Gravity-related Issues in Boiling and Condensation

JSC Perspective

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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 $\text{Bo} < 1$

$$\text{Bo} = \frac{(d/2)^2}{\sigma/[g(\rho_f - \rho_g)]}$$

• where $\sigma$ is the surface tension of the fluid

• $g$ is the acceleration of gravity

• $\rho_f$ and $\rho_g$ are the liquid and gas phase densities

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

Gravity Independence

• Inertia dominated flows (high annular) Fr>1

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

• \( u_{sg} \) is the vapor superficial velocity

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 $\rho_f/\rho_g$, $\text{We}_g$, $\text{Re}_f$, $\text{Re}_g$, 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, $\rho_f/\rho_g$, We₉, Re₉, Re₉, 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
  • \( \rho_f \) = liquid density
  • \( \rho_g \) = vapor density
  • \( \sigma \) = surface tension

• 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