Multiphase Research toward the Development of Novel Fluid Management Systems aboard Spacecraft

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• ISS Fluids Experiments…
  - Handheld: CFE
  - Automated: CCF

• Applications…
  - Coffee cups to micro-fluidics
Spacecraft Capillary Fluid Systems

- Liquid propellants
- Life Support systems, primarily water processing: plants, animals, crew
- Phase-change thermal systems and power cycles
- Routine fluids management: medical, experiments, food…

Challenges…
Capillary-Driven Corner Flow

Drop tower test
Review of Theory

N.S. equation: \[ Su \frac{DU}{Dt} = -\nabla P + \nabla^2 U + Bo \mathbf{g} \]

Assumptions:
• Wetting fluid satisfying Concus-Finn condition, i.e. \( \theta < \frac{\pi}{2} - \alpha \)
• Locally parallel flow—slender fluid column

z-comp. N.S.:
\[ \frac{1}{\mu} \frac{\partial P}{\partial z} = \frac{\partial^2 w}{\partial x^2} + \frac{\partial^2 w}{\partial y^2} \]

Global mass balance:
\[ \frac{\partial A}{\partial t} = - \frac{\partial \dot{Q}}{\partial z} = - \frac{\partial}{\partial z} \left( A\langle w \rangle \right) \]

Sample Gov. PDE:
\[ \frac{\partial h}{\partial t} = 2 \left( \frac{\partial h}{\partial z} \right)^2 + h \frac{\partial^2 h}{\partial z^2} \]

…leads to analytic solutions…needs B.C.s…
Corner Networks:
Elements, surfaces, volumes...

Curves
Sub-elements
Non-planar

‘Surfaces’
‘Porous Structures’
‘Sections’
Containers
CFE on ISS

ICF-1

VG-1

W. McArthur

CL-2
Sunita Williams, CFE-VG-2

Crew procedures

Camcorder

Test cell

Backlight

MWA
Existence - A Necessary Condition

\[ R_\gamma = \frac{\Omega}{\Sigma \cos \gamma} \]

Integrating YLG over \( \Box^* \)

\[ \left( \frac{\Sigma}{\Omega} \Omega^* - \Sigma^* \right) \cos \gamma = \int_\Gamma \nu \cdot Tu \, ds \]

\[ |Tu| = \frac{|\nabla u|}{\sqrt{1 + |\nabla u|^2}} < 1 \]

Necessary condition:

\[ \Phi(\Omega^*) \equiv \Gamma - (\cos \gamma) \Sigma^* + \left( \frac{\Sigma \cos \gamma}{\Omega} \right) \Omega^* > 0 \]

Remark: Existence if no arc \( \Box \) admitted; at \( \Box = 0 \), existence depends.

P. Concus and R. Finn, 1974
CFE: Interior Corner Flow...

2-D taper

Phase Separation

64x

24x
CFE-2; ICF-2, linear taper
$h(z, t)$
Table 5.1: Dimensional Solutions

<table>
<thead>
<tr>
<th>Flow Type</th>
<th>( A_s )</th>
<th>( Q_{\text{cap}} )</th>
<th>Solution</th>
</tr>
</thead>
<tbody>
<tr>
<td>( A_s )</td>
<td>( \frac{F_Q \sigma A_s}{3 \mu} \left[\frac{2}{z_2} \right]^{1/2} )</td>
<td>( t = \frac{3z_2}{A_s \left[\frac{C}{z_2} F_Q \right]^{1/2}} )</td>
<td>( z_2 = \left( \frac{V(0)^2}{A_0} + \frac{2 \sigma}{3 \mu} A_0^{1/2} F_Q t \right)^{1/2} )</td>
</tr>
<tr>
<td>( A_0 )</td>
<td>( mWF_A H^2 \left[\frac{2}{z_2} \right]^{1/2} )</td>
<td>( z_2 = \left( \frac{9}{10} \left( 1 + \frac{z_2}{z_s} \right)^{2/3} \left( \frac{z_2}{z_s} - 3 \right) + \frac{27}{10} \right) )</td>
<td>( t = \frac{2}{F_Q A_0^{1/2} \left[\frac{C}{z_2} \right]^{3/5}} )</td>
</tr>
<tr>
<td>( A_0 (1 + z/z_s)^{2/3} )</td>
<td>( F_Q \sigma A_0^{3/2} \left[\frac{z_2}{z_s} \right] )</td>
<td>( z_2 = \left( \frac{A_0^{1/2} \sigma}{F_Q t} \right)^{3/5} )</td>
<td>( z_2 \gg z_s )</td>
</tr>
<tr>
<td>( A_0 )</td>
<td>( F_Q \sigma A_0^{3/2} \left[\frac{z_2}{z_s} \right] )</td>
<td>( t = F_Q A_0^{1/2} \left[\frac{C}{z_2} \right] \left( \frac{A_0}{Q_{\text{imp}}} \right)^{2} \left[ \frac{z_2 Q_{\text{imp}}}{F_Q A_0^{3/2}} + \ln(1 + \frac{z_2 Q_{\text{imp}}}{F_Q A_0^{3/2}}) \right] )</td>
<td>( t = F_Q A_0^{1/2} \left[\frac{C}{z_2} \right] \left( \frac{A_0}{Q_{\text{imp}}} \right)^{2} \left[ -\frac{z_2 Q_{\text{imp}}}{F_Q A_0^{3/2}} - \ln(1 + \frac{z_2 Q_{\text{imp}}}{F_Q A_0^{3/2}}) \right] )</td>
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<td>( (z/z_s)^2 )</td>
<td>( F_Q \sigma A_0^{3/2} \left[\frac{z_2}{z_s} \right] )</td>
<td>( Q_{\text{cap}} \left</td>
<td>_{z_1} = A_s \right</td>
</tr>
<tr>
<td>( (z/z_s)^{2/3} )</td>
<td>( F_Q \sigma A_0^{3/2} \left[\frac{z_2}{z_s} \right] )</td>
<td>( z_1 = \left( \frac{A_0^{1/2} \sigma}{F_Q t} \right)^{3/5} )</td>
<td>( \left( \frac{A_0}{V_u} \right)^{3/2} )</td>
</tr>
<tr>
<td>( A_s )</td>
<td>( mWF_A (H_3^3 - H_1^3) )</td>
<td>( z_2 = \frac{V_u}{A_2} - \left[ \frac{V_u}{A_2}^2 - \frac{2 mWF_A (H_3^3 - H_1^3)}{3 A_2} A (1 - A) \right]^{1/2} )</td>
<td>( z_2 = mWF_A (H_3^3 - H_1^3) )</td>
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<td>( \left( \frac{3 V_u}{A_2} \right) )</td>
</tr>
<tr>
<td>( A_s )</td>
<td>( mWF_A (H_2^3 - H_1^3) )</td>
<td>( z_1 (1 - \Lambda) = F_A W_3 \left( H_2^3 - H_1^3 \right) )</td>
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</table>
CCF...
Bubble in Wedge
Single ...all in
Singles...all in
Singles...all out
Single Mergers ...and out (MSG camera)
$f = 0.2 \text{Hz}$

- **Liquid Flowrate (ml/s)**
- **Gas Flow Rate (ml/s)**

- **Choking Limit**
- **Single: All**
- **Single: Near-All**
Applications:

Drink...
Condensing HX
Animal and plant habitats
$\mu$-g spray cooler
EMU LHP (freezable)
EMU CO$_2$ sensor design
3 waste water systems
HP wick structures
AIDS fluidics chip
...

Confidence in Capillary design is increasing quickly...

1. Passive phase separations
2. Ullage positioning
3. Geometry optimizations
4. It is possible to re-assess ALL fluid systems aboard spacecraft in light recent progress stemming from ISS experiments

Some notes...
1. Exciting, frightening, exhausting, trying, but you can adapt...
2. You may be surprised to find that ISS experiments are far more successful than you planned. ISS can be quite close to a normal lab—you can adapt.
3. Every fluid element must be considered a phase separator or distributor or a bubble/slug generator
4. Short duration low-g fluids experience do not guarantee long duration low-g outcomes
$S = S(R,r,l,V,ICs)$
$S = S(R,r,l,V,\text{ICs},d,\delta,\gamma,\theta_1,\theta_2,\theta_3,g,\phi,\psi,\sigma,\rho)$
MA-07 Interface Configuration (SE-FIT)

www.se-fit.com
Repeatability Demonstration
Capillary Rise (imbibition)
CFE story…

Initially part of Unscheduled Payloads Program…
- Zero hazard
- Low mass < 2.5kg
- Low volume < 2 liters
- Minimal to no electrical interfaces and power requirements
- Minimal to no crew training
- Short hardware delivery schedule (~ months)

Since…

Short operations window, < 3 hrs…
- Approaching 50 operations
- > 10 astronauts
- 8 test cells with 7 more to launch
- Publications, Patents, Applications, Insight…(earth and space)