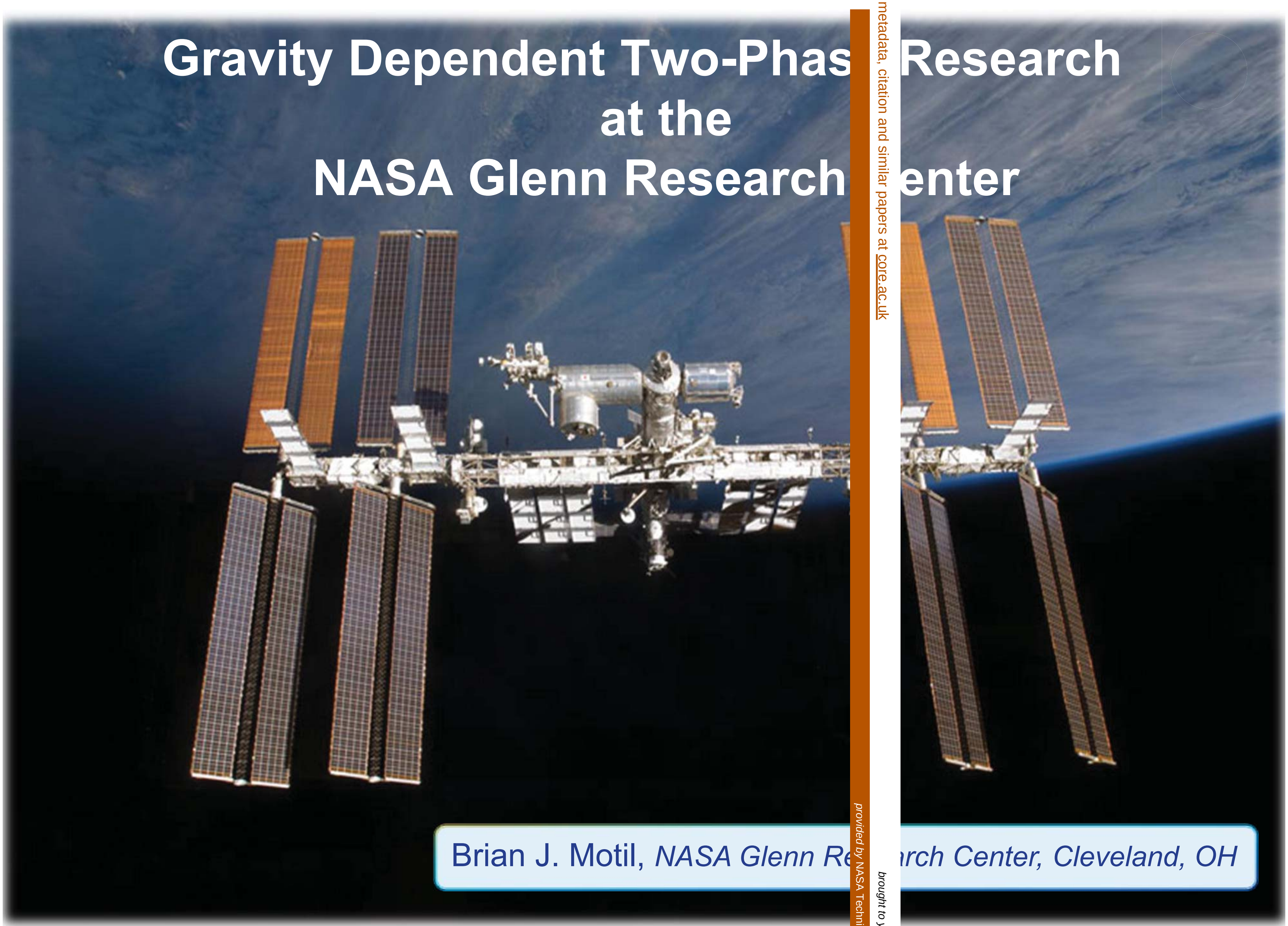
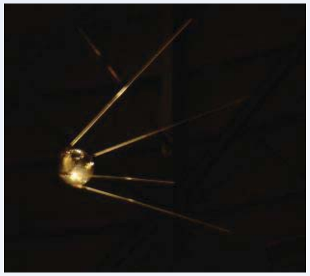
Gravity Dependent Two-Phas Research at the NASA Glenn Research enter



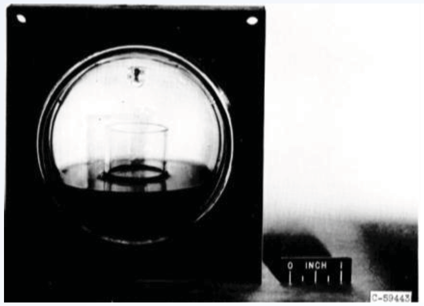
Brian J. Motil, *NASA Glenn Re arch Center, Cleveland, OH*

Fluids in Space

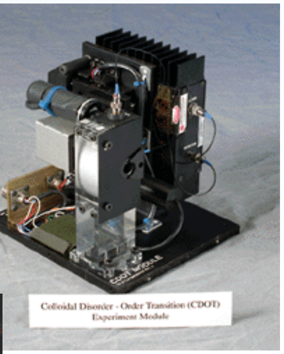
1957: The same year that Sputnik-1 orbited the planet – Robert Siegel (GRC) conceived a drop tower experiment to study a force often masked by gravity yet critical to almost every life form.



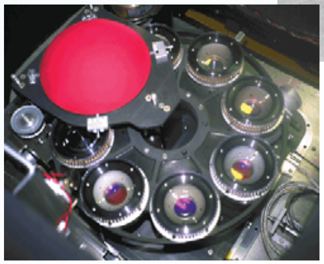
1962: The first “fluids” experiment was conducted in space on the Mercury-Atlas 07 by Scott Carpenter to study the liquid-vapor interface in a baffled tank in weightlessness.
(NASA TN D-1577, 1963).



1995: The Colloidal Disorder-Order Transition (CDOT) shuttle flight experiment tested fundamental theories that model atomic interactions in USML-2 on Columbia.

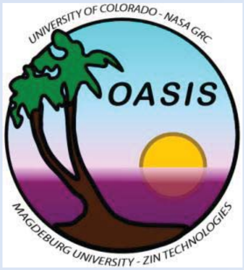


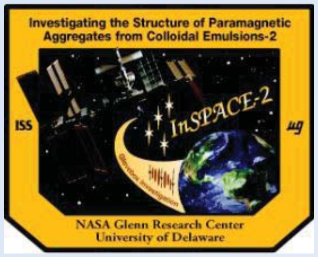
2001: Physics of Colloids in Space (PCS) flew as the first US Rack Level experiment on the ISS.

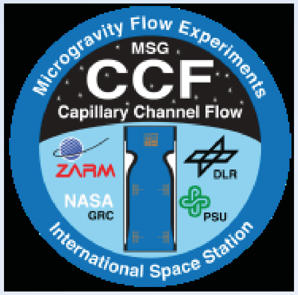


TODAY….

Fluid Physics and Complex Fluids Today





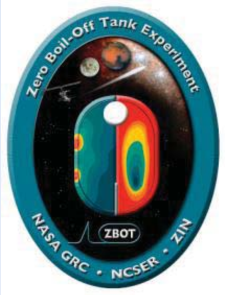


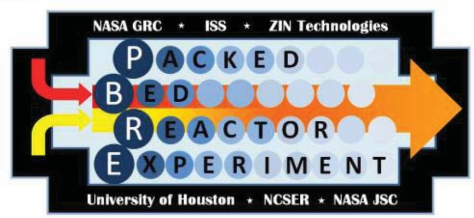
Fluid Physics

- Two-phase flow
- Phase separation
- Boiling, condensation
- Capillary and interfacial phenomena

Complex Fluids

- Colloids
- Liquid crystals
- Foams
- Granular flows





Capillary and Interfacial Phenomena

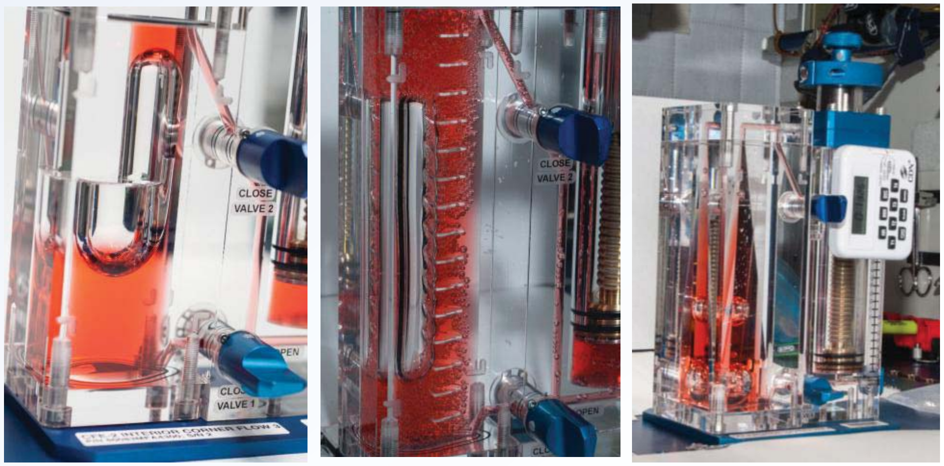
The Capillary Flow Experiment (CFE 1&2) -2004 through 2014

- Series of handheld vessels with various test chamber geometries to investigate the behavior of capillary flow phenomena in wicking structures such as interior corners and small gaps created by a vane and the test chamber wall.
- The working fluid is silicone oil of various viscosities, depending on the individual unit geometry.
- The results of CFE have applications in propellant management for fluid storage tanks, thermal control systems, and advanced life support systems for spacecraft.
- Critical wetting vane angles have been determined to within 0.5 degrees for Vane Gap 1 and 2 experiments.
- A bulk shift phenomena has been characterized that has implications for tank designs.

Astronaut Karen Nyberg adjusting the liquid volume during a CFE-2 Interior Corner Flow 9 (ICF9) experiment on ISS (June 15, 2013)

45°vane angle in earth gravity.

45°vane angle in microgravity.



Interior Corner Flow Modules (ICF3, ICF 8 and ICF9)

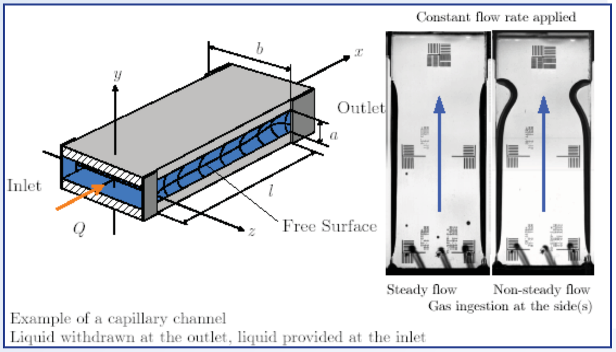
PI: Prof. Mark Weislogel, Portland State University

Capillary and Interfacial Phenomena

The Capillary Channel Flow (CCF) Experiment 2011–2014

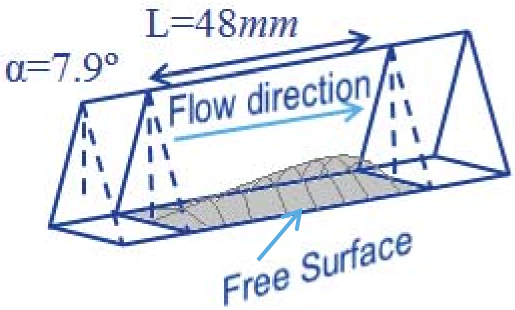
- Led by the German Space Agency (DLR) with a US/NASA Co-Investigator.
- Study of open channel capillary flow in microgravity.
  - The cross section of the flow path is partly confined by free surfaces.
- Experiment has led to high fidelity models that accurately predict maximum flow rates for an open capillary channel
- Research is critical to on-orbit fuel transfers and in space propulsion systems that utilize capillary vanes.
  - Current design of spacecraft fuel tanks rely on additional reservoirs (higher mass) to prevent the ingestion of gas into the engines during firing.

Astronaut Scott Kelly installing CCF in MSG in Dec 2010.

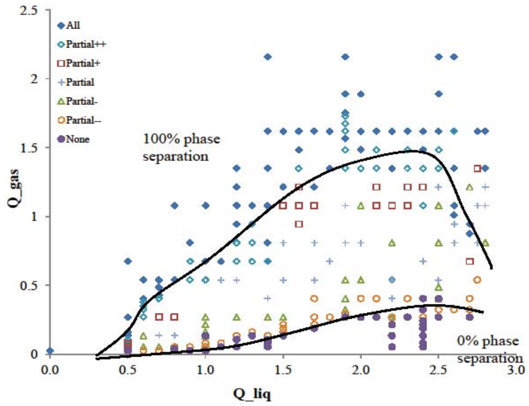


Example of a capillary channel
Liquid withdrawn at the outlet, liquid provided at the inlet

Capillary Channel Flow Test Unit 1 (flat plate and groove geometries)



Capillary Channel Flow Test Unit 2 (interior corner (wedge) geometry)



Gas-Liquid Phase Separation Flow Regime Map

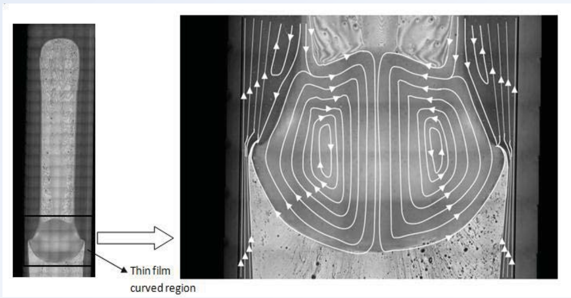
PI: *Prof. Michael Dreyer, ZARM*
US Co-I: *Prof. Mark Weislogel, Portland State University*

Boiling (Evaporation) and Condensation

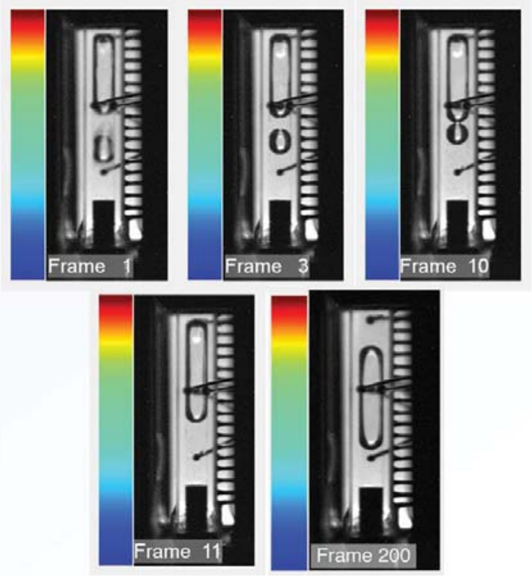
Constrained Vapor Bubble (CVB) Experiment – 2009 & 2013

- Prototype for a wickless heat pipe in microgravity – based on corner flows.
- Used pure Pentane as operating fluid for first set of experiments.
- Provided fundamental transport data including the overall stability, flow characteristics, average heat transfer coefficient in the evaporator, and heat conductance as a function of heat flow rate and vapor volume.
- Interferometry technique obtained direct measurements of fluid curvature and thickness.
- Visualized film stability and shape of dry out regions with a microscope in detail never obtained before in microgravity.
- CVB-2 (2013) extended data to a *binary mixture* rather than a pure fluid (Pentane – Isohexane).
- Discovered a new limit for heat pipe operation: Marangoni or Flooding limit.
    - First performance limitation is flooding, not dryout of the heater end.
    - Wickless designs can pump more than enough liquid to the heater end.
- Flooding limitation can be broken by the addition of a second, liquid, component. This may be the origin of reported enhancements using mixtures.
- Unexpected phenomena were observed and enhanced in microgravity including meniscus oscillations, autophobic droplet formation, and controlled single bubble nucleation phenomena (a hybrid pool/flow boiling experiment not accessible in 1-g environments).

PI: Prof. Joel L. Plawsky, Rensselaer Polytechnic Institute
Co-I: Prof. Peter C. Wayner, Jr., Rensselaer Polytechnic Institute



Marangoni limit and flooding of heater end with flow streamlines.



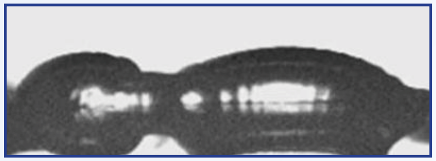
Unexpected Explosive Nucleation in 0-g.

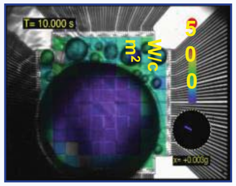
Boiling and Condensation

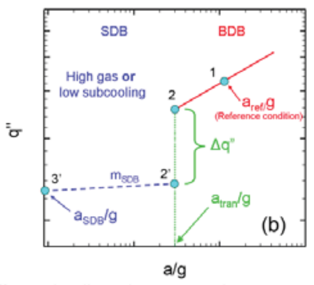
PI: Prof. Jungho Kim, University of Maryland
PI: Prof. Vijay K. Dhir, University of California, LA

Boiling eXperiment Facility (BXF) – 2011

- BXF included two separate pool boiling investigations:
  - **Microheater Array Boiling Experiment (MABE)**
  - **Nucleate Pool Boiling Experiment (NPBX)**.
- Advanced understanding of local boiling heat transfer mechanisms & critical heat flux in microgravity for nucleate and transition pool boiling.
- Detailed measurements of bubble growth, detachment and subsequent motion of single and merged (larger) bubbles.
- Developed a criteria for Boiling Transition
  - Buoyancy Dominated Regime (BDB)
    - Heat transfer by bubble growth and departure
    - Heat flux increases with gravity
  - Surface Tension Dominated Regime (SDB)
    - Dominated by the presence of a non-departing primary bubble
    - Effect of residual gravity is very small
  - Transition Criteria based on Capillary Length







***(Top)** Paulo Nespoli installing BXF in MSG. **(Middle left)** Coalescence of vapor bubbles on NPBX wafer. **(Middle right)** Subcooled nucleate boiling in μg. The MABE microheater array is colorized with actual heat flux data. **(Bottom)** Transition of boiling Heat Flux as a function of acceleration.*

Multiphase Flow and Heat Transfer Experiment (MFHT) - 2020

- Will develop models that incorporate two-phase flow regimes and fluid conditions to predict local heat transfer coefficients from subcooled nucleate boiling through critical heat flux (CHF) and dryout.
- Will obtain local measurements of the wall heat transfer coefficient with high temporal and spatial resolution using an infrared video (IR) camera.

ESA PI: Catherine Colin, Institut de Mecanique des Fluides
Co-I: Prof. Jungho Kim, University of Maryland

Two-Phase Flow (adiabatic)

PI: Dr. Brian Motil, NASA GRC
Co-I: Prof. Vemuri Balakotaiah, U. of Houston

Packed Bed Reactor Experiment (PBRE) - 2015

- Will investigate the role and effects of gravity on gas-liquid flow through porous media which is a critical component in life-support; thermal control devices; and fuel cells.
- Will validate and improve design and operational guidelines for gas-liquid reactors in partial and microgravity conditions.
- Preliminary models predict significantly improved reaction rates in 0-g.
- Models developed from early 0-g aircraft tests led to the successful operation of **IntraVenous fluid GENeration (IVGEN)** in 2010 providing the ability to generate IV fluid from *in situ* resources on the ISS.
- Provides test fixture to test future two-phase flow components.

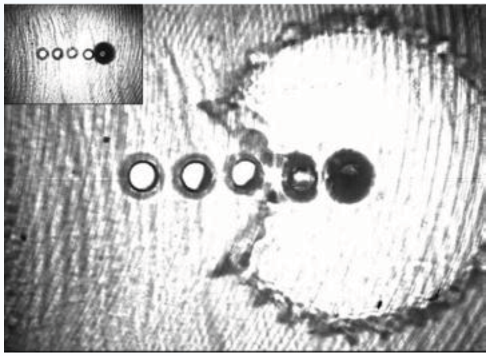
Volatile Reactor Assembly (VRA) on STS 89

IVGEN Deionizing resin bed

Dynamics of Liquid Film/ Complex Wall Interaction (DOLFIN II)

- ESA led experiment to develop continuum models to describe interactions between spreading fluids and chemically and/or morphologically complex surfaces using 0-g environment.
- Developing the ability to manipulate surface flows in microgravity is a key to thermal management solutions in space exploration.
- US PI (Yarin) will perform experiments on spray cooling over specially patterned surfaces.

US Co-I: Prof. Alexander Yarin, University of Chicago
ESA PI: Prof. Cameron Tropea, Institute of Fluid Mechanics and Aerodynamics (SLA)
Technische Universität Darmstadt

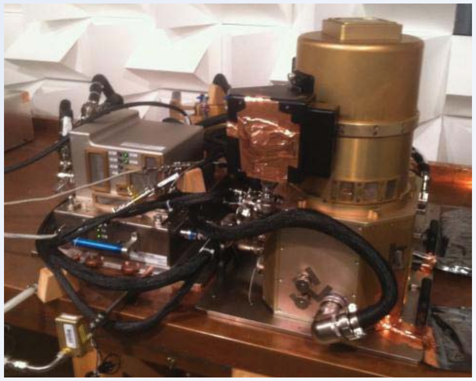


Drop impact onto a porous target

Boiling and Condensation

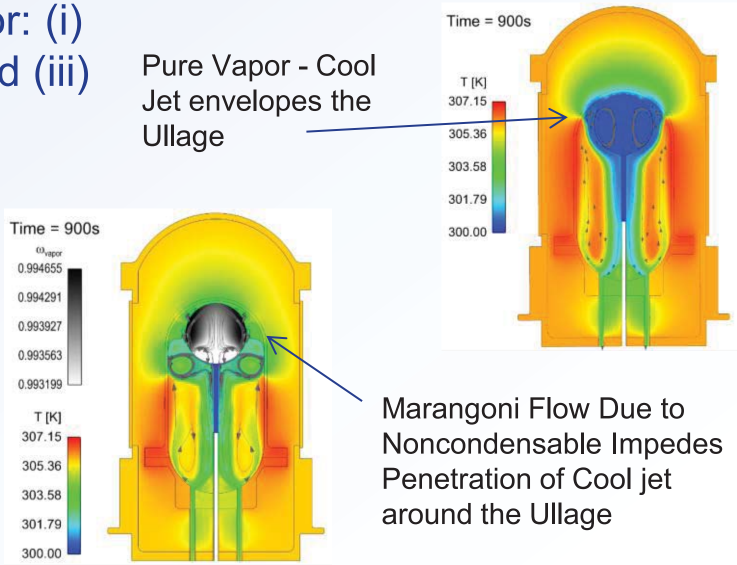
Zero Boil-Off Tank Experiment (ZBOT) - 2014

- Will study storage tank pressurization & pressure reduction through fluid mixing in microgravity (ZBOT-1).
- Add the effects of non-condensable gasses (ZBOT-2). The presence of non-condensables produces barriers to the transport of vapor to and from the interface creating gradients of the gaseous concentrations along the interface may give rise to Marangoni convection. This changes the pressurization and pressure reduction rates.
- ZBOT-3 will characterize tank thermal destratification and pressure reduction through active cooling schemes for: (i) sub-cooled jet mixing (ii) droplet spray-bar mixing; and (iii) broad area cooling with intermittent mixing.
- ZBOT provides an instrumented test section with controllable BCs; velocimetry; and flow visualization.



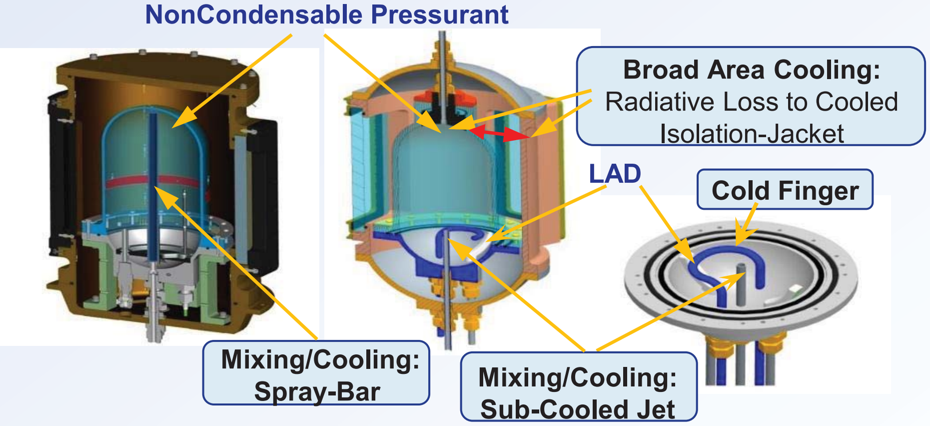
ZBOT EU

Effect of Noncondensable on Flow and Temperature Fields during Jet cooling Pressure Control



Pure Vapor - Cool Jet envelopes the Ullage

Marangoni Flow Due to Noncondensable Impedes Penetration of Cool jet around the Ullage



NonCondensable Pressurant

Broad Area Cooling: Radiative Loss to Cooled Isolation-Jacket

LAD

Cold Finger

Mixing/Cooling: Spray-Bar

Mixing/Cooling: Sub-Cooled Jet

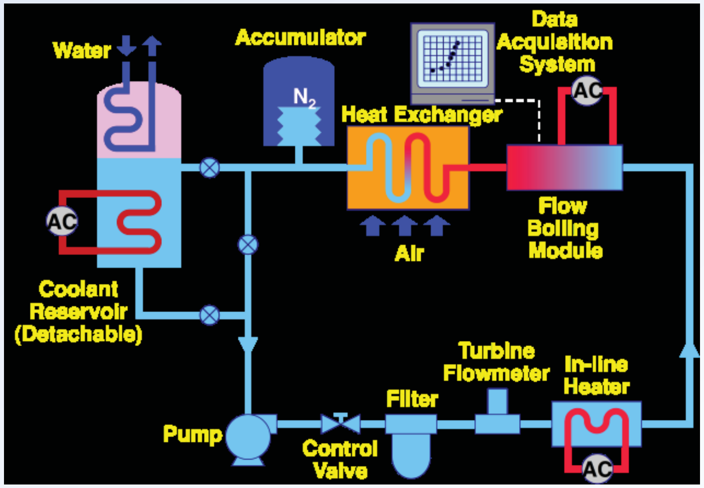
PI: Dr. Mohammad Kassemi, NCSER
Co-I: Dr. David Chato, NASA, GRC

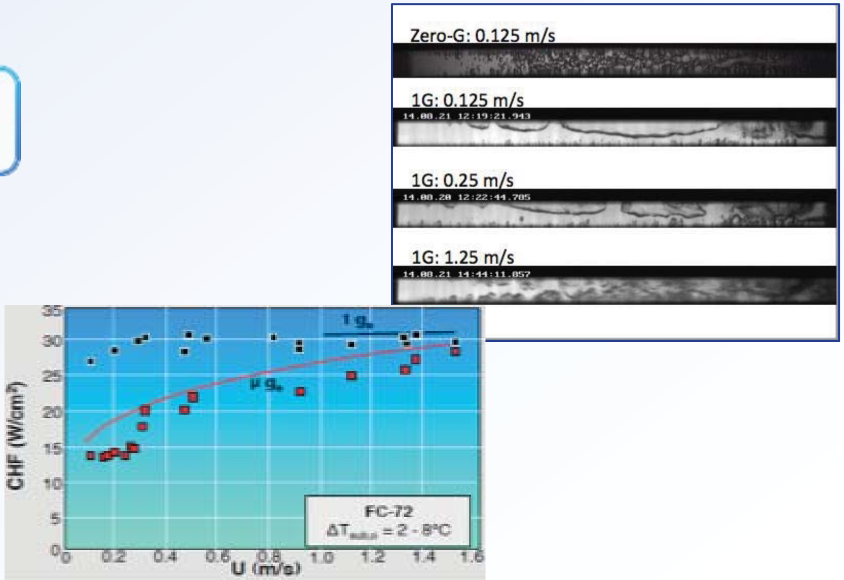
Boiling and Condensation

Flow Boiling and Condensation Experiment (FBCE) – 2017

- Will develop mechanistic models for microgravity flow boiling Critical Heat Flux (CHF) and dimensionless criteria to predict the minimum flow velocities required to ensure gravity-independent CHF along with boiling heat transfer coefficients and pressure data correlations.
- Will develop mechanistic model for microgravity annular condensation and dimensionless criteria to predict minimum flow velocity required to ensure gravity-independent annular condensation; also develop correlations for other condensation regimes in microgravity.
- Recently concluded successful 0-g aircraft testing for flow boiling CHF and condensation.
- Approach will be to develop an integrated flow boiling/condensation experiment to facility follow-on researcher.

PI: Prof. Issam Mudawar, Purdue University
Co-I*:* Dr. Mojib Hasan, NASA GRC

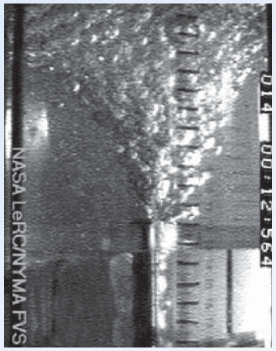




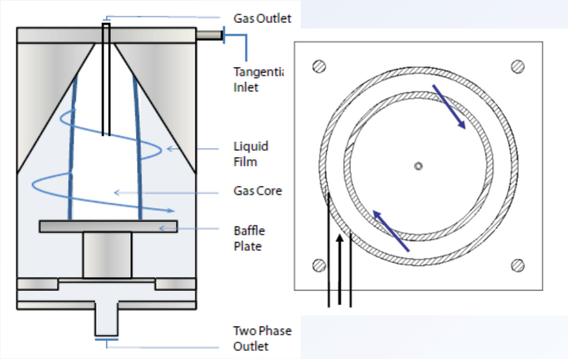
Critical Heat Flux (CHF) data and model predictions for microgravity and Earth gravity for flow boiling.

Gas-Liquid Separation Devices

Pumped Separator for PBRE



Reduced Gravity
Bubble Vortex



Cyclonic Concepts

PI: Dr. Georges Chahine and Xiongjun Wu, DynaFlow, Inc.
PI: Prof. Yasuhiro Kamotani, Case Western Reserve University
Co-I: Prof. Jaikrishnan Kadambi, Case Western Reserve University

Two-Phase Flow Separator Experiment (TPFSE) – 2018

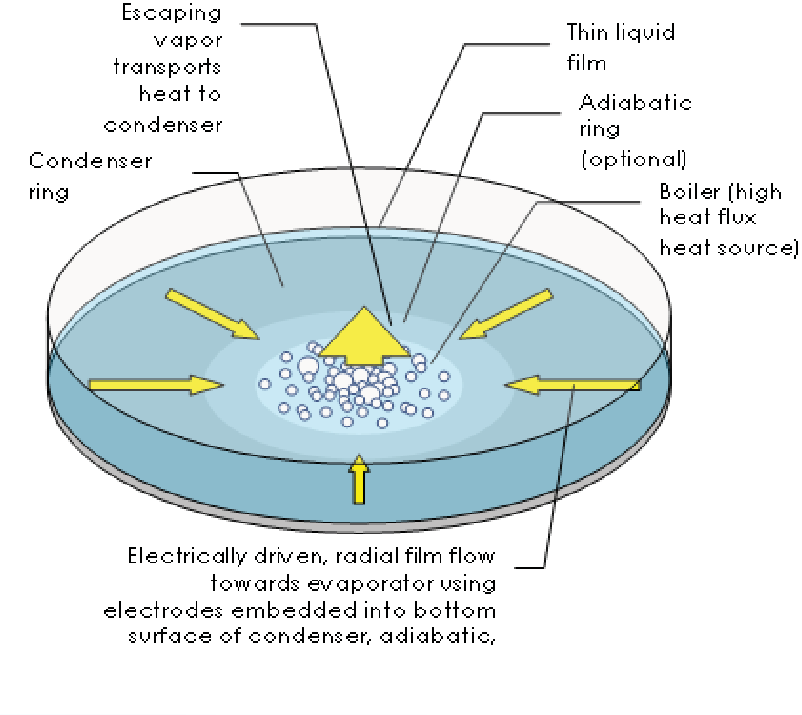
- Two PI Teams will share common test hardware to study different aspects.
- Will address the design and performance of passive two-phase flow separator technologies.
- Determine range of flow rates for acceptable performance.
- Quantify the effect of fluid properties and separator geometry.
- Determine separator response and stability envelope to startup, shutdown and liquid slugging conditions.
- Passive separation is critical to high reliability and low power gas-liquid systems for used in thermal control and life support.

Boiling and Condensation

Two-Phase Electro-hydrodynamics (EHD) Conduction-Driven Heat Transport Device – 2020

- Will develop fundamental understanding and physical models to characterize the effects of gravity on the interaction of electric and flow fields in the presence of phase change.
- Will characterize electrowetting effect on boiling and CHF in the absence of gravity.
- Electro-wetting of the boiling section will repel the bubbles away from the heated surface in microgravity environment.
- Micro-scale devices have extremely high heat fluxes due to the small heat transfer surface area.
- Provides a robust, non-mechanical, lightweight, low-noise and low-vibration device.
- Recently concluded successful 0-g aircraft testing demonstrating EHD pump works well in 0-g.

PI: Prof. Jamal Seyed-Yagoobi, Worcester Polytechnic Institute
Co-I: Jeffrey Didion, NASA GSFC



State of the Art in Two-Phase Flow

- The nature of low-gravity applications and limited access to the low-gravity environment creates unique difficulties in the creation of reliable predictive (CMFD) models.
- Integrating modeling and experiment provides a potentially productive approach, especially if DNS is included as a supplement to experiments.
- <u>Unique opportunity exists for limited experiments on ISS in this decade</u> to resolve microgravity two-phase flow challenges. These are critical to many areas of spaceflight (power, propulsion, life support, thermal control, etc.).
- There is also a strong need to simply build a quality database of operating parameters for the most common components particularly those that can either operate in a more efficient manner in 0-g or those that solve common anomalies faced in 0-g fluids systems that frequently bring an entire system off-line until it can be fixed or replaced.

Horizontal pipe on Earth.

Aboard the Space Shuttle.

The radically different flow morphologies require different theoretical models in order to be able to predict these flows.