TFAWS Aerothermal Paper Session

Hydrodynamics of Two-Phase Flows through Porous Media in Microgravity: Packed Bed Reactor Experiment onboard of the International Space Station

Mahsa Taghavi[a], Brian J. Motil[b], Henry Nahra[b], and Vemuri Balakotaiah[a]

[a]Department of Chemical and Biomolecular Engineering, University of Houston, Houston TX, USA

[b]NASA Glenn Research Center, Cleveland, OH, USA

THERMAL & FLUIDS ANALYSIS WORKSHOP

TFAWS

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Presented By

Henry K. Nahra, Ph.D.

NASA GRC ⋆ ISS ⋆ ZIN Technologies

PACKED BED REACTOR EXPERIMENT

University of Houston ⋆ NCSER ⋆ NASA JSC

Thermal & Fluids Analysis Workshop
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Presentation Outline

- Introduction to Packed Bed Reactors
- Objective, Motivation and Operating Parameters of Packed Beds
- Aircraft Summary
- PBRE and PBRE-2 Summary
- Experiment
  - Fluid System Description
  - Experimental Parameters
  - Experiment Operation
- Experimental Results
  - Flow Regimes in Microgravity
  - Pressure Gradient and Friction Factor
    - Correlation by Regime
  - Gas Build-up in Packed Bed
  - Effects of Liquid and gas Initial Flush

Packed Bed Reactor Description

- Many chemical and biochemical reactions and separation processes in industry are carried out in packed bed reactors because of their low power consumption and compact size compared to other reactor configurations.
- One or more fluids and phases can flow through the fixed solid particle packing
- Solid packing is used for biological growth processes as catalysts in chemical reactions
- Packing shapes and characteristic length depend on the application and the distribution of the flow through the pores or interstitial space
  - Goal is to minimize operational requirements in terms of pressure drop
- Due to their low operational power demand, packed beds present viable unit operation for long duration space mission
- Packed bed reactors with space applications operate using very low liquid flow rates.
  - Operating parameters such as pressure gradient, and phase distribution are dominated by capillary and viscous forces.

Objective and Motivation

Objective

- Study hydrodynamics of packed bed reactors in microgravity and under different flow regimes

Motivation

- Many chemical and biochemical reactions and separation processes in industry are carried out in packed bed reactors because of their low power consumption and compact size compared to other reactor configurations.

Current/Future Packed Bed Space Applications:

Aqueous-Phase Catalytic Oxidation (APCO) System

- Prototype catalytic oxidation system (post-processor for water recovery systems)

Microbial Check Valve (MCV)

- Potable water with 2 ppm iodine to prevent microbial growth

Activated Carbon/Ion Exchange (ACTEX)

- Removes iodine from potable water before crew consumption

Ion Exchange for Calcium Removal (in development)

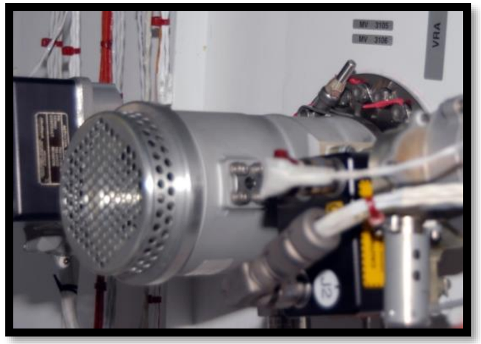
- Removes Ca++ ions from urine to prevent calcium sulfate precipitation in the ISS Urine Processor Assembly

Volatile Removal Assembly (VRA)

- Catalytic oxidation system for water treatment

IntraVenous Fluid GENeration (IVGEN)

- Deionizing resin bed to remove contaminants to standards of the United States Pharmacopeia (USP)



Summary of PBRE Aircraft Campaigns

- Two separate test series were initially conducted on a reduced gravity aircraft →Limited low gravity test duration to <20 s
- Particle diameter, liquid viscosity, and both, liquid and gas were varied to generate a database used for developing a form of the modified Ergun equation which is used to predict the pressure drop in microgravity conditions at moderate to high gas and liquid flow rates where inertial forces played a more significant role.
- Moreover, a flow map was developed for predicting an important transition from dispersed bubble to pulse flow.
- Limited duration of microgravity time (<20 s) in these experiments was not sufficient to achieve steady state conditions at lower flow rates relevant in space-based packed beds

This led to

- Development of the Packed Bed Reactor Experiment (PBRE) for testing on the ISS to obtain experimental results in the range of flow rates of interest.

PBRE and PBRE-2 Flight Campaigns

First PBRE Campaign

- Two beds were tested on ISS: One bed with wetting glass spherical packing and one bed with Teflon non-wetting beads
- Packed bed was initially flushed with liquid ONLY before each new flow condition to establish similar initial conditions for all test points
- From the generated database, an extended Microgravity Modified Ergun Equation (MMEE) was developed for predicting the pressure drop in the viscous-capillary (V–C) regime
- Bubble to pulse flow regime transition observed on the aircraft was verified in ISS
- In the MMEE, three contributions to the pressure gradient were quantified
  - Viscous, inertial and capillary
- Capillary contribution was dominant for the wetting particles whereas the viscous contribution was dominant for the nonwetting particles.

PBRE and PBRE-2 Flight Campaigns

Second PBRE-2 Flight Campaign

- Smaller glass packing and fluid system design improvements
- Some test runs were executed with initial flushing of the packed bed with liquid water and other runs with nitrogen gas before each new flow condition to establish initial conditions
- Higher gas hold-up and pressure gradients were observed with initial liquid flush compared with initial gas flush
- Developed a correlation for prediction of two-phase pressure gradient in packed beds operating in microgravity and outside of the viscous capillary regime
  - Capillary forces were shown to be dominant contributor to pressure drop
  - Pressure gradient was found to be linear with the superficial liquid velocity and a weaker function of the gas velocity

PBRE and PBRE-2/Interest in Pressure Drop

Interest in Pressure Drop

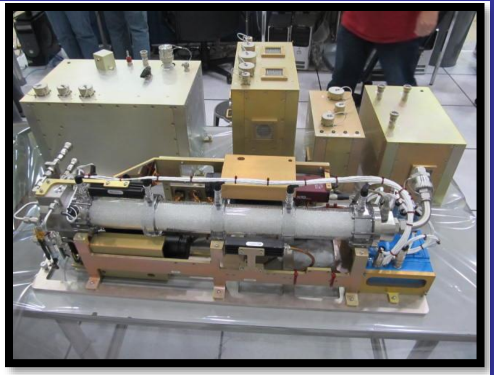
- NASA identified the need to conduct aircraft flights to develop an empirical prediction for pressure drop in two-phase flows through porous media for water reclamation processes.
  - ✓ Limitation: Short time interval of low gravity (20 s)
  - ✓ Development of the ISS PBRE experiment to deliver a wide range of gas and liquid flows
  - ✓ Reducing the particle size in PBRE-2 from 3 mm to 2 mm to enhance the accuracy in the pressure drop measurements
  - ✓ Modifying the inlet mixing head to minimize the external disturbances

- Goal: Developing a simple method to estimate pressure drop and flow regime through porous media in the microgravity environment.

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

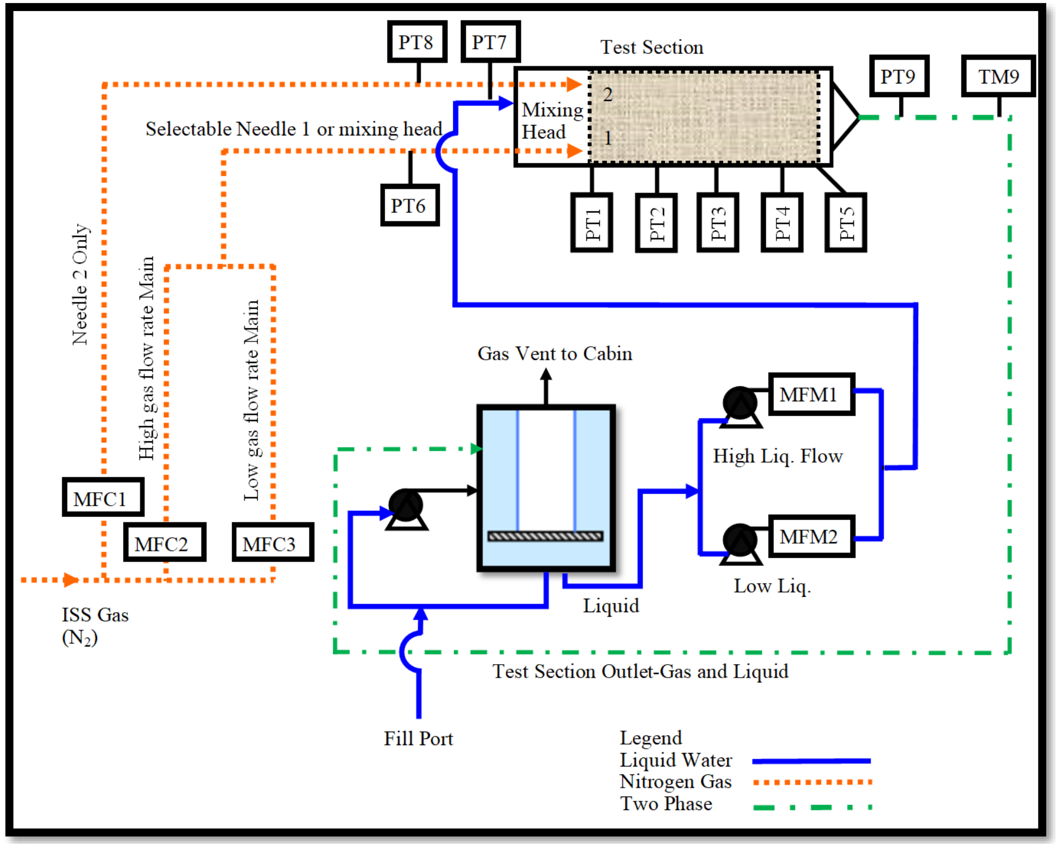
PBRE Modules

- Packing Materials:
  - PBRE-Glass and Teflon
  - PBRE-2-Glass
  - PBRE/WR-Alumina
- Particle size:
  - PBRE: 3 mm spherical
  - PBRE-2: 2 mm spherical
  - PBRE/WR-with Alumina pellets 3-3.5 mm diameter
- Test section length: 60 cm
- Test section diameter: 5.08 cm
- Instrument:
  - 5 absolute pressure transducers (+/- 0.14 kPa at 1000 Hz)
- Data Storage:
  - 8 1-TB (removable hard drives)
  - Downlinking also available

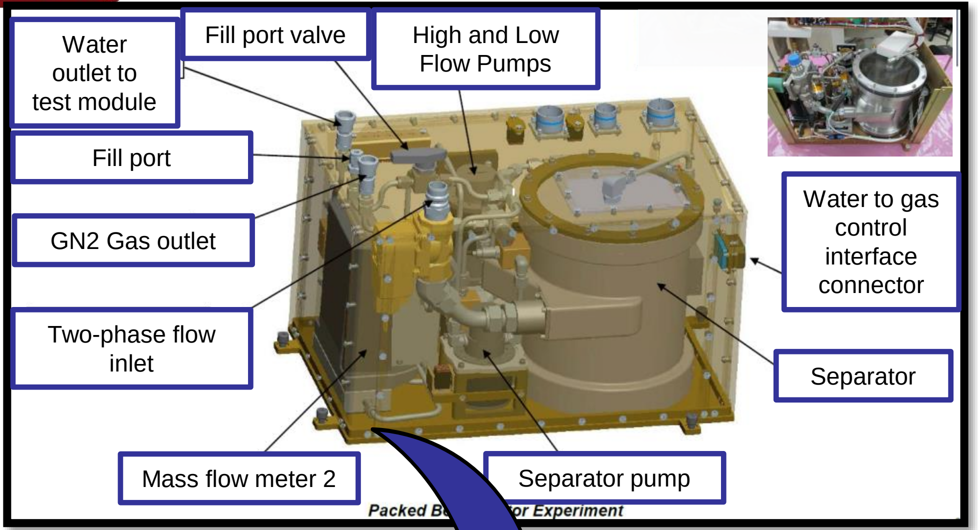


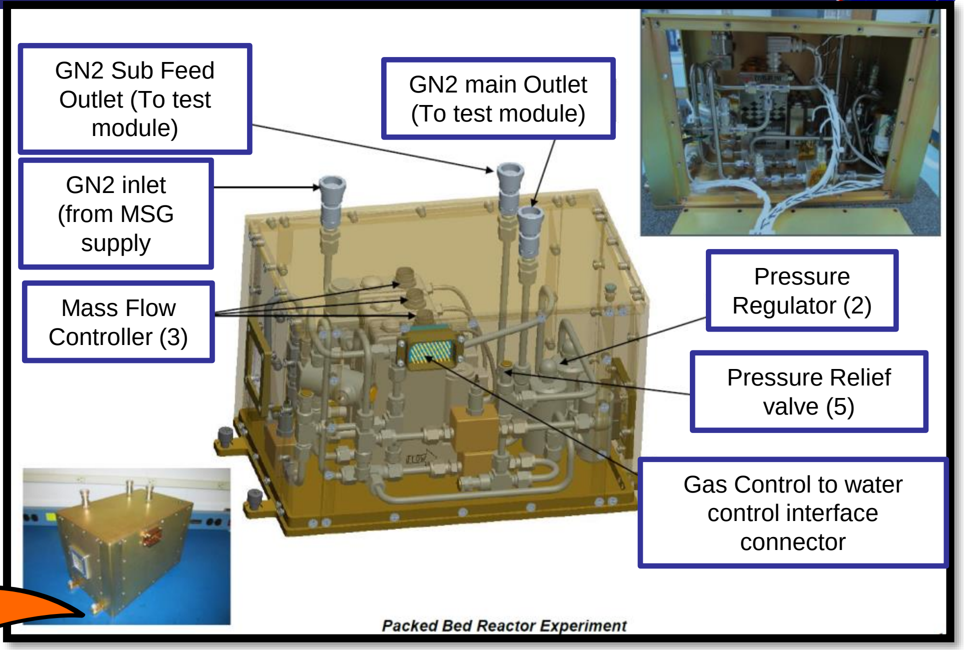
Fluid	Range
Nitrogen Gas (kg/hr)	$0.001 < G < 1$ $0.02 < Re^{*}_{GS} < 23$
Water (kg/hr)	$1 < L < 150$ $0.5 < Re^{*}_{LS} < 72$

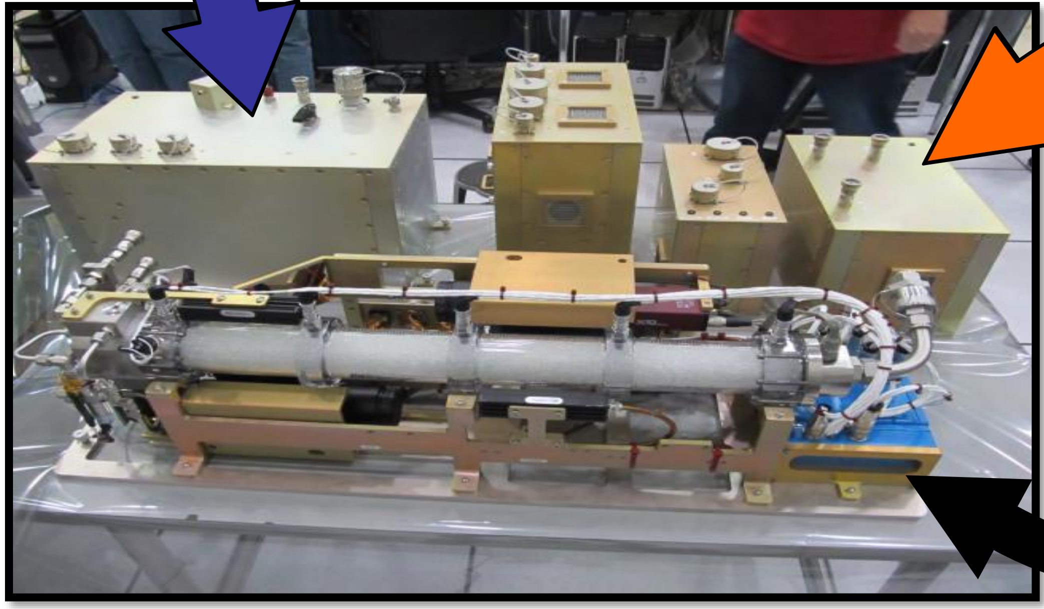
- High Speed Video:
  - Two orthogonal pairs of views (selectable speed up to 150 fps)
  - Resolution: 1000 pixels in direction of flow with 6x optical zoom

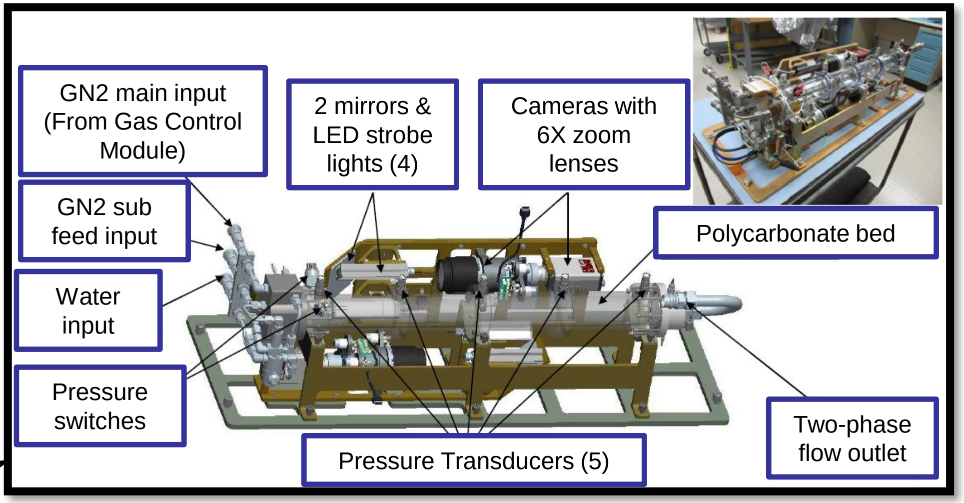


PBRE Modules

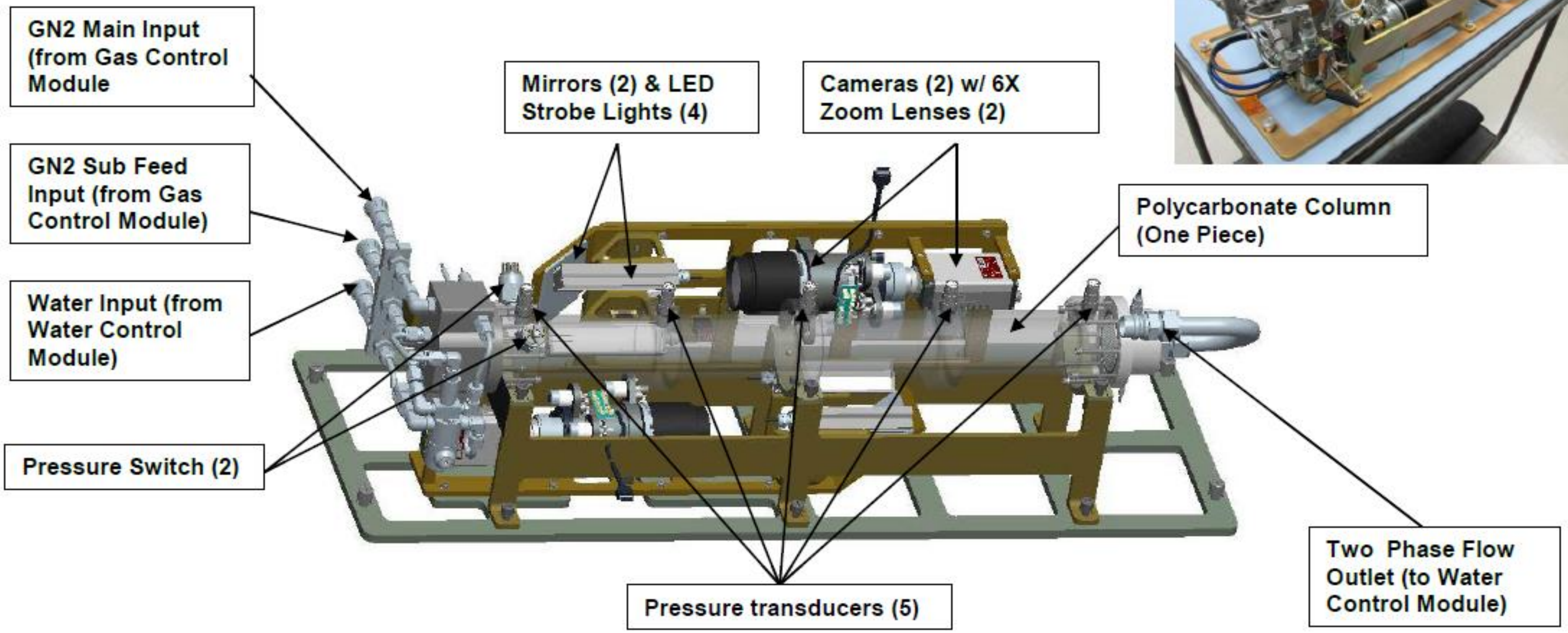








PBRE Test Section(s)



ISS Testing Sequence

Start-up:

- Initial condition of each bed is dry.
- Liquid flush and Gas flush between each test.

Steady Flow:

- *Liquid flush:*
  - Flowing liquid at 150 kg/hr for 30 seconds, followed by 20 kg/hr for 120 seconds, and then flowing the selected gas and liquid flow rates for a duration long enough to establish pseudo-steady flow
- *Gas flush:*
  - Flowing gas at 0.1 kg/hr for 30 seconds, followed by 0.3 kg/hr for an additional 30 seconds and then flowing the selected gas and liquid flow rates for a duration long enough to establish pseudo-steady flow

Unsteady/Transient Flow:

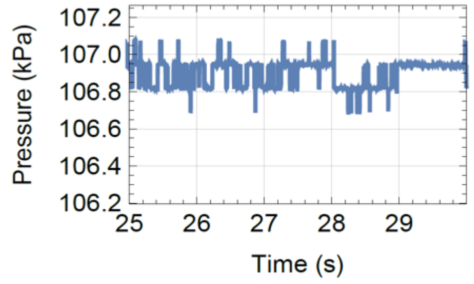
- Evaluate hysteresis effects on flow regime transitions and pressure drop
- Approach from increasing/decreasing gas and liquid flows

Microgravity Flow Regimes in Packed Bed

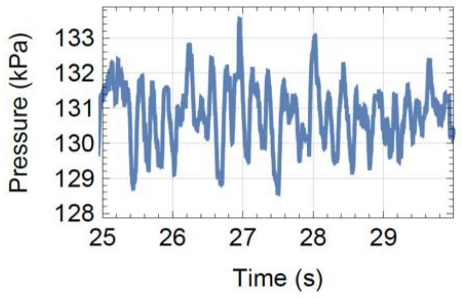
- Objective methods to predict transition from bubbly to pulsed flow regimes
  - Sudden increase in the intensity of a frequency component in a power spectrum of pressure signals
  - Sudden increase in the standard deviation in pressure fluctuation signal
  - Auto correlation and cross correlation functions of pressure signal
- Motil et al.
  - Based transition on sudden increase in the intensity of frequency components in the power spectrum of the pressure fluctuations
  - Based transition on visual observations
  - Data from flight experiment and aircraft on dispersed bubble to pulse flow regime transition were in agreement
- Taghavi et al.
  - Found two other flow regimes that occurred at low liquid flow rates
    - Elongated or large bubbles and gas channeling flow regimes

Pressure Signal and Standard Deviation of Pressure Fluctuation

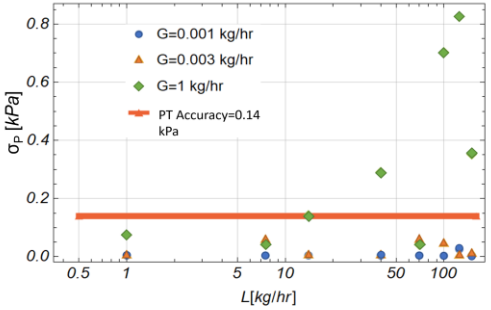
- At high liquid flow rates (10 to 150 kg/hr)
  - Two flow regimes observed in low gravity aircraft and ISS experiments
    - Dispersed bubble flow (DB) and pulse (P) flow
- At high liquid inertia
  - Increasing the flow rate of gas (N_2) results in transitioning from dispersed bubble to the pulsed regime
  - Standard deviation increases beyond the accuracy of the pressure transducer (+/-0.14 kPa) which is an indication of the onset of pulse flow



(c) Dispersed Bubble
L=70 kg/her, G=.03 kg/hr

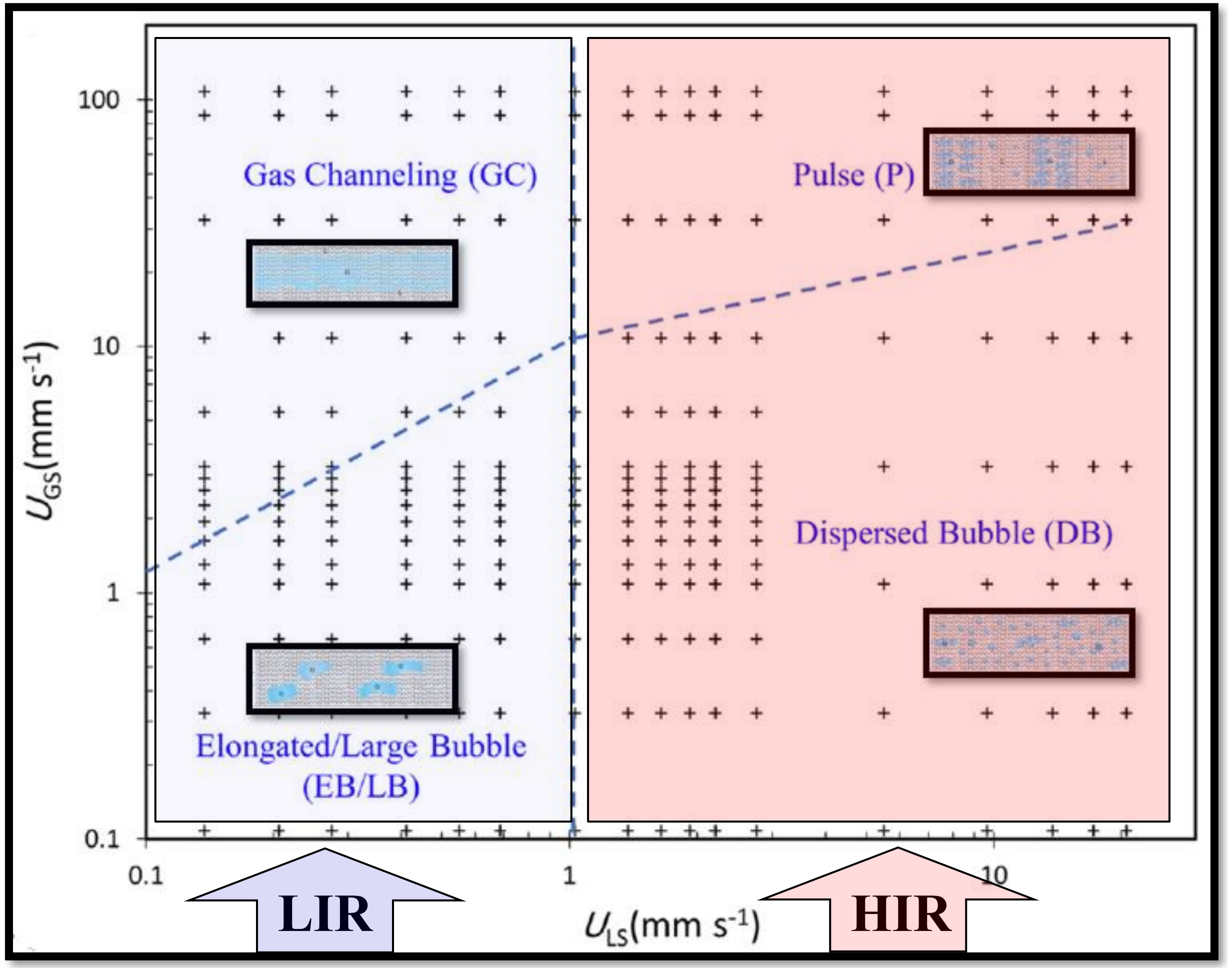


(d) Pulse Flow
L=125 kg/hr, G=1 kg/hr

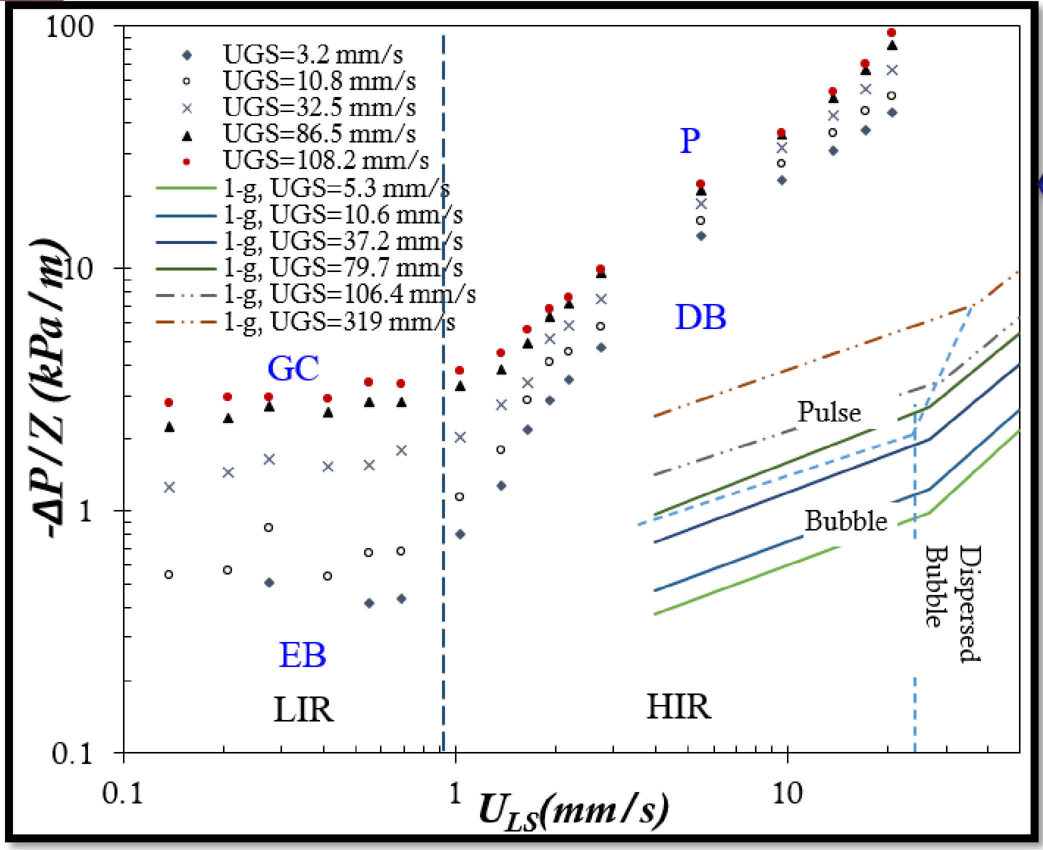


Microgravity Flow Regimes in Packed Bed

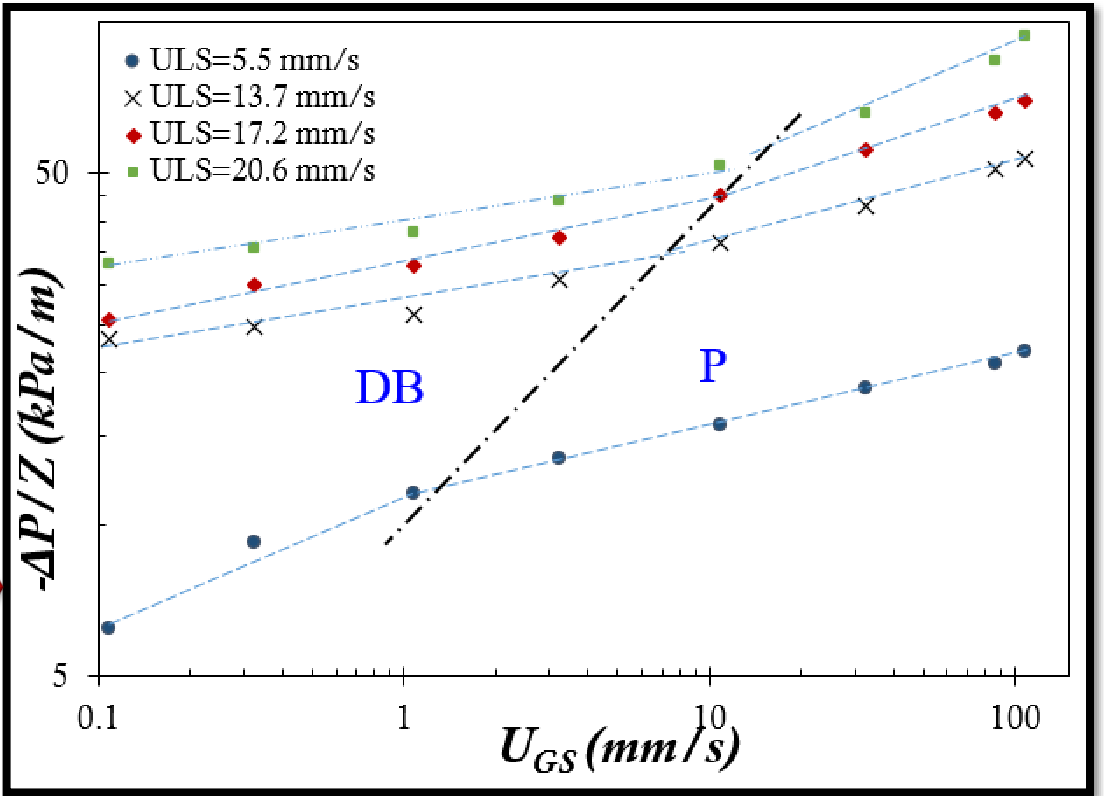
- A novel quantitative method for detecting flow regime transition
  - Based on changing slope of pressure gradient when plotted as a function of liquid or gas flow rates or the corresponding Reynolds numbers
- Low Interaction Region (LIR) is defined as consisting of large elongated bubbles and gas channeling regimes
- High Interaction Region (HIR) is defined as consisting of dispersed bubble and pulsed flow



Transitions Between Regimes



- Observed that transition from LIR to HIR happens at $Re^*_{LS} = 3.6$ (or $U_{LS} \cong 1$) and independent of gas superficial velocity or U_{GS}
- Transition is characterized by the change in slope



- Increasing the gas flow rate results in transition from Dispersed Bubble to Pulsed flow
- Transition occurs in the HIR

Single Phase Flow in Porous Media in Microgravity

Prior to conducting any two-phase flow experiments

- Conducted high liquid-only flow experiments to determine the single-phase Ergun equation coefficients
- Apparent/global bed porosity was measured in normal gravity to be 0.34
- Local bed porosity could not be measured
- With high liquid flow rate, pressure gradient (−ΔP/Z) was measured accurately
- Coefficients from Ergun equation can be determined

$$\frac{-\Delta P}{Z} = C_V \frac{(1-\varepsilon)^2}{\varepsilon^3}\frac{\mu_L U_{LS}}{d_p^2} + C_I \frac{(1-\varepsilon)}{\varepsilon^3}\frac{\rho_L U_{LS}^2}{d_p}$$

Three unknowns: C_V, C_I *and* $\boldsymbol{\varepsilon}$

- Varied porosity analytically between 0.34 and 0.37
- From best fit determined

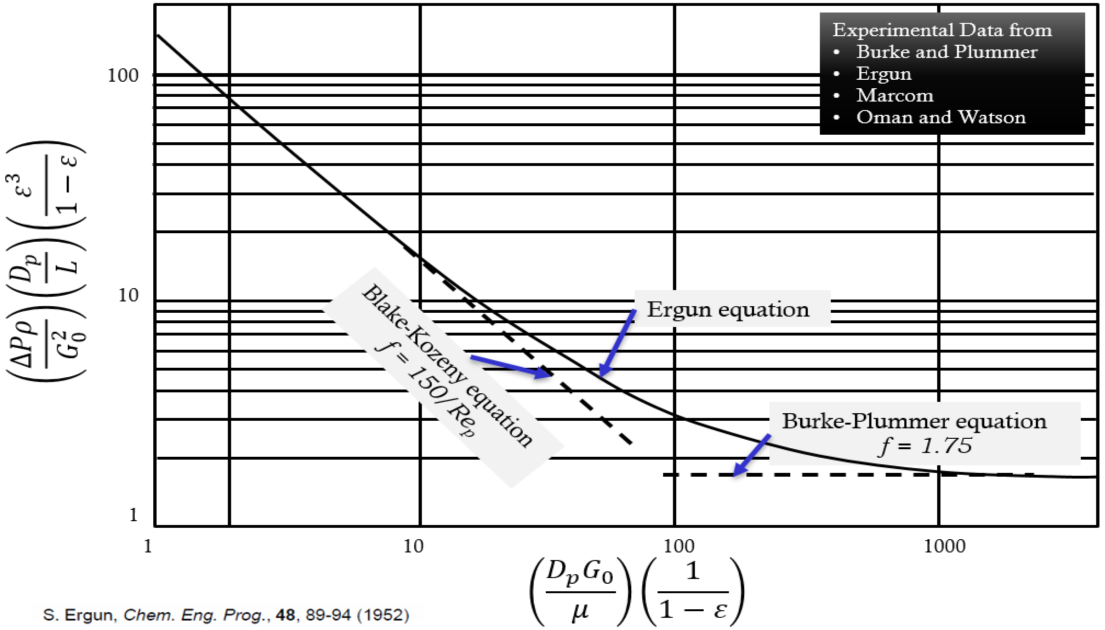
$C_V = 150.8$; $C_I = 1.78$; $\varepsilon = 0.358$

$$f_{SP} = \frac{150.8}{Re_{LS}^*} + 1.78; \text{ and } Re_{LS}^* = \frac{\rho_L U_{LS} d_p}{\mu_L (1-\varepsilon)}$$

$$\frac{-\Delta P}{Z} \equiv f_{SP}\frac{\rho_L U_{LS}^2}{d_p}\left(\frac{1-\varepsilon}{\varepsilon^3}\right)$$

$$f = \frac{C_V}{Re_p} + C_I$$

$$\frac{-\Delta P}{Z} \equiv f_{SP}\frac{\rho_L U_{LS}^2}{d_p}\left(\frac{1-\varepsilon}{\varepsilon^3}\right)$$

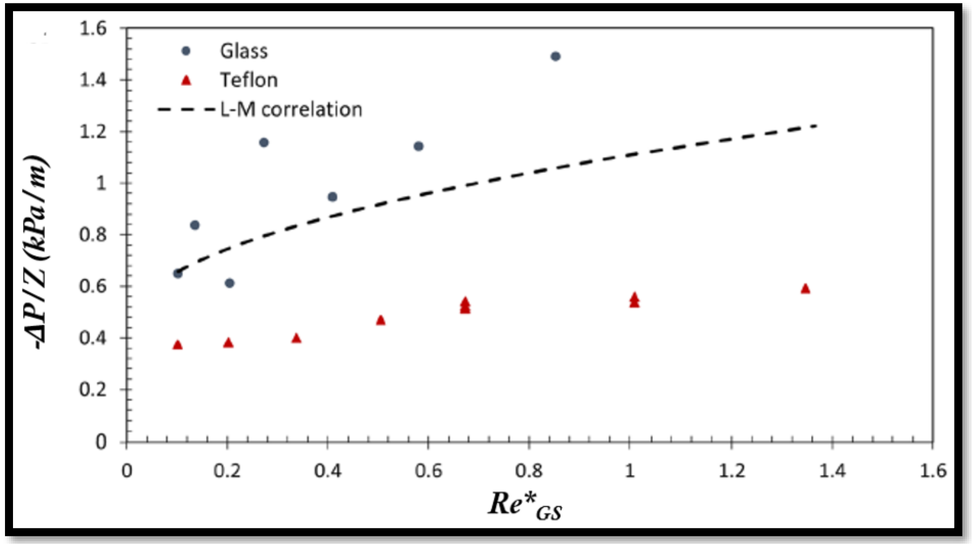


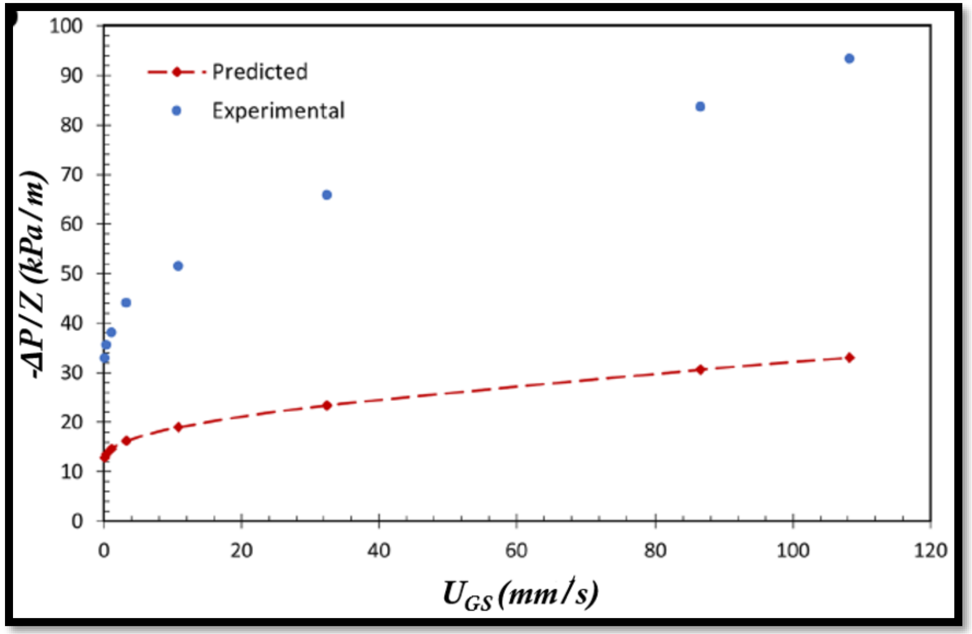
S. Ergun, *Chem. Eng. Prog.*, **48**, 89-94 (1952)

Prediction of Two-phase Pressure Drop in Microgravity

Three approaches in open literature

- 1-Lockhart-Martinelli
  - Not effective for Microgravity where capillary forces are dominant
- 2-Macro-scale Momentum Balance for each Phase
  - Pressure gradient for each phase is written as the sum of a viscous, inertial and interfacial drag terms
  - Use of bed permeability in the viscous term and passability in the inertia term
  - For each of the phases, use of relative permeability and passability (which are functions of the gas holdup) with viscous and inertia terms respectively
  - In empirical models to predict pressure drop, the interfacial drag force are proportional to Earth gravity.
  - In Microgravity, the interfacial drag force → 0





3. Motil et al. Ergun-Type Formulation

- **Microgravity Modified Ergun Equation (MMEE) is**
  - Sum of Single-phase friction factor + a dynamic phase interaction

Dynamic Phase Interaction Term

$$f_{TP} \equiv \frac{-\Delta P}{Z}\frac{d_p}{\rho_L U_{LS}^2}\frac{\varepsilon^3}{1-\varepsilon} \Rightarrow f_{TP} = f_{SP} + \overbrace{C_S {Re_{GS}^*}^{\alpha} \times {Re_{LS}^*}^{\beta} \times Su_L^{\gamma}}$$

$$f_{TP} = C_I + \frac{C_V + C_S {Re_{GS}^*}^{\alpha} \times {Re_{LS}^*}^{\beta+1} \times Su_L^{\gamma}}{Re_{LS}^*}$$

Dynamic Phase Interaction Term

$$-\frac{\Delta p}{Z} = C_V \frac{(1-\varepsilon)^2}{\varepsilon^3}\frac{\mu_L U_{LS}}{d_p^2} + C_I \frac{(1-\varepsilon)\rho_L U_{LS}^2}{\varepsilon^3 d_p} + \overbrace{C_S \frac{(1-\varepsilon)}{\varepsilon^3}\left(\frac{\rho_L U_{LS}^2}{d_p}\right)\left(\frac{\rho_G U_{GS} d_p}{\mu_G(1-\varepsilon)}\right)^{\alpha}\left(\frac{\rho_L U_{LS} d_p}{\mu_L(1-\varepsilon)}\right)^{\beta}\left(\frac{d_p \rho_L \sigma}{\mu_L^2}\right)^{\gamma}}$$

Relevant Dimensionless Groups

Dimensionless Group	Formula
Liquid Reynolds Number	$Re_{LS} = \frac{\rho_L U_{LS} d_p}{\mu_L}$
Gas Reynolds number	$Re_{GS} = \frac{\rho_G U_{GS} d_p}{\mu_G}$
Weber number	$We_{LS} = \frac{\rho_L U_{LS}^2 d_p}{\sigma}$
Suratman number	$Su_L = \frac{\rho_L \sigma d_p}{\mu_L^2} = \frac{Re_{LS}^2}{We_{LS}}$
Modified Dimensionless Group	$\frac{Dimensionless\ Group}{(1-\varepsilon)^n}$ *n=exponent of U_{LS} in dimensionless parameter*

Capillary Contribution to Pressure Gradients per Regime

- For the high interaction region which covers pulse and dispersed bubble flow regimes
  - Exponents on the modified liquid Reynolds number and modified gas Reynolds number were estimated as $\alpha = 0.2$, and $\beta = -1$ using data fitting of PBRE-2 pressure drop data.
- However, exponents could not be used to extrapolate the prediction of the two-phase friction factor accurately when the whole data series were considered.
- It was found that a single correlation cannot predict the two-phase pressure gradient over all the different flow regimes accurately enough.
- Thus, data is binned into the four regimes and using non-linear regression

- Developed a specific correlation for the prediction of the two-phase friction factor and pressure gradient for each of the flow regimes
- Define the capillary contribution to pressure drop as:
  - $Capillary\ Contribution = f_{TP} - f_{SP} = C_S {Re^{*}_{GS}}^{\alpha} \times {Re^{*}_{LS}}^{\beta} \times Su_L^{\gamma}$
- Capillary contribution is the pressure loss due to gas-liquid interfacial friction
- Also due to the passage of gas bubbles through the pores and the repeated expansion and contraction in such a passage
- At low gas flow rates and liquid flow rates, the capillary/interfacial contribution to pressure loss is dominant.

Capillary Contribution Correlations per Regime

$$f_{TP} - f_{SP} = C_S {Re_{GS}^*}^{\alpha} \times {Re_{LS}^*}^{\beta} \times Su_L^{\gamma}$$

Flow Regime	Coefficient and Exponents			
Low Interaction Regime	C_S	α	β	γ
Large Bubbles	0.26	0.24	-1.83	2/3
Gas Channeling	0.21	0.66	-1.86	2/3
High Interaction Regime	C_S	α	β	γ
Dispersed Bubbles	0.07	0.26	-0.5	2/3
Pulsed Flow	0.11	0.35	-0.82	2/3

Why is γ the same???

- In PBRE flight experiment, liquid Suratman number was not varied by more than a factor of 2
- Exponent on the Suratman number of 2/3 was taken the same as that obtained in the aircraft-based experiments which covered a wide range of Suratman numbers based on varying liquid viscosity, surface tension, and particle size.

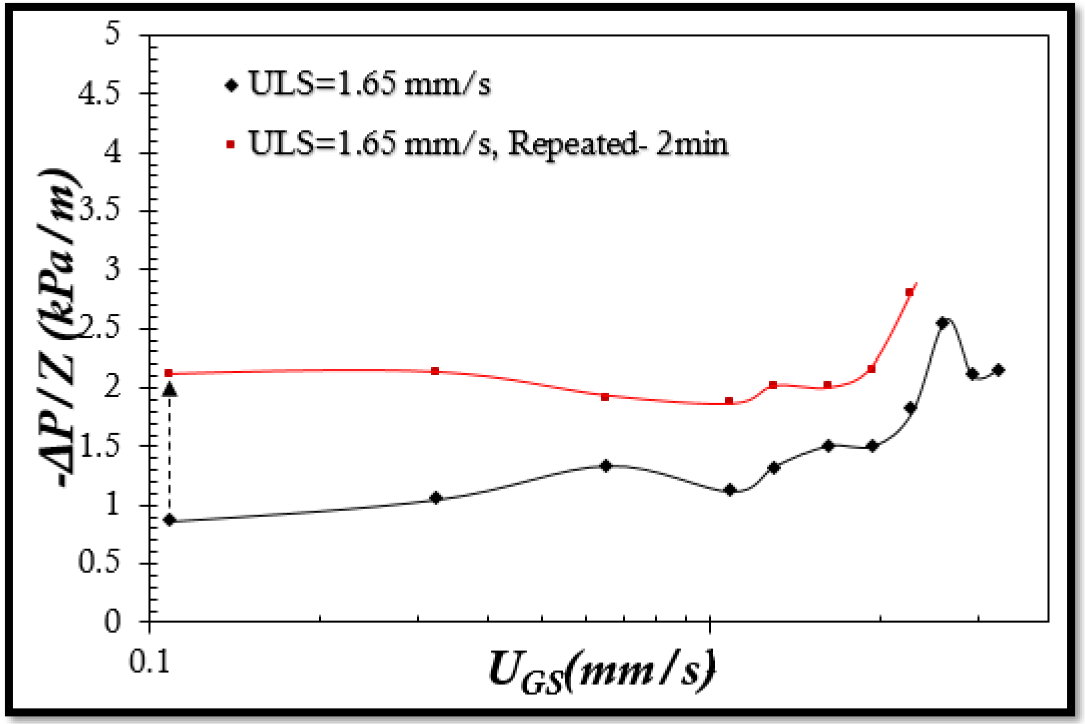
Gas Build-up in Packed Bed

Observations

- Some test runs were repeated with a data collection time of 120 s.
- Increased pressure gradient was observed over 120 s compared to 30 s collection time
- ⇒ *Gas accumulation during flowing gas and liquid through the column even after reaching the defined steady-state condition*

Residence Time

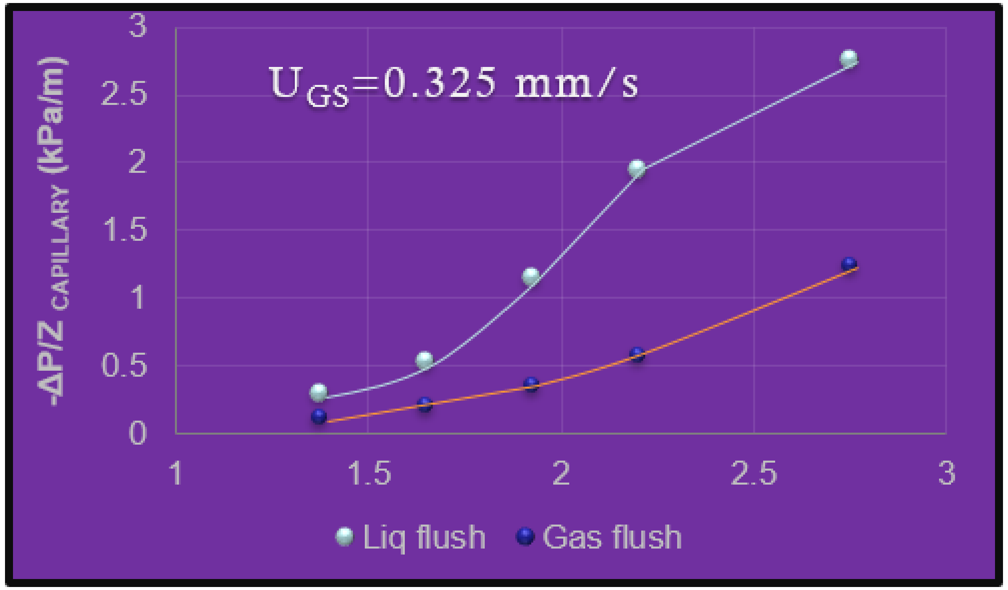
- Time required for traveling the column length for liquid velocities ranging from 1.03 to1.65 mm/s is between 5.7 and 9 min
  $\Rightarrow 5.7 \leq \tau_{residence} \leq 9\ min$

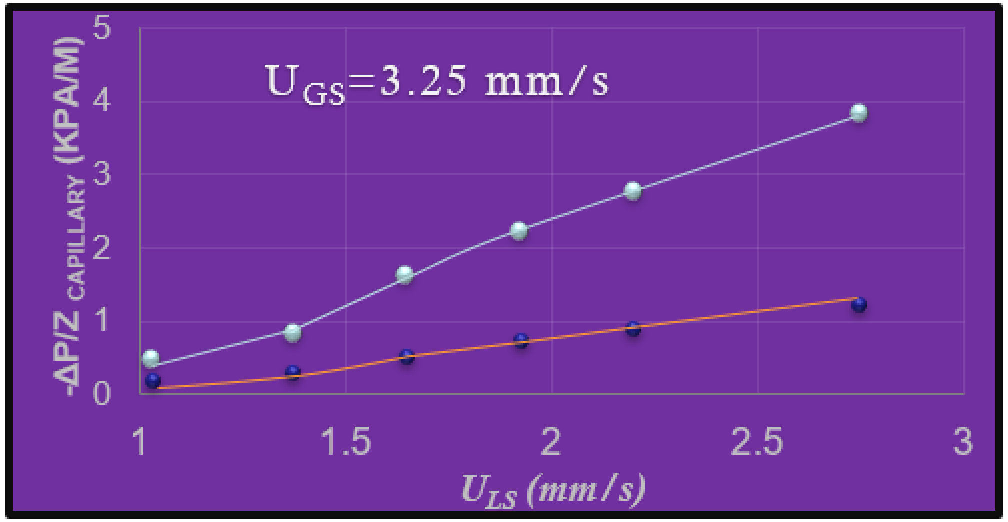


- ⇒ the experiments need more time to reach a steady-state condition especially at the low flow rates
- ⇒ Gas accumulation and pressure gradients would be higher than the shown values in the figure

Effects of Liquid and Gas Initial Flush

- In order to establish similar initial conditions before testing, pre-flows of liquid flush, as well as gas flush, were used
- Higher pressure gradient associated with liquid flush cases was observed
- Higher pressure gradient are attributed to having more trapped gas bubbles and therefore higher gas holdups in liquid flush tests
- *Removal of the stagnant bubbles by the gas flush preceding the test was shown to result in lower gas hold-up and pressure gradients*

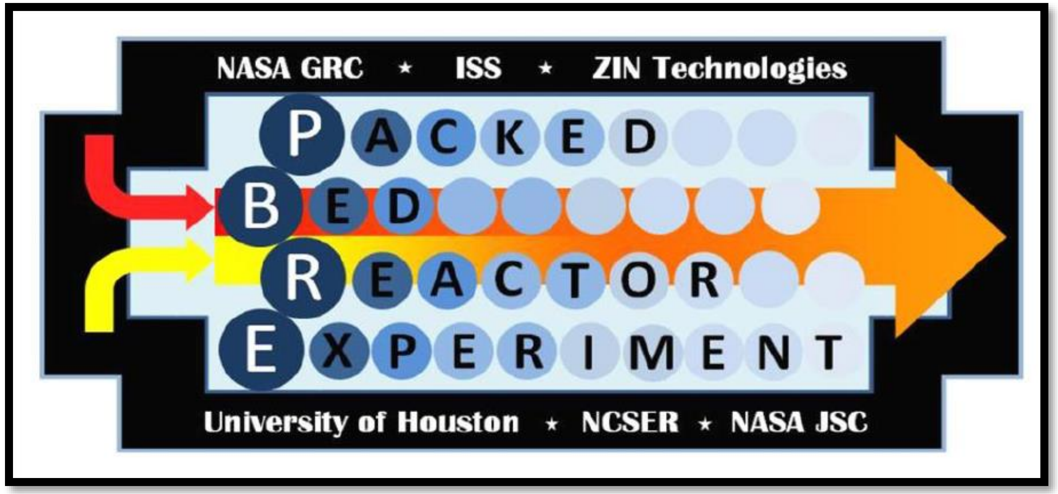




Concluding Remarks

- Presented summaries of Findings from PBRE and PBRE-2
- Flow Regimes
- Capillary Contribution to Pressure Gradients
- Effects of Gas Build-up
- Effect of Initial Flush
- Another packed Bed with Alumina 3-3.5 mm beads was flown on PBRE-2 campaign
  - Data analysis is ongoing at MSFC

- There are future flights of PBRE with different test sections, planned for the near future
  - Collaboration between MSFC and GRC



Selected Publications Related to PBRE

- Taghavi, M., Motil, B.J., Nahra, H., Balakotaiah, V., The international space station packed bed reactor experiment: capillary effects in gas-liquid two-phase flows, npj Microgravity (2023) 9:55
- Taghavi, M., Motil, B. J., Nahra, H. & Balakotaiah, V., Gas-liquid flows through porous media in microgravity: Packed Bed Reactor Experiment-2. AIChE J. 68, e17727 (2022).
- Motil, B. J., Rame, E., Salgi, P., Taghavi, M. & Balakotaiah, V. Gas-liquid flows through porous media in microgravity: The International Space Station Packed Bed Reactor Experiment. AIChE J. 67, e17031 (2020).
- Motil, BJ., Rame, E., Taghavi, M., Balakotaiah, V., Gas-liquid flows through porous media in microgravity: The International Space Station Packed Bed Reactor Experiment, AIChE J, 67 (1), e17031 (2020).
- Taghavi, M. & Balakotaiah, V., Gas hold-up and bubble behavior in an upflow packed bed column in the limit of low flow rate. AIChE J. 65, e16624 (2019).
- Patton, M., Bruzas, A., Rame, E. & Motil, B. J. Development of packed bed reactor ISS flight experiment. in 50th AIAA Aerospace Sciences Meeting including the New Horizons Forum and Aerospace Exposition (2012).
- Motil, B. J., Nahra, H. & Balakotaiah, V. Hydrodynamics of packed bed reactor in low gravity. SAE Trans. J. Aerosp. 114, 504–508 (2005).
- Motil, B. J., Balakotaiah, V. & Kamotani, Y. Gas-liquid two-phase flow through packed beds in microgravity. AIChE J. 49, 557–565 (2003).

Thank you

- Thank you for your attention
- Questions?