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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

<table>
<thead>
<tr>
<th></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</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%</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>
Packed Bed Reactor Experiment

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.

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

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):

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

- 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:

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

- $0.03 < G < 0.8 \text{ kg/(s m2)}$

- $3 < L < 50 \text{ kg/(s m2)}$

- $0.18 < \text{Re}_{LS} < 100$

- $4 \times 10^{-4} < \text{We}_{LS} < 0.2$

- $900 < \text{Su}_L < 365,000$
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
  - $0 = G < 1 \text{ kg/(s m}^2\text{)}$
  - $7 < L < 50 \text{ kg/(s m}^2\text{)}$
  - $25 < Re_{LS} < 150$
  - $Su_L = 250,000$
Pressure Drop Results for Aircraft

Single Phase Ergun Equation

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

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

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

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

Packed Bed Reactor Experiment
Pressure Drop Results in 0-g

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

Transition Region

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

Liquid Velocity

Pressure Drop

Increasing Gas Flow Rate

No Gas Flow
ISS EXPERIMENT

Packed Bed Reactor Experiment
Steady State ISS Test Matrix

FHS TEST MATRIX
2.5 inch diameter
2 mm packing
Su=146,000

Increasing Gas Flow
Increasing Liquid Flow
Lowest Gas/Liquid Flow Rates on Aircraft (water)

Single Phase Ergun Equation

Packed Bed Reactor Experiment
Pressure Drop for Life Support Equipment

Packed Bed Reactor Experiment

- 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
- OGA

: Startup flow rates

Re_{LS} / (1-\varepsilon)

10^0 10^1 10^2 10^3 10^4 10^5

$0.1 1 10 100 1000$
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

Re*$_{\text{GS}}$ = 0.13

Re*$_{\text{GS}}$ = 0.26

Re*$_{\text{GS}}$ = 0.39

Re*$_{\text{GS}}$ = 0.98

Packed Bed Reactor Experiment
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

- $Re^*_{GS} = 9.8$
- $Re^*_{GS} = 19.5$
- $Re^*_{GS} = 26.0$
- $Re^*_{GS} = 32.9$
Transient Flows

(a) Glass Packing

L = 150 l/hr
L = 80 l/hr
L = 30 l/hr
L = 5.1 l/hr
Increasing Gas
Decreasing Gas

(b) Teflon Packing

L = 150 l/hr
L = 80 l/hr
L = 30 l/hr
L = 5 l/hr
Increasing Gas
Decreasing Gas

(c) Glass Packing

G = 0.8 kg/hr
G = 0.16 kg/hr
G = 0.02 kg/hr
Decreasing Liquid
Increasing Liquid

(d) Teflon Packing

G = 0.8 kg/hr
G = 0.16 kg/hr
G = 0.02 kg/hr
Increasing Liquid
Decreasing Liquid
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