Perspectives on Thermal-Fluid Physics in Microgravity and Its Broader Applications to Space Exploration

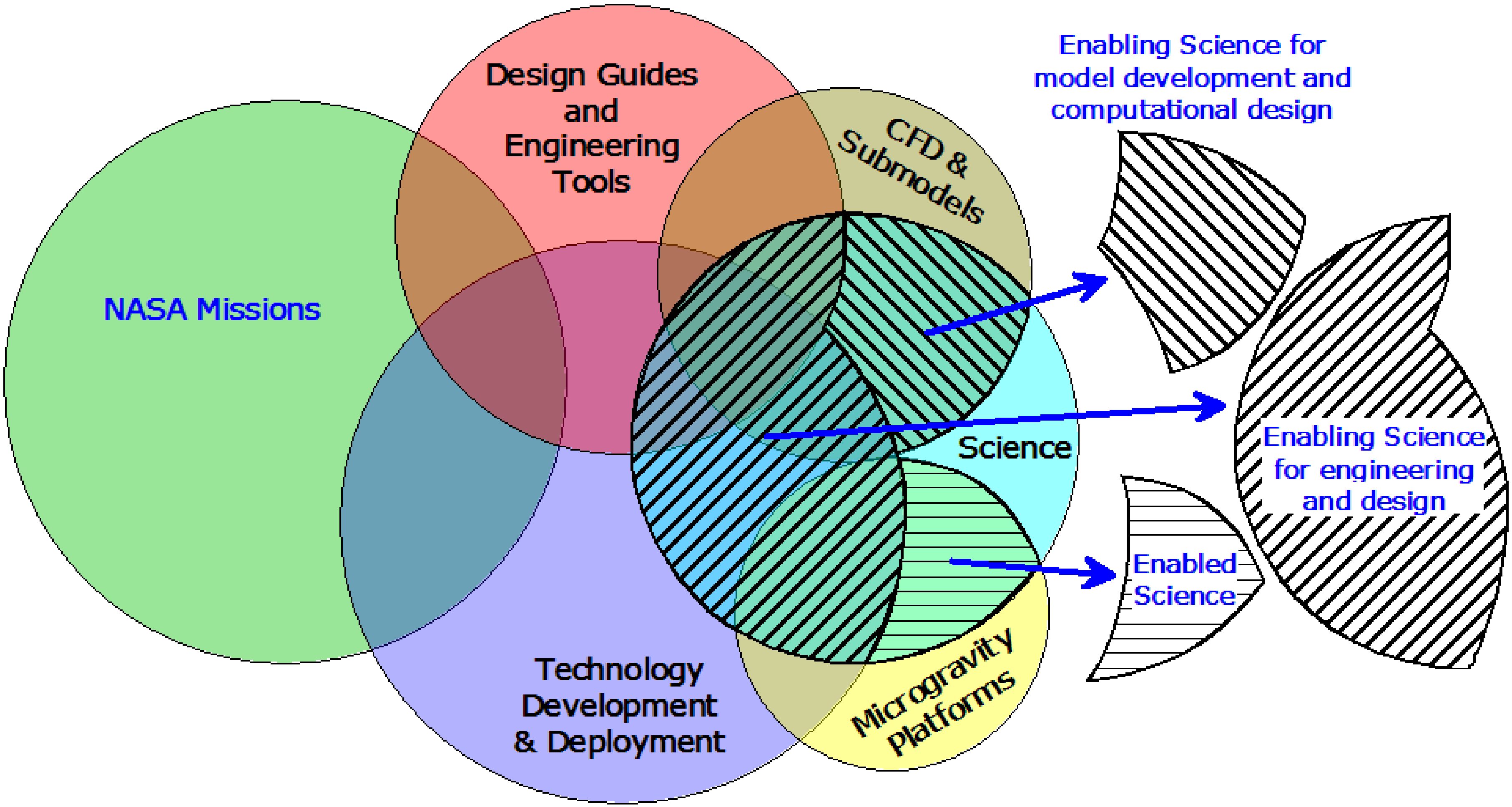
Jeffrey S Allen
Michigan Technological University

Key Science Questions:

- **What are the mechanisms by which organisms sense and respond to physical properties of surroundings, and to applied mechanical forces including gravitational forces?**
- **What are the fundamental principles that organize structure and functionality of materials, including but not limited to soft and active matter?**
- **What are the fundamental laws that govern the behavior of systems that are far from equilibrium?**
- **What new physics, including particle physics, general relativity, and quantum mechanics, can be discovered with experiments that can only be carried out in space?**

Thermal-Fluid Physics in Microgravity

A complex picture of needs and opportunities



Microgravity Fluid Physics Research Opportunities & Needs

Enabled Science

- Physics of moving contact lines
- Colloids & complex fluids
- Protein crystallography
- Fundamentals of phase change
  - Evaporation
  - Condensation
  - Solidification
- Capillary flow
- Thermocapillary flow

Enabling Science for engineering and design

- Scaling Laws for 2-Phase Flow and Heat Transfer & Thermal Management
- Flow Boiling, Pool Boiling, Film Boiling
- Stability of Closed Loop 2-Phase Thermal Control Systems
- Cryogenic Fluid Management
- Tank-to-Tank Cryogenic Transfers
- Energy Generation & Storage
- Stability of Packed Bed Reactors

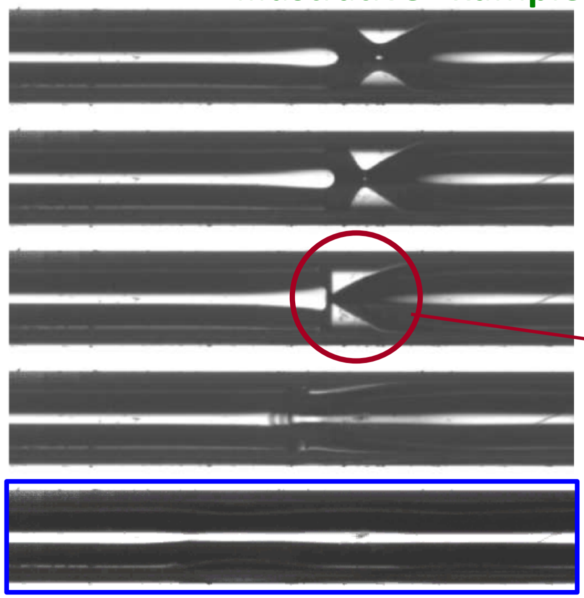
Enabling Science for model development and computational design

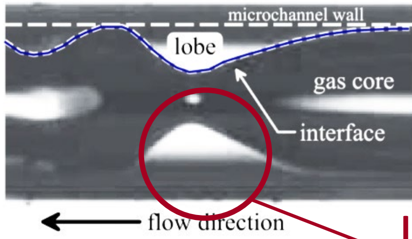
- Reliable low-g or capillary dominated models of moving contact lines suitable for CFD
- Reliable transient phase change models; particularly evaporation and condensation
- Reliable slosh/underdamped interface models
- Reliable models of "microgravity interfacial transport" within CFD framework

Two-Phase Flow (gas & liquid) – Why is this so hard?

Managing fluctuations associated with phase change is a challenge for ensuring reliability and consistency of operations in pressure fluctuations, flow instabilities, and cross talk between components. [2023 BPS Decadal]

Illustrative Example without Phase Change





Air/water flow in a 500 µm channel;
Image is 4 mm long;
10000 images/second

Interfacial instabilities generate a liquid lobe encircling the channel creating a nozzle for gas flow

At this instant, capillary pressure reaches 60 MPa!

1/10000 second later – liquid lobe implodes creating shock wave

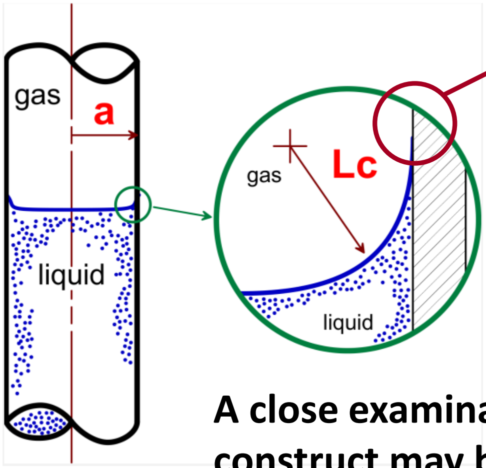
For the fluid physicists in the audience, $Re_{gas} < 100$, $Re_{liq} < 2$
Per standard engineering laws, this ought to be stable, well-behaved laminar flow!

Any small perturbation results in an inertial exchange between water and air with a capillary forces forcing unstable flow. The air is compressible so there are phase lags in dynamic response. As the size increases, so does the inertial exchange. In microgravity, there is no gravitational forces to saturate these instabilities. And this is without heat transfer and phase change!

We cannot predict when or how a localized perturbation will manifest into a system-level excursion (e.g., density wave oscillation) or unstable operation.

Phase Transformation (liquid & vapor) – Non-Equilibrium

Phase transformation phenomenon is not well understood fundamentally or well predicted in the space environment. [2023 BPS Decadal]



Liquid film in this region cannot be seen (absorbed film).

The absorbed film is treated as being static and unchanging during evaporation. This is an equilibrium construct, which works well for modeling efforts. In a terrestrial environment gravitational drainage keeps the capillary region small.

A close examination of the kinetic model for evaporation indicates that this equilibrium construct may be incorrect. Condensation can occur simultaneously with evaporation in the absorbed film region, which can increase and decrease in thickness.

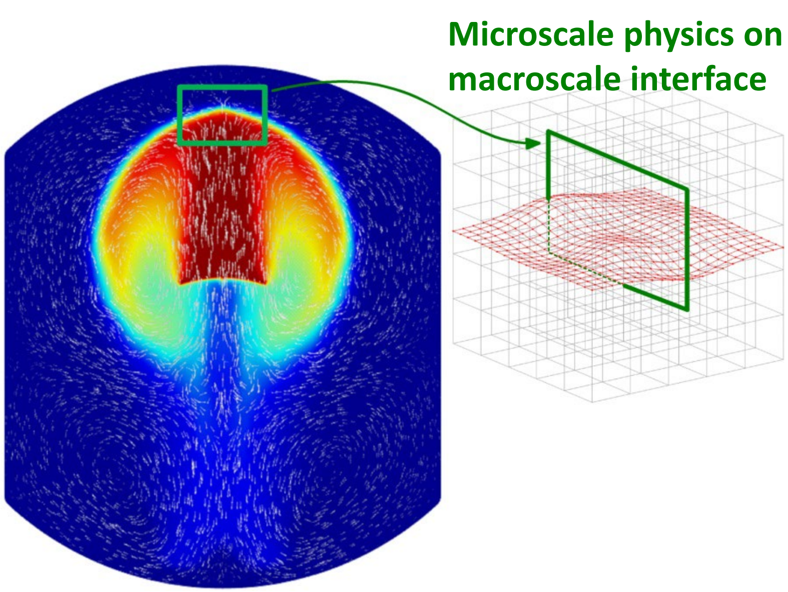
Implications of a non-equilibrium absorbed film?

- **Destabilization of a meniscus during evaporation**
- **Destabilization of a microlayer under a nucleating vapor bubble**
- **Generation of long wave instabilities**

Requires computing nanoscale physics to predict large-scale behavior.

Cryogenic Fluid Management – Worst-Case Scenario

… existing correlations used in [lumped node codes] do not agree with available cryogenic flow boiling data … [2023 BPS Decadal]



Cryogenic Tank ~ 10 m diameter

- **Perpetually in non-equilibrium.**
- **Significant inertial exchange between liquid & vapor.**
- **Need nanoscale resolution in CFD models over a huge computational domain (meters) with liquid sloshing and variable heat loads during orbit.**
- **Lack of accurate dynamic contact line submodels suitable for CFD.**
- **Lumped node computational codes do not capture how localized perturbations cascade to system level disruptions.**
- **In µg, absence of of buoyancy-driven convection can result in localized superheating of liquid, especially at very small heat flux, which can result in violent boiling (flashing).**
- **With nuclear propulsion, cryogenic hydrogen goes from 20k to 2000k in seconds.**

Broader Application to Space Exploration

Multiphase Flow with and without Heat Transfer has been part of NASA's research portfolio since the beginning of space exploration due to the inherent engineering advantages over single-phase systems:

- Lighter mass for equivalent heat transfer
- Higher heat rejection temperatures = smaller radiators
- Greater flexibility in cooling multiple components/systems operating at different temperatures

Sustained human exploration of space beyond low earth orbit requires answers to fundamental thermal-fluid physics because thermal management remains a limiting factor for all space exploration technologies, including:

- Environment conditioning and control (space craft and planetary surface)
- Nuclear power, nuclear propulsion

After these many decades, why haven't we solved these problems?

- Microscale thermal-fluid physics is critical when gravity is absent. Microscale events have macroscale effects. And we don't fully understand non-equilibrium microscale thermal-fluid physics nor the relationship to macroscale system behavior.
- We do not know how large (or small) of a µg experiment will scale to full-size systems. Computational design tools require more fidelity to capture the microscale physics, but finer and finer meshing is not the solution.
- There remains a perception that µg fluid and thermal management is a "engineering problem".