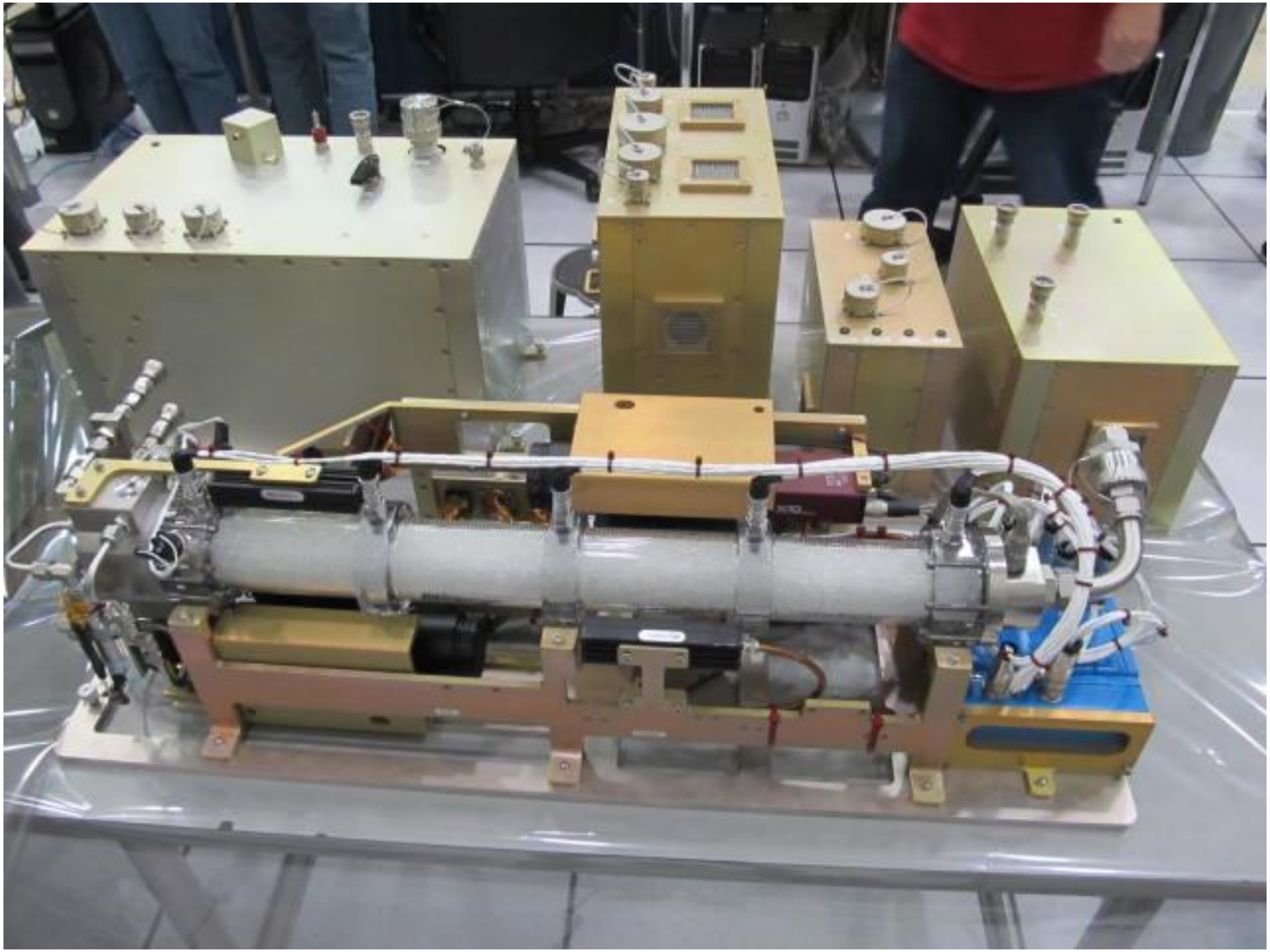
Packed Bed Reactor Experiment (PBRE)-2: Pressure Drop Measurements in Microgravity

Principal Investigator: Dr. Brian Motil, *NASA Glenn Research Center*

Co-Investigator: Prof. Vemuri Balakotaiah, *University of Houston*
Mahsa Taghavi, *University of Houston*

Project Scientist: Dr. Henry Nahra, *NASA Glenn Research Center*

PBRE Modules



PBRE Flow Loop

Absolute Pressure Measurements (test section):

- +/- 0.5 kPa (.073 psi) at 1000 Hz (up to 5 locations)

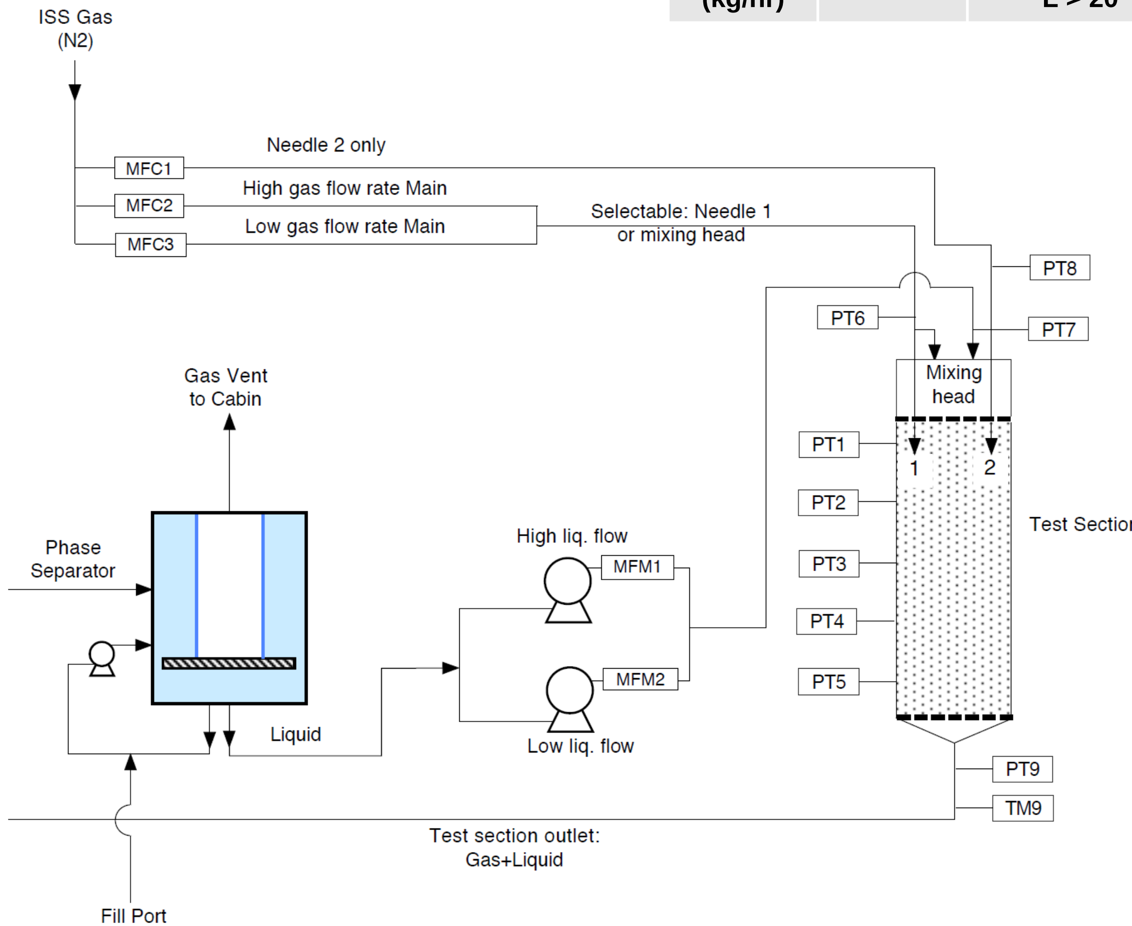
Data Storage:

- 8 1-TB (removable hard drives)
- Downlinking also available

Hi Speed Video:

- Two orthogonal pairs of views (selectable speed up to 150 fps)
- Resolution: 1000 pixels in direction of flow with 6x optical zoom

Fluid	Max Flow Rate	Range	Increment between set points	Control
Nitrogen Gas (kg/hr)	1.1	G < 0.01 0.01 < G < 0.1 G > 0.1	0.0005 0.01 0.1	+/- 0.0002 +/- 0.005 +/- 0.05
Water (kg/hr)	150	L < 20 L > 20	1 5	+/- 0.5 +/- 1



ISS Testing Sequence

Repeat all tests with a wetting and non-wetting packing material.

Start-up:

- Initial condition of each bed is dry.
- Incrementally increase liquid flow up to maximum to determine minimum liquid flow to flood column (~100% liquid).
- Once column is flooded, introduce low gas flow rates (with no liquid flow) to evaluate intrusion pattern (viscous fingering). Flush with liquid between each test.

Steady Flow:

- Operate bed under full set of steady conditions over range typical for NASA applications.
- Some overlap with aircraft experiments to fully validate hydrodynamic models.

Transient Flow:

- Evaluate hysteresis effects on flow regime transitions and pressure drop. Will approach from increasing/decreasing gas and liquid phases.

PBRE-1 Operations

- Launched December, 2015 – Ops Completed February, 2017
- More than 1800 test points collected over four successive operations in the MSG facility

Ops 1: 6/1/16 – 6/24/16

- Glass Beads
- 226 test points
- Completed full test matrix (SS, Transient, Bubble Generation)

Ops 2: 12/1/16 – 12/21/16

- Glass Beads
- 356 test points
- Completed refined test points based on transitions observed in Ops 1

Ops 3: 12/28/16 – 1/31/17

- Teflon Beads
- 954 test points
- Completed full test matrix (SS, Transient, Bubble Generation)
- Plus additional refined test points similar to Ops 2

Ops 4: 2/1/17 – 2/10/17

- Glass Beads
- 288 test points
- Original test matrix with increased magnification

Tim Kopra

Peggy Whitson

PRESSURE DROP

- Application: Need a simple method to estimate pressure drop through porous media/packed reactor beds in the microgravity environment.

- Hypothesis: With gravity (buoyancy) forces removed, can the semi-empirical Ergun approach be extended to multiphase flow?

Two-Phase Pressure Drop in 0-g

- Starting Point: Single Phase Ergun Eqn.

$$\frac{(-\Delta P)}{L} = 150 \frac{(1-\varepsilon)^2}{\varepsilon^3} \frac{\mu U_D}{d_p^2} + 1.75 \frac{(1-\varepsilon)}{\varepsilon^3} \frac{\rho U_D^2}{d_p}$$

Ergun (1952)

or $$f = \frac{(-\Delta P)}{\rho U_D^2} \frac{d_p}{L} \frac{\varepsilon^3}{(1-\varepsilon)} = \frac{150}{Re_p} + 1.75$$

- Viscous limit: $Re_p<10$, (ΔP proportional to U)

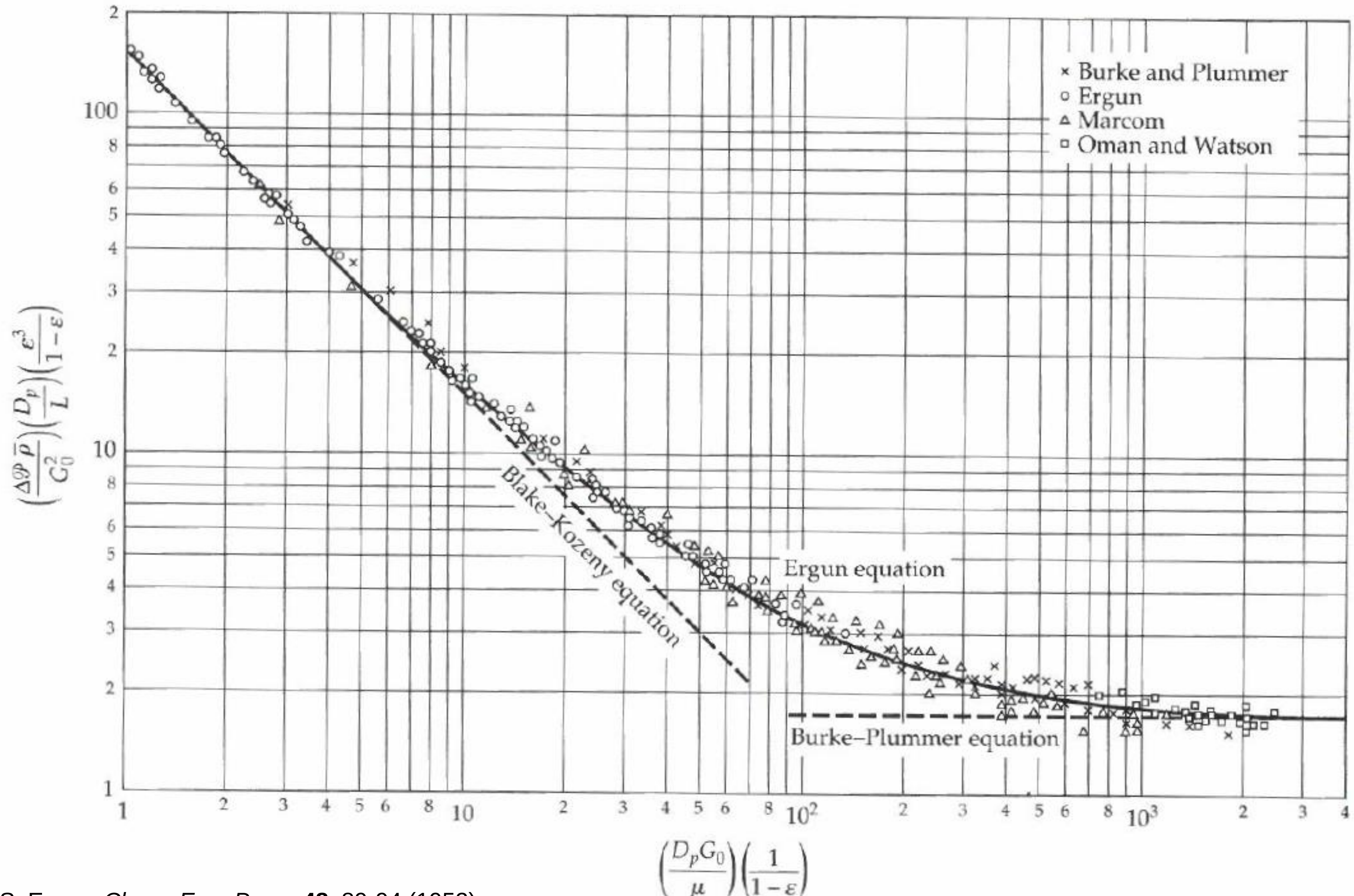
$$f = \frac{150}{Re_p}$$

(Blake-Kozeny) (1922 – 27)

- Inertial limit: $Re_p>1000$, (ΔP proportional to U^2)

$$f = 1.75$$

(Burke-Plummer) (1928)



S. Ergun, *Chem. Eng. Prog.*, **48**, 89-94 (1952)

Packed Bed Reactor Experiment

Two-Phase Pressure Drop in 0-g

Dimensionless two-phase pressure drop (assumes continuous liquid phase):

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

Limiting cases requirements:

- Zero interfacial tension between fluids: reduces to single phase.
- Zero gas flow: reduces to single phase (liquid).
- Inertia dominant regime: neglects gas phase

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

Determining parameters by regression:

$$f_{TP} = \frac{-\Delta P}{Z}\frac{d_P}{\rho_L U_{LS}^2}\frac{\varepsilon^3}{1-\varepsilon} = \frac{1-\varepsilon}{Re_{LS}}\left[\mathbf{C_V} + \underbrace{\mathbf{C_S}\left(\frac{Re_{GS}}{1-\varepsilon}\right)^{\frac{1}{2}}\left(\frac{Su_L(1-\varepsilon)}{Re_{LS}}\right)^{\frac{2}{3}}}_{\text{Dynamic phase interaction term}}\right] + \mathbf{C_I}$$

Motil, B. J., Balakotaiah, V., and Kamotani, Y., AIChE J., vol 49, no. 3, pp. 557-565 (2003).

Where: $\mathbf{C_V} = 180$, $\mathbf{C_I} = 1.8$, and $\mathbf{C_S} = 0.8$

PBRE-1

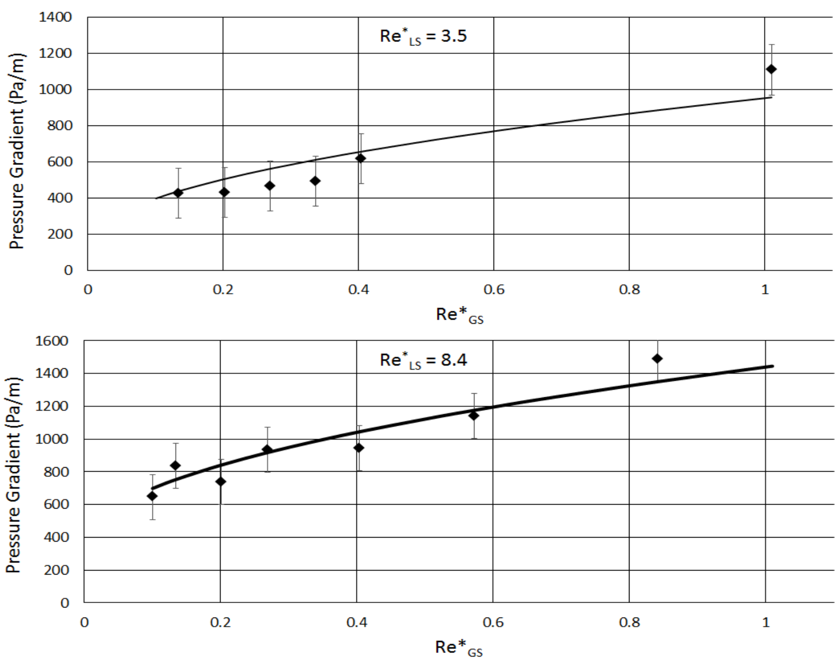
Focus was on the viscous-capillary (V-C) regime ($0.1 < Re^*_{GS} < 1$ and $1 < Re^*_{LS} < 10$)

Glass (wetting):

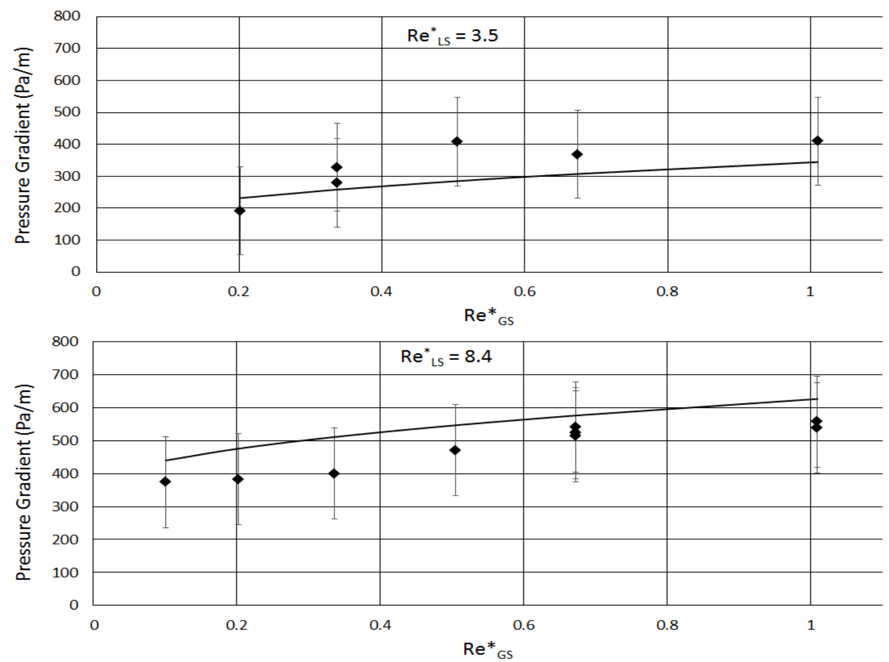
- Phase interaction term ~ 75%
- Viscous term ~ 23%
- "Best" fit with $\mathbf{C_S}$ = 0.6

Teflon (non-wetting):

- Phase interaction term ~ 25%
- Viscous term ~ 75%
- "Best" fit with $\mathbf{C_S}$ = 0.15



Glass Packing



Teflon Packing

Motil, B. J., Rame, E., Salgi, P., Taghavi, M., and Balakotaiah, V., "Gas–liquid flows through porous media in microgravity: The International Space Station Packed Bed Reactor Experiment," AIChE J., DOI: 10.1002/aic.17031 (2020)

PBRE-2

PBRE-1

- 3 mm glass vs Teflon packing to compare effects of wettability.
- Check valves and inlet mixing section led to oscillations in pressure (external to test section)
- Limited Video (<10s and 50 fps)
- For all steady state runs, used a technique developed in 1-g (vertical downflow) of flushing column with high water flow prior to each test condition.

PBRE-2

- Reduced packing size to 2mm glass to increase pressure drop. Will also test 3mm Alumina packing (not completed yet).
- Removed check valves to minimize external pressure oscillations
- Video fully functional (<30 secs, 150 fps)
- Water only flush did not have same effect in 0-g, so repeated all tests with a high gas flush prior to each test condition.

Completed PBRE-2 testing for 2mm glass packing on September 17, 2020

- Analysis based on preliminary data downlinked. Hard Drives with full data set, including video due in mid-November.
- 1090 total test conditions completed

Preliminary Observations:

- Pressure drop V-C regime indicates an unexpected slow accumulation of the gas phase even after a pseudo steady state operation was observed. Not observed at higher flow rates or in earlier ISS testing.
  - May help explain why reactor beds in microgravity tend to degrade in performance over the first several hours of operation.
- Gas flush prior to running a test point appears to remove bubbles better than high liquid flush.
  - Will continue to evaluate with Alumina packing
  - May be a method to reclaim/extend reactor bed operation.