

Gas-Liquid Packed Bed Reactors in Microgravity

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Why Packed Bed Reactors in Microgravity?

⇒ *Motivation*

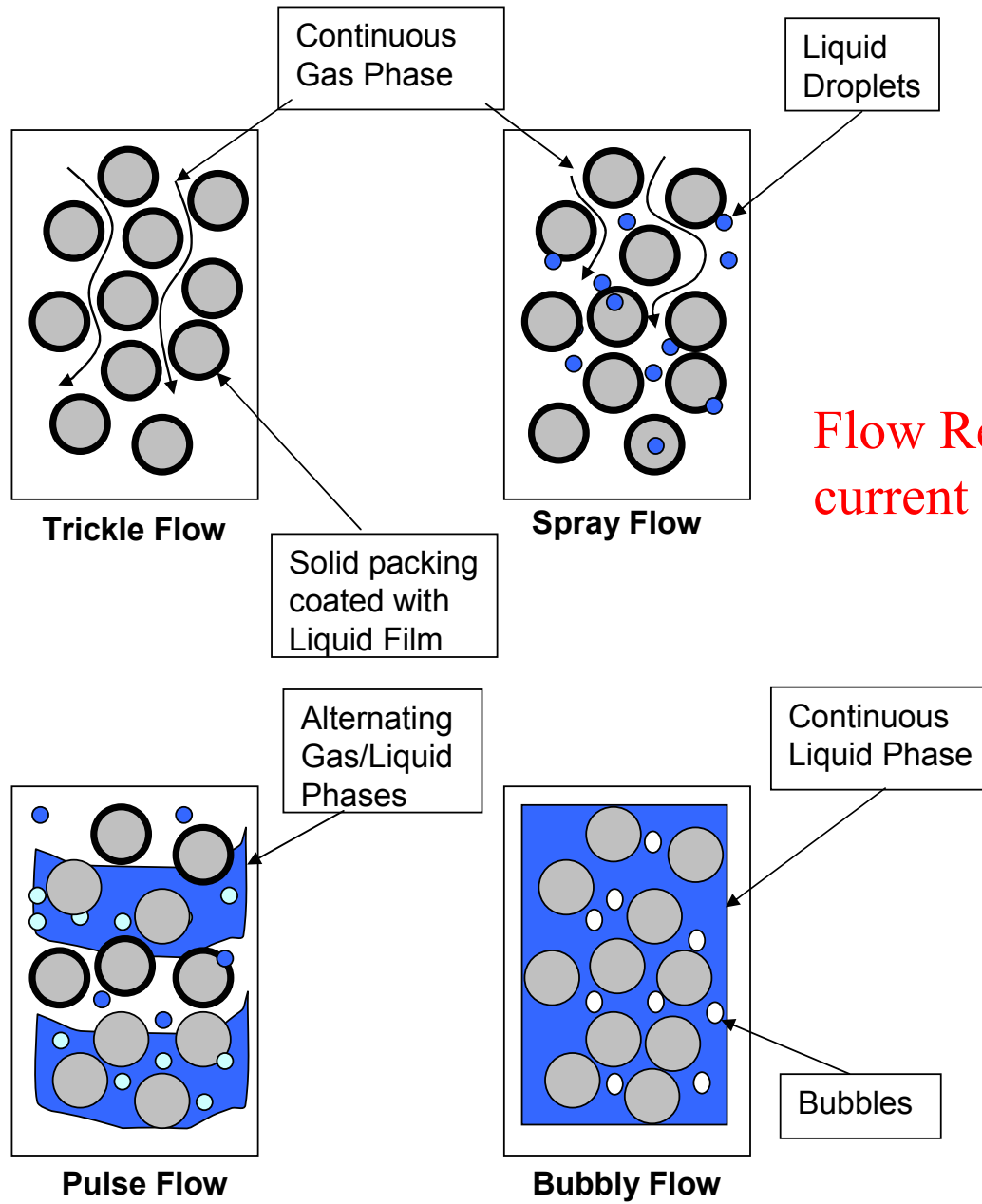
- Packed Bed is the ‘workhorse’ of the Chemical Industry.
 - Used to carry out many single and multiphase reactions
 - Used in many Unit Operations (Gas Absorption/Purification, Extraction/Leaching, Adsorption/Chromatography, etc.)

- Considered an “enabling technology” for long duration manned space flights
 - Water Recovery (catalytic beds/biological reactors) Critical Technology
 - Air Revitalization (CO₂ absorption) Severely Limiting

[Workshop on Critical Issues in Microgravity Fluids, Transport and Reaction Processes, NASA-TM-212940-2004]

⇒ *NASA funded grants and projects*

- University of Houston, V. Balakotaiah (Principal Investigator).
 - M. McCready, U. of Notre Dame,
 - B. Motil, NASA GRC; Y. Kamotani, CWRU
- Purdue University, S. Revankar (Principal Investigator).
- AHLS-1 flight definition experiment.



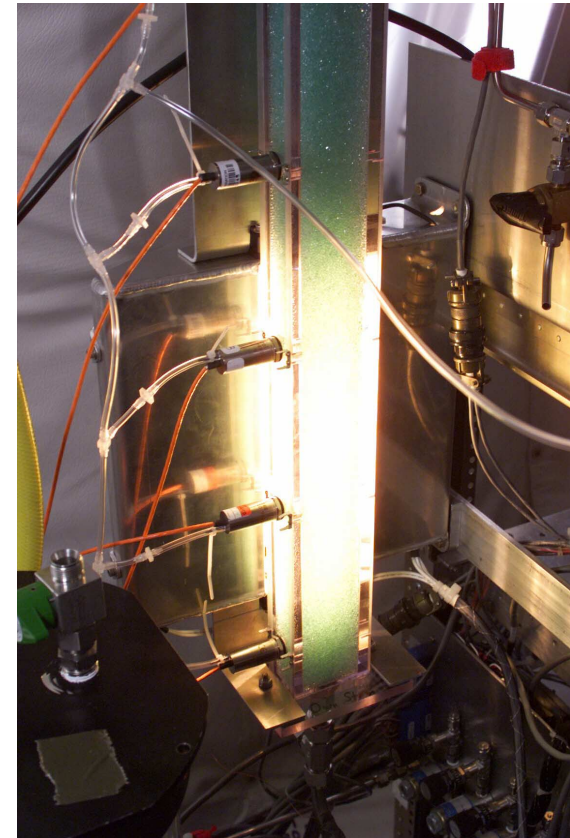
Flow Regimes in 1-g co-current downflow

Similarities and Differences Between 1-g and 0-g Cocurrent Downflow Through Packed Beds

- Low Interaction Regime (trickle flow) does not exist without gravity.
- All fluid flow is driven by pressure gradient with capillary and shear forces playing a more significant role. No steady countercurrent flow.
- Pulse flow occurs at a much lower flow rate and enhances interaction.
- Liquid holdup in 0-g is 100%
- Pressure drop measured in 0-g is the true frictional pressure drop
- Spray flow is inertia driven and not effected by change in gravity.

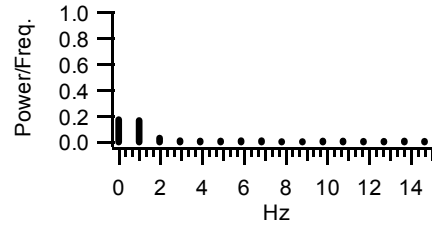
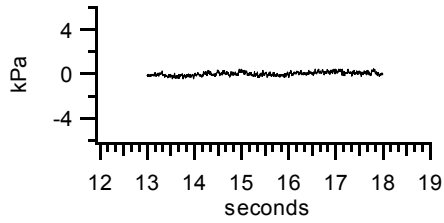
First Experiments in 0-g

- 12 flights - over 300 test conditions flown on NASA KC-135 aircraft (20 sec/run)
- Rectangular cross section
2.5 cm x 5 cm x 60 cm long
- 5 differential pressure trans. (1000 Hz)
- 2 mm and 5 mm spherical glass beads
- High speed video (500 fps)
- Air and Water-Glycerin (1 to 20 cP)
- $0.03 < G < 0.8 \text{ kg}/(\text{s m}^2)$
- $3 < L < 50 \text{ kg}/(\text{s m}^2)$
- $0.18 < \text{Re}_{LS} < 100$
- $8.5 < \text{Re}_{GS} < 175$
- $4 \times 10^{-4} < \text{We}_{LS} < 0.2$
- $900 < \text{Su}_L < 365,000$

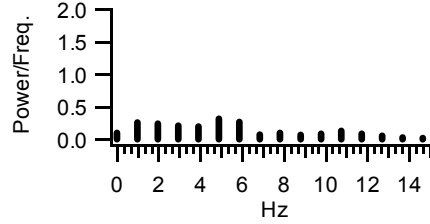
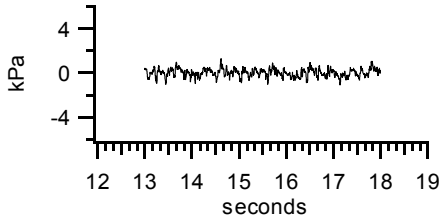


$$\text{Re}_{LS} = \frac{\rho_L U_{LS} d_p}{\mu_L} \quad \text{We}_{LS} = \frac{\rho_L U_{LS}^2 d_p}{\sigma} \quad \text{Su} = \frac{d_p \rho_L \sigma}{\mu_L^2} = \frac{\text{Re}_{LS}^2}{\text{We}_{LS}} \quad \text{Re}_{GS} = \frac{\rho_G U_{GS} d_p}{\mu_G}$$

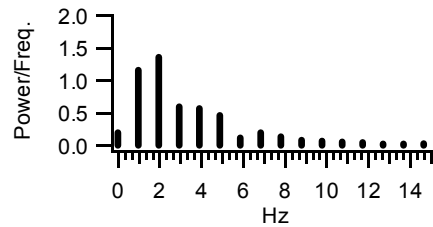
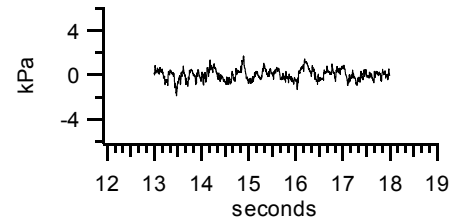
Identification of Flow Regime Transitions



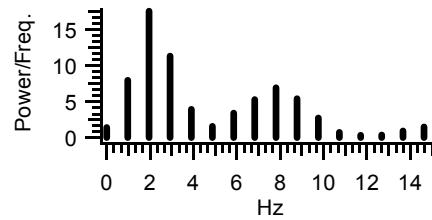
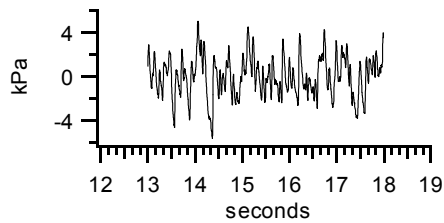
Bubble flow



Bubble flow "near" transition



Pulse flow "near" transition



Pulse flow

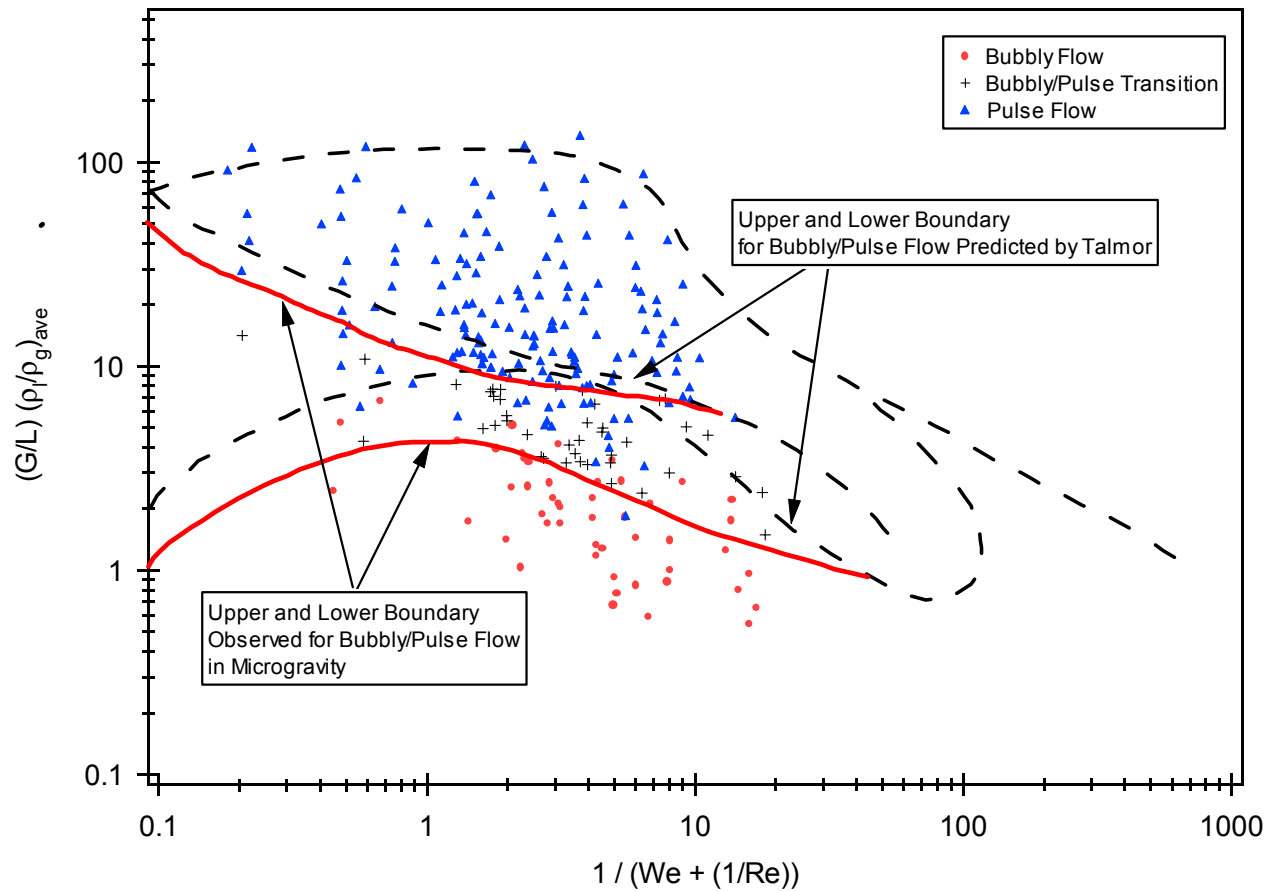
Microgravity Experimental Results Compared to Talmor Map

$$X = \frac{\text{inertia} + \text{gravity}}{\text{interface} + \text{viscous}} = \frac{1 + \frac{1}{Fr}}{\frac{1}{We} + \frac{1}{Re}}$$

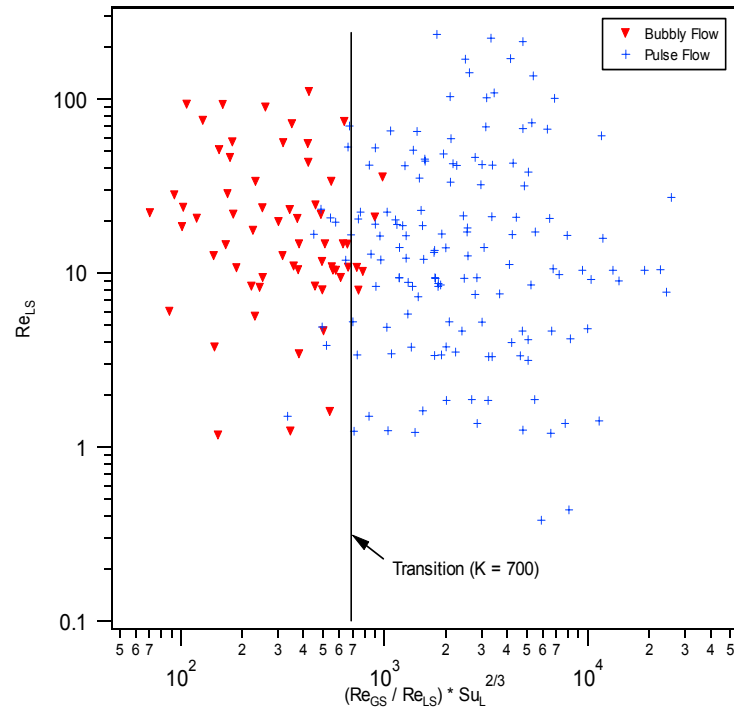
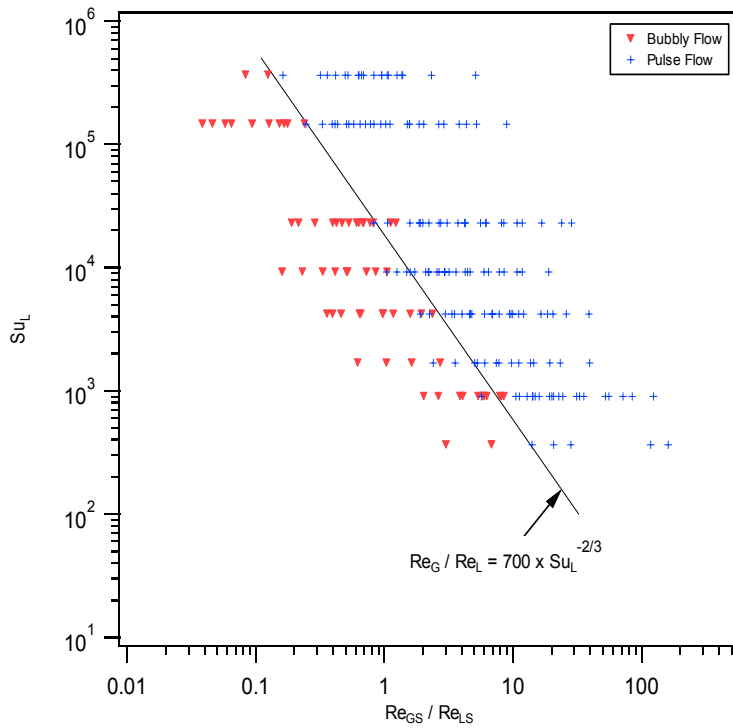
$$We = \frac{D^*(L+G)v_{LG}}{\sigma} \quad Re = \frac{D^*(L+G)}{\mu_{LG}} \quad Fr = \frac{[(L+G)v_{LG}]^2}{gD^*}$$

$$v_{LG} = \frac{v_L(L/G) + v_G}{1 + (L/G)}$$

Packed Bed in Microgravity



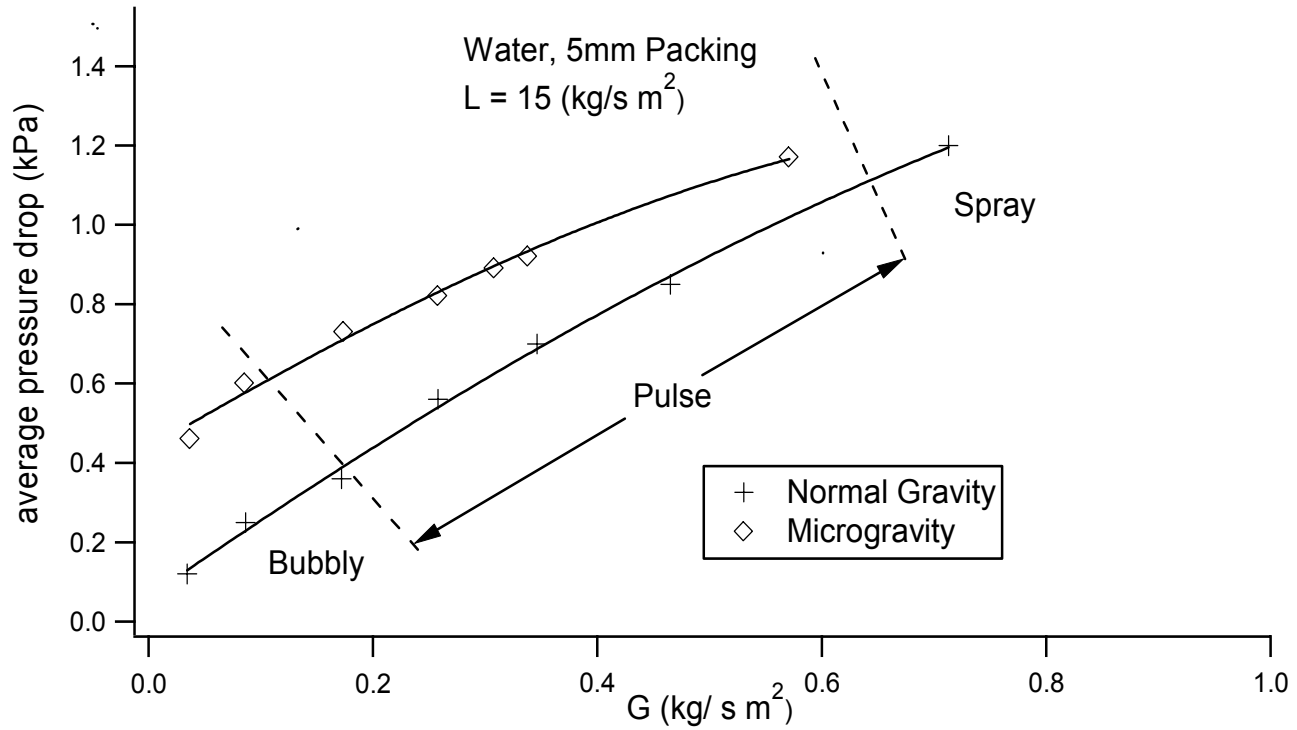
Flow Regime Transition in Microgravity



- Bubble-Pulse transition is a function of gas and liquid Reynolds numbers and the liquid Suratman number, where:

$$Su_L = \frac{Re_{LS}}{Ca_{LS}} = \frac{Re_{LS}^2}{We_{LS}} = \frac{d_P \rho_L \sigma}{\mu_L^2}$$

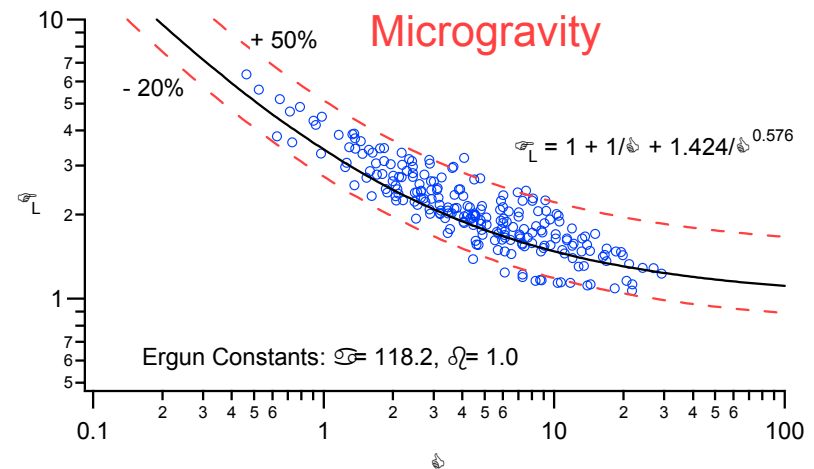
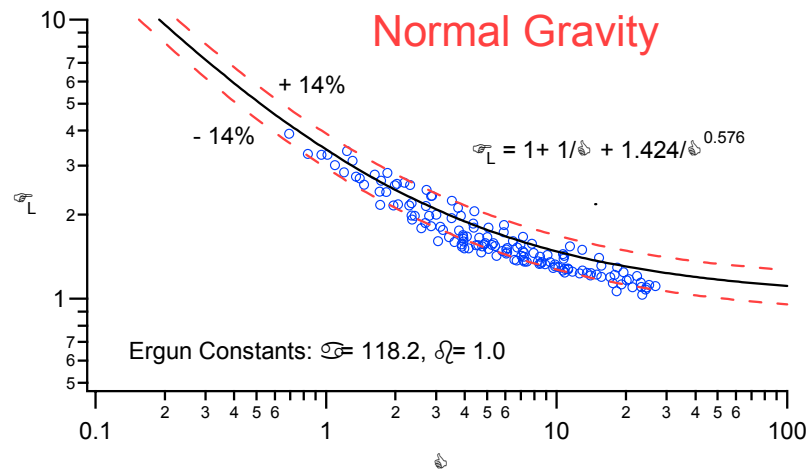
Pressure Drop



Comparison of average pressure drop for normal and microgravity conditions.

Pressure Drop

Lockhart-Martinelli Correlation



- Scatter is increased in the microgravity environment, an indication of the degree to which the capillary or surface tension effects are masked by hydrostatic head.

Pressure Drop

- Dimensionless pressure drop:

$$\frac{-\Delta P}{Z} \frac{d_p}{\rho_L U_{LS}^2} = f \left[\frac{Su_L}{Re_{LS}^2}, \frac{1}{Re_{LS}}, Re_{GS}, \epsilon \right]$$

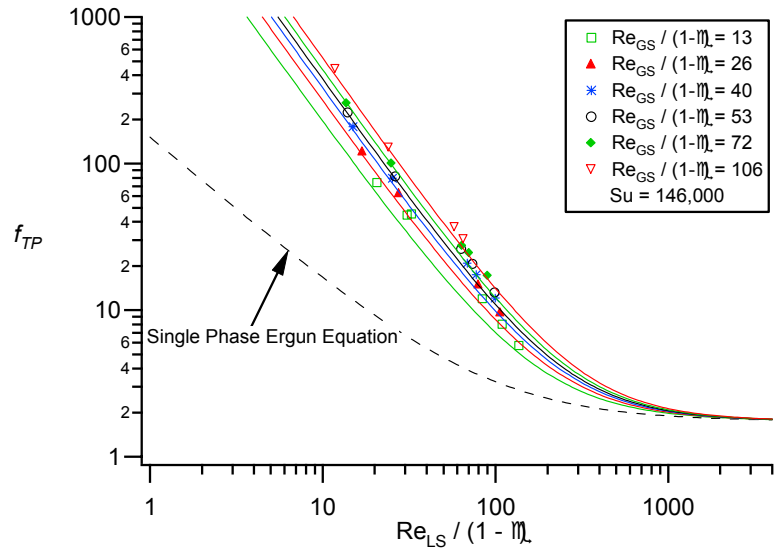
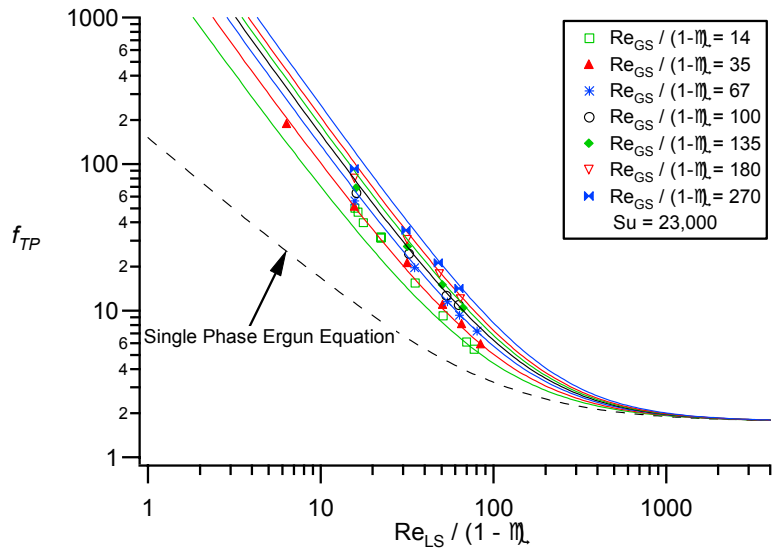
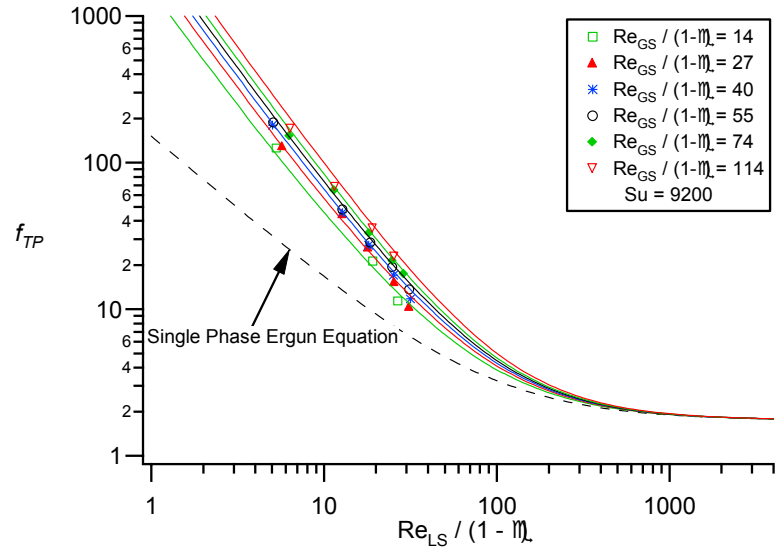
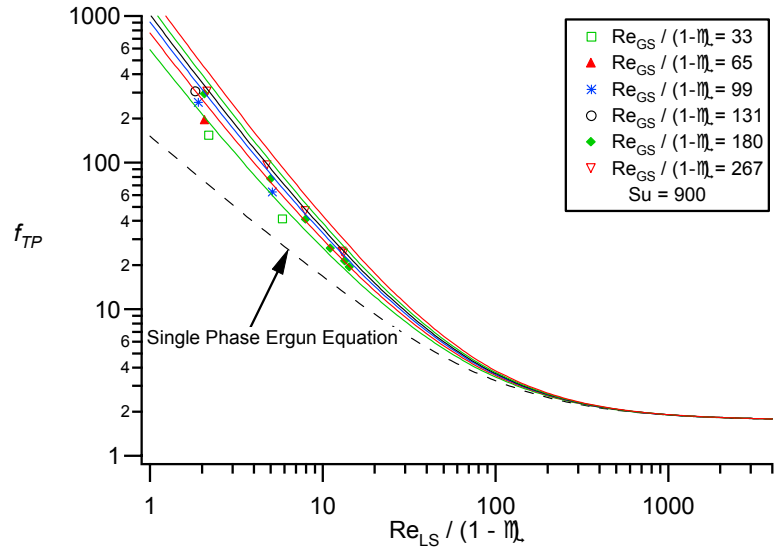
- Apply limiting cases in terms of the Ergun equation:

1. In limit of zero interfacial tension between fluids, reduces to single phase.
2. In the limit of zero gas flow, reduces to single phase.
3. In the inertia dominated limit, the friction factor should be independent of the interfacial and viscous terms.

$$f_{TP} - f_{SP} = \gamma \left(\frac{Re_{GS}}{1-\epsilon} \right)^a \left(\frac{1-\epsilon}{Re_{LS}} \right)^b \left(\frac{(1-\epsilon)^2 Su_L}{Re_{LS}^2} \right)^c$$

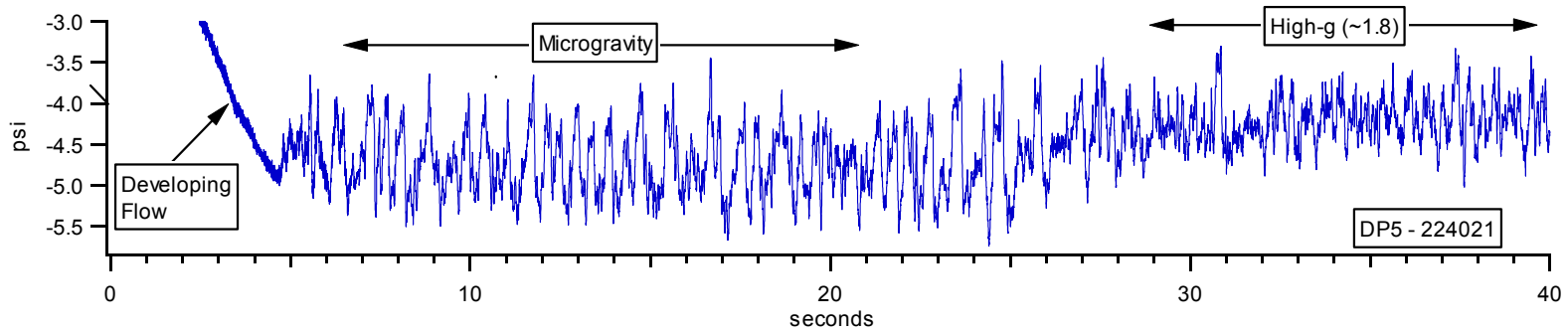
- Determining parameters by regression, reduces to (two-phase friction factor):

$$f_{TP} = \frac{-\Delta P}{Z} \frac{d_p}{\rho_L U_{LS}^2} \frac{\epsilon^3}{1-\epsilon} = \frac{1-\epsilon}{Re_{LS}} \left[180 + 0.8 \left(\frac{Re_{GS}}{1-\epsilon} \right)^{\frac{1}{2}} \left(\frac{Su_L (1-\epsilon)}{Re_{LS}} \right)^{\frac{2}{3}} \right] + 1.8$$



Pressure Drop & Pulse Characteristics with varying g

- Pulse amplitude decreases with increasing gravity.



	Microgravity (10-18 s)	High Gravity (32-40 s)	Difference
Average Pressure Drop	4.15 psi	4.75 psi	.6 psi
Pulse Amplitude	2.22 psi	1.69 psi	.5 psi

Summary

- Flow regime and pressure drop data was obtained and analyzed
- Pulse flow exists at lower liquid flow rates in 0-g compared to 1-g
- 1-g flow regime maps do not apply in microgravity
- Pressure drop is higher in microgravity (enhanced interfacial effects)

Work in Progress

- Flow Regimes and Pressure Drop with Alumina/Catalyst Particles
[Summer, 2004]
- Flow Regimes and Pressure Drop with Structured Packed Beds (2-D
beds and monoliths) [Summer/Fall 2004]
- Mass Transfer Studies in Microgravity
 - Gas-liquid interfacial area
 - Gas to liquid mass transfer coefficient
 - Solid-liquid mass transfer coefficient
- Modeling/Computational and Scale-up Studies