Gravity-related Issues in Boiling and Condensation

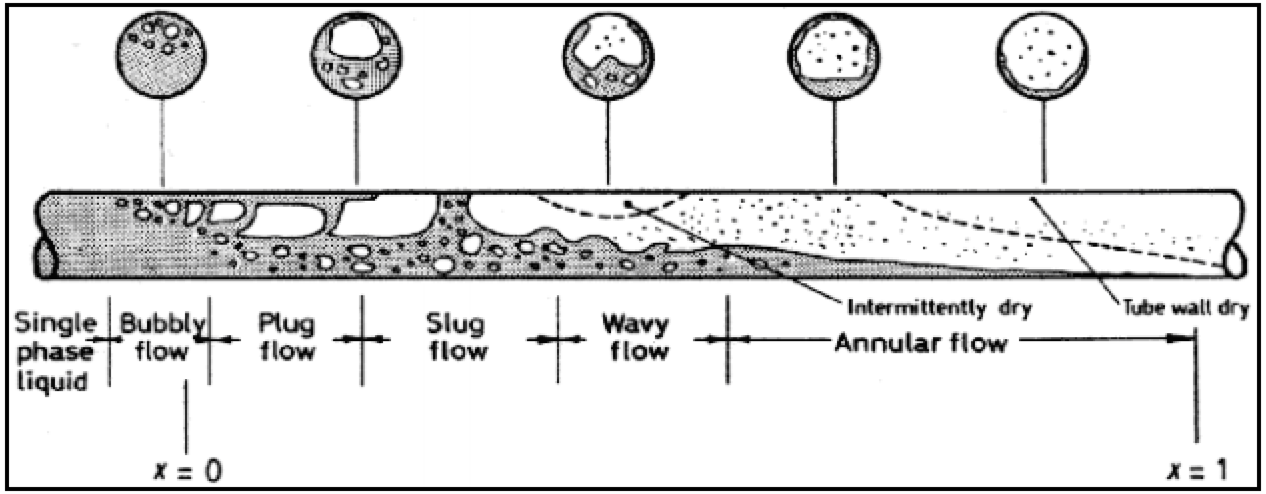
JSC Perspective

Eugene K. Ungar, Ph. D
Senior Thermal and Fluids Analyst
NASA/Johnson Space Center
October 2019

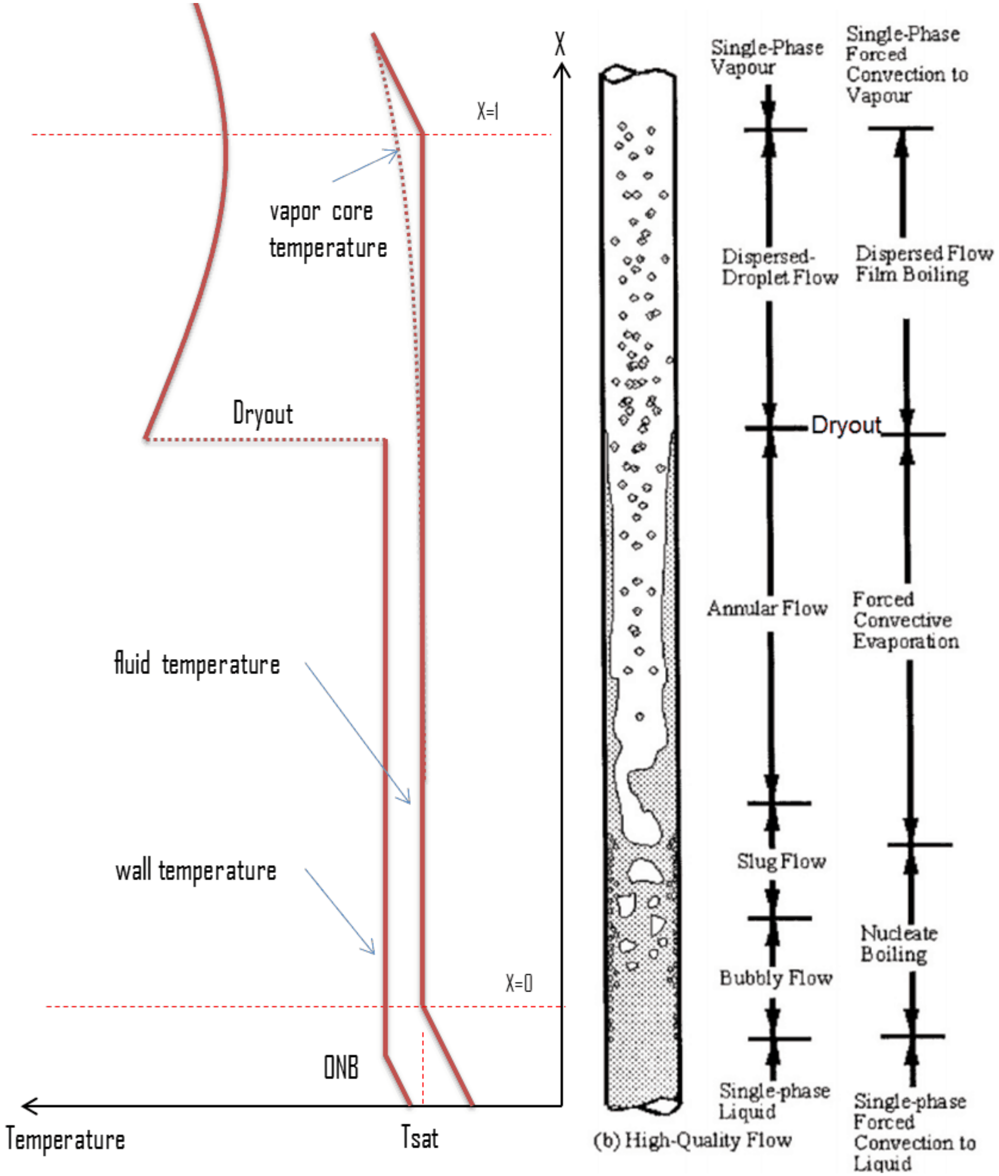
Problem Statement

- For a flight center, gravity-related issues in boiling and condensation take on a unique perspective
- Flight systems must be
  - highly reliable
  - developed and qualified in a cost effective manner
- Must work in 0-g and partial gravity as applicable

Gravity Effects

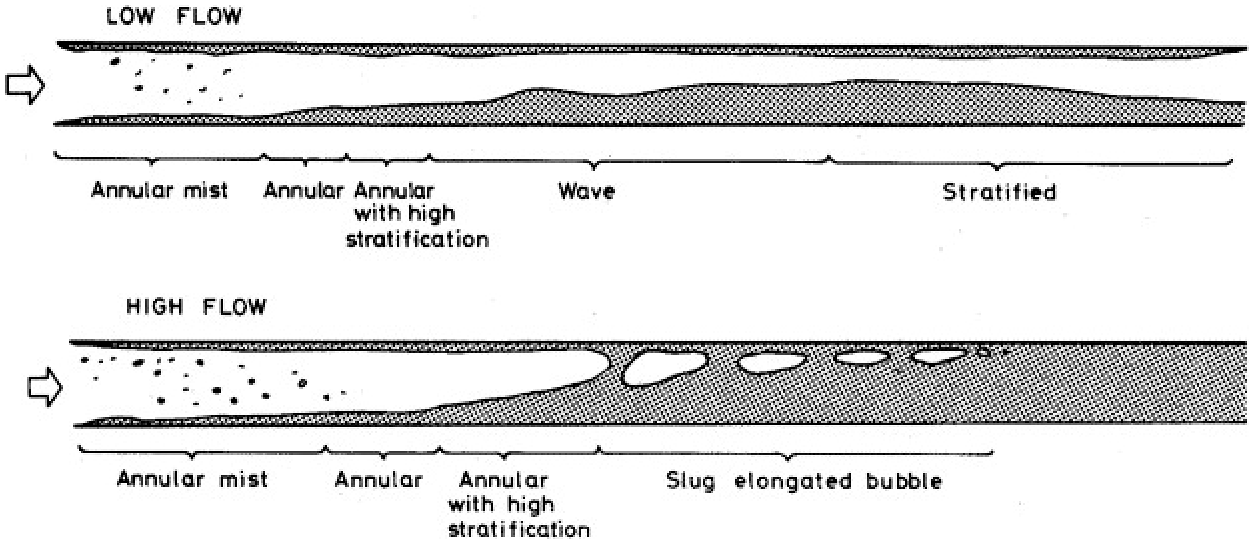


Heat transfer regions in convective boiling in a horizontal tube from Collier and Thome (1994)



Heat transfer regions in convective boiling in a vertical tube from Collier and Thome (1994)

Gravity Effects



Condensation in a horizontal tube from Liebenberg and Meyer 2006

0-g System Options

- Full scale testing in 0-g
- Gravity independent systems tested in 1-g
    - small channel surface tension dominated flows
    - high velocity inertia dominated flows
- Scaled testing in 0-g

Gravity Independence

- Surface tension dominance Bo<1

$$\mathrm{Bo} = \frac{(\mathrm{d}/2)^2}{\sigma/[\mathrm{g}(\rho_\mathrm{f}-\rho_\mathrm{g})]}$$

  - where σ is the surface tension of the fluid
  - g is the acceleration of gravity
  - ρ_f and ρ_g are the liquid and gas phase densities

- Bo$\leq$1 means that a vapor bubble growing quasi-statically will completely fill a horizontal liquid-filled tube before growing axially

Reinarts, T. R., Ungar, E. K., and Butler, C. D., "Adiabatic Two-Phase Pressure Drop in Microgravity: TEMP2A-3 Flight Experiment Measurements and Comparison with Predictions," presented at the 33st AIAA Aerospace Sciences Meeting & Exhibit, Reno, NV, January 9-12, 1995, AIAA 95-0635

Gravity Independence

- Inertia dominated flows (high annular) Fr>1

$$\mathrm{Fr} = \sqrt{\frac{\rho_g}{(\rho_f - \rho_g)}}\frac{u_{sg}}{\sqrt{d\ g}}$$

  - u_{sg} is the vapor superficial velocity

Taitel, Y., and Dukler, A. E., 1976, "A Model for Predicting Flow Regime Transitions in Horizontal and Near Horizontal Gas-Liquid Flow," AIChE Journal, Vol. 22, no. 1, pp. 47-55

Gravity Independence

- Are small Bond number and/or large Froude number sufficient for gravity independence?
  - There will be low quality regions where Froude number is small
  - Bond number will be irrelevant for champagne bubbles
- A good topic for further study

Scaling in 0-g

- Testing full scale systems in 0-g is difficult
- 0-g testing usually requires geometrical scaling and a change in working fluid
- What are the proper scaling parameters?
  - Case can be made to include ρ_f/ρ_g, We_g, Re_f, Re_g, and X, the Martinelli parameter
- A good topic for further study

Partial Gravity Boiling and Condensation

- Scaling is critical
  - Flying experiments on partial-g aircraft almost always involves a fluid substitution
  - Gravity is just another parameter
- What are the proper scaling parameters?
  - Case can be made to include Fr, ρ_f/ρ_g, We_g, Re_f, Re_g, and X
- A good topic for further study
  - Might involve partial-g aircraft experiments for proof
- These should be the last partial-g experiments required

Conclusion

- Development of zero and partial gravity flight systems requires extensive testing
- Zero-g aircraft testing for 0-g systems
  - Safety concerns usually require fluid substitution
  - +/- 0.01 g is a spec, not a guarantee
  - <30 seconds of 0-g time is problematic
- Partial gravity aircraft testing for partial-g systems
  - ~30 seconds of partial time is problematic
- Testing recommendations should come from an understanding of the physics

Backup

1-g Behavior of Bubbles in Vertical Tube

- Bond number is the relevant dimensionless group
- $Bo = \frac{(d/2)^2 g(\rho_f - \rho_g)}{\sigma}$
    - where
        - r = tube diameter
        - g = gravitational acceleration
        - ρ_f = liquid density
        - ρ_g = vapor density
        - σ = surface tension

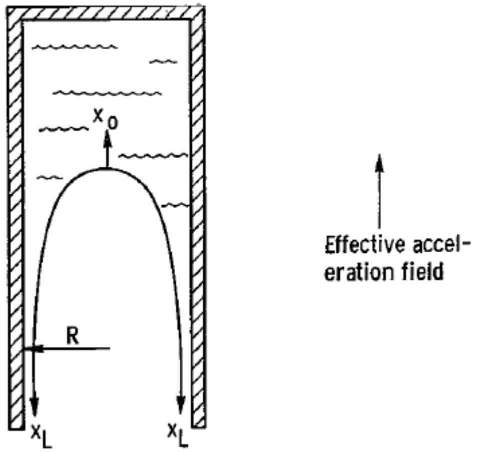


Figure 1. - Interface profile under imposed acceleration directed perpendicular from vapor to liquid phase (where x_0 is vapor penetration displacement and x_L is leading-edge displacement).

- From the literature at Bo<0.84 the liquid/vapor interface would be stable
- For Bo>0.84 counterflow can occur

Motion of Liquid-Vapor Interface in response to Imposed Acceleration,
William J. Masica, Donald A. Petrash, NASA TN D-3005, September 1965