BUBBLE FORMATION ON A WALL IN CROSS-FLOWING LIQUID AND SURROUNDING FLUID MOTION, WITH AND WITHOUT HEATING

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ABSTRACT

Application of gas-liquid two-phase flow systems for space-based thermal management and for the HEDS program demands a precise control of bubble size distribution in liquid. The necessity of bulk liquid motion for controlling bubble size and frequency in the space environment has been suggested by recent studies on pool [1], forced convection boiling [2] and bubble formation in flowing liquid [3, 4]. The present work, consisting of two parts, explores bubble generation at wall in a cross-flowing liquid, i.e., in a forced convection boiling configuration. A schematic is shown in figure 1. The first part looks into the bubble formation process under isothermal conditions in a reduced gravity environment, by injecting gas through a hole in the wall of a flowing liquid channel. In the latter part with channel wall heating, flow and temperature fields near a single bubble are studied under normal (1-g) and micro-gravity (µ-g) conditions.

The objective of the isothermal experiments is to experimentally investigate the effects of liquid cross-flow velocity, gas flow rate, and orifice diameter on bubble formation. Data were taken mainly under reduced gravity conditions but some data were taken in normal gravity for comparison. The reduced gravity experiment was conducted aboard the NASA DC-9 Reduced Gravity Aircraft. The results show that the process of bubble formation and detachment depends on gravity, the orifice diameter (Dₐ), the gas flow rate (Qₐ), and the liquid cross-flow velocity (Uₐ). The reduced gravity data are shown in figure 2. The data are analyzed based on a force balance, and two different detachment mechanisms are identified. When the gas momentum is large, the bubble detaches from the injection orifice as the gas momentum overcomes the attaching effects of liquid drag and inertia. The surface tension force is much reduced because a large part of the bubble pinning edge at the orifice is lost as the bubble axis is tilted by the liquid flow. When the gas momentum is small, the force balance in the liquid flow direction is important, and the bubble detaches when the bubble axis inclination exceeds a certain angle.

With wall heating, liquid motion around an air bubble in cross-flowing 2cs silicone oil is experimentally investigated in 1-g. A spectral element based steady 2D numerical model is also developed. The traces of particles from experimental flow visualization and the corresponding computed streamlines are shown in figure 3. At the upstream side of the bubble facing the cross-flow, thermocapillary and forced convection create liquid motion away from the wall, up along the surface. At the downstream side, a competing interaction between the two creates a recirculation cell, causing the bulk liquid to stagnate on the surface and separate thereafter. The important dimensionless parameters are - Surface tension and local cross-flow Reynolds numbers Rₑ (Uₑref/ν) and Re₁(μ₁U₁a/ν₁), respectively based on reference thermocapillary Uₑref(σγΔT/μ₁ΔT=ΔTwall−ΔTliquid) and local cross-flow velocity U₁, Prandtl number Pr and Grashoff number Gr(ρgβΔTa³/ν). Variation of the stagnation point with Rₑ and Re₁ is shown in figure 4. Figures 3 and 4 show good agreement between experimental and numerical results in 1-g. The
A computational model is extended to μ-g condition to investigate temperature and velocity on the bubble surface, stagnation and reattachment points of the recirculation cell and wall heat transfer. It is observed that wall heating significantly alters the flow field around the bubble and thus the forces acting on the bubble, which control its detachment. Thus a combination of heating and liquid cross-flow can be utilized to precisely control bubble formation in a μ-g environment.

Figure 1: Schematic of bubble generation in Cross-flowing liquid.

Figure 3: Streamlines for $Re_{bo}=3.6, Ro=194$
(a) Experimental and (b) Computational.

Figure 2: Schematic of bubble generation in Cross-flowing liquid.

Figure 4: Dimensionless stagnation point in 1-g. Lines - computational. Symbols - exp.

REFERENCES

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- Two-phase flow applications
  - HEDS program
  - Cryogenic storage
  - Thermal management
  - Propulsion system

- Bubble detachment in stagnant liquid
  Uncontrolled bubble size and frequency

- Need for an additional control mechanism
  - Flowing liquid
    - Co-flow and cross-flow
    - Wall injection in cross-flow
  - Combination of cross-flow and wall heating
Bubble generation from wall injection in a cross-flowing liquid

- Parabolic flight experiment
- Analytical modeling based on
  \[ F_B + F_D + F_I + F_M + F_\sigma = 0 \]

- \( F_B \) - Buoyancy
- \( F_D \) - Liquid drag
- \( F_I \) - Liquid inertia
- \( F_M \) - Gas momentum
- \( F_\sigma \) - Surface tension at bubble base
Sequence of Bubble formation process

Reduced gravity

2-g period

\[ D_N = 0.15 \text{ cm}, \quad Q_g = 0.2 \text{ cc/s}, \quad U_L = 7.7 \text{ cm/s} \]
Bubble axis inclination angle vs. $U_L$ and $(F_D + F_I)/F_\sigma$ vs. $F_I/F_D$
Bubble generation on heated wall of a flowing liquid channel

Focus

Flow and temperature fields around the bubble, 1-g & μ-g.

2 cs silicone oil

$U_{av} = 1 - 2$ cm/s

$T_m \sim 23^\circ$C

$\Delta T = 0 - 12^\circ$C

Bubble radius $a \sim 2$ mm
Objectives

Understand the role of convection mechanisms -

- Thermocapillary
- Forced
- Natural

Importance

Flow field governs forces on the bubble $\iff$
bubble size & frequency $\iff$ Two-phase flow and heat transfer.

Approach

- 1-g experimental work
- 2-D numerical model - Spectral element method - 1-g & $\mu$-g
Flow & Temperature fields $\sim f (R_\sigma, \text{Re}_{loc}, \delta_T/a, B_d, Pr)$

$R_\sigma = \frac{U_{ref} a}{\nu_1} = \sigma_T \Delta T a / \mu_1 \nu_1$

$\text{Re}_{loc} = \frac{U_{loc} a}{\nu_1}$

$\overline{V} = \frac{U_{ref}}{U_{loc}} = \frac{\sigma_T \Delta T}{\mu_1 U_{loc}}$

$B_d = \frac{\rho g \beta \Delta T a^2}{\mu_1 U_{ref}}$

$\delta_T(L)/a = 5L/(a \text{Re}_{loc}^{0.5} \text{Pr}^{0.33})$

Experimental

Numerical

$Pr = 27, \overline{V} = 43.9 (R_\sigma = 155), \text{Re}_{loc} = 3.6, \delta_T/a = 3.0, B_d = 0.6$
Favoring and opposing effects: Forced & Thermocap. convection

- Stagnation point on bubble surface
- Re-circulation cell at the downstream side

![Graphs showing stagnation point and length of recirculation cell](image)
Conclusions

- Flowing liquid promotes bubble detachment
  - Various forces interact in complex manner during detachment
  - Wall plays an important role (Loss of pinning edge)
- Effects of wall heating -
  - 3 convection modes govern Flow & Thermal fields -
    - Thermocapillary  ° Forced  ° Natural
      - Favoring interaction at front & Competing interaction at downstream end  - Recirculation
      - Significant change in flow field  → Forces on bubble  → Bubble size and frequency can be controlled better