Packed Bed Reactor Experiment -1 Results

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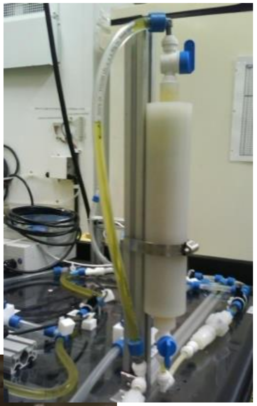
Packed Bed Applications in Space

- **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 Assy
- **Volatile Removal Assembly (VRA)**
  - a catalytic oxidation system for water treatment
- **IntraVenous Fluid GENeration (IVGEN)**
  - a deionizing resin bed to remove contaminants to standards of the United States Pharmacopeia (USP)



Operating Parameters

	Aqueous-Phase Catalytic Oxidation (APCO) System	Microbial Check Valve (MCV) 	Activated Carbon/Ion Exchange (ACTEX) 	Ion Exchange for Calcium Removal (in development) 	Ion Exchange for ISS Oxygen Generating Assembly
Purpose	Prototype post-processor for water recovery systems	Dose potable water with 2 ppm iodine to prevent microbial growth	Remove iodine from potable water for crew consumption	Remove Ca^{++} from urine to prevent Ca sulfate precipitation in Urine Processor	Electrolyze water from the WRS to produce oxygen and hydrogen
Flow Rate	10 L/hr		50-200 lb/hr	0.5-10 L/hr	250 L/hr
Resin Type	Catalytic oxidation resin (Pt-Ru on alumina bead)	Iodinated resin, UMPQUA Research Co.	• Purolite NRW36SC, Nuclear Grade Mixed Bed Resin • DARCO activated carbon	Strong acid/gel-type or weak acid macroporous cation exchange	TBD
Resin Diameter	2.0-3.0 mm		0.65-0.90 mm 0.425-0.85 mm	0.65-0.80 mm	TBD
Porosity	N/A		45.5% 47.6%	45.5%	33%
Re_LS	7		6 to 25	0.1 to 2.3	70

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: $Re_p<10$, $f = \frac{150}{Re_p}$ (Blake-Kozeny)

- Inertial limit: $Re_p>1000$, $f = 1.75$ (Burke-Plummer)

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

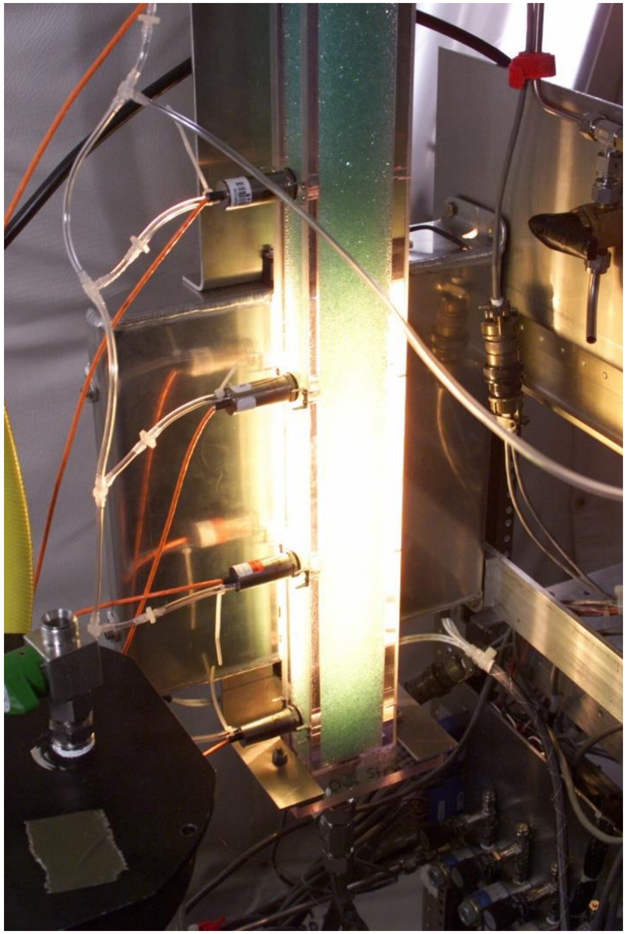
$$f_{\mathrm{TP}} = \gamma\left(\frac{Re_{GS}}{1-\varepsilon}\right)^a \left(\frac{1-\varepsilon}{Re_{LS}}\right)^b \left(\frac{(1-\varepsilon)^2 Su_L}{Re_{LS}^2}\right)^c$$

- Determining parameters by regression:

$$f_{\mathrm{TP}} = \frac{-\Delta P}{Z}\frac{d_P}{\rho_L U_{LS}^2}\frac{\varepsilon^3}{1-\varepsilon} = \frac{1-\varepsilon}{Re_{LS}}\left[150 + 0.8\left(\frac{Re_{GS}}{1-\varepsilon}\right)^{\frac{1}{2}}\left(\frac{Su_L(1-\varepsilon)}{Re_{LS}}\right)^{\frac{2}{3}}\right] + 1.75$$

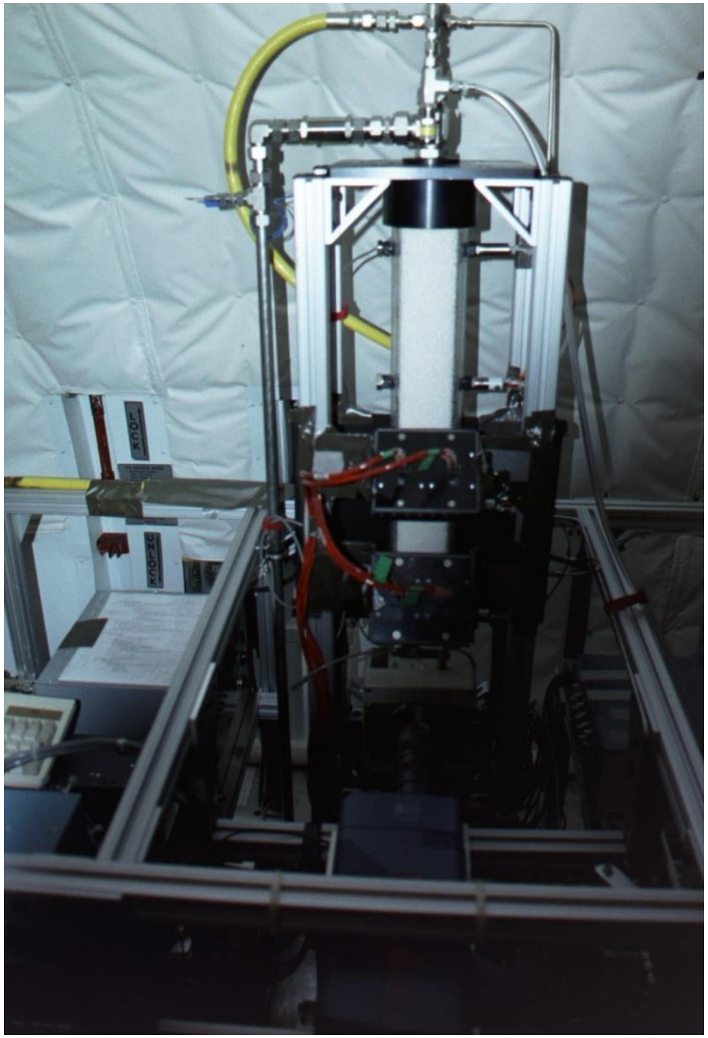
Aircraft Flights: Rectangular Test Section

- 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)
- $0.03 < G < 0.8$ kg/(s m2)
- $3 < L < 50$ kg/(s m2)
- $0.18 < Re_{LS} < 100$
- $4 \times 10^{-4} < We_{LS} < 0.2$
- $900 < Su_L < 365{,}000$

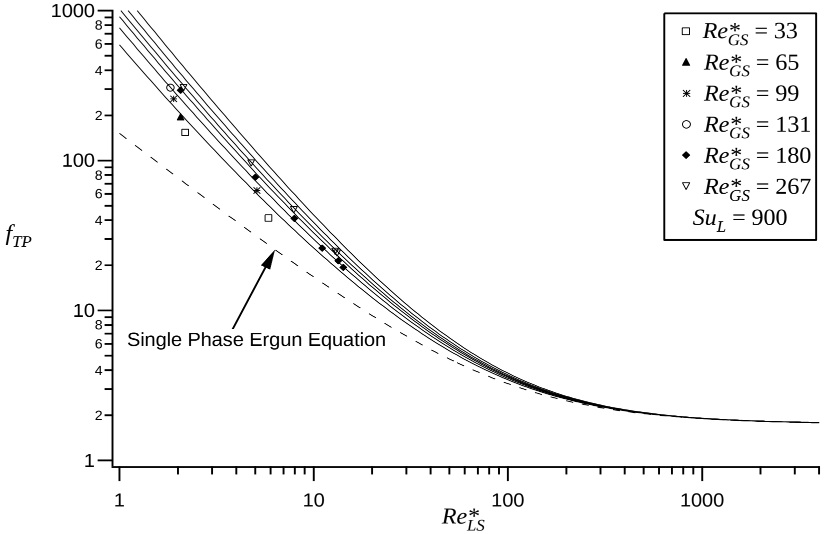


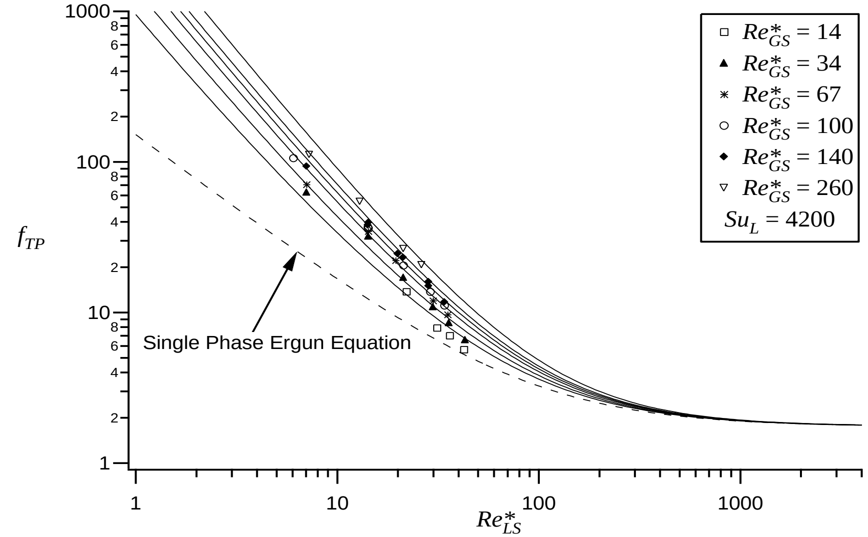
Aircraft Flights: Cylindrical Test Section

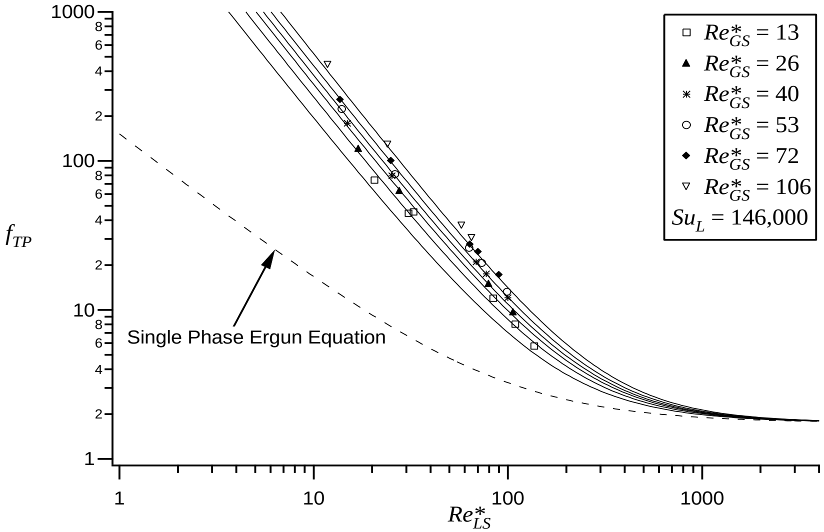
- 4 flights – Approximately 150 test conditions flown on NASA KC-135 aircraft (20 sec/run)
- Cylindrical cross section
  - 7.6 cm x 92 cm long
- 5 differential pressure trans. (1000 Hz)
- 3 mm spherical glass beads and 3.5 mm activated alumina beads ("semi"-spherical).
- High speed video (500 fps)
- Volume Averaged Void Fraction Sensor
- Air and Water only
- 0 = G < 1 kg/(s m2)
- 7 < L < 50 kg/(s m2)
- $25 < Re_{LS} < 150$
- $Su_L = 250{,}000$

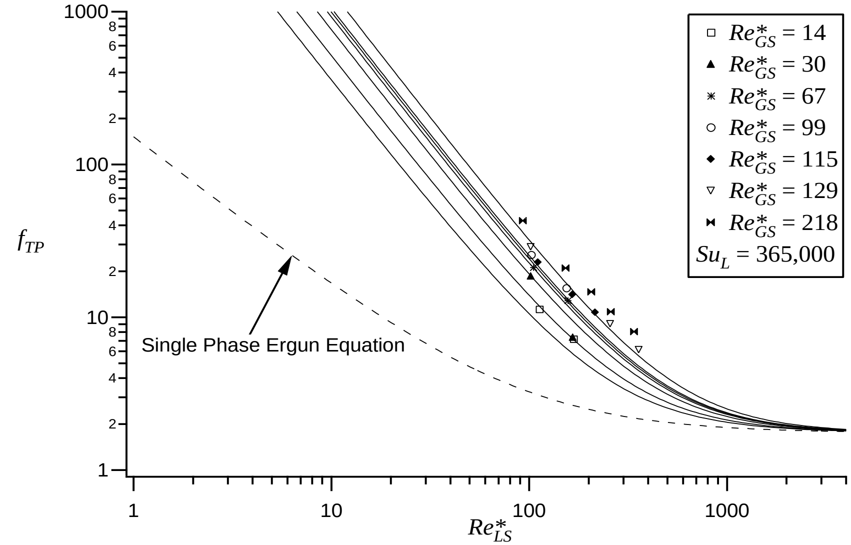


Pressure Drop Results for Aircraft



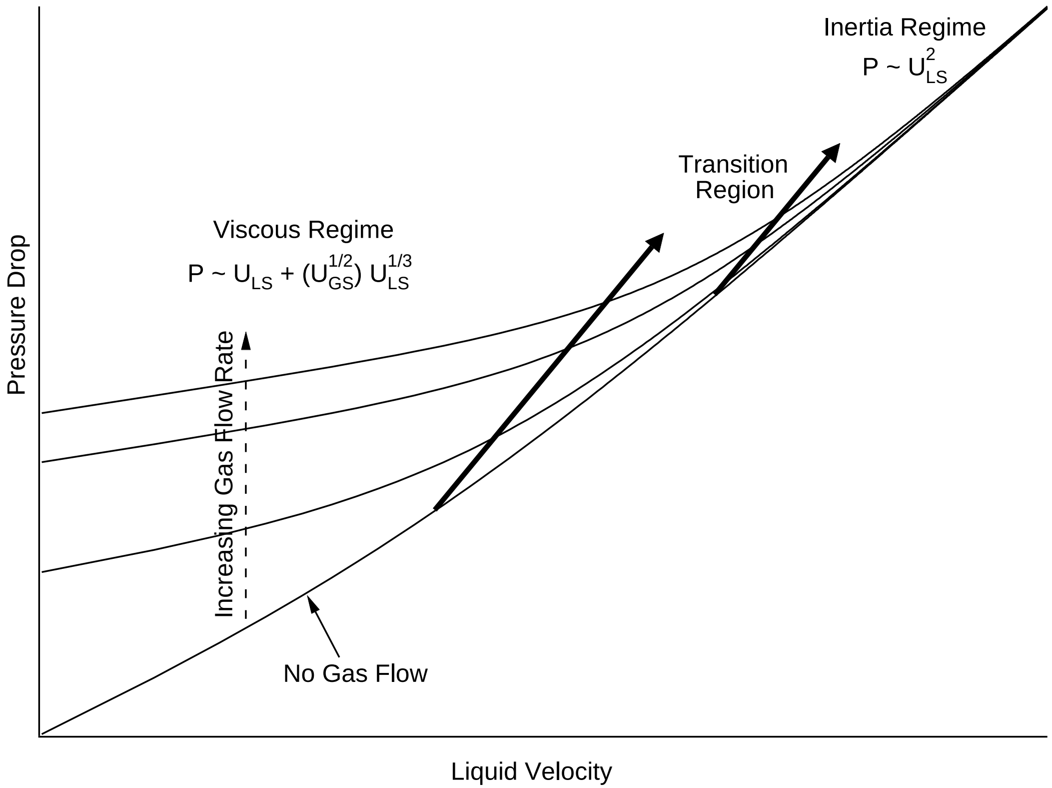






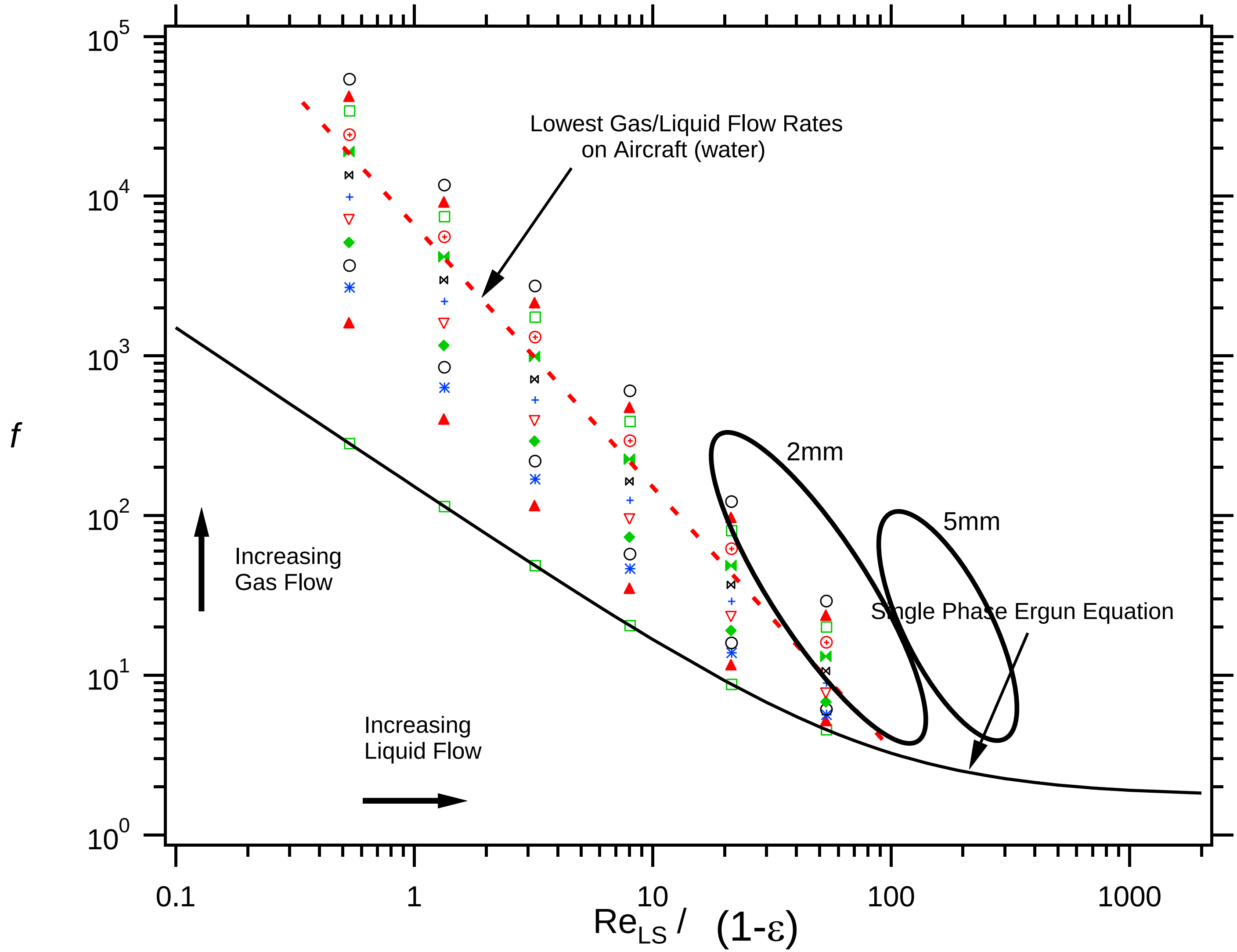
Packed Bed Reactor Experiment

Pressure Drop Results in 0-g



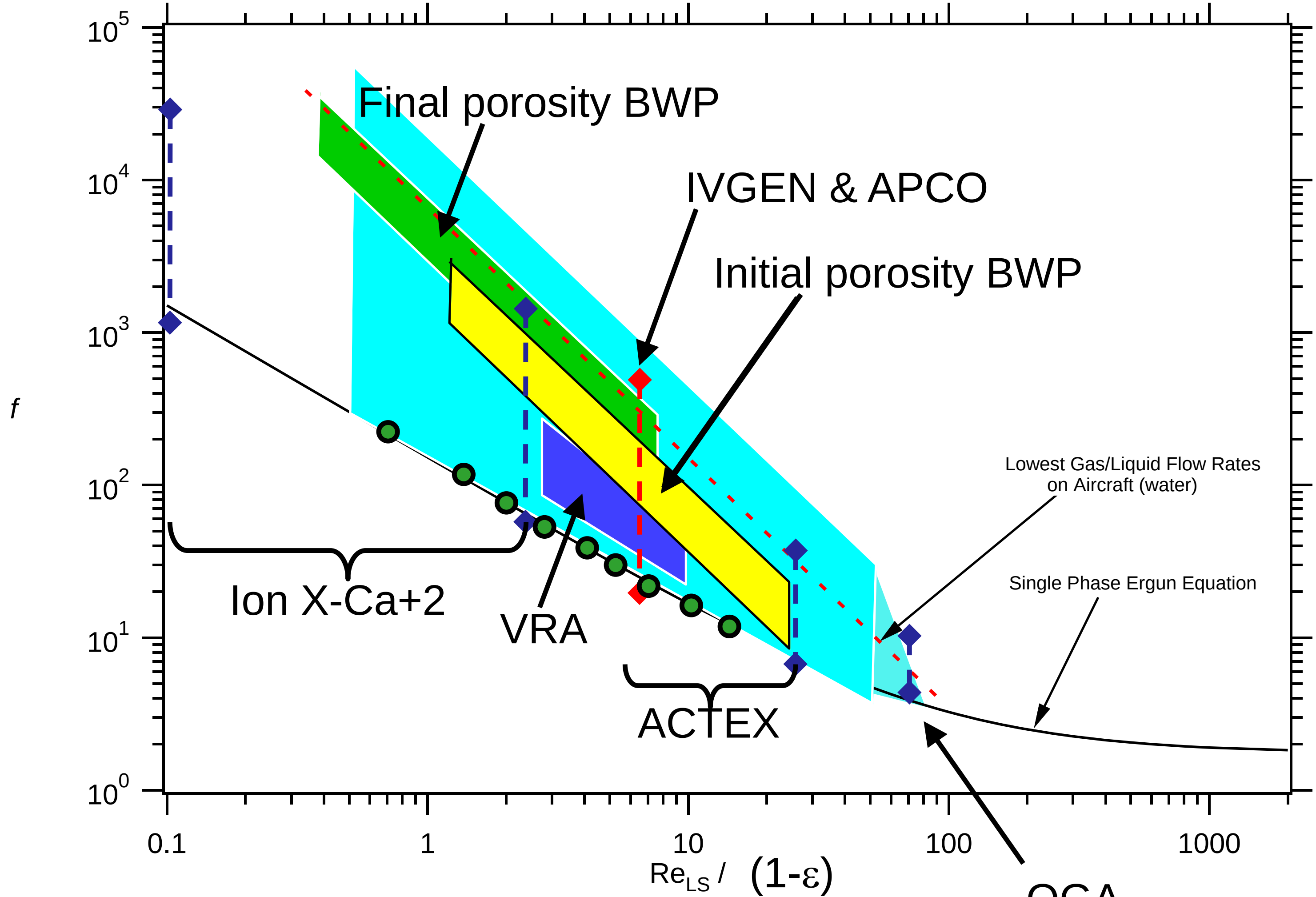
ISS EXPERIMENT

Steady State ISS Test Matrix



Packed Bed Reactor Experiment

Pressure Drop for Life Support Equipment



●: Startup flow rates

Packed Bed Reactor Experiment

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:

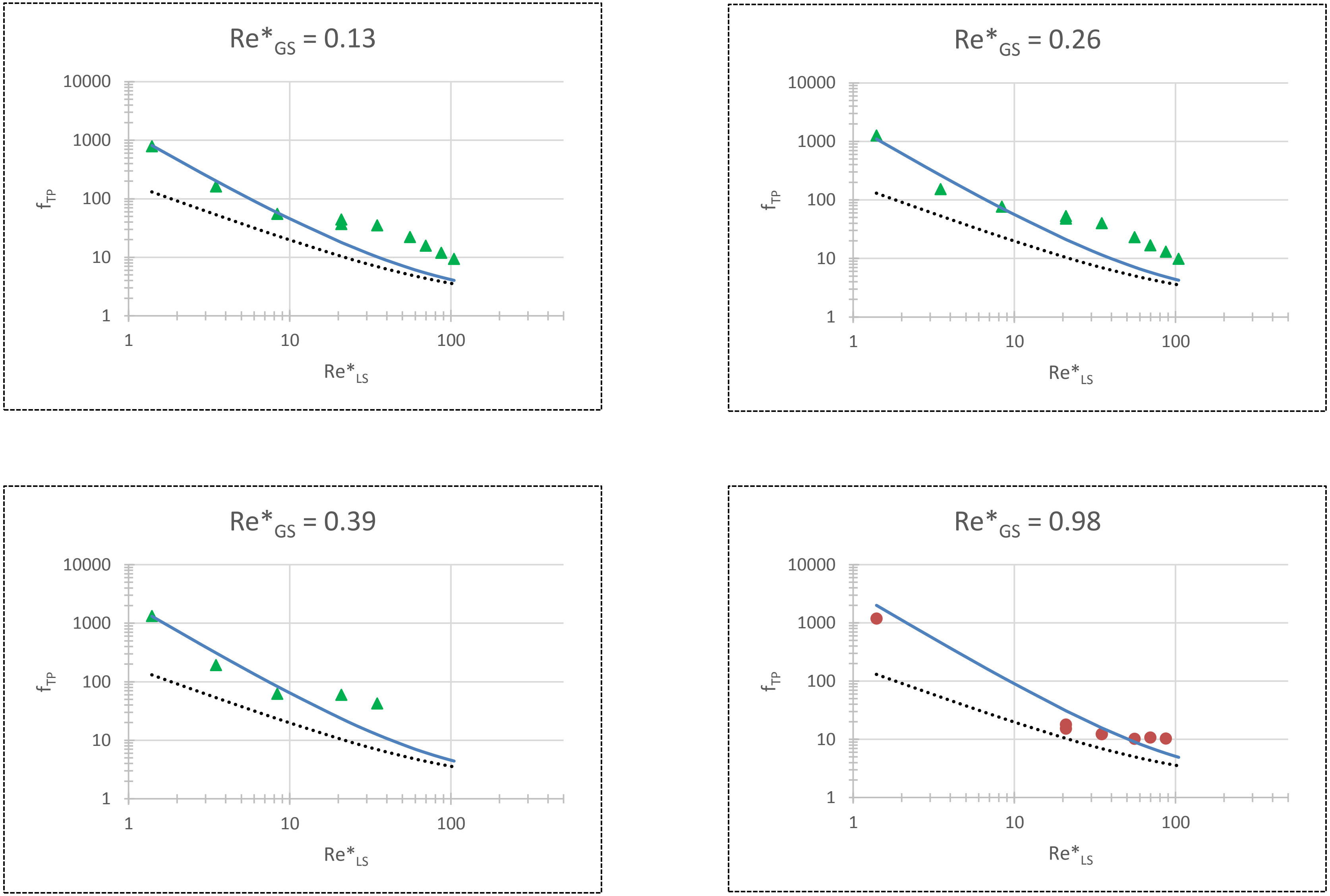
- Operate bed under full set of steady conditions over range typical for NASA applications.
- Some overlap with aircraft experiments to fully validate hydrodynamic models.

Transient Flow:

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

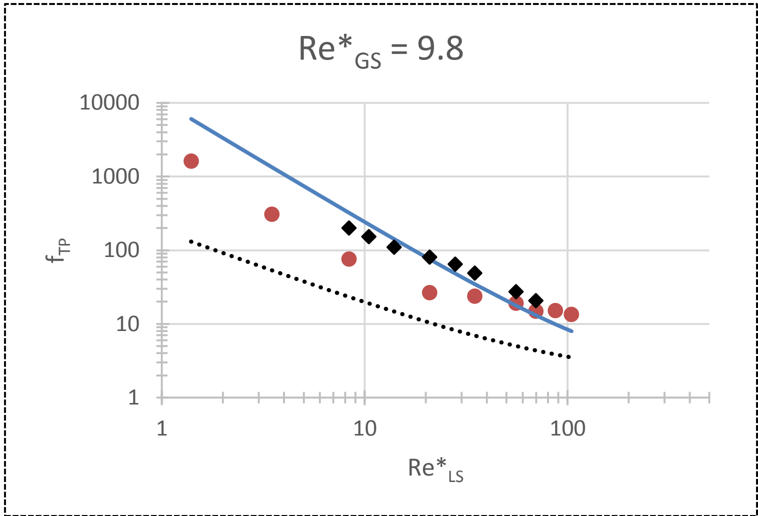
ISS RESULTS

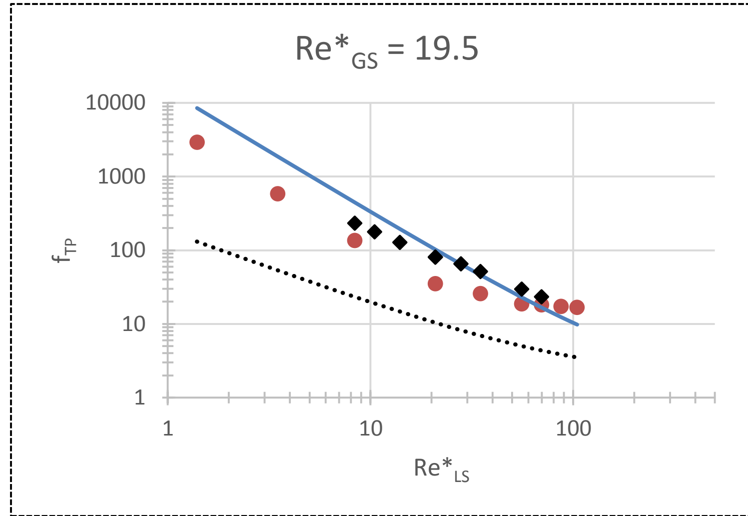
Steady State ISS Glass Packing

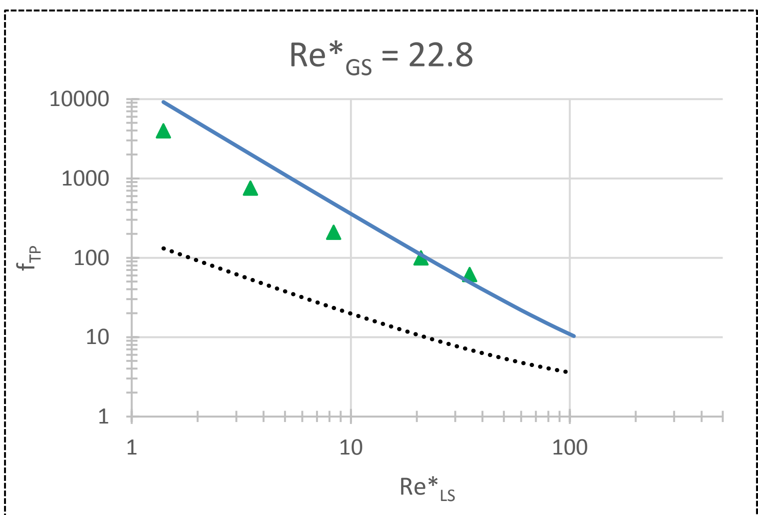


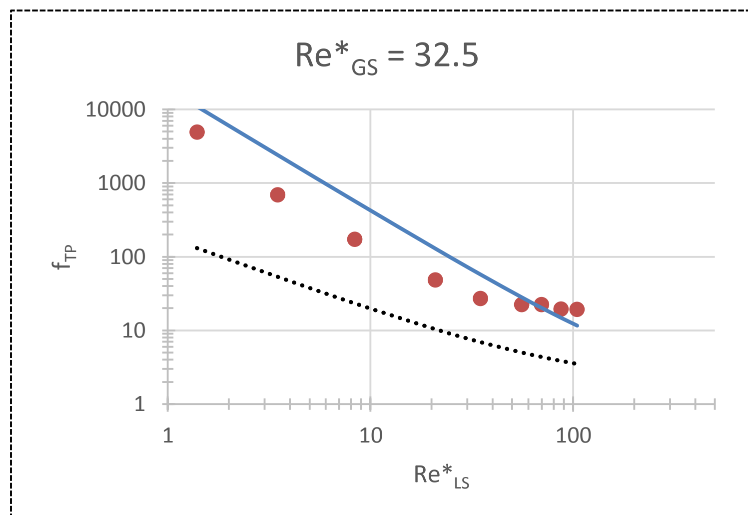
Packed Bed Reactor Experiment

Steady State ISS Glass Packing

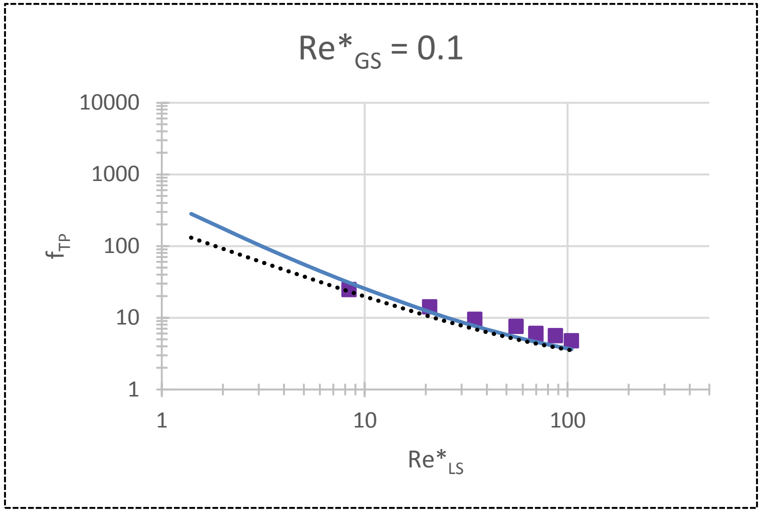


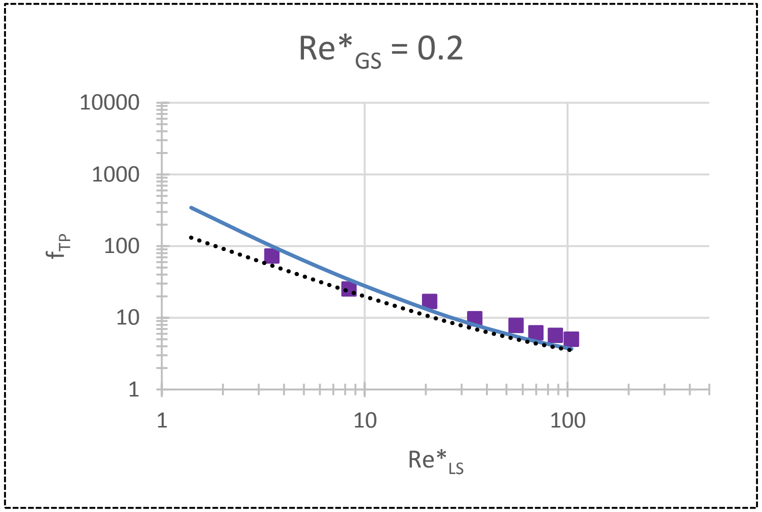


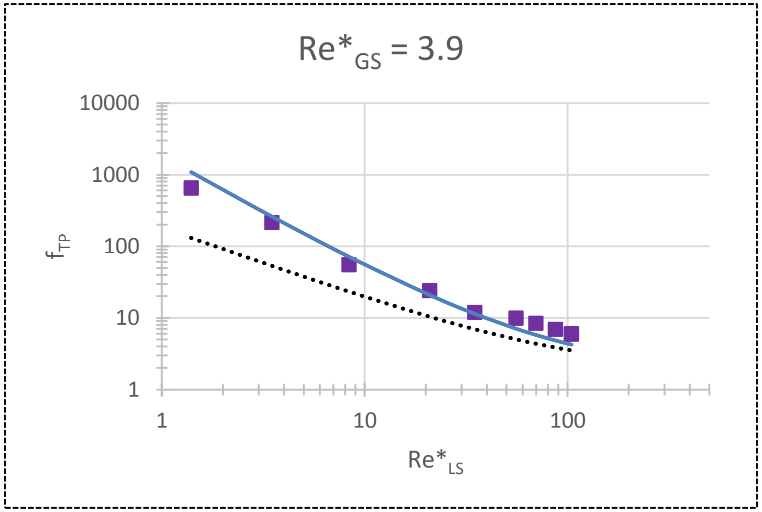


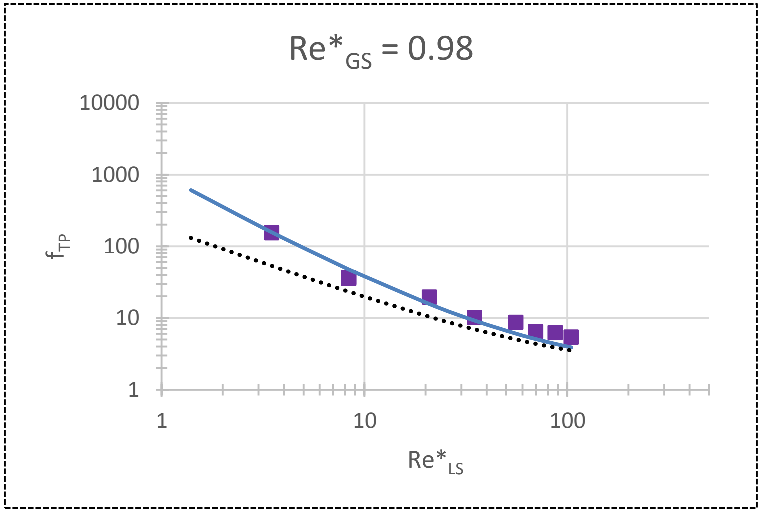


Steady State ISS Teflon Packing



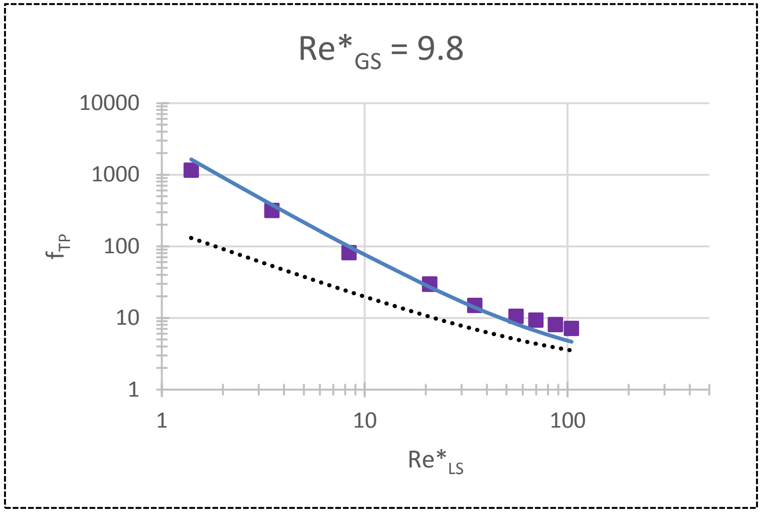


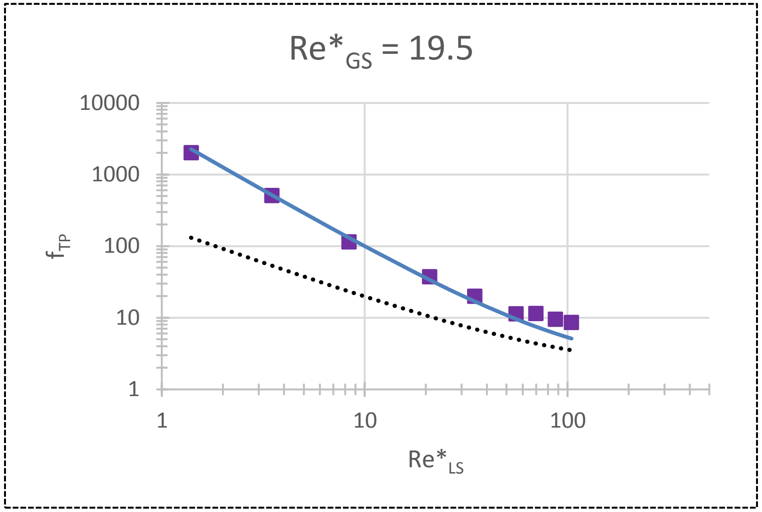


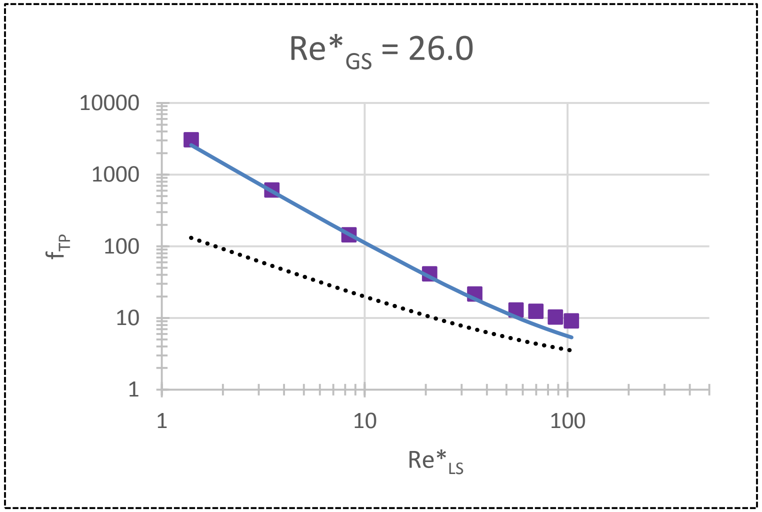


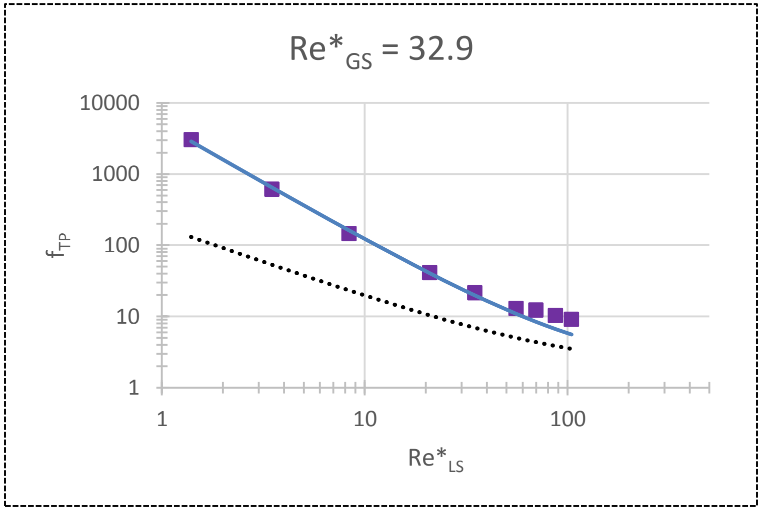
Packed Bed Reactor Experiment

Steady State ISS Teflon Packing

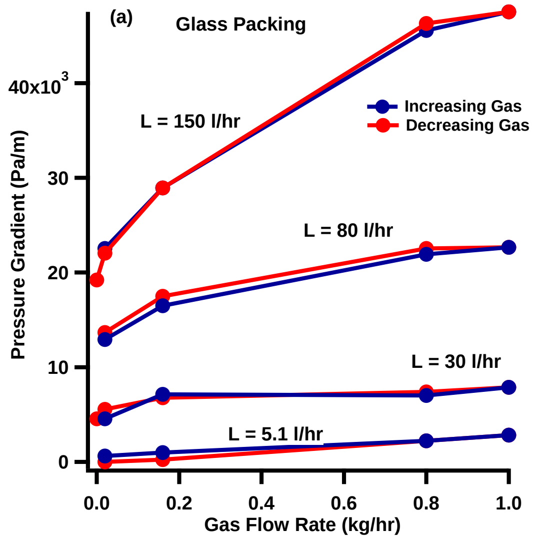


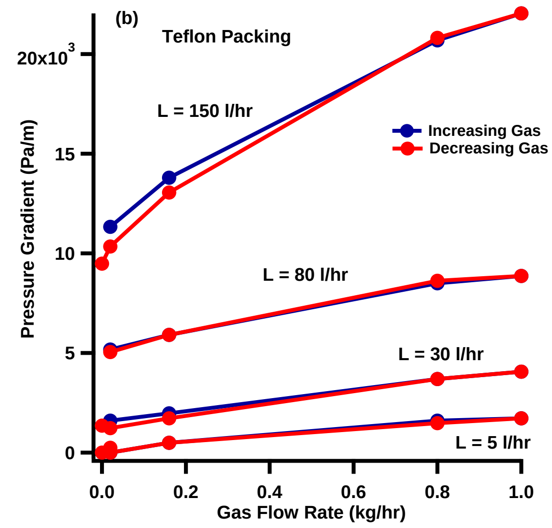


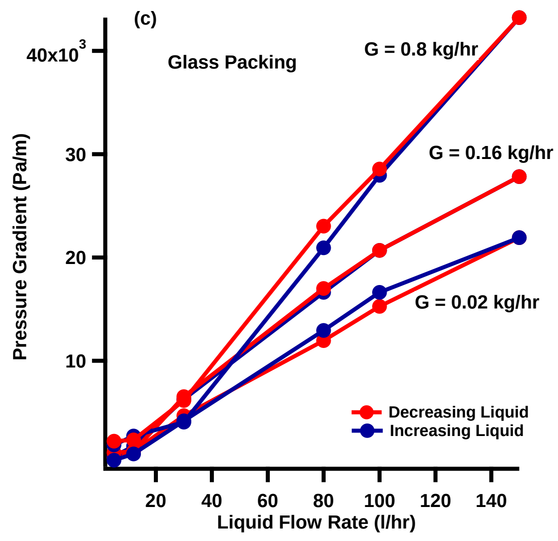


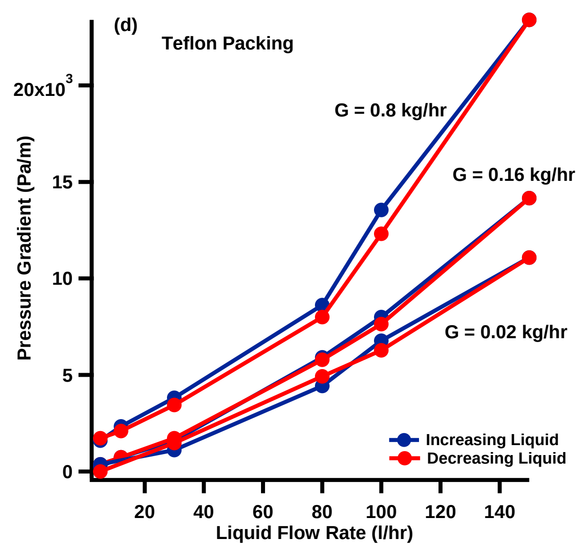


Transient Flows









Packed Bed Reactor Experiment

Summary

- Pressure drop model for air/water system:
  - Excellent agreement in viscous regime (Re_{LS} <10) with lower phase interaction term
  - No hysteresis observed
  - Transition to inertia regime does not fully capture presence of gas phase.
    - Flow structure is transitioning