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Flow velocity effect on the sliding and detachment of a bubble

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Abstract: As part of this numerical study, we attempted to analyze the sliding and detachment of a vapor bubble after it grew on a heated plate in a convective flow. We then proceeded to simulate the sliding process and the detachment of a vapor bubble located in a channel. The fluid has a flow velocity varying from 0.4 to 1 m/s. The contact angle of the bubble with the hot wall was taken equal to 44, 54, and 64°. We followed the evolution of the time and the distance of sliding until the detachment of the bubble. The contours of temperature and the coefficient of heat transfer were also analyzed.

Keywords: Bubble; Sliding; Detachment; Contact angle; Thermal boundary layer.

1. INTRODUCTION

Boiling is a very efficient mode of heat transfer since it can absorb a consistent amount of heat for low-temperature gradients. It finds its application in two-phase equipment in chemical, petrochemical, food, and refrigeration.

Convective nucleate boiling remains a highly complex and elusive phenomenon and depends on several parameters. Among these parameters, the effect of surface wetting on the

performance of convective boiling, studied experimentally by Kim et al. [1], Sarafraz et al. [2] investigated several parameters, including the effect of flow velocity on convective boiling. Understanding the boiling phenomenon requires a microscopic examination of the dynamics of the bubble and its environment. The detachment of the bubble from an inclined surface has been revised by varying the orientation angle of the wall [3]. The wall tilt effect was also studied by Nishikawa et al. [4], Manickam et al. [5] experimentally followed the sliding of a bubble by interferometry on the low side of a heated surface. They found that the sliding of the bubble improves heat transfer. Mukherjee et al. [6] simulated the growth and detachment of vapor bubbles and the coalescence of two and three vapor bubbles. Van der Geld et al. [7] presented measurements of the development of the vapor bubble and its detachment for a certain orientation, and compared them with 2D numerical simulations. An analysis of the forces acting on the bubble during its slide was examined.

2. NUMERICAL MODEL PROPOSED

2.1.Method

The growth and detachment constitute the dynamics of the bubble. For the simulation, we retain the detachment of the bubble, and we assume that it had reached the volume necessary to start its process. Using the Fritz correlation [9] detailed in Equation (1), we determine the starting equivalent diameter *d*.

$$d = 0.02008 \times \theta \sqrt{\frac{\sigma}{g(\rho_l - \rho_v)}} \quad (1)$$

Table 1: Thermal and physical properties of water

Properties	Unit	Liquid	Vapor
P	kg/m^3	958	0.598
c_p	kJ/kg·K	4.212	2.02
Λ	W/m·K	0.68	0.0248
M	m²/s	2.85×10^{-4}	1.2×10^{-5}
L	kJ/kg	2.257	
T_{sat}	K		373.15
β	K^{-1}	7.5×10^{-4}	
σ	N/m	0.0589	

The study is done in two dimensions, the flows are laminar, the wall temperature remains constant and the thermodynamic properties of the liquid and vapor phases remain unchanged and are insensitive to small variations in temperature and pressure. The liquid is at saturation temperature. The process followed is detaching a water vapor bubble from the hot surface.

During the simulation, we do not include the mass transfer from the liquid to the vapor phase; Table 1 shows the thermal and physical properties for the case of water at the atmospheric pressure and temperature of 100 °C.

2.2.Initial conditions

During the simulation, the bubble is considered as a semi-circle with a radius of 1.75 mm. The equivalent diameter given by Fritz's formula for a contact angle of 54° is $d = 2.72\ mm$. The temperature of the vapor and the liquid is considered equal to the saturation temperature. On the other hand, the wall temperature has an overheating of 5 ° C. The pressure is taken equal to atmospheric pressure. The properties of the liquid and vapor phases are taken for water at 100° C.

2.3.Governing equations

The VOF (Volume Of Fluid) model can capture and model the interface between two immiscible fluids, by introducing a variable α, which is, in fact, the volume fraction of phase p or q in the calculation cell. It is used in the whole domain when the corresponding phase is complete when it is worth one. Otherwise, it is empty. The mesh contains the two phases when the variable α is between 0 and 1, and the interface is inside the mesh. The interface is then configured by knowing the value of this variable α, and the properties of the mixture are a function of the volume fraction value of each phase. The equations governing the phenomenon are described above. The equation for the phase presence rate is defined by Equation (2):

$$\frac{1}{\rho_q}\left[\frac{\partial}{\partial t}\left(\alpha_q \rho_q\right) + \nabla.\left(\alpha_q \rho_q \overrightarrow{v_q}\right)\right] = S_{\alpha_q} + \sum_{p=1}^{n}\left(\dot{m}_{qp} - \dot{m}_{pq}\right) \qquad (2)$$

The equation for conservation of momentum is defined by Equation (3):

$$\frac{\partial}{\partial t}(\rho\vec{v}) + \nabla.(\rho\vec{v}\vec{v}) = -\nabla p + \nabla.[\mu(\nabla\vec{v} + \nabla\vec{v}^{T})] + \rho\vec{g} + \vec{F} \qquad (3)$$

and the heat equation is given by formulation (4) and defines as follows:

$$\frac{\partial}{\partial t}(\rho E) + \nabla.\left(\vec{v}(\rho E + p)\right) = \nabla.\left(\lambda_{eff}\nabla T\right) + S_h \quad (4)$$

2.4.Boundary conditions

The chosen control area is of dimensions 20 mm × 10 mm (Figure 1). The lower part is the inlet (velocity inlet), the left side is the hot surface (wall). The right side is symmetrical, and the top is the pressure outlet. The calculations were made in cartesian coordinates. Geometry and mesh were generated using CFD code. At the level of the heating surface at $x = 0$, $u = 0$, $v = 0$, $T = T_w$. Above the domain, we have at $y = y_{max}$, $u = 0$, $v = 0$, $T = T_l$. On the low side, we have at $y = 0$, $u = U$, $v = 0$, $T = T_l$. In all the domain at the instant $t = 0$, we have $T = T_l$ and the velocities are zero. The bubble is positioned at (0.5) away from disturbances of the fluid inlet, with the shape of a semi-circle of radius 1.75 mm, which corresponds to the growth matures before the start of detachment. The nucleation site is ignored in the simulation since its size is much smaller than the bubble size.

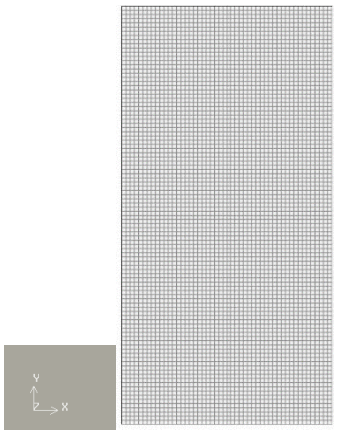


Figure 1: Simulation domain

2.5.Simulation parameters

After entering the initial conditions and the specifications of the boundary conditions, the time step is of the order of 10^{-4} seconds; the contour of the fraction of volume which evolves along the wall is obtained (Figure 2). The latter shows three stages of the evolution of the bubble, the first a semi-circle placed on the hot wall at a distance away from the fluid inlet, which corresponds to the initial state. The second happens at half time, where we notice that the base narrows by the shearing of the fluid and the volume of the bubble remains at the back. The third step is just before the detachment leaving only a point of contact with the wall. The evolution of the present bubble has a contact angle of 54°, and the fluid flow velocity is of 0.4

m/s. This bubble is sliding to the point of detachment corresponding to the distance of 9.8 mm for a duration of 64 ms .

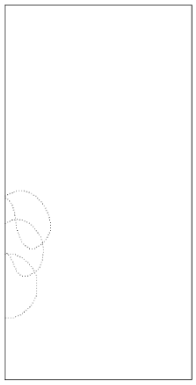
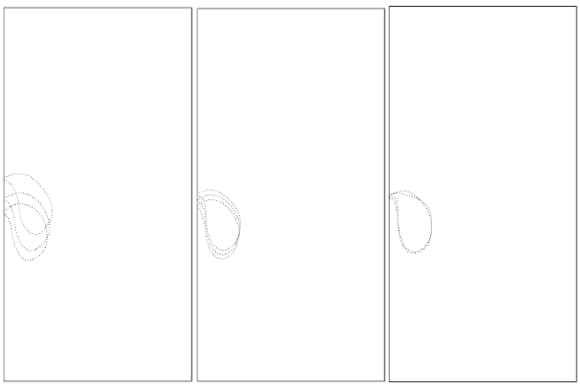


Figure 2: Bubble displacement

3. RESULTS AND DISCUSSIONS

Figure 3 shows the detachment of bubbles for different flow velocities and contact angles. The simulation was made for each of the bubbles alone. Then they were superimposed. The flow velocity in figure 3a is 0.4 m/s that of 3b is 0.7 and 1 m/s for Figure 3c. The more the speed increases and the more the gap between the detachment of the bubbles decreases. At a speed of 1 m/s, the bubbles detach at almost the same point and appear confused. The bubble having a larger contact angle will have traveled a long distance, and the more the contact angle decreases the detachment is early.



a) b) c)

Figure 3: Bubbles Detachment

Figure 4 compares the bubble sliding time for contact angles of 44, 54, and 64°, where the fluid velocities took the values of 0.4, 0.7, and 1 m/s. For low rates, the deviation between the

sliding times is significant. As the flow velocity increases, the deviation decreases until the detachment times become the same, and the contact angle fades.

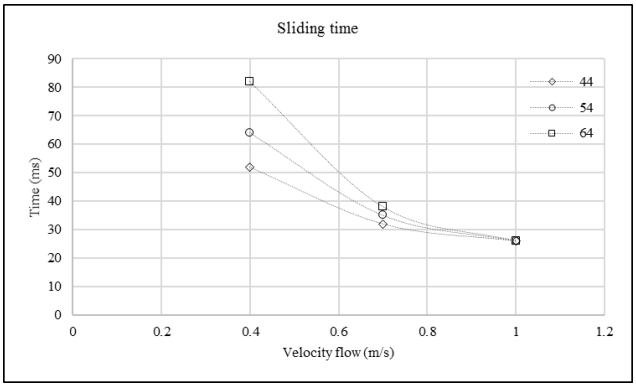


Figure 4: Sliding time before detachment

Figure 5 shows the distance where the bubble detaches off for different contact angles and under a fluid flow velocity varying from 0.4 to 1 m/s. We note that for the contact angle of 54°, the distance did not vary despite the increase in flow speed. At a low rate, the contact angle affects the distance traveled. The more the angle increases and the more the length also increases. When the fluid velocity is high, the effect of the contact angle is no longer visible.

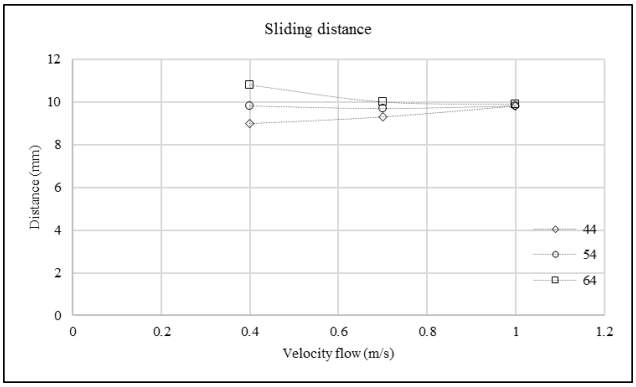


Figure 5: Sliding distance before detachment

The evolution of the thermal boundary layer at the instant 64 ms is shown in Figure 6. The figure is plotted when the bubble detachment had a contact angle of 54° and a fluid velocity of 0.4 m/s from the hot wall. We can see the disturbance of the thermal boundary layer, which follows the bubble during sliding, and some isotherms take on the appearance of the bubble during detachment.



Figure 6: Temperature contour before detachment

During the detachment of the bubble from the wall, the thermal boundary layer is strongly disturbed, the heat transfer coefficient is improved, as shown in Figure 7. The coefficient is significantly increased over the distance traveled by the bubble. The minimum peak is due to the transfer at the bubble level contact with the steam wall.

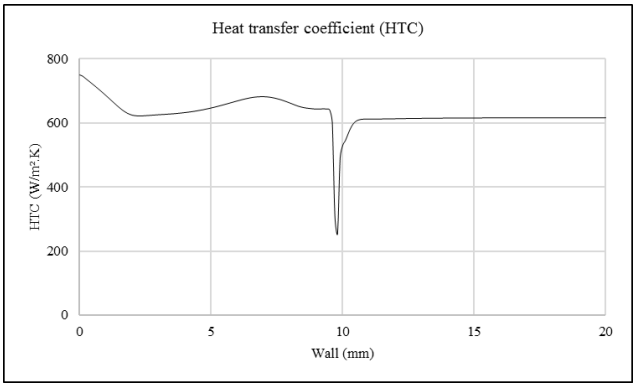


Figure 7: Heat transfer coefficient

4. CONCLUSION

The simulation of the dynamics of the bubble allowed us to follow the evolution of sliding and detachment by modifying two parameters. These parameters were the fluid flow velocity and the contact angle of the bubble with the hot wall.

As the fluid flow velocity increased, the sliding time to bubble detachment decreased. The influence of the contact angle was noticeable at a low rate, and the effect wore off with increasing velocity. The sliding distance varied little with speed or contact angle, and this difference was reduced at high velocities.

NOMENCLATURE

A	Area	m²
a	Thermal diffusivity	m²/s
B	Bubble volume	m^3
c_p	Heat capacity	J/kg·K
D	Domain	
d	Bubble departure diameter	m
E	Energy	J
F	Force	N
Fr	Froude number	
g	Acceleration due to gravity	m/s²
h	Heat transfer coefficient	W/m²K
L	Latent heat of vaporization	J/kg
m	Mass transferred	kg
p	Pressure	Pa
q	Surface heat flow	W/m²
S	Source term	
T	Temperature	K
t	Time	s
u	Velocity	m/s
v	Velocity	m/s
x	Direction	m
y	Direction	m

Greek Symbols

α	Volume fraction	
β	Thermal expansion	K^{-1}
Δ	Difference	
δ	Thermal boundary layer	m
ϕ	Contact angle	
λ	Thermal conductivity	W/m·K
μ	Dynamic viscosity	kg/m·s

v	Kinematic viscosity	m^2/s
θ	Angle of orientation of the wall	
ρ	Density	kg/m^3
σ	Surface tension	N/m
τ	Reference time	S

Indices

eff	Effective
h	Heat
l	Liquid
max	Maximum
o	Reference
p	p phase
q	q phase
sat	Saturation
t	Thermal
v	Vapor
w	Wall

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