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

Avijit Bhunia[1], Yasuhiro Kamotani[2] and Henry K. Nahra[3]
[1,2] Department of Mechanical & Aerospace Engineering, Case Western Reserve University, Cleveland, OH 44106, [2] Corresponding Author, e-mail: yxk@po.cwru.edu
[3] NASA-GRC Lewis Field, MS 500-102, Cleveland, OH 44135

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 (D_N), the gas flow rate (Q_g), and the liquid cross-flow velocity (U_L). 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 $R_\sigma(U_{ref}a/\nu)$ and $Re_{loc}(U_La/\nu)$, respectively based on reference thermocapillary $U_{ref}(\sigma_T\Delta T/\mu,\ \Delta T=T_{wall}-T_{liquid})$ and local cross-flow velocity U_L, Prandtl number Pr and Grashoff number $Gr(\rho g\beta\Delta Ta^3/\mu\nu)$. Variation of the stagnation point with R_σ and Re_{loc} is shown in figure 4. Figures 3 and 4 show good agreement between experimental and numerical results in 1-g. The

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.

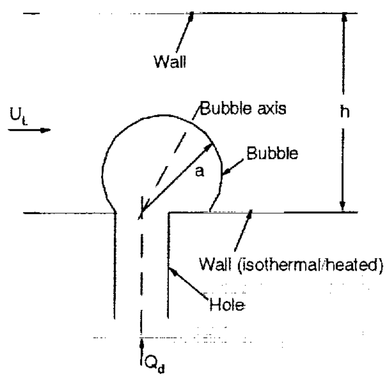

Figure 1: Schematic of bubble generation in Cross-flowing liquid.

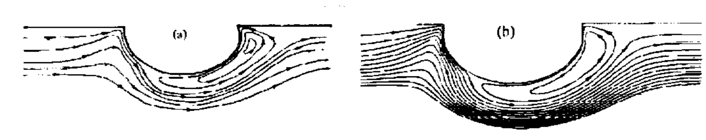

Figure 3: Streamlines for Re_{loc}=3.6, R_σ=194 (a) Experimental and (b) Computational.

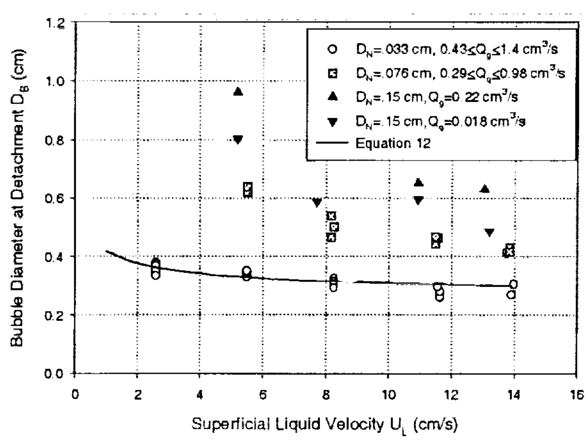

Figure 2: Schematic of bubble generation in Cross-flowing liquid.

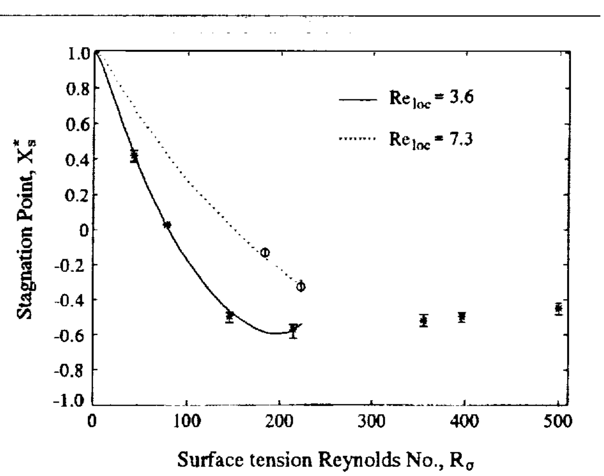

Figure 4: Dimensionless stagnation point in 1-g. Lines - computational. Symbols - exp.

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4. A. Bhunia, S. C. Pais, Y. Kamotani and I. Kim, AIChE J., 44(7), 1998, 1499-1509.

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Principal Investigator

Prof. Yasuhiro Kamotani

Department of Mechanical & Aerospace Engineering

Case Western Reserve University

Cleveland, OH 44106

- **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

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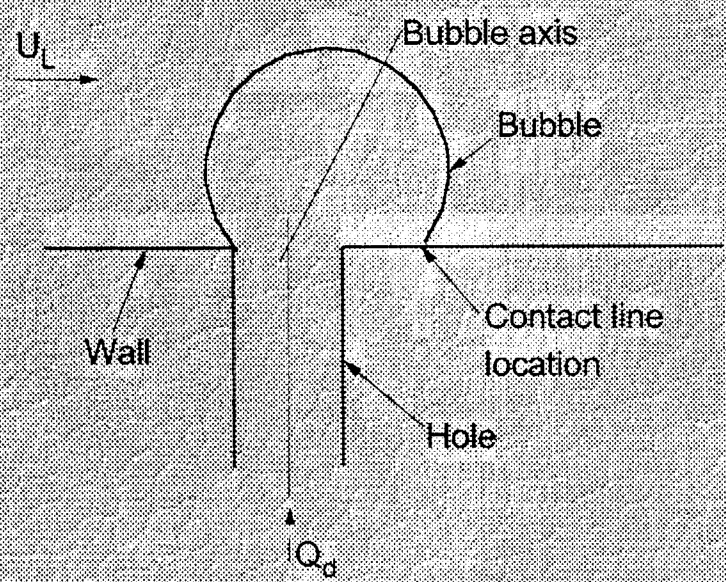
Bubble generation from wall injection in a cross-flowing liquid

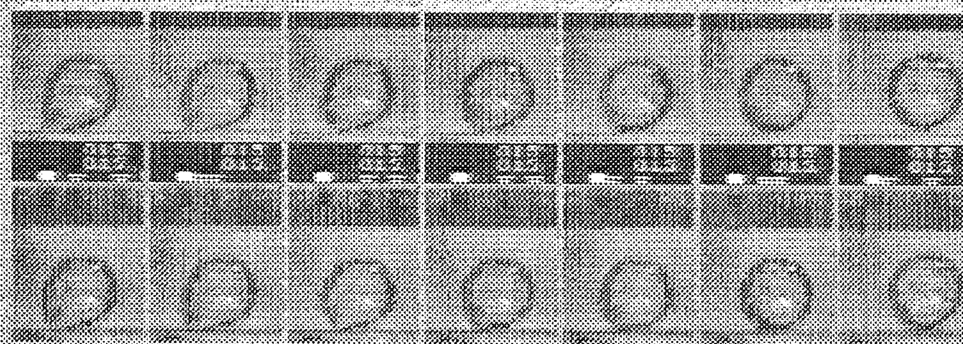


- Parabolic flight experiment
- Analytical modeling based on

$$\mathbf{F_B + F_D + F_I + F_M + F_\sigma = 0}$$

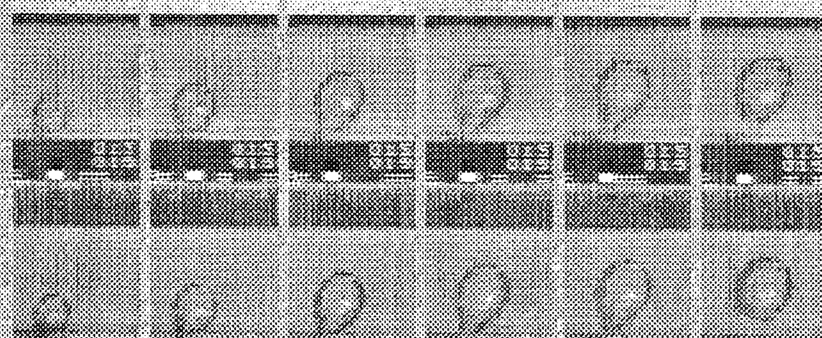
- F_B - Buoyancy
- F_D - Liquid drag
- F_I - Liquid inertia
- F_M - Gas momentum
- F_σ - Surface tension at bubble base

Sequence of Bubble formation process



7.622 7.630 7.638 7.646 7.654 7.662 7.694

Reduced gravity



13.358 13.422 13.486 13.518 13.514 13.542

2-g period

$D_N = 0.15$ cm, $Q_g = 0.2$ cc/s, $U_L = 7.7$ cm/s

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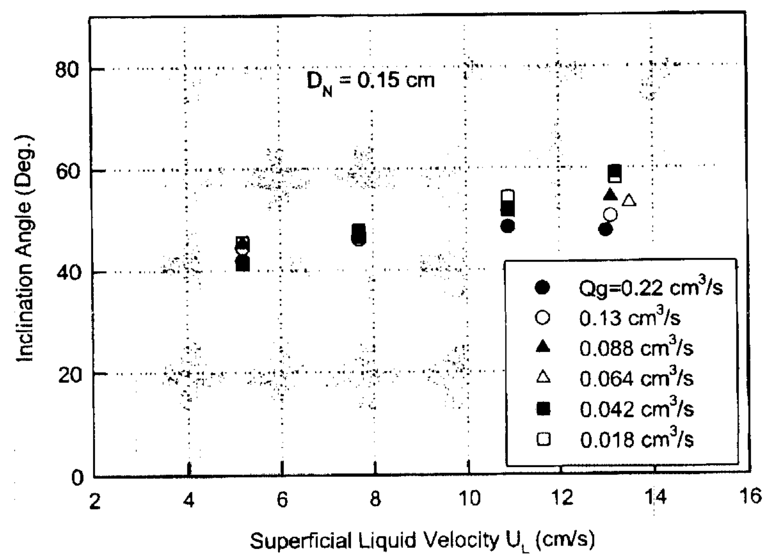
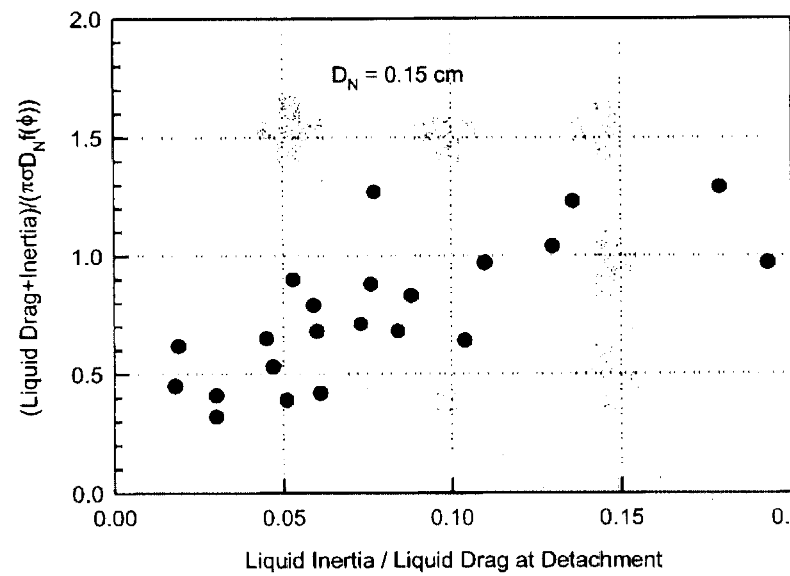


Bubble axis inclination angle vs. U_L

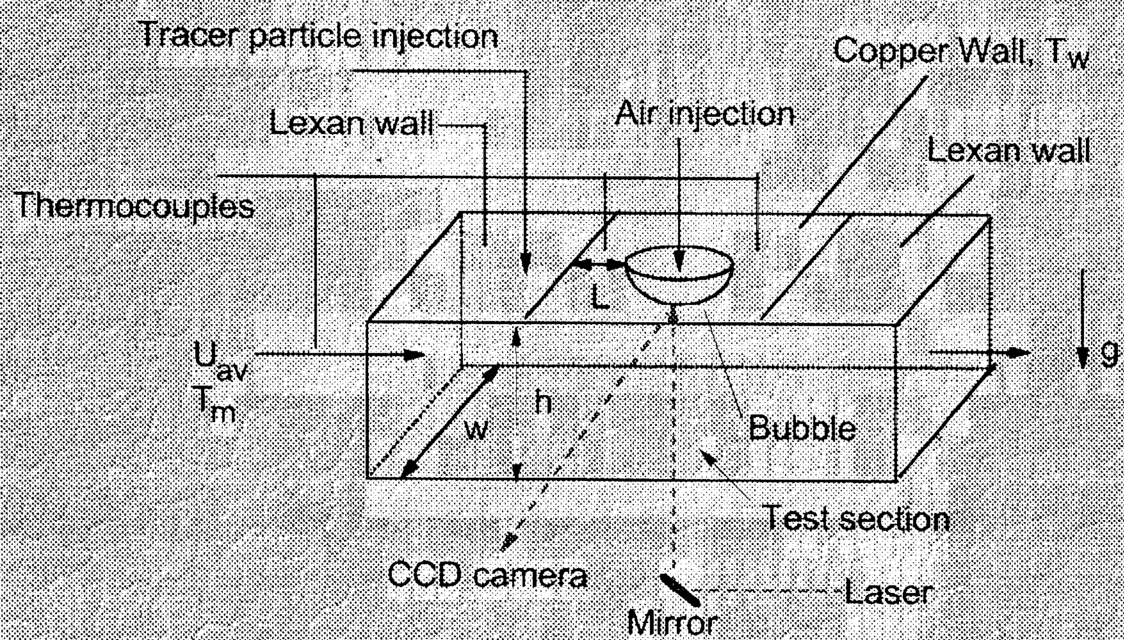


$(F_D + F_I)/F_\sigma$ vs. F_I/F_D

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

$T_m \sim 23°C$

ΔT = 0 - 12°C

Bubble radius a ~ 2 mm

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Objectives

Understand the role of convection mechanisms -

- Thermocapillary • Forced • Natural

Importance

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

Approach

- 1-g experimental work
- 2-D numerical model - Spectral element method - 1-g & μ-g

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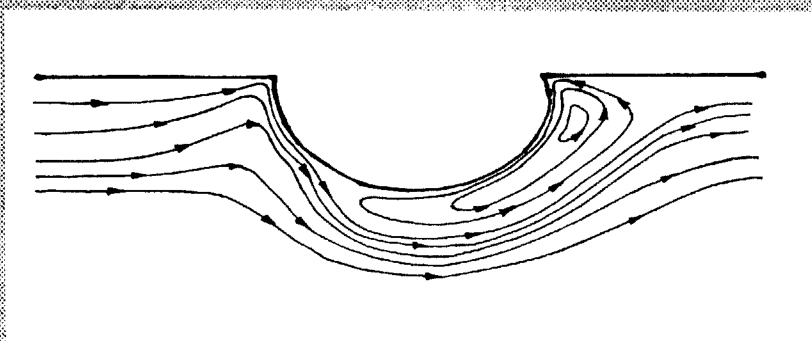
Flow & Temperature fields $\sim f(R_\sigma, Re_{loc}, \delta_T/a, B_d, Pr)$

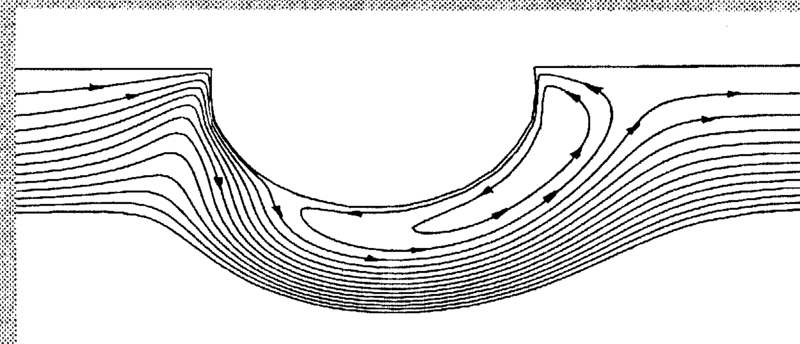
$\sim f(V, Re_{loc}, \delta_T/a, B_d, Pr)$

$R_\sigma = U_{ref}a/\nu_1 = \sigma_T \Delta T a/\mu_1 \nu_1$ $\quad Re_{loc} = U_{loc}a/\nu_1$ $\quad \overline{V} = \dfrac{U_{ref}}{U_{loc}} = \dfrac{\sigma_T \Delta T}{\mu_l U_{loc}}$

$B_d = \rho g \beta \Delta T a^2/\mu_1 U_{ref}$ $\quad \delta_T(L)/a = 5L/(aRe_{loc}^{0.5}Pr^{0.33})$



Experimental



Numerical

$Pr = 27, V = 43.9\ (R_\sigma = 155), Re_{loc} = 3.6, \delta_T/a = 3.0, B_d = 0.6$

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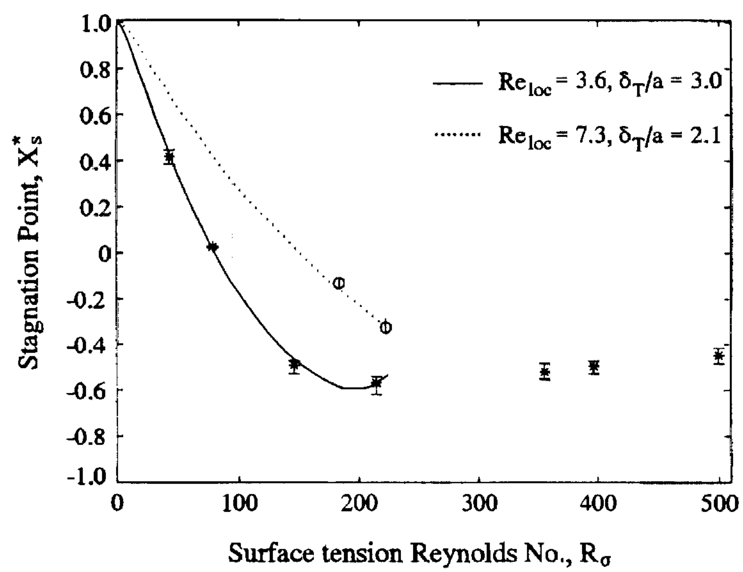
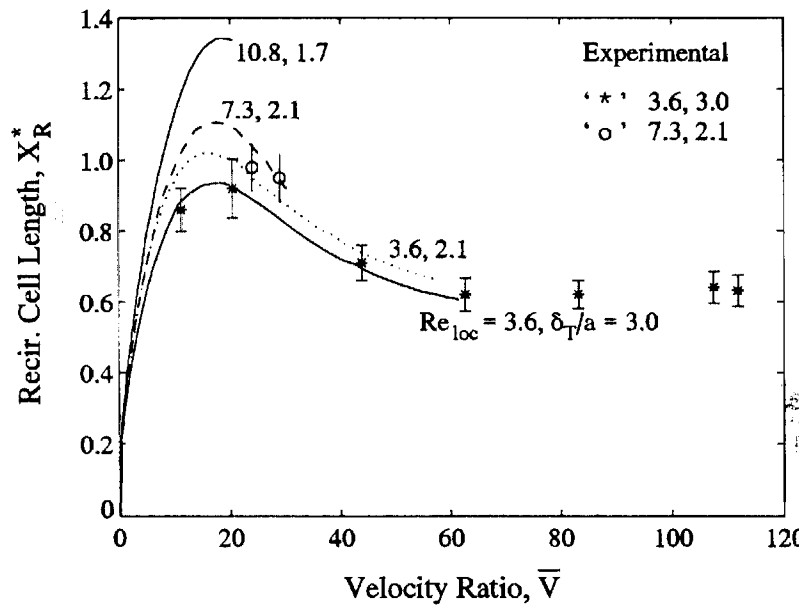
Favoring and opposing effects: Forced & Thermocap. convection

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



Stagnation point



Length of recirculation cell

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

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