FUNDAMENTAL STUDIES ON TWO-PHASE GAS-LIQUID FLOWS THROUGH PACKED BEDS IN MICROGRAVITY

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ABSTRACT

In the typical operation of a packed-bed reactor, gas and liquid flow simultaneously through a fixed bed of solid particles. Depending on the application, the particles can be of various shapes and sizes and provide for intimate contact and high rates of transport between the phases needed to sustain chemical or biological reactions. The packing may also serve as either a catalyst or as a support for growing biological material. NASA has flown two of these packed-bed systems in a microgravity environment with limited or no success (Motil et al. [1]). The goal of this research is to develop models (with scale-up capability) needed for the design of the physicochemical equipment to carry out these unit operations in microgravity. New insight will also lead to improvements in normal gravity operations.

Our initial experiment was flown using an existing KC-135 two-phase flow rig with a modified test section. The test section is a clear polycarbonate rectangular column with a depth of 2.54 cm, a width of 5.08 cm, and 60 cm long. The column was randomly packed with spherical glass beads by slowly dropping the beads into the bed. Even though care was taken in handling the column after it was filled with packing, the alternating high and low gravity cycles with each parabola created a slightly tighter packed bed than is typically reported for this type. By the usual method of comparing the weight difference of a completely dry column versus a column filled with water, the void fraction was found to be .345 for both sizes of beads used. Five flush mounted differential pressure transducers are spaced at even intervals with the first location 4 cm from the inlet port and the subsequent pressure transducers spaced at 13 cm intervals along the column. Differential pressure data was acquired at 1000 Hz to adequately observe pulse formation and characteristics. Visual images of the flow were recorded using a high-speed SVHS system at 500 frames per second. Over 250 different test conditions were evaluated along with a companion set of tests in normal gravity. The flow rates, fluid properties and packing properties were selected to provide a range of several orders-of-magnitude for the important dimensionless parameters.

The well known Ergun equation for single phase flow through porous media is written by superposing the pressure drop expression for purely viscous (Blake-Kozeny) and purely inertial losses (Burke-Plummer):

$$\frac{-\Delta P}{Z} = 150\frac{(1-\varepsilon)^2}{\varepsilon^3}\frac{\mu U}{D_p^2} + 1.75\frac{(1-\varepsilon)}{\varepsilon^3}\frac{(\rho U)U}{D_p} \quad \text{where}$$

ε = void fraction, U = fluid superficial velocity, D_P = packing diameter, and Z = column length.

For two-phase flow in the microgravity environment, the measured pressure drop is the true frictional pressure drop since the hydrostatic head is nearly zero. Through dimensional arguments (neglecting gravity and the bed inclination), the non-dimensional form of the pressure drop is:

$$\frac{-\Delta P}{Z}\frac{D_P}{\rho_L U_{LS}^2} = f\left[\varepsilon,\ Re_{GS},\ \frac{1}{Re_{LS}},\ \frac{1}{We_{LS}},\ \frac{\rho_G}{\rho_L},\ \frac{\mu_G}{\mu_L}\right]$$

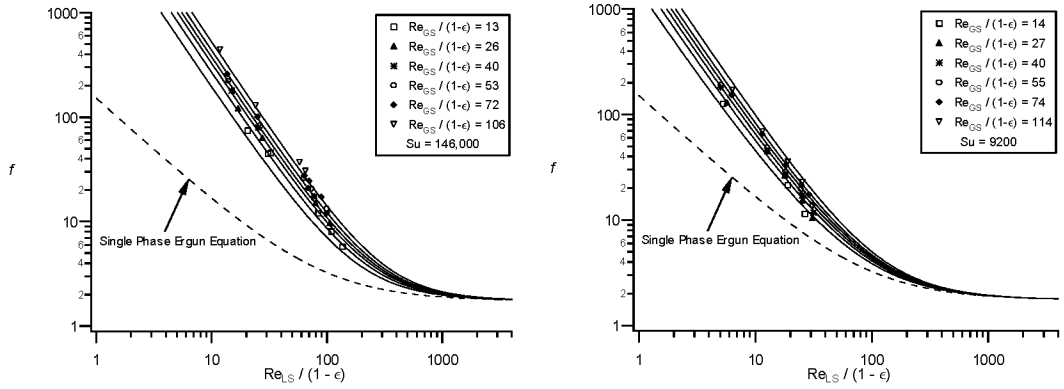
The pressure drop may be assumed to be a weak function of the last two ratios (density and viscosity) as they are small and do not vary significantly. Rearranging into a dimensionless form and adding an expression for the gas Reynolds number and liquid Weber number, the form of the modified Ergun equation becomes:

$$\frac{-\Delta P}{Z}\frac{D_P}{\rho_L U_{LS}^2} = \frac{150(1-\varepsilon)}{Re_{LS}} + \beta\left(\frac{Re_{GS}}{(1-\varepsilon)}\right)^a\left(\frac{(1-\varepsilon)}{Re_{LS}}\right)^b\left(\frac{1}{We_{LS}}\right)^c + 1.75$$

Determining the parameters by regression, we find that a=1/2, b=1/3, c=2/3 and β=0.8. Recognizing that $\frac{1}{Ca_{LS}} = \frac{Re_{LS}}{(1-\varepsilon)We_{LS}}$, the final form of the modified Ergun equation is:

$$f = \frac{-\Delta P}{Z}\frac{D_P}{\rho_L U_{LS}^2} = \frac{(1-\varepsilon)}{Re_{LS}}\left[150 + 0.8\left(\frac{Re_{GS}}{(1-\varepsilon)}\right)^{\frac{1}{2}}\left(\frac{1}{Ca_{LS}}\right)^{\frac{2}{3}}\right] + 1.75$$

The figure below shows two examples of the experimental data and the corresponding modified Ergun equation. Each plot represents a specific Suratman number indicated in the legend: $\left(Su = \frac{Re_{LS}}{Ca_{LS}(1-\varepsilon)} = \frac{\rho_L D_P \sigma}{\mu_L^2(1-\varepsilon)}\right)$



Plot of modified Ergun equation for two Suratman numbers.

[1] Motil, B. J., Balakotaiah, V., Kamotani, Y., "Effects of Gravity on Cocurrent Two-Phase Gas-Liquid Flows Through Packed Columns," AIAA-2001-0767 (2001).

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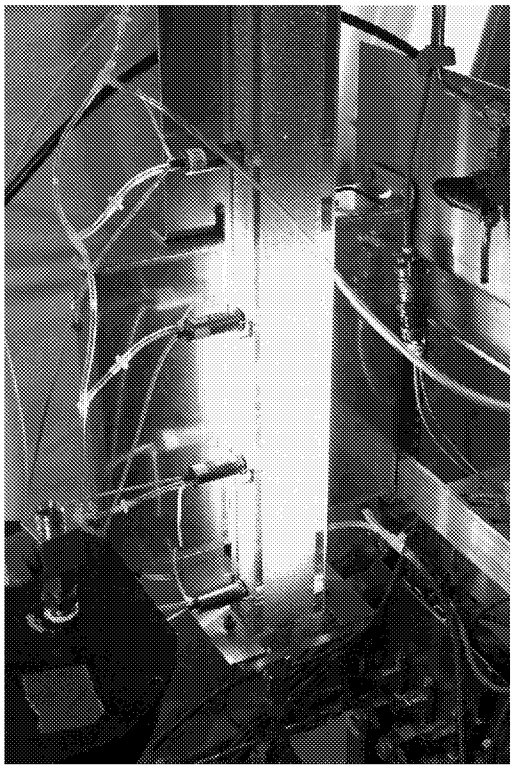
Our goal is to develop a fundamental understanding of the role of gravity on two-phase gas-liquid flow through a fixed bed of solid particles by:

- Determining the flow patterns and transition boundaries in microgravity and testing the validity of flow regimes maps based on data in 1-g.
- Measuring the true frictional pressure drop for co-current gas-liquid flow through packed-beds and testing the validity of pressure drop correlations based on 1-g data.
- Studying the influence of gravity on pulse frequency and amplitude.

Experimental Setup for KC-135 Aircraft

- 8 flights - over 250 test conditions flown on NASA KC-135 aircraft (20 sec/run)
- Duplicated conditions for 1-g
- Rectangular cross section
  2.5 cm x 5 cm x 60 cm long
- 5 differential pressure trans. (1000 Hz)
- 2 cm and 5 cm spherical glass beads
- High speed video (500 fps)
- Air and Water-Glycerin (1 to 20 cP)
- $0.03 < G < 0.8$ kg/(s m^2)
- $3 < L < 50$ kg/(s m^2)
- $0.18 < Re_{LS} < 100$
- $4 \times 10^{-4} < We_{LS} < 0.2$
- $900 < Su_L < 365{,}000$



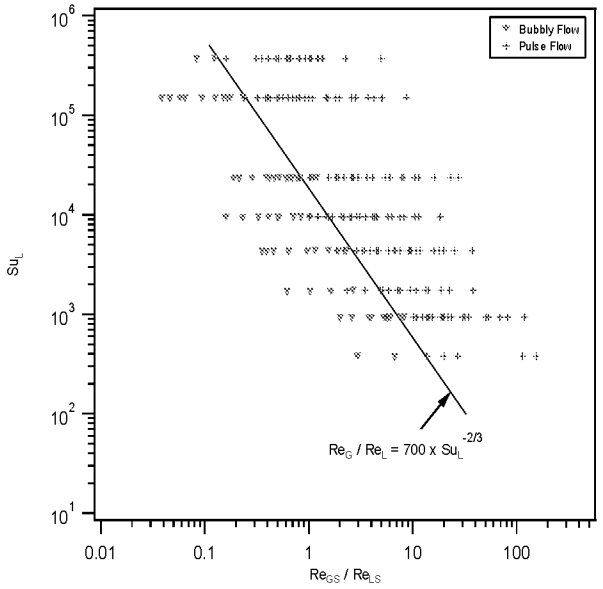
Why Packed Bed Reactors in Microgravity?

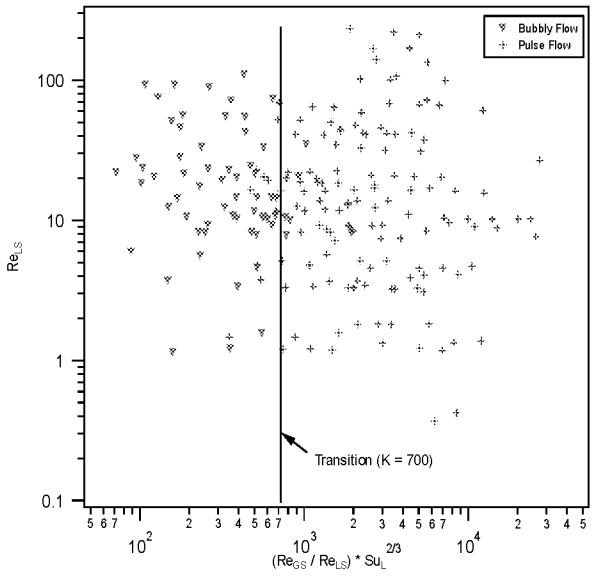
- Considered an "enabling technology" for NASA
  - Water processing (catalytic beds)
  - Reduce expendables (biological reactors)

- Two systems flown in microgravity environment with limited or no success
  - Volatile Removal Assembly Flight Experiment (VRAFE) STS-89
  - Biological Reactor tests on KC-135

- Better understanding of the role of gravity can lead to improved models for terrestrial reactors

Flow Regime Transition in Microgravity

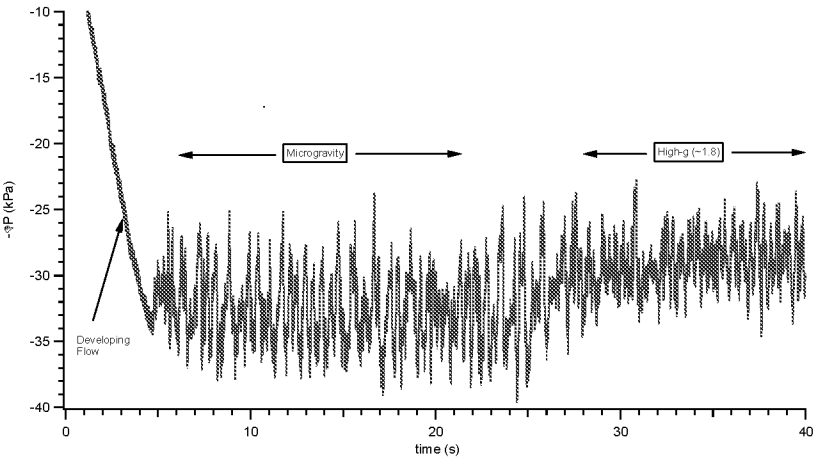




- Bubble-Pulse transition is a function of gas and liquid Reynolds numbers and the liquid Suratman number, where:

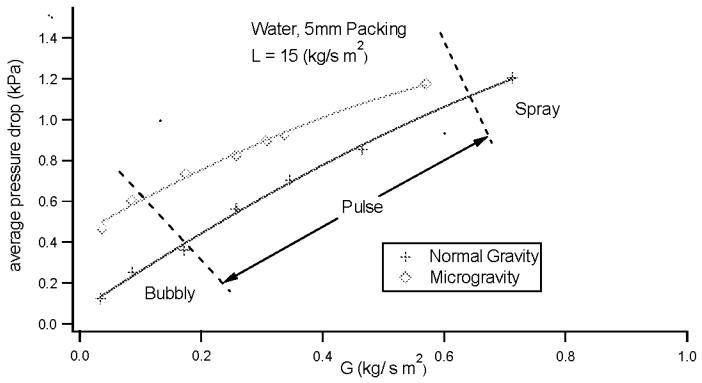
$$Su_L = \frac{Re_{LS}}{Ca_{LS}} = \frac{Re_{LS}^2}{We_{LS}} = \frac{d_P \rho_L \sigma}{\mu_L^2}$$

Effects of Gravity on Pulse Characteristics and Pressure Drop

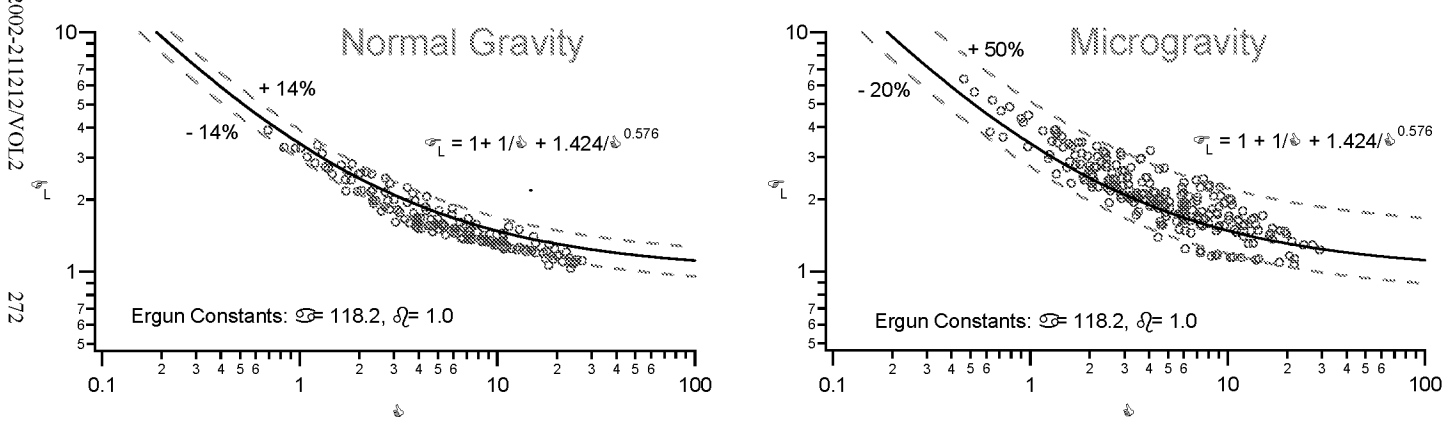


- With increasing gravity:
  - Pulse amplitude decreases
  - Pulse frequency increases

- As gas flow is increased, the average pressure drop difference between normal and microgravity decreases.



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.

Frictional Pressure Drop in Microgravity

- Using Buckingham-Pi theorem, the dimensionless two-phase pressure drop can be written as:

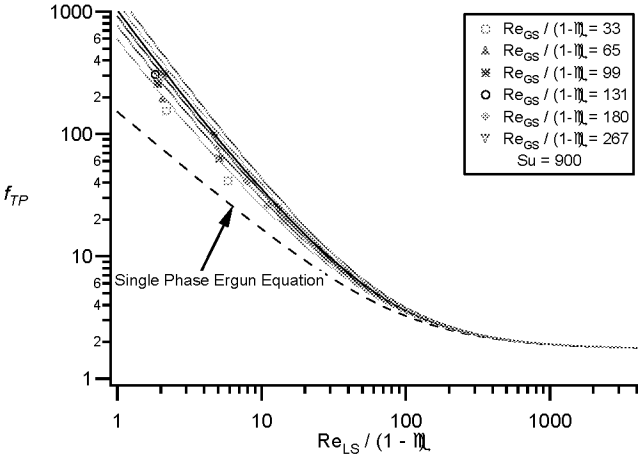
$$\frac{-\Delta P}{Z}\frac{d_P}{\rho_L U_{LS}^2} = \mathrm{f}\left[\frac{Su_L}{Re_{LS}^2}, \frac{1}{Re_{LS}}, Re_{GS}, \varepsilon\right]$$

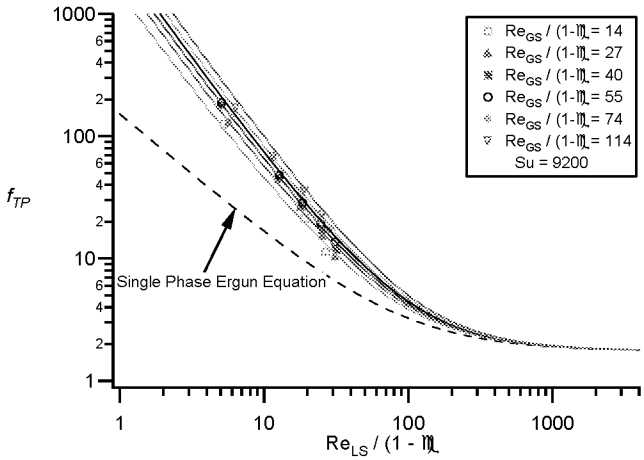
- Apply limiting cases
  1. In limit of zero interfacial tension between fluids, reduces to single phase.
  2. In the limit of zero gas flow, reduces to single phase.
  3. In the inertia dominated limit, the friction factor should be independent of the interfacial and viscous terms.

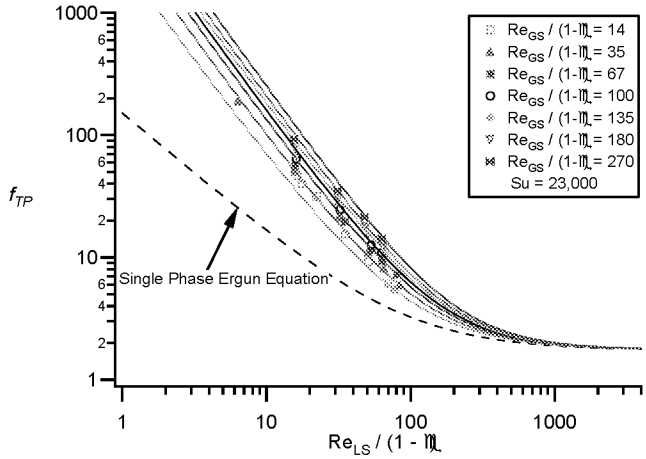
$$f_{\mathrm{TP}} - f_{\mathrm{SP}} = \gamma\left(\frac{Re_{GS}}{1-\varepsilon}\right)^a\left(\frac{1-\varepsilon}{Re_{LS}}\right)^b\left(\frac{(1-\varepsilon)^2 Su_L}{Re_{LS}^2}\right)$$

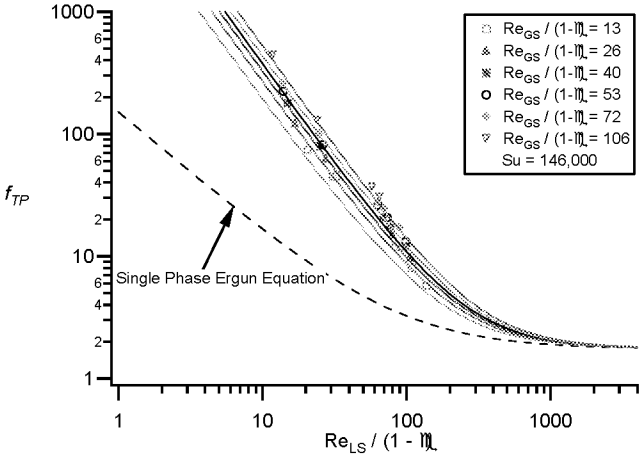
- Determining parameters by regression, reduces to:

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


f_{TP}
$Re_{LS} / (1 - \varepsilon)$
$Re_{GS} / (1-\varepsilon) = 33$
$Re_{GS} / (1-\varepsilon) = 65$
$Re_{GS} / (1-\varepsilon) = 99$
$Re_{GS} / (1-\varepsilon) = 131$
$Re_{GS} / (1-\varepsilon) = 180$
$Re_{GS} / (1-\varepsilon) = 267$
Su = 900
Single Phase Ergun Equation


f_{TP}
$Re_{LS} / (1 - \varepsilon)$
$Re_{GS} / (1-\varepsilon) = 14$
$Re_{GS} / (1-\varepsilon) = 27$
$Re_{GS} / (1-\varepsilon) = 40$
$Re_{GS} / (1-\varepsilon) = 55$
$Re_{GS} / (1-\varepsilon) = 74$
$Re_{GS} / (1-\varepsilon) = 114$
Su = 9200
Single Phase Ergun Equation


f_{TP}
$Re_{LS} / (1 - \varepsilon)$
$Re_{GS} / (1-\varepsilon) = 14$
$Re_{GS} / (1-\varepsilon) = 35$
$Re_{GS} / (1-\varepsilon) = 67$
$Re_{GS} / (1-\varepsilon) = 100$
$Re_{GS} / (1-\varepsilon) = 135$
$Re_{GS} / (1-\varepsilon) = 180$
$Re_{GS} / (1-\varepsilon) = 270$
Su = 23,000
Single Phase Ergun Equation


f_{TP}
$Re_{LS} / (1 - \varepsilon)$
$Re_{GS} / (1-\varepsilon) = 13$
$Re_{GS} / (1-\varepsilon) = 26$
$Re_{GS} / (1-\varepsilon) = 40$
$Re_{GS} / (1-\varepsilon) = 53$
$Re_{GS} / (1-\varepsilon) = 72$
$Re_{GS} / (1-\varepsilon) = 106$
Su = 146,000
Single Phase Ergun Equation

Preliminary Conclusions

- Pulse flow exists in a wider range of gas and liquid flow rates compared to normal gravity.
- 1-g flow regime maps (with Fr number set to zero) were found to be not valid for predicting microgravity flow regime transitions.
- Interfacial effects were found to increase the pressure drop by as much as 300% compared to that predicted by single-phase Ergun equation.
- Lockhart-Martinelli correlation gives much larger errors in microgravity and is not reliable in predicting the pressure drop either in the bubble or pulse flow regimes.
- Pulse amplitude depends strongly on gravity level (with high gravity levels suppressing pulse formation).