Gas-Liquid Flows and Phase Separation

by

John McQuillen

Strategic Research to Enable NASA's Exploration Missions

June 22 - 23, 2004

Cleveland, Ohio
Common Issues for Space System Designers

- Ability to Verify Performance in Normal Gravity prior to Deployment.
- **System Stability**
- Phase Accumulation & Shedding
- **Phase Separation**
- Flow Distribution through Tees & Manifolds
- **Boiling Crisis**
- Heat Transfer Coefficient
- Pressure Drop

* Two Phase Flow Facility
Space-Based Technologies
Using Two Phase Flow

Advanced Life Support Systems
- Condensing heat exchanger
- Wastewater processing
  - Distillation systems
  - Evaporation systems
- Storage transport systems
- Two-phase tolerant pumps
- Low pressure liquid drainage

Thermal Control Systems
- Working fluids for internal/external systems
- Heat pump
- Two-phase tolerant pump
- Thermal bus
- Multiple heat source
  - Multiple temperatures
- Systems
  - EVA, ECLSS, Power

Nuclear Power Conversion Systems
- Two-phase distribution problems in condenser manifold
- Gas bubbles in pump
- Interaction between components
- Liquid droplet carry over into turbine inlet
- Thermal transients affecting fatigue of the boiler

Output
- Design Tools
- Engineering Handbooks
- Models

Applied Research
- Boiling
- Condensation
- Phase Separation
- Two-Phase Stability

Microgravity Fluid Physics Branch
Glenn Research Center at Lewis Field
## Partial Listing of Where Gas-Liquid Flows are in Life Support Systems

<table>
<thead>
<tr>
<th>Stream Type</th>
<th>Air Revitalization</th>
<th>Water Reclamation</th>
<th>Thermal Management</th>
<th>Solid Waste Management</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cabin Humidity Condensate</td>
<td>✓</td>
<td></td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>Urine</td>
<td></td>
<td>✓</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Spills</td>
<td></td>
<td>✓</td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td>Dish Washing</td>
<td></td>
<td>✓</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Laundry</td>
<td></td>
<td>✓</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sabatier CO₂ Reaction</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Waste Solids Drying</td>
<td></td>
<td></td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td>Food Processing</td>
<td></td>
<td></td>
<td></td>
<td>✓</td>
</tr>
</tbody>
</table>
Life Support Systems

• Commonality of Source Stream
  – Aqueous-based Working Fluid (Water)
  – Into Waste Water Tank
  – Low Pressure Inlet
  – Gas Phase Present
  – Particulate Matter may be Present

• Differences
  – Dissolved Matter → Fluid Property Effects
  – Batch vs. Continuous Input
  – Flow Rates
  – Void Fraction
Thermal Management Systems

Heat Source Temperature

\[ T \approx 50 ^\circ C \]

\[ T \approx 20 ^\circ C \]

\[ T \approx 2 ^\circ C \]

\[ T_{Source} < T_{Radiator} \]

\[ T_{Source} > T_{Radiator} \]

Pumped Loop

Vapor Compression

T ≈ 20 °C

T ≈ 50 °C

T ≈ 2 °C

Heat Source Temperature

Q → Q → Q → Q

Source > Radiator

Source < Radiator

Microgravity Fluid Physics Branch
Glenn Research Center at Lewis Field
Vapor Compression Cycle

Two Phase Issues

- Evaporators
- Condenser
- 2Ø Separator
- Liquid Droplet Carryover
- Lubricant Management
- Parallel Channel Instability
- 2Ø ΔP & Heat Transfer Coefficient

System Stability
Flight Demo
The Effect of Reduced Gravity on Gas-Liquid Flows

Negating the Effect of Buoyancy

- Axisymmetric flows
- Reduced Hydrostatic Pressure
- Spherical Bubbles vs. Ellipsoid
- No Gravity-Induced Shearing:
  - Gas Phase Rising relative to Liquid Falling
- Co-flow of Gas and Liquid Phases.

Radial void fraction distributions

- □ upward
- ▲ downward
- ○ microgravity
What Do We Know?
Flow Regimes

• 3 (½) Flow Regimes: Bubble, Slug, Annular (Transitional Slug Annular)
• Multiple Models that work well
  – Constant Void Fraction
  – Weber Number Model
  – Suratman Number Criteria
What Do We Know?
Pressure Drop

- Modified Homogenous Equilibrium Model works well
  - Mixture Density
  - Mixture Velocity
  - Liquid Viscosity
Wall Friction Factors $f_L$ in Bubbly Flow:

Reduced Gravity Two Phase Flow:
- D=6 mm, □ D=10 mm, △ D=19 mm,
- ■ D=12.7 mm, ◇ D=40 mm

Single-Phase Flow:
+ D=6 mm, _ D=10 mm, - D=19 mm

Blasius, Poiseuille relationship
Concerns

• Phase Accumulation and Shedding

• Liquid Film Rupture and Dryout
Example: Sabatier Reactor

\[ \text{CO}_2 + 4\text{H}_2 \rightarrow \text{CH}_4 + 2(\text{H}_2\text{O}) + \text{heat} \]

2Ø Issues

- Separator
- Liquid in Gas Outlet Stream
  - Detection
  - Response
- Influence of Fines
Crew Exploration Vehicle
Thermal Management System

- Capsule-type vehicle
- Functional during Orbital, Re-entry, and Post-Landing Phases
- Closed Loop System – Desire No Flash Evaporators
- Heat Load Estimate
  - Fuel Cells: 7 kW at 50 °C
  - Electronics: 3 kW at 40 °C
  - Cabin: 0.5 kW at 7 °C
- Limit Total Radiator Area < 200 ft²
- Body Mounted Radiator
- Working Fluid
  - Non-Toxic
  - Non-Corrosive
  - Low Freezing Point
Why Separate?

• Critical Process or Component that is intolerant of one Phase
  – Centrifugal pumps with gas bubbles
  – Phase Specific Sensors, i.e., hot wires
  – Biological media negatively impacted by gas

• Better System Performance
  – Condensors Work Better if no liquid present at inlet.
  – Control of Phase Distribution into a manifold
Requirements to Consider

- **Available Power**
  - Mars Transfer Vehicle has MW but for propulsion
  - CEV has up to 10 kW

- **Vibration**
  - Wear & tear
  - Noise

- **System Life**
  - Most will be Life of Mission or Vehicle
  - Some systems may have cleanliness/sterile concerns

- **Separator Life**

- **Flow Rate range**
  - ml/min to l/min
Requirements to Consider

• Acceleration Environments
  – Pre Launch 1 G
  – Launch – hi-G’s
  – Transit - microgravity
  – De-Orbit – hi-G’s
  – Moon (1/6 G) or Mars (3/8 G)
  – Post Landing 1 G

• Degree of Separation Desired

• Contamination Sensitivity
  – Separation process negatively impacted by solids or immiscible 2\textsuperscript{nd} liquid phase

• Tolerance of “Slugging” or “flooding” Events
  – System capacitance

• Startup & Shutdown
## Range of Separator Requirements

<table>
<thead>
<tr>
<th>Stream Type</th>
<th>Near Continuous or Batch</th>
<th>Inlet Void Fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cabin Humidity Condensate</td>
<td>Continuous</td>
<td>?</td>
</tr>
<tr>
<td>Urine</td>
<td>Batch</td>
<td>Low</td>
</tr>
<tr>
<td>Dish Washing</td>
<td>Batch</td>
<td>Low-Initially</td>
</tr>
<tr>
<td>Laundry</td>
<td>Batch</td>
<td>Low-Initially</td>
</tr>
<tr>
<td>Sabatier CO$_2$ Reaction</td>
<td>Continuous</td>
<td>High</td>
</tr>
<tr>
<td>Waste Solids Drying</td>
<td>Continuous</td>
<td>High</td>
</tr>
<tr>
<td>Food Processing</td>
<td>Batch</td>
<td>High</td>
</tr>
<tr>
<td>Bioreactor</td>
<td>Continuous</td>
<td>Low</td>
</tr>
</tbody>
</table>
Mechanical Phase Separation

- Centrifuge – Very high G’s
  - Spin outside housing
  - Spin internal float
- Use rotational acceleration to also develop “hydrostatic” pressure rise to pump liquid
  - Rotary Fluid Management Device (Sundstrand)
  - Two Phase Pump (Foster-Miller)
  - MOBI
Passive Separation: Membranes

- Use of Hydrophilic Membranes and Surfaces to position liquid interface and withdraw liquid.
- Liquid Acquisition Devices (LAD’s) are used in upper stage propellant tanks to ensure start of rocket motor.
- Gas Phase Breakthrough based on bubble point or LaPlace Eqn using membrane pore size.
- Prone to contamination.
Passive Separation: Inertial

- Phase Separation achieved due to inertial differences in liquid and gas phase inertia
Passive Separation: Inertial

- Phase Separation achieved due to inertial differences in liquid and gas phase inertia

Click here to play movie
Passive Separation: Cyclonic

- Two Phase Flow Injected Tangentially into Cylinder.
- Separation driven by Flow
- Cyclones designed for microgravity will work well in multiple gravity levels
Summary

• Guidance similar to “A design that operates in a single phase is less complex than a design that has two-phase flow”\(^1\) is not always true considering the amount of effort spent on pressurizing, subcooling and phase separators to ensure single phase operation.

• While there is still much to learn about two-phase flow in reduced gravity, we have a good start.

• Focus now needs to be directed more towards system level problems.

References

- Low Gravity Two Phase Flow Movies
  http://microgravity.grc.nasa.gov/6712/2phase_flow/2phase.html