

ON THE MOTION OF AN ANNULAR FILM IN MICROGRAVITY GAS-LIQUID FLOW

John B. McQuillen

Microgravity Fluid Physics Branch
 NASA Glenn Research Center
 21000 Brookpark Road,
 Cleveland, OH 44135
 PH (216)433-2876
 FAX (216)433-8050
 j.mcquillen@grc.nasa.gov

ABSTRACT

Three flow regimes have been identified for gas-liquid flow in a microgravity environment: Bubble, Slug, and Annular. For the slug and annular flow regimes, the behavior observed in vertical upflow in normal gravity is similar to microgravity flow with a thin, symmetrical annular film wetting the tube wall. However, the motion and behavior of this film is significantly different between the normal and low gravity cases. Specifically, the liquid film will slow and come to a stop during low frequency wave motion or slugging. In normal gravity vertical upflow, the film has been observed to slow, stop, and actually reverse direction until it meets the next slug or wave.

Using the unit slug approach, as seen in Figure 1, a quick estimate for the film thickness can be derived by the following relationship:

$$\alpha = 1 - \left(\frac{2h}{D} \right)^2$$

Combined with the following from the drift flux model:

$$\alpha = \frac{\frac{\rho_L}{\rho_G} \frac{x}{1-x}}{C_0 \left(1 + \frac{\rho_L}{\rho_G} \frac{x}{1-x} \right)}$$

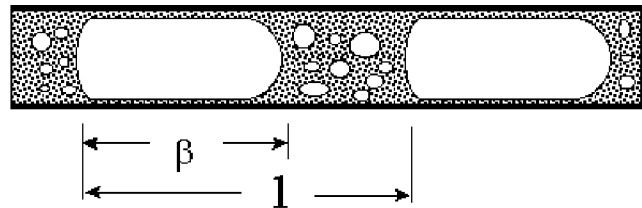


Figure 1: Unit Slug Concept

Rearranging yields the film thickness, however, this estimate assumes that the vapor and liquid phases are either distributed in an annular flow with very thin liquid slugs separating annular pockets or with significant gas entrainment in the liquid slugs.

A minimum film thickness can be attained by assuming that most of the gas is contained in the Taylor bubble. Therefore, if one slug unit consists of both a liquid slug and a Taylor bubble and assuming that the void fraction is zero in the slug, a mass balance performed on the Taylor bubble portion of the slug unit will obtain the following:

$$\alpha_B V + (1 - \alpha_B) U_{LB} = j_L + j_G$$

By rearrangement, the void fraction in the Taylor bubbles is given by:

$$\alpha_B = 1 - \frac{V - (j_G + j_L)}{V - U_{LB}}$$

where V is the velocity of the Taylor bubble and U_{LB} is the velocity of the liquid film. Within the Taylor bubble, the film thickness decreases from the nose to the tail. Far from the nose, it reaches its fully developed thickness. This thickness may be found directly by noting that there is no driving force acting on the film except for the interfacial shear stress. By disregarding this effect, the film does not experience a driving force and its velocity must be zero with respect to the standing frame ($U_{LB}=0$). This has been experimentally confirmed by watching small bubbles that are entrained in the thin liquid film around the Taylor bubble and gives the minimum film thickness in these bubbles:

$$h_{min} = \frac{D}{4} \frac{V - (j_G + j_L)}{V}$$

If $V \approx C_0(U_{LS} + U_{GS})$, then

$$h_{min} = \frac{C_0 - 1}{C_0} \frac{D}{4}$$

For values of $C_0=1.2$, the minimum film thickness is approximately 0.8 mm, which is significantly smaller than the values found using the drift flux model.

Data obtained for air-water, air-water and glycerine mixture (50 w/o and viscosity @), and an air-water and surfactant mixture (Zonyl FSP™, 1 w/o and surface tension of 20 dynes/cm) was obtained at in a 1.27 cm ID tube at low gravity¹. 16 mm movie film data was obtained at 400 frames per second. Bubbles located within the thin liquid annular film were tracked for their position as a function of time and analyzed as a measure of the liquid axial velocity relative to the passage of slugs or annular roll waves. It was found that there was always a slowing of the thin liquid film or substrate until the next slug or roll wave accelerated the film again.

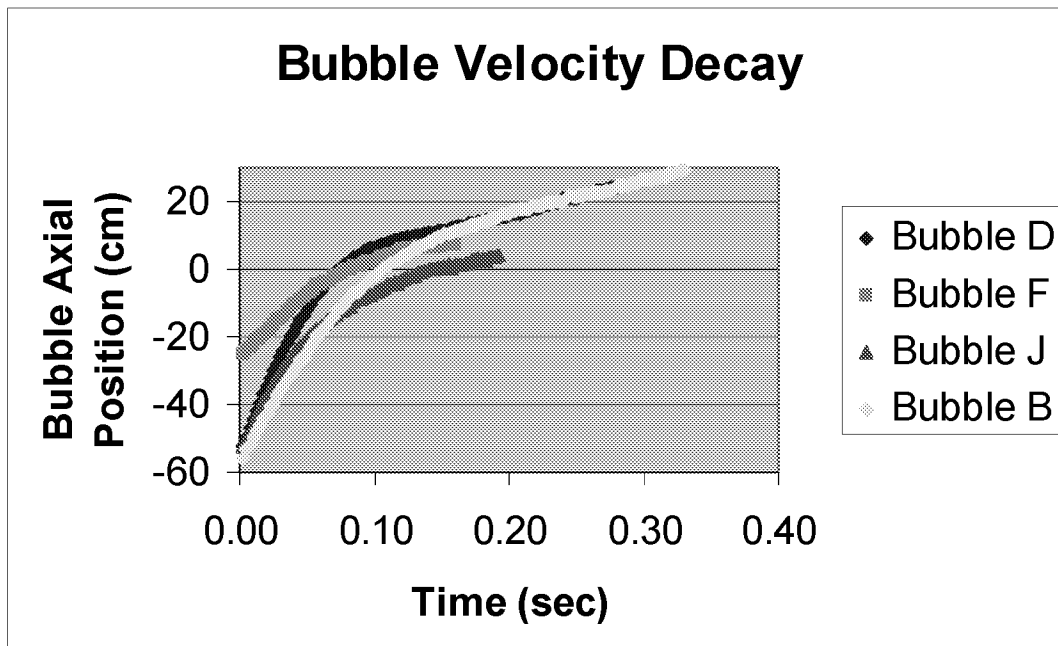
Liquid film thickness data was obtained at 1000 Hz from thin wire conductivity probes. Their accuracy was about 0.02 mm. A histogram analysis was used to obtain a truncated film thickness, by excluding values greater than 1.5 mm film thickness, the mode, and a minimum film thickness. These are compared with an average value that includes wave heights or slugs. In several cases, for both when the liquid film motion stopped or even just significantly slowed, it was found that, for obvious reasons, that the truncated averaged film thickness was less than the average film thickness, the mode value was less than both of the averages and that the “minimum” experimental film thickness was typically less than half of the both averages.

¹ Bousman, W. S., “Studies of Two-Phase Gas-Liquid Flow in Microgravity,” *NASA Contractor Report 195434*, 1995.

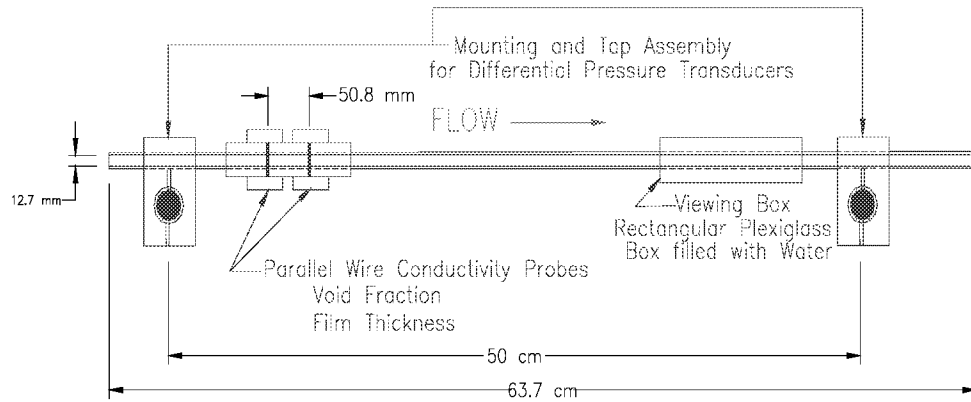
In Normal Gravity Vertical
Upflow, Liquid Film reverses
Direction Between Slugs,
Churns and/or Roll Waves

Visual Observations of
Microgravity Gas-Liquid
Flow Data Reveal that Liquid
Substrate slows significantly
between Liquid Slugs or Roll
Waves.

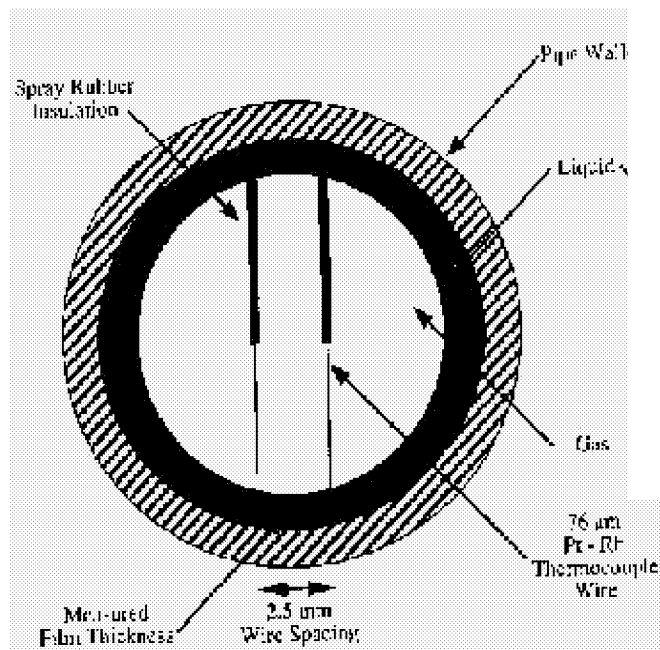
Film Velocity as a Function of Entrained Gas Bubbles



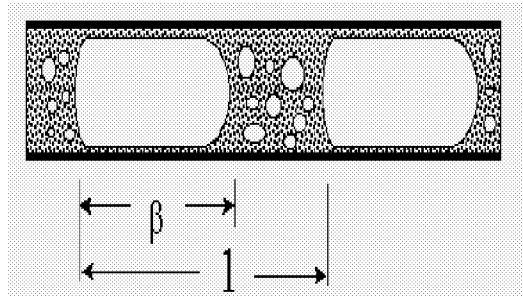
Test Section Layout



Cross-sectional View of Conductivity Probes



Unit Slug Concept



Film Thickness and Void Fraction Relationship

$$\alpha = 1 - \left(\frac{2h}{D} \right)^2$$

From Drift Flux Model

$$\alpha = \frac{\frac{\rho_L}{\rho_G} \frac{x}{1-x}}{C_0 \left(1 + \frac{\rho_L}{\rho_G} \frac{x}{1-x} \right)}$$

Mass Balance on Taylor Bubble Portion of Unit Slug

$$\alpha_B V + (1 - \alpha_B) U_{LB} = j_L + j_G$$

Only Force on Film is Interfacial Shear ~ 0 based on Bubble motion

Minimum Film Thickness

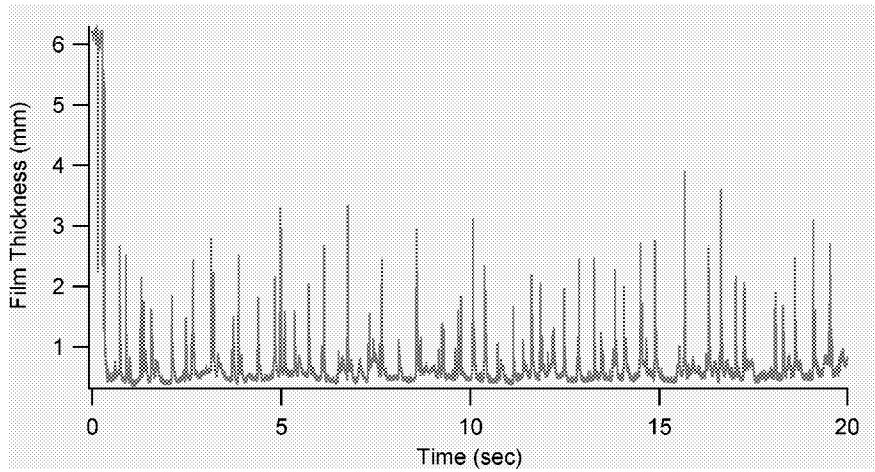
$$h_{min} = \frac{D V - (j_G + j_L)}{4 V}$$

If $v \approx C_0 (U_{LS} + U_{GS})$

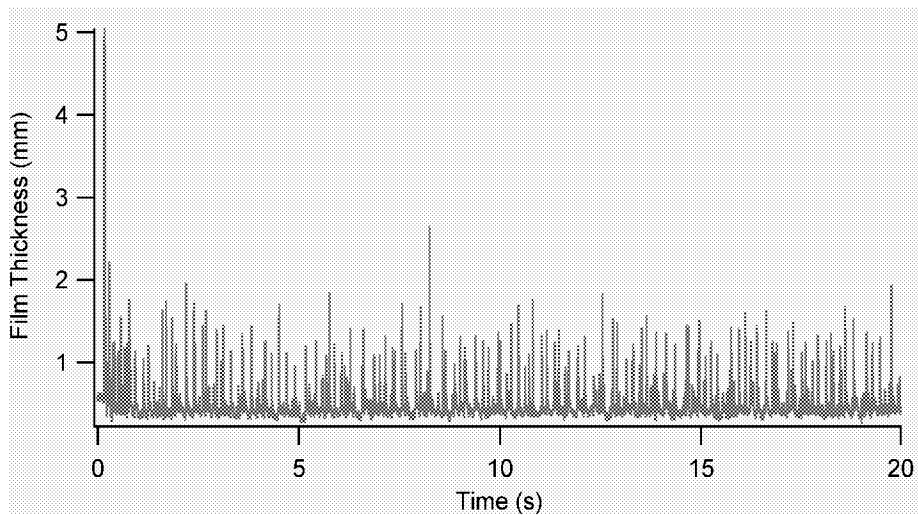
$$h_{min} = \frac{C_0 - 1}{C_0} \frac{D}{4}$$

For values of $C_0 = 1.2$, $h_{min} = 0.8$ mm.

Film Thickness Time Traces

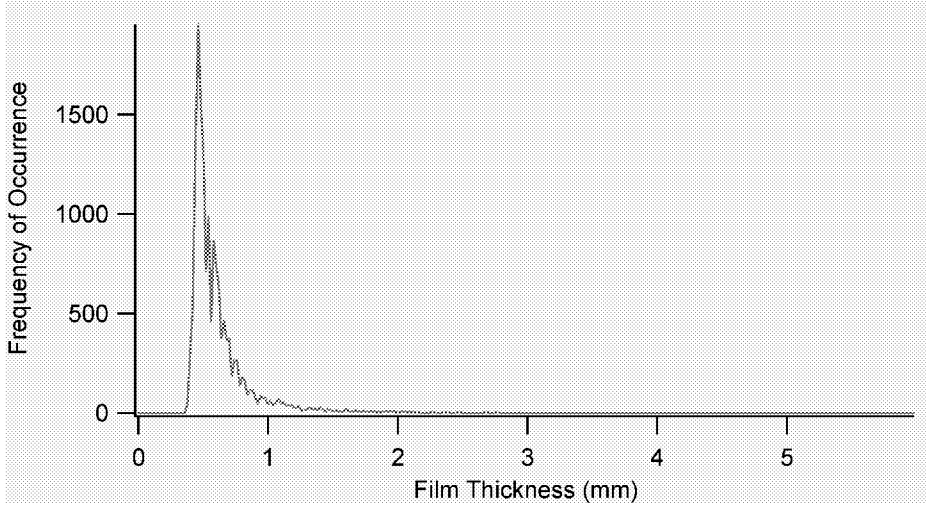


Slug

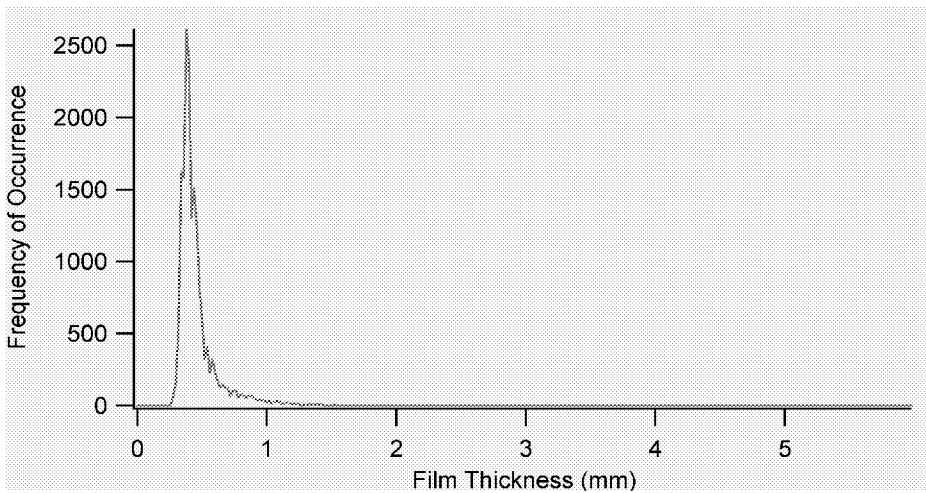


Annular

Histogram Plots



Slug



Annular

Comparison of “Film Thicknesses”

| Test | Film Thickness Average | Film Thickness Standard Deviation | Average Liquid Substrate Thickness | Liquid Substrate Thickness Standard Deviation | Film Thickness Mode | Minimum Film Thickness |
|--------|------------------------|-----------------------------------|------------------------------------|---|---------------------|------------------------|
| 82t1 | 0.51 | 0.23 | 0.49 | 0.09 | 0.42 | 0.24 |
| 82t2 | 1.03 | 0.74 | 0.72 | 0.28 | 0.62 | 0.28 |
| 83t1 | 0.90 | 0.38 | 0.71 | 0.21 | 0.74 | 0.50 |
| 93t1 | 1.13 | 0.73 | 0.79 | 0.31 | 0.74 | 0.58 |
| 93t2 | 1.43 | 1.34 | 0.74 | 0.21 | 0.84 | 0.50 |
| 96t1 | 1.05 | 0.24 | 0.98 | 0.24 | 0.80 | 0.48 |
| 99t12 | 1.08 | 0.49 | 0.96 | 0.18 | 0.86 | 0.38 |
| 99t22 | 1.18 | 0.68 | 1.07 | 0.39 | 0.86 | 0.52 |
| 101t12 | 0.46 | 0.16 | 0.46 | 0.15 | 0.38 | 0.26 |
| 102t12 | 0.61 | 0.22 | 0.43 | 0.11 | 0.46 | 0.36 |
| 103t13 | 0.46 | 0.24 | 0.45 | 0.21 | 0.34 | 0.22 |
| 103t22 | 0.75 | 0.32 | 0.70 | 0.16 | 0.60 | 0.28 |

Summary

- Liquid Film Substrate Motion Slows Between Slugs and Roll Waves Based on Liquid Properties and Slugging Frequency(taylor Bubble Length)
- Liquid Film Substrate Based on Unit Slug Concept
 - Independent of Fluid Properties
 - Agrees Well With “Average Film Thickness Measurements for Slug and Annular Flow
 - Histogram Analysis Reveals That Mode and Actual Minimum Film Thickness