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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)
## Packed Bed Reactor Experiment

### Operating Parameters

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

\[
\frac{(-\Delta P)}{L} = 150 \frac{(1 - \varepsilon)^2}{\varepsilon^3} \frac{\mu U_D}{d_p^2} + 1.75 \frac{(1 - \varepsilon)}{\varepsilon^3} \frac{\rho U_D^2}{d_p^2} \quad \text{Ergun (1952)}
\]

or

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

- 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):

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

- 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

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

- Determining parameters by regression:

\[
f_{TP} = \frac{-\Delta P}{Z} \frac{d_p}{\rho_L U_{LS}^2} \frac{\varepsilon^3}{1-\varepsilon} = \frac{1-\varepsilon}{Re_{LS}} \left[ 150 + 0.8 \left( \frac{Re_{GS}}{1-\varepsilon} \right)^{\frac{1}{2}} \left( \frac{Su_L (1-\varepsilon)}{Re_{LS}} \right)^{\frac{2}{3}} \right] + 1.75
\]
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
- 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
- $0 = G < 1 \text{ kg/(s m}^2\text{)}$
- $7 < L < 50 \text{ kg/(s m}^2\text{)}$
- $25 < \text{Re}_{LS} < 150$
- $S_u_L = 250,000$
Pressure Drop Results for Aircraft

Single Phase Ergun Equation

$Re_{LS}^*$ = 33
$Re_{GS}^*$ = 65
$Re_{GS}^*$ = 99
$Re_{GS}^*$ = 131
$Re_{GS}^*$ = 180
$Re_{GS}^*$ = 267
$Su_L = 900$

$Re_{LS}^*$ = 14
$Re_{GS}^*$ = 34
$Re_{GS}^*$ = 67
$Re_{GS}^*$ = 100
$Re_{GS}^*$ = 140
$Re_{GS}^*$ = 260
$Su_L = 4200$

$Re_{LS}^*$ = 13
$Re_{GS}^*$ = 26
$Re_{GS}^*$ = 40
$Re_{GS}^*$ = 53
$Re_{GS}^*$ = 72
$Re_{GS}^*$ = 106
$Su_L = 146,000$

$Re_{LS}^*$ = 14
$Re_{GS}^*$ = 30
$Re_{GS}^*$ = 67
$Re_{GS}^*$ = 99
$Re_{GS}^*$ = 115
$Re_{GS}^*$ = 129
$Re_{GS}^*$ = 218
$Su_L = 365,000$

Packed Bed Reactor Experiment
Pressure Drop Results in 0-g

Viscous Regime
\[ P \sim U_{LS} + (U_{GS})^{1/2} U_{LS}^{1/3} \]

Inertia Regime
\[ P \sim U_{LS}^2 \]

Transition Region

Increasing Gas Flow Rate

No Gas Flow

Liquid Velocity

Pressure Drop

Packed Bed Reactor Experiment
ISS EXPERIMENT
Steady State ISS Test Matrix

Lowest Gas/Liquid Flow Rates on Aircraft (water)

Increasing Gas Flow
Increasing Liquid Flow

Single Phase Ergun Equation

Packed Bed Reactor Experiment
Pressure Drop for Life Support Equipment

- Final porosity BWP
- IVGEN & APCO
- Initial porosity BWP
- Lowest Gas/Liquid Flow Rates on Aircraft (water)
- Single Phase Ergun Equation
- Ion X-Ca+2
- VRA
- ACTEX

- \( \text{Startup flow rates} \)

Packed Bed Reactor Experiment

\( f \): 0.1 1 10 100 1000

\( \text{Re}_{LS} / (1 - \varepsilon) \)

OGA

13
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

\[ \text{Re}^*_{\text{GS}} = 0.13 \]

\[ \\text{Re}^*_{\text{LS}} \]

\[ f_{\text{TP}} \]

\[ \text{Re}^*_{\text{GS}} = 0.26 \]

\[ \\text{Re}^*_{\text{LS}} \]

\[ f_{\text{TP}} \]

\[ \text{Re}^*_{\text{GS}} = 0.39 \]

\[ \\text{Re}^*_{\text{LS}} \]

\[ f_{\text{TP}} \]

\[ \text{Re}^*_{\text{GS}} = 0.98 \]

\[ \\text{Re}^*_{\text{LS}} \]

\[ f_{\text{TP}} \]
Steady State ISS Glass Packing

Re*_{GS} = 9.8

Re*_{GS} = 19.5

Re*_{GS} = 22.8

Re*_{GS} = 32.5
Steady State ISS Teflon Packing

1. When $Re^*_{GS} = 0.1$
   - $f_{TP}$ vs $Re^*_{LS}$

2. When $Re^*_{GS} = 0.2$
   - $f_{TP}$ vs $Re^*_{LS}$

3. When $Re^*_{GS} = 3.9$
   - $f_{TP}$ vs $Re^*_{LS}$

4. When $Re^*_{GS} = 0.98$
   - $f_{TP}$ vs $Re^*_{LS}$

Packed Bed Reactor Experiment
Steady State ISS Teflon Packing

\[ \Re^*_\text{GS} = 9.8 \]
\[ \Re^*_\text{GS} = 19.5 \]
\[ \Re^*_\text{GS} = 26.0 \]
\[ \Re^*_\text{GS} = 32.9 \]
Transient Flows

Glass Packing

(a) Gas Flow Rate (kg/hr)

- L = 150 l/hr
- L = 80 l/hr
- L = 30 l/hr
- L = 5.1 l/hr

(b) Teflon Packing

- L = 150 l/hr
- L = 80 l/hr
- L = 30 l/hr
- L = 5 l/hr

(c) Liquid Flow Rate (l/hr)

- G = 0.8 kg/hr
- G = 0.16 kg/hr
- G = 0.02 kg/hr

(d) Teflon Packing

- G = 0.8 kg/hr
- G = 0.16 kg/hr
- G = 0.02 kg/hr

Packed Bed Reactor Experiment
Summary

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