inertia forces retain their values in viscous, rotational flows. The results of section 2.2 are therefore directly applicable to boiling in rifled tubes, and such an application will be performed in section 3.

### 2.2. Analytical modelling of forces

Ideally, bubble creation in boiling is fast, not hampered much by the slow mechanism of diffusion of heat, and bubbles are rapidly transported away from the evaporator tube wall towards the tube centre. In order to make this happen, hydrodynamic forces on bubbles have to be controlled or even invoked. A first and necessary step in the optimization of rifled tubes is therefore a precise knowledge of the hydrodynamic forces involved and of way to adjust them.

The added mass of a bubble is a function of the shape of the bubble and of its distance to a wall. For example, the usual added mass \( \alpha \) corresponding to velocity \( U \) can be defined from kinetic energy \( T \) with \( T / (\rho V_b) = \frac{1}{2} \alpha U^2 \). There are other added mass coefficients that account for expansion, or more complex deformation, and the connection of deformation to the motion of the centre-point. The resulting added mass tensor depends on distance to the wall and parameters describing the shape of the bubble, as will be shown below. If this dependency is known, the hydrodynamic inertia forces can all be computed, which is done in the present section. Vorticity in the approaching flow leads to a lift force that can be added to the inertia forces (section 2.1). Also drag can be added, but is usually negligible (section 2.1).

Consider a bubble footed at a plane wall with rotational symmetry around the axis perpendicular to the wall through the centre of the bubble. Let \( A_{ld} \) denote the area of the interface between liquid and bubble content, \( A_{bm} \) the area between the wall and the bubble, \( r_{foot} \) the radius of the foot of the bubble, \( \Delta x_{cm} \) the location of the centre of mass of the bubble in a coordinate system with its origin in the centre of the bubble foot. The pressure inside the bubble, \( p_{int} \), is taken to be homogeneous, constant in time and corresponding to the saturation temperature at the bubble interface. The shape of the bubble is now assumed to be that of a truncated sphere footed on a plane wall, see section 2.1. Two generalized parameters describe the interface: \( R \) and \( h \). The time rate of change of \( R \) is \( \dot{R} \) and that of \( h \) is \( \dot{h} \). Let \( F_3 \) be the hydrodynamic force component on the bubble, normal to the wall and positive if pushing it away from the wall. We intend to evaluate the
Lagrangian equation of motion corresponding to parameter $h$:

$$\frac{d\gamma}{dt} - \frac{\partial T}{\partial \gamma} = -F_3 \quad (2)$$

Force $F_3$ is minus the force on the liquid and is the sum of all generalized forces acting on the bubble, including the body forces. They have to be identified before the kinetic energy in the liquid, $T$, is assessed.

In the case of the dynamics of bodies moving in a fluid and/or partly on a wall there is a straightforward and unambiguous way to identify the generalized forces. It starts with the computation of the time rate of change of the kinetic energy in the liquid with the so-called mechanical energy balance. The volume integral over the contribution from body forces like gravity $g$ in the mechanical energy balance is with the lemma of Gauss converted into surface integrals. Let now $b$ denote the body force component that is active normal to the surface. It gets special attention here since it accounts for a body force that is invoked by swirl created by helical structures in a rifled tube. The surface integral over the bubble-liquid interface, $A_{bL}$, of the contribution of $b$ yields the following two terms:

$$-\rho_b V_b \cdot \gamma_{CM} - \rho_b b \cdot \gamma_{CM} dV_b / dt. \quad (3)$$

The first term on the LHS of Eq. (3) is the well-known buoyancy force that in vertical tubes only has a component parallel to the wall. It yields a contribution to the generalized forces if boiling occurs on horizontal surfaces, because the position of the centre of mass depends on distance $h$. Similar manipulations of terms in the mechanical energy balance that comprise pressure lead to the generalized forces on the RHS of the following equation [7,8]:

$$- F_3 = \rho_b \frac{\partial V_b}{\partial h} - \sigma \frac{\partial A_b}{\partial h} - \Delta\sigma \frac{\partial A_w}{\partial h} -$$

$$\{p_w - \rho_b b \gamma_{CM,z}\} \frac{\partial V_b}{\partial h} +$$

$$+ V_b \rho_b b \frac{\partial \gamma_{CM,z}}{\partial h} - F_{\text{drag}}. \quad (4)$$

Here $\Delta\sigma$ denotes $\sigma_{bw} - \sigma_{wl}$, $\gamma_{CM,z}$ is the distance to the wall of the centre of mass (unequal to $h$, generally) and $F_{\text{drag}}$ is the drag force that needs no further consideration because of the low viscosity (section 2.1). The surface tension between liquid and bubble, $\sigma$, and the hydrostatic pressure at the wall, $p_w$, do not appear in Eq. (4) in a familiar way. However, since $\frac{\partial V_b}{\partial h}$ is equal to $\pi r^2$ it is easy to see that the sum of the terms containing this derivative in Eq. (4) gives rise to the force that is usually denoted with 'pressure correction force', or such [4]:

$$\pi r^2 \{p_b - p_w\}. \quad (5)$$

Similarly, the sum of the surface tension terms can be shown to be equal to the usual expression for the component of the surface tension force that attracts the bubble to the wall [4].

$$2\pi r_{\text{foot}} \sigma \sin(\theta), \quad (6)$$

where $\theta$ denotes the contact angle.

![Figure 3. Added mass coefficients for spheres and truncated spheres](image)

Now all generalized forces have been identified, application of the Lagrangian equation (2) requires the evaluation of the kinetic energy. For this, a velocity potential is required. In the literature solutions for this potential were often found by matching series expansions, implying some arbitrariness in defining the type of expansion. There is a straightforward alternative [7] that sets off with a suitable expansion in elementary functions. The boundary condition, in terms of the generalized velocities that are supposedly not all zero, is written as a matrix equation such that a Fredholm alternative. An inverse exists because of the Fredholm alternative. The solution for the velocity potential is subsequently obtained by application of this inverse to a combination of generalized velocities, as prescribed by the velocity boundary condition at the interface of the bubble, see ref. [7]. A suitable expansion in elementary functions can for the case of a truncated sphere be obtained in various ways, one based on Legendre polynomials of the first order. These have been applied to obtain the added mass coefficients $\alpha, \alpha_2, \text{tr}(\beta)$, and $\psi$ in the following expression for the kinetic energy:
\[ T \ell (\rho, V_o) = \frac{1}{2} \alpha U^2 + \frac{1}{2} \text{tr}(\beta) \hat{R}^2 + \frac{1}{2} \psi R \bar{R} U + \frac{1}{2} \alpha_p U^2, \]  

(7)

Here \( V_o \) denotes \( 4\pi R^3/3 \), and \( U_2 \) is the uniform approach velocity component parallel to the wall, see Fig. 2. The added mass coefficients and the volume of the truncated sphere are only dependent on the geometrical parameter \( \lambda \equiv R/(2h) \). The dependencies of the added mass coefficients are shown in Figure 3. Equations (2, 7) yield

\[ F_3/\ell (\rho, V_o) = -\alpha \dot{U} - \frac{1}{2} \psi \bar{R} + F, \]  

(8)

with

\[ F = -U \dot{\bar{R}} \left[ \frac{\partial \alpha}{\partial R} + \alpha 4\pi R^2 / V_o \right] - \frac{1}{2} U^2 \frac{\partial \alpha}{\partial h} + \frac{1}{2} \psi R \bar{R} \frac{\partial \psi}{\partial R} \]  

\[ - \frac{1}{2} \hat{R}^2 \left[ \frac{\partial \psi}{\partial R} - \frac{\partial \text{tr}(\beta)}{\partial h} + \psi 4\pi R^2 / V_o \right] + \frac{1}{2} U_2^2 \frac{\partial \psi}{\partial h}. \]  

(9)

Here \( \dot{U} \) is the time rate of change of velocity \( U \), and \( F \) is a hydrodynamic lift force, divided by \( \rho, V_o \), that would be difficult to be captured in analytical form with an approach other than the Lagrangian approach. The derivatives occurring in Eq. (9) can all be expressed as derivatives with respect to \( \lambda \), since the added mass coefficients only depend on \( \lambda \).

Figure 3 shows that the derivatives that occur in Eq. (9) change sign when the bubble shape changes from a truncated to a full sphere, i.e. when \( \lambda = \frac{1}{2} \). It can be shown that because of this change of sign in most practical cases force \( F \) changes drastically [14]. It turns out in practice that \( F \) can be promoting detachment of a bubble shaped as a truncated sphere, if \( U_2 \) is large enough, but that \( F \) is driving a spherical bubble back towards the wall once detached.

The actual bubble dynamics before detachment is determined by the combination of equation (4) and (8), and depends on the coupling of volume with pressure of the bubble content. Because bubble growth in boiling is a nearly isothermal process, the interplay of surface energies induces oscillations at relatively low frequency [8, 14]. These oscillations are only possible if the bubble foot is on the wall and if motion of the contact line is not hampered.

### 2.3 Conclusions for the design of evaporator tubes

The main conclusion to be drawn from the above computations is that high-pressure boiling bubbles after detachment in upflow of water in a vertical tube stick close to the wall. All vorticity-related and inertial hydrodynamic forces near the wall act towards the wall. If downflow of liquid is not an option, migration towards the centre of the tube must be caused by

- Interaction with other bubbles and turbulence
- Deformation after coalescence
- Body forces induced by swirl.

Optimal control is only achieved with the last option. The first design recommendation is therefore to induce swirl. This can either be done with special inserts or by helical structures on the inner tube wall, as shown in Fig. 1. This recommendation explains the focusing on rifled tubes of this study. However, the above analysis also makes clear that hydrodynamic forces not only have a negative effect on boiling heat transfer: before detachment bubble growth can be positively influenced. Bubble growth time is then reduced by hydrodynamic forces that promote detachment irrespective of the direction of the flow parallel to the wall. At places on a structured inner wall of a tube where this velocity component is relatively high bubbles must be expected to leave the position with a relatively small diameter. This leaving place can imply actual detachment or being swept away further downstream, the so-called sliding of bubbles.

The above findings will now be used in a design study of the geometry of a rifled tube.
3. APPLICATION TO DESIGN IMPROVEMENT OF RIFLED TUBES

It has been attempted by our group to implement a mechanistic model for the prediction of bubble detachment and heat transfer that was available in the literature, work of Basu et al. [13], in the commercially available CFD package Fluent™ [11]. Correlations used account for the sliding of bubbles, for example, but are essentially 1D in the sense that heat transfer between the bulk of the fluid and the wall is predicted. A locally applicable, equivalent 3D version of these correlations had to be found. The main conclusion that must be drawn from this attempt is that with the existing mechanistic models such an implementation is awkward. Apparently, the prediction of two-phase flow with heat transfer in rifled tubes with commercial CFD codes, with special extensions to account for boiling, is all but straightforward with the present state of knowledge.

However, single phase flow with heat transfer is readily modelled with such packages [10, 11], see for example Figure 4. It is therefore possible to apply the conclusions of section 2.3 with the assumption of a one-way coupling in the following way. Single-phase flow in rifled tubes of various geometries is modelled with the aid of commercially available packages, i.e. CFX™ and Fluent™. Conclusions are drawn with respect to local conditions (velocity field, temperatures) that are important for bubble detachment. Lastly, resulting bubble escape and migration conditions are estimated. Such a one-way coupling is of course valid in case the bubble density is low, but conclusions are expected to pertain to void fractions as high as 30% since surprisingly enough many two-phase flow phenomena at void fraction up to 30% can be interpreted with the aid of single bubble behaviour [1, 2].

The velocity field in the vicinity of the wall is nowhere uniform, of course. There exist, however, locations where boundary layers thickness is negligible as compared to bubble size at detachment. These are the places upstream of a rifle where the flow field resembles stagnation flow, see Figure 5. Heat transfer rates are high there, resulting in relatively low wall temperatures (Fig. 4) and most likely a lower rate of bubble production. Even though fewer bubbles are created there, they still need to be removed efficiently. However, the lift forces due to inertia and vorticity are in up-flow both pushing a detached bubble towards the wall (section 2). Bubble detachment diameter is relatively small (section 2.3) which causes body forces to be relatively small because they are proportional to the volume of the bubble (section 2.2). The axial flow rotation around the tube axis, the swirl, must therefore be significant near the helixes, the rifles, in order to drive bubbles towards the centre. Stagnation flow is more pronounced with rectangular helixes (Figure 5) than with rounded edges (Figure 6) while swirl can be comparable. A rifle with a rounded upstream edge is therefore recommended.

The swirl developed follows the sweep of the helix structure and increases with increasing height of the helix structure. However, this is at the cost of an increase in pressure drop. The critical heat flux of relatively short tubes with relatively high helixes is expected to be highest. The swirl should be small in the centre of the tube, which with four or more structures at the wall is readily achieved.

In the wake areas relatively high temperatures and relatively low velocities occur (Fig. 4). Bubble detachment sizes are relatively large (section 2.3) which is beneficial for bubble migration to the core (section 2.2). These are not the wakes that appear behind bluff bodies in a stream of liquid, when bubbles are known to coagulate and even coalesce. The difference is a presence of a strong axial velocity component since the sweep of the helix structure is followed. Nevertheless, the high temperatures are likely to enhance boiling and bubble transport rates are less hampered by the above mentioned lift forces since velocity and vorticity are smaller. If excess heating of the tube wall is not an issue, it is therefore advantageous to have a large wake area. This can be promoted by increasing the pitch or increasing the rib height.

Suppose that a rifled tube has been found working satisfactorily at a certain range of mass flow rates, and that another design must be specified for higher mass flow rates. Based on the above findings, the pitch and rib height of the new design are recommended to be increased in order to foster the additional body force that stimulates migration to the centre. At lower mass flow rates the restraining hydrodynamic forces have lesser...
influence, as discussed above, and the compensating body force can be less.

A summary of the above findings is provided in section 4.

4. CONCLUSIONS

The inertia forces induced by expansion of a bubble in a homogeneous flow near or at a wall depend on derivatives of the added mass tensor. It has been shown that these derivatives all change sign at the time the bubble detaches from the wall. As a result, the sum of the inertia forces on a growing truncated sphere at a plane wall is rather different from that on a growing sphere that has escaped from the wall. The lift force due to vorticity, see Eq. (1), can be added to these inertia forces, and drives in upflow an escaped bubble back towards the wall. As a consequence, bubble migration from the wall to the centre of a vertical tube can in upflow only be promoted by creating a swirl in the tube. This study has not only shown that swirl is the only mechanism to this effect. It has also demonstrated that bubble detachment is fostered by the homogeneous flow component parallel to the wall, irrespective of the direction of this flow. The mass flow rate in an evaporator tube cannot be unlimitedly reduced without affecting bubble detachment diameter and boiling heat transfer. Reducing the mass flow rate promotes migration of vapour to the centre, but reduces wall heat transfer.

These findings appeal to common sense and are in accordance with existing correlations. They are nevertheless useful for optimization of the design of rifled tubes since it has been found difficult to let commercial 3D CFD codes accommodate for the essentially 1D correlations. In addition, experiments to provide design recommendations for evaporator tubes are elaborate, costly and seldom provide the detailed information necessary to assess local characteristics. Such design experiments are a proper final step in the design process, but should preferably be based on insights and recommendations like the ones provided in the present paper.

Based on one-way coupling of flow with bubble production and bubble motion, and taking full advantage of the above analytical predictions, the following geometry of a rifled tube is recommended. Four or more helix structures with rounded upstream edges with a pitch and with rib heights that in principle should be selected dependent on the prevailing bulk mass flow rates of liquid. An increase in prevailing mass flow rates should be accompanied with an increase in rib heights and pitch. These recommendations are purely based on an assessment of hydrodynamic effects of helical structures on motion of bubbles, and not on such effects as extended fin area of the helical structures, since the hydrodynamic effects are expected to be most important for safe operation and for a high critical heat flux.

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