The Effect of Gravity on Single Vapor Elongated Bubbles

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Flow boiling combines liquid latent heat and convection to improve heat transfer efficiency.

- Application of two-phase technology to space systems is desired, but better heat transfer predictions are needed.
- Mechanistic heat transfer models may serve as an improvement over traditional empirical correlations.
- This work was aimed at identifying the heat transfer mechanisms for the slug flow regime.

Vapor quality \( \frac{m_v}{m_v + m_l} \)
Taylor Bubble Introduction

- **Fluid motion**
  - Drift velocity of bubble requires liquid to move to trailing slug
  - Steady liquid film formed as wall shear balances with gravitational force
  - Circular jet diffuses into slug causing vortices

- **Define**
  - $U_l$ – average liquid velocity
  - $U_b$ – bubble velocity
  - $U_f$ – liquid film velocity
  - $U_d$ – drift velocity, $U_b - U_l$
  - $\delta$ – liquid film thickness
UMD Variable Gravity Flow Boiling Experiment

- Designed for parabolic flight testing
- Working fluid – HFE 7100
  - $T_{sat} = 60^\circ$ C at 1 bar
  - $\mu_i = 0.38$ cP (water: 1 cP)
  - $\sigma_i = 0.013$ N/m (water: 0.073 N/m)
- Measurements available
  - Local heat transfer
  - High-speed flow visualization
  - Film thickness
Flow Loop

High Speed Video Camera

Transparent Adiabatic Section

Counter-flow Heat Exchanger

Film Thickness Sensor

Bellows-type Accumulator

IR Camera

To Vacuum Pump

Three-Way Valve

Differential Pressure Transducer

De-gassing Membrane

Bubble Generation Segment

Absolute Pressure Transducer

Stainless Steel Coil Pre-heater

Turbine Flowmeter

Gear Pump

Bypass Segment
IR technique from Kim et al. (2012)

Flow Visualization

Wall Temperatures
Experimental heat transfer coefficient compared to:

- Dittus-Boelter correlation with Al-Arabi (1982) correction for thermal entry length
- Thermally developing mixed convection correlation (Shah & London, Davis & Perona)
Data Collection

- Studied single, elongated vapor bubbles
- Ground and parabolic flight experiments
- Why variable gravity?
  → Wider range of drift velocities
  \[ U_d = U_b - U_l = (C - 1)U_l + U_{b,0} \]
  → \( U_{b,0} = f(\Delta \rho_{l,v}, g, \mu_l, \sigma_l, D) \)

- Conditions:
  - \( G = 50 - 200 \text{ kg/m}^2\text{s} \)
  - \( Re_l = 790 - 3090 \)
  - \( q'' = 800 - 1700 \text{ W/m}^2 \)
  - \( a/g = 0.01, 0.34, 1, \text{ and } 1.8 \)
  - \( Bo = \frac{(\rho_l-\rho_v)gD^2}{\sigma} = 0.5 - 87 \)

  → Micro/Macro-channel threshold: \( Bo=0.9-19.7 \)
  → Capillary and Taylor bubbles
Bubble Velocity

Bubble Dynamics

Buoyancy Term Comparison

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Re_l  | 1525 | 3051 | 3051 | 3051
a/g   | 0.01 | 0.01 | 0.34 | 1.8
U_d   | 20 mm/s | 41 mm/s | 94 mm/s | 214 mm/s
Heat Transfer: Mechanism Distinctions

0.01g

\(Re = 1525, \ U_d = 20 \text{ mm/s}, \ q'' = 1.1 \text{ kW/m}^2\)

1g

\(Re = 1525, \ U_d = 124 \text{ mm/s}, \ q'' = 2.2 \text{ kW/m}^2\)
Local, time resolved heat transfer profiles
- Variation in peak magnitude and axial position
- Secondary peaks downstream

Wake history contour plot
- Streaks indicate vortices moving away from tail
- Penetration length \( L_p \) is seen to vary with time

\[ Re = 790, \quad U_d = 105 \text{ mm/s}, \quad a/g = 1, \quad q'' = 1.4 \text{ kW/m}^2, \quad h_{sp} = 130 \text{ W/m}^2 \text{K} \]
Heat Transfer: Wake Analysis

\(a/g=1, \quad U_d=105 \text{ mm/s}\)

\(Re_F=790, \quad q''=1.4 \text{ kW/m}^2, \quad h_{sp}=130 \text{ W/m}^2K\)

\(Re_F=3090, \quad q''=1.7 \text{ kW/m}^2, \quad h_{sp}=192 \text{ W/m}^2K\)
Heat Transfer: Wake Analysis

\[ \text{Re}_l = 790, \quad q'' = 1.4 \text{ kW/m}^2, \quad h_{sp} = 130 \text{ W/m}^2\text{K} \]

\[ \text{Re}_l = 790, \quad q'' = 1.1 \text{ kW/m}^2, \quad h_{sp} = 104 \text{ W/m}^2\text{K} \]
Near-wake region

Near-wake behavior:
- Broadening of profile
- Decrease in peak magnitude
- Shift of peak location downstream
Onset of Wake Turbulence

Campos and Carvalho (1988)

- Pinto et al. (1998) suggested that turbulence in the wake occurred when

\[ Re_{U_d} = \frac{\rho U_d D}{\mu} > 525 \]

- Present results predict an onset of vortices at \( Re_{U_d} = 741 \)

- A Strouhal number can be assigned

\[ St = \frac{f_v \delta}{(U_d-U_{d,cr})} = 0.19 \pm 0.01 \]
Conclusions

- Identification of main heat transfer mechanisms for flow boiling regimes necessary for development of prediction models
- An experimental study was conducted to determine the effect of flow parameters and gravity on rising Taylor bubbles
- The drift velocity was found to have a strong effect on the bubble shape and the heat transfer profiles
- Characteristics of the wake structure were identified (vortex frequency and penetration length) were identified and characterized
- These results can be used as validation for numerical simulations and physics-based model predictions
Acknowledgements

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Thank you!